Fire Safety of Historical Buildings: Principles and Methodological Approach

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Abstract. This paper addresses an issue rarely contemplated in the management of historical buildings, fire safety. There is an implication that “compliant” means “safe” and that the goals and objectives of compliance are perfectly aligned with those of fire safety. In the case of historical buildings, this is a mistake that has resulted in the loss of major historical buildings through the centuries. This paper presents a framework of analysis that uses adequate tools to evaluate and establish true performance assessment. The objective is to adequately define and implement the goal of fire safety. This paper is not a traditional research paper in that it does not describe experiments, computations or analysis. Instead, this paper proposes, through an example of application, a critical overview of problems incurred when evaluating fire safety on the basis of solutions issued from prescriptive approaches. In the process, this paper highlights the value of a comprehensive performance-based approach. A performance-based analysis emphasizes an approach to design that values the inherent features of historic buildings. This could potentially result in minimum and rational alterations that meet the goals of fire safety while also achieving other restoration objectives.

Keywords: fire safety, fire protection, regulatory compliance, fire dynamics, life safety.

1 Introduction

The implementation of fire safety in the built environment has been traditionally a very prescriptive process. The goal is one of protecting life against the hazard of fire. While fire safety is directly related to the laws of physics and the management of human behavior in a high-risk situation, these laws of physics are rarely invoked and instead its implementation is generally associated to code compliance. Codes, incorporate elements of human behavior and fire dynamics, nevertheless they are the result of multiple compromises, many of which are associated to a temporal perception of safety, the available tools and the construction typologies. What was perceived as safe in the past might not be perceived as safe today. Buildings are thus constantly being retrofitted so as to be updated to new code requirements. These code requirements, in turn, are deemed to provide an acceptable level of safety as it is perceived today. The implication is that compliance means safe and that any building that is not code compliant, to the current prescriptive requirements, is therefore unsafe and needs to be retrofitted. Obviously, there is a limit to this approach. Many times, buildings cannot be retrofitted and therefore codes provide provisions for grandfathering non-compliant structures as well as for the use of performance based tools. Grandfathered buildings will never be perceived as safe and therefore many concessions on the building use become necessary. Performance based design is rarely used as such, and when it comes to historic

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buildings, its use is mostly directed towards obtaining certain specific equivalencies that allow to ascertain that omissions to the codes are acceptable.

When it comes to historic buildings, the building incorporates a contextual value that is generally not accounted by codes. Certain features of the building (ex. architecture, ornaments, construction techniques) cannot be modified without diminishing the value of the building. Furthermore, many times the building will house inherently valuable objects that are part or not of the fabric of the building (ex. murals, paintings, art object, religious objects, etc.). Many of these objects and their use can represent a hazard themselves (ex. preservation fluids in a natural history museum, fabrics in a textile museum, candles in a church, etc.). These features of historic buildings make them a challenge because it becomes unacceptable to alter the building to include modern fire protection features (ex. smoke detectors, sprinklers, fire rated stairs, etc.) and it is many times impossible to manage hazards in a manner consistent with code assumptions (ex. no combustibles in egress paths, fuel characteristics corresponding to the assumptions embedded in the design of fire protection systems, etc.). Thus, the fire safe design of a historic building represents a challenge. The challenge is based on the need to achieve an adequate level of safety, in a building that has many alteration constraints and where common tools for fire protection become unacceptable.

The conventional approach of attaining compliance or to implement equivalent solutions by means of bridging performance-based design has proven inadequate resulting in many losses where the final explanation is that the building was non-compliant and therefore the failure should be expected.

Detailed reviews of many aspects of fire safety in the context of historical buildings have been written [1] and the unique features of historical buildings that affect fire safety have been recognized by many and have been discussed many times in great detail. Nevertheless, these reviews focus on framework type explanations of the different problems but do not offer a means to take advantage of the inherent features of the historical buildings.

Carattin and Brannigan [2] provide one of the most eloquent reviews of the complexities associated to the implementation of fire safety in historical buildings. Not only they address the multiple variables of the problem, the major constraints associated by the nature and value of the buildings but they also study in detail the many limitations of the analytic tools commonly used for establishing if a building is fire safe. Carattin and Brannigan establish in their review [2] the weakness of codes and standard design practices when addressing historic structures. Their concern is summarized when they state that: “because they are called “buildings,” designers and code writers and enforcers routinely assume that they are simply older versions of the modern buildings they work with. But they are not.” The review covers several examples and relevant issues nevertheless is centered around life safety and only briefly discusses other issues associated to the fire safety strategy.

The focus of most of the work on fire safety of historical buildings remains on life safety and the means to quantify in a comparative manner the importance of the building and its contents is not clearly discussed. A very good example of this approach is the review by Bernardini [1] where, after a detailed explanation of the
issues, the focus is placed back on effective means of wayfinding as a mechanism to aide egress without major modifications to the building fabric. Reviews that address recent advances in codes and legislation treat fire in a simple manner and remain focused in the adaptation of buildings to meet current standards while taking into account the desire to minimize intervention (“older versions of the modern buildings” [2]). None of these changes take advantage of the inherent safety of the historic buildings or propose novel approaches towards a quantitative analysis of safety [3].

Studies have addressed management as a means of improving life safety in historical buildings, but the principles evoked are a simple and direct extrapolation of approaches used for modern buildings [2] without a direct link to the inherent features specific to historic buildings [4].

The review by Marrion [5] attempts to describe performance criteria that could be used as a basis for design. In this review a lessons-learnt approach is presented, where a series of assumed causes for fires are presented but which are not based on thorough fire investigations. Thus, the link to adequate intervention is tenuous. Methods to deliver performance based designs have even been codified [6, 7], nevertheless as described by Watts and Solomon [8], much of what is presented in NFPA 914 [6] relies on judgments that are partly subjective and on agreement of the involved parties, including the authority having jurisdiction. The focus therefore still reverts back fully to life safety and is tainted by expert judgement. Carattin and Brannigan [2] warn against expert judgement as a means to address fire safety in historic buildings.

One of the clearer attempts to use a performance approach towards the analysis of a historic building addresses the refurbishment of the “Teatro Comunale Niccolò Piccinni” in Bari [9]. Here, a combination of fire protection measures and calculation tools are used to deliver what is deemed as an acceptable solution. This solution incorporates structural components, new compartmentalization requirements, active fire protection measures and major modifications of the architecture (stairs). Despite the detailed explanations provided on the measures taken, there is no quantitative assessment on how the objectives of the refurbishment were attained or on how the inherent features of the building supported the proposed solution. The exception is the structural analysis where performance criteria are defined but they are established either in regulatory terms (i.e. Fire Resistance [10]) or by means of arbitrary thresholds (i.e. 400°C fires). These criteria are valuable in that they serve to assess the robustness of the structure but do not take account the actual fires possible within the building. In some manner, the treatment of the historic building remains as that of an older version of a modern building [2].

Approaches that deviate from life safety have also been published. Many of these studies have produced frameworks that analyze in a systematic manner risk within historic buildings or the potential upgrade options that can be used to upgrade the fire safety of historic buildings. These studies use complex tools such as Analytic Hierarchy Process [11] where all options are tested against constraints such as cost or valuable historical attributes. Many of these studies rely on expert opinion but do not define what constitutes an expert (against the warnings of reference [2]) or how the risk assessment can be transformed into design approaches that take
advantage of the inherent features of the building [12]. In some cases, these risk assessment tools have even been incorporated into Geographic Information Systems (GIS) [13] without resolving the basic principles of fire safety and many times defining fire safety on the basis of incorrect principles such as ignition risk. In a similar manner, studies have suggested the use of BIM for the purposes of addressing fire safety, in particular the Historical Building Information Modelling (H-BIM) approach. While accurate digital representations of historic buildings will be with no doubt valuable to achieve an optimized approach to fire safety, none of these approaches has yet incorporated any of the fundamental issues of fire safety [14]. These studies fail in several manners, first they do not establish in a quantifiable manner the safety objectives, second, they do not take into account the beneficial attributes of the building and finally they do not address in a quantifiable manner the impact of proposed modifications. In the absence of these three fundamental features these approaches cannot be used.

What would be discussed here is an alternative approach that puts forwards the fact that life safety and fire dynamics are processes that evolve in space and time and that are governed by the laws of physics and by well characterized human behavior. A such, if the objectives are clearly established and the tools are mastered by competent professionals, a safe but non-compliant historic building can be obtained with minimum intrusion to the historic value and significance of the building and without limiting its use or contents.

2 Current Approach to the Fire Safety Strategy

2.1 Fire Risk Analysis

Currently, a prescriptive fire safety strategy is based on the following premises. A building is expected to have a fire in its life. Fires, if considered in the most general way, are much higher event probabilities for a building than any other hazard. Therefore, the probability of a fire is effectively one. This is very important because it changes the concept of risk. Normally, risk is defined by equation (1) [15]

\[
R_g = P_g \times C_g = P_f \times C_f \approx C_f
\]

where \(R_g\) is defined as the general risk, \(P_g\) is the probability of the event and \(C_g\) the consequences. The sub-index “f” corresponds to a fire where \(P_f \approx 1\) and therefore risk in the event of a fire is purely the management of consequences.

The assumption that a fire will occur equates to the acceptance that an ignition event will happen. This does not imply that this event will have significant consequences, but simply that it will happen. What is termed here as a fire event includes all possible scenarios and thus is an event that precedes the progression of the fire. For an ignition event to become a fire scenario, there have to be interactions between the fire, the building fabric, the fire safety measures and potentially the occupants. Form this initial fire event, scenarios will develop and there will be some that are more probable than others. Nevertheless, for the purpose of this paper, the evolution towards a scenario will be incorporated in the analysis of consequences.
This approach to event probabilities is not common when analyzing other hazards like earthquakes or floods. In these fields, the consequences need to be managed but they are generally subordinated to the evaluation of the event probability [1]. For other hazards, we design for events of a certain acceptable probability and therefore we can define loads against which we can evaluate the design (ex. one in one-hundred-year event). Therefore, performance assessment becomes a natural path. In the case of fire, the objective is simply to manage the consequences of an event that will happen. In the absence of a fire safety strategy many fires will result in unacceptable consequences, so the purpose of the fire safety strategy is to manage the consequences in a manner such that the probability of a fire resulting in unacceptable consequences is sufficiently low. The manner by which codes establish what is a probability that is low enough that it can become acceptable to society is integrally based on life safety [16-18]. In the case of historical buildings, given the value society assigns to the building and its contents, this approach is insufficient.

The focus on life safety has limited the capacity to develop fire safety strategies that carefully incorporate the characteristics and value of the building and its contents. This is a fundamental weakness when it comes to respectful restoration but also limits the rigor applied to the development of strategies that pertain the approaches used towards safe management of restoration sites.

2.2. Current Prescriptive Approach

Prescriptive approaches will manage fire events by first defining the characteristics of the event. First, the event will be considered a single accidental fire that will be placed and defined according to scenarios that are considered possible. For example, if a building includes a kitchen, a kitchen fire becomes part of the consideration. Multiple events are excluded by separating them as criminal events (i.e. arson). A designer is therefore not required to design for multiple events. Many historical monuments have been destroyed in acts of war by circumventing this assumption [19] which demonstrates that proactive introduction of multiple events fully dismantles the fire safety strategy [20].

Buildings are classified as a function of their occupancy. Occupancy not only defines the use of the building but also defines the type and quantity of combustibles that will be expected to be present. Statistics have been developed for traditional occupancies (ex. assemblies, residential, hotels, hospitals, etc.) determining typical fuels and typical quantities. Thus, by providing a classification the potential fires against which the countermeasures will be defined are fixed. Codes will define then the fire growth as a function of tabulated fires. The most common approach is presented in equation (2) [21]:

\[
\dot{Q} = \pi \Delta H_c \dot{m}'' \Gamma(t^2) = a t^2 [kW]
\]

where \(\dot{Q}\) is the heat release rate and is the primary quantity that characterizes the fire size, \(\Delta H_c\) (heat of combustion), \(\dot{m}''\) (burning rate) and \(\Gamma(t)\) (flame spread rates) are material properties that define the propensity of a combustible to release energy. \(t^2\) corresponds to the time from ignition and represents the rate of growth. All material properties are then integrated into a global parameter, \(a\), which is then classified. Most codes will
classify materials as sustaining a slow growing fire \((0.0029 \leq \alpha < 0.0117 \ [kW/s^2])\), medium growing fire \((0.0117 \leq \alpha < 0.0469 \ [kW/s^2])\), fast growing fire \((0.0469 \leq \alpha < 0.1876 \ [kW/s^2])\) and ultra-fast growing fire \((0.1876 \leq \alpha \ [kW/s^2])\)[21].

The classification of the fire event (as a pre-defined evolution of the heat release rate in time) allows to establish the event that is to be used as input when analyzing the impact of a fire on a building and its occupants. As explained before, the primary objective of a fire safety strategy is life safety. Thus, a primary objective of a fire safety strategy is to allow people to evacuate safely. Given the occupancy, the characteristics and quantity of people will be defined and thus typical egress times can be established. To guarantee appropriate notification of the occurrence of a fire, so that the onset of egress can be well controlled, building regulations will require appropriate detection and alarm systems. These systems are consistent with the occupancy, so while in residential buildings point detectors will alarm the residents and only the residents, in hospitals, smoke detectors will be connected to alarm systems and to building managers for a coordinated egress approach. Many variables will affect egress, these include behavioral variables as well as building characteristics [1,2]. These egress times are called the Required Safe Egress Time (RSET) [22]. The building will then be designed in a manner such that a fire that follows a certain growth classification will not attain untenable conditions anywhere in the building before all occupants have evacuated. Tenability is difficult to define but in general terms means conditions that challenge the safety and wellbeing of occupants or that are perceived as challenging by occupants. As such, carbon monoxide concentrations can be used as a tenability criteria because it can incapacitate occupants but also visibility because occupants will feel challenged by waking into a smoke laden space. Many guidelines will provide quantitative criteria on tenability mostly based on carbon monoxide concentrations, temperatures and visibility [21].

The Available Safe Egress Time (ASET) is the time required for any specific environment in a building to attain untenable conditions. In a building deemed to be safe ASET will always be much greater than RSET [22]. When the fire grows too fast and the occupants do not have sufficient time to evacuate then other provisions have to be put in place. If spaces are too large and therefore travelling distances are too long, then compartmentalization can be introduced either to protect egress paths or to stop smoke from entering adjoining spaces. The fire growth rate can also be controlled to increase the ASET. Sprinklers can be used to reduce the fire growth rate while requirements for fuel control can also be introduced. Both will effectively reduce or limit the value of “\(\alpha\)” (Equation (2)). Compartmentalization is generally referred to as passive fire protection while sprinklers as active fire protection. Engineering tools can be used to determine different combinations of active and passive measures that deliver an adequate level of safety.

Compartmentalization includes all components of the barriers including doors and service penetrations. To guarantee compartmentalization strict rules of testing are implemented to provide certification to all building components. Certification is attained by means of fire resistance testing [10] which is a furnace test that is intended to reproduce a worst-case scenario and provide a time to failure for all components (i.e. a time to attain a critical failure temperature).
To facilitate egress all paths (ex. corridors, stairs, doors, etc.) for evacuation have to be designed ergonomically so that people can flow freely. The direction of egress shall also be signaled appropriately.

Redundancies have to be introduced, so compartmentalization is supported by active control of pressure in areas that need to be free of smoke so that air flows from the safe place towards the fire and not the opposite (ex. Pressurized stairs). Means of egress can be duplicated in case one is blocked by smoke or fire. The fire service is the ultimate redundancy to the overall strategy. Details on the components and implementation of a fire safety strategy can be found in reference [22].

Redundancies and factors of safety are introduced not only to provide robustness to the design but also to compensate for variability and uncertainties. The development of a fire as well as the behavior of people carry significant uncertainties. Any analysis needs to consider these uncertainties. In the case of prescriptive design, the treatment of variability and uncertain is implicitly incorporated in the code provisions, while in the case of performance based design appropriate treatment of uncertainties is part of professional practice. Given that this paper focuses on establishing a methodological approach, there will be no further discussion on variability and uncertainties, nevertheless, their appropriate treatment is clearly part of the methodological approach.

Through the entire egress process the structure needs to maintain stability, so all load bearing structural components will be thermally protected so that their temperature does not reach critical values were significant reduction of structural strength occurs. The required thermal performance is defined once again as a fire resistance by means of large scale testing [10]. Under these circumstances, codes will establish that there is no need to check for stability of the structure under the effects of a fire [23]. A fire that can challenge stability and is capable of leading to progressive collapse is therefore considered as an extraordinary (i.e. low-probability) event. Buildings have included an explicit structural performance analysis for fire only in the last 20 years and even then, only unusual, highly important or unique buildings have justified this engineering effort [24].

2.3 Outcome of a Fire Safety Strategy

A key weakness of the fire safety prescriptive approach is the fact that the overall outcome is never assessed. Codes will deliver solutions that are fitting to the classification, nevertheless, these solutions are not solutions to the fire safety strategy but to the components of the strategy. As an example, the National Fire Protection Association (NFPA) in the USA [25] has two opening codes NFPA1 and NFPA101, NFPA1 states the life safety goals of the code and NFPA 101 the different classifications and the basic principles of the solutions proposed. Other documents within the code will describe in more detail some special classifications (ex. hospitals, industrial facilities, etc.) but in general most other documents within the code will prescribe detailed solutions to the different protection components. As such, documents like NFPA 13 will describe sprinkler systems, NFPA 72 Detection and Alarm systems, etc. Compliance with the code is therefore defined as incorporating the correct components and implementing them adequately. There are no explicit objectives of overall fire safety defined by the codes. Given this approach, it is extremely complex to establish an “equivalent level of safety.” For historic buildings this is paramount because code compliance then is only possible if all the protection
measures prescribe by the code for the occupancy are implemented and implemented according to the requirements of the code.

3. Historic Buildings

Historic buildings differentiate themselves from other buildings in that the building in itself has sufficient value that it not only needs to be preserved in as intact a manner as possible but also needs to be explicitly protected. In contrast to conventional code compliant buildings, where life safety is the primary and single goal of compliance, in historic building other objectives gain significant importance. Life safety will remain a primary goal but it is no longer the single primary goal of fire safety. Historic buildings are part of national patrimony, many times hold objects of unquantifiable value and in most cases buildings and contents are irreplaceable. This added constraint requires changes to the approach towards fire safety. This change has to improve the strategy to account for the protection of the building and objects of material and historic value [1-9].

3.1. Fire Growth and Fire Damage

Fire growth no longer can be assumed simply as a function of material properties and a growth rate that is allowed to increase as a function of time. In a conventional building fire growth will, when unattended, lead to flashover. Flashover corresponds to the moment when the smoke layer produced by the fire reaches a sufficient temperature and soot volume fraction that results in enough radiation so that all other combustible objects ignite. At this point the compartment gets filled with hot smoke. The fire in this case will result in major damage to that compartment and all its objects [26]. Figure 1(a) shows a typical photograph of the aftermath of a post flashover fire. As it can be seen, all objects within the compartment have been destroyed and it is very likely that significant structural damage would have occurred. If this would have been a historical building, it is very likely that this type of fire would have resulted in unacceptable damage, even if life safety was not compromised. In a conventional building this might not be a major issue but in a historic building this could potentially represent a major loss. Thus, for historic, buildings a fire generally cannot be allowed to grow. There are two means by which fire growth can be controlled, by means of compartmentalization and by means of active fire suppression. Compartmentalization is many times impossible in a historic building because the structure cannot be modified, thus the importance of fire suppression increases. There is generally reluctance to introduce fire suppression systems in historic buildings for two primary reasons. The first is that it represents an intrusion to the architecture, and this is many times unacceptable. Second, in case of an accidental sprinkler activation, water damage can be as devastating as a fire [2]. The second issue is truly not a significant one. While conventional suppression systems might experience these problems, tailor made systems should not. A dry pipe with higher level of reliability and multiple activation devices is always a possibility [25]. The first issue is more relevant and needs to be carefully considered. Concealed sprinklers are possible but still represent an intrusion to the architecture and many times it is impossible to introduce the piping without damaging valuable features of the building.
3.2. Controlling Fire Growth

As an example, Figure 1(b) presents an image of the University of Geneva building after a significant fire [28]. In some areas of the building the fire reached flashover damaging objects but also the fabric of the building. Sectors of the roof were severely damaged and require complete replacement. Instead, other areas, like those illustrated on Figure 1(b) only showed localized damage. Thus, the loss was not complete and many valuable elements of the architecture could be cleaned and reconditioned during the 2014 rehabilitation of the building [28]. This example serves to illustrate that given certain characteristics of a building, conditions might be such that flashover will not occur. While this example will be discussed in much more detail later, it is useful to show that these characteristics can be exploited to protect the building.

The main reason why flashover did not occur is because of the large volume of the public areas. Flashover requires for the smoke to reach a certain temperature (generally assumed to be around 600°C [6,7]) and contain a certain concentration of soot. The soot volume fraction defines the emissivity of the smoke and the temperature its radiative power [21]. Radiation from the smoke layer delivers heat to all combustible materials and once a critical value for ignition is attained, all combustible materials will ignite and flashover will occur [26]. The temperature and species concentrations of the smoke layer are defined by the smoke migrating upwards from the fire and into the smoke layer. The temperature of the smoke and species concentrations are correlated through energy and mass conservation equations [21]. Equation (3) shows an example of the energy conservation equation for the smoke

\[ T_S = T_\infty + \frac{\dot{Q}_c}{\dot{m}_A C_p} \]  

(3)

Where \( T_S \) is the temperature of the smoke, \( T_\infty \) the ambient temperature, \( \dot{Q}_c \) is the fraction of the energy released by the fire delivered to the smoke, \( \dot{m}_A \) is the mass of air entrained by the fire and \( C_p \) the specific heat capacity of the smoke. A similar conservation equation can be constructed for the soot volume fraction showing
that it will also depend on the heat released by the fire ($\dot{Q}_c$) and the mass of air entrained ($\dot{m}_A$). The mass of air entrained can be obtained by a simple correlation of the form [29]

$$\dot{m}_A = C \dot{Q}_c^{1/3} H^{5/3}$$

(4)

Where $C$ is called the entrainment constant and is an empirical value corresponding to a specific type of fire and $H$ is the smoke free height between the floor and the smoke layer. This height will initially be the floor to ceiling height of the room but later as the smoke accumulates it will decrease. Combining Equations (3) and (4) it can be established that the temperature (and similarly concentrations) will increase as the fire increases in size and will decrease as the floor to ceiling height increases. Conventionally, sprinklers will be used to reduce the fire size and thus prevent flashover but also the building design can be used to increase the floor to ceiling height and also prevent or delay flashover. While this analysis is simplistic in nature it shows that a feature of an existing building, such as the floor to ceiling height, can be used to compensate for the omission of a sprinkler system.

3.3. Compartmentalization and Life Safety

Compartmentalization is also a very important issue when it comes to historic buildings. General building code requirements worldwide will indicate the need to use protected means of egress (ex. [25]). This generally means that emergency stairs need to be provided and that these have to be introduced with a predefined separation that does not excede prescriptive maximum egress distances. Emergency egress paths have to be enclosed by fire resistant construction. The layout of most historic buildings was defined most times prior to the introduction of maximum egress distances in the codes (in most countries these requirements appear no earlier than 1920’s [19, 20]). Therefore, most historic buildings do not have provisions of enclosed stairs. Adding or enclosing stairs generally requires extraordinary interventions. When addressing a historic building, it is therefore necessary to establish if these enclosed stairs are necessary and what alternative means and provisions can be used to compensate for the absence of such enclosures. In a similar manner, corridors many times exceed maximum egress distances, thus codes will require barriers to break the corridor to guarantee safe egress. Again, these barriers represent major intrusions and therefore need to be addressed with some care. The management of smoke to allow for extended travel distances and unenclosed stairs in a historic build will be used as an example of the type of analysis required.

It is important to clarify, that smoke management is used here only as an example of an alternative form of intervention. There will be situations or potential occupants groups that will not benefit from this specific approach. A detailed performance analysis should take into account all those considerations.

3.3. Fire Resistant Doors

A critically important feature of compartmentalization are the doors. Performance assessment of fire doors requires testing of a door system that includes the door, the frame, the hinges and all other fixtures. The system
needs to protect the safe area from ingress of fire and smoke. In historic buildings, doors are many times, inherent fixtures of the architecture and therefore it is desirable not to intervene to attain a required level of fire resistance. Figure 2 shows a good example of such doors. The doors come from the same building at the University of Geneva and during the refurbishment it was highly desirable not to alter the doors and fixtures. Maintaining these doors requires a detailed analysis of their capacity to withstand the penetration of smoke and flames. In general, it is easy to demonstrate that massive timber doors are capable of sustaining the heat fluxes of a generalized fire for an adequate period. It is much more difficult to address their capacity to contain smoke. It is very common that minor modifications, that introduce adequate seals and manage the relative motion between frame and door, will be required and therefore detailed dialogue with other stakeholders (i.e. architects and heritage experts) will be necessary.

**Figure 2.** Historic doors and detail of fixtures used at the Bastions Building, University of Geneva

### 3.4. Fire Resistance and Structural Integrity

When following a prescriptive approach, structural integrity and compartmentalization is guaranteed by means of fire resistance testing. Structural elements and compartmentalization components need to be tested in a destructive manner to establish their fire resistance. This will generally be impossible for historic buildings. Structural solutions of historic buildings tend to be very different from current constructive methods. Therefore, these solutions have never been tested for compliance and therefore do not represent rated construction. Code compliant constructive solutions are generally included within official listings [30] that describe performance as obtained through testing. Figure 3 shows examples of structural systems with protection dating to the 19th century. A system of the nature of Figure 3(b) will most likely achieve the required fire resistance, nevertheless
it will not be certified (and therefore non-compliant) and will require cover if the building was to be rehabilitated. As structural system like Figure 3(a) is very similar to that of 3(b) but it has no fire protection. This system will also be deemed non-compliant. Both cases are different but will both be treated in a similar manner by codes. Detailed Finite Element Models (FEM) can establish the structural behavior of these systems. To establish if the structural behavior meets the needs, a temperature distribution for the structural system is needed [31]. The temperature distribution of the gas phase and associated heat transfer coefficients can be obtained using Computational Fluid Dynamics (CFD) models but in most cases (due to the simple geometries and very different time scales for the heating of solids and gases) much simpler models can also be used [26]. A simple zone model will be illustrated in the next section [21]. A subsequent heat transfer analysis will then deliver the temperature evolution of the structural elements. The FEM models can serve to provide a time equivalency for the structure that defines what could be the potential fire rating for a historical structure. As indicated above, this is a significant departure from prescriptive methods where performance assessment of the structure is not required.

![Figure 3. Historic structural slab (a) photograph of a historic vaulted ceiling (b) Section of a 19th century protected beam](image)

**Figure 3.** Historic structural slab (a) photograph of a historic vaulted ceiling (b) Section of a 19th century protected beam

An important aspect of structural assessment is the determination of the thermal solicitation potentially imposed by a fire. Structural analysis traditionally uses a concept of a load being applied to the structure. This load will follow a probabilistic distribution that will be defined within a code or a guideline. In the case of fire, this is not the case. The nature of the fire is affected by the building and the fuel available. As indicated by Equations (3) and (4) temperatures depend on geometrical features such as floor to ceiling heights. Furthermore, the nature of the constructive materials (ex. Wood) might make the construction part of the available fuel. All these aspects need to be carefully considered. Once the temperature evolution within the building is established and heat transfer to the structural systems is calculated, then the structure will evolve as the temperature increases. The evolution can result in the deterioration of mechanical properties (ex. As indicated in Eurocode 5 [31]) but also thermal expansion and thermal bowing can result in the generation or relaxation of mechanical loads. This opens the possibility to the introduction of structural interventions, of minor impact to the historic value of the building, that could nevertheless reduce the loads generated during a fire. While the potential for this type of intervention exists and could be immensely valuable to the preservation of a historic building, to the knowledge of
the author, this approach has never been implemented. Instead the conventional approach is to ignore all the potential benefits of the existing structural design and to either replace it by a rated alternative or to add encapsulation to a level where the thickness of the encapsulation is in itself sufficient to comply with the prescriptive requirements. In the domain of structural integrity, current prescriptive practices in the structural and fire safety engineering community have not evolved in a manner that enables the use of modern analytical tools to determine the true capacity of a historical structure to withstand a fire.

4. Example – Smoke Management for The Bastions Building University of Geneva

Overall, the basic principle of analysis of fire safety for historic buildings implies the migration from “compliance” to “performance” and the acceptance of a much more complex series of safety objectives. Life safety needs to be accompanied by property protection and the implicit safety associated to code compliance has to be substituted by a detailed assessment of performance using state of the art engineering tools. This section will provide a simple example to illustrate a methodological approach. This example is not intended to be exhaustive nor to solve the fire safety strategy in its integrity. Instead, it takes some aspects of the comprehensive analysis to highlight the value of a performance-based approach.

4.1. Brief Description of the Building

The Bastions Building at the University of Geneva was constructed between 1869-1871 undergoing two series of renovations a first renovation of the Aula Magna in the period 1940-1944 and a retrofit of the roof in the period 1961-1963. The renovation of the Aula Magna changed its layout and introduced a series of vitreaux considered to be unique glass work from Geneva. The building has a central building and two wings covering a total surface area of 25,000 m². Figure 4 shows an image of the building and Figure 5 images of some of the vitreaux. The building is not only a remarkable example of classic architecture of the late 19th century but also houses murals, stone work and woodwork of exceptional value. Rehabilitation of the building will require adaptation to modern codes that not only implied significant reconfiguration of space but also the potential elimination of the vitreaux to maintain compartmentalization of the means of egress. This example does not correspond to any existing analysis or official documentation associated to this renovation. It is an independent alternative approach that is only used for illustration.
4.2. Proposed Compliant Solution

Extracts from an existing code compliance analysis [32] are presented here to describe a series of modifications that will enable the building to comply with current building regulations. Figure 6 shows the existing building layout (ground floor). The main transit area is completely open and it includes the vitreaux with the second set of vitreaux forming part of the Aula Magna. The building in its current form has multiple deficiencies when it comes to addressing the egress of people. Addressing these deficiencies could potentially imply covering or eliminating the vitreaux to ensure fire resistance compliance. The corridors in all floors exceed maximum travel distances – 30 m.

A solution implemented in a very similar building of the same complex compartmentalizes the corridors by means of an electrically activated mirror door that is intended to vanish by reflecting the corridor (as seen in Figure 6(b)). This type of solution has a questionable impact on the internal architecture of the building but also deteriorates circulation during normal operation of the building. As an emergency solution is not ideal because it relies on a mechanical device to close the door and compartmentalize the corridor in the event of a fire. Normally, solutions that require many moving parts are not deemed as robust and generally require high levels of maintenance.
Figure 5. Vitreaux in the monumental stair and Aula Magna by Emilio Beretta (1958) and Alexandre Cingria (1940) [32]

The monumental stair (Figures 6(c) and 6(d) and Figure 7) cannot be fully enclosed therefore cannot serve as a means for emergency evacuation. As can be seen in Figure 6(d) there are attempts to partially enclose the stairs, but given the ceiling height and the architecture of the stair, these will all be very intrusive. Thus, alternative egress paths need to be constructed. Figure 6(a), 6(c) and 6(d) shows the proposed alternative and the location of two external stairs. In red are the modifications required. As it can be seen, the addition of external means of egress implies significant alteration to the façade which represents a potentially unacceptable intrusion on the architecture of the building. It is also important to note that internal stairs are generally a preferred solution for egress because smoke can be better managed and adequate egress conditions are easier to guarantee, particularly in areas where extreme weather conditions are possible [22]. Codes like NFPA [25] will normally suggest internal stairs.
4.3. Alternative Approach to Smoke Management

The alternative approach to introducing the mirror doors and the external escape stairs is to evaluate the potential fire growth (Equation (2)) use a zone model [21] to establish the time required for the smoke layer to descend to a point where it interacts with occupants. This is clearly a viable proposition because the floor to ceiling height is approximately 6 m and the corridors can be as wide as 7 m, which gives a very significant volume. The larger the volume the slower the descent of the smoke layer and the easier to manage egress. The objective would be to achieve egress without any physical intervention on the building. The zone model was built specifically for this application based on the equations of reference [21].
A series of fires were analyzed and an example of the results is presented in Figure 8. The egress time has been calculated using simple empirical data for displacement velocities [22] and pre-movement times corresponding to educational facilities [22]. For the example illustrated in Figure 8 the egress time (RSET) is between 180-240 sec. These values were calculated using extremely conservative estimates. The methodology used is based on a free flow approach for the corridors and a density based approach for doors. It is important to note that the calculations presented in Figure 8 are only used for illustration purposes and are not intended as definitive quantifications. While sensitivity analyses were conducted with the fire and the parameters associated to egress, the presentation of these details goes beyond the scope of this paper.

The red and black curve correspond to the height of the smoke layer and the temperature of the smoke layer. The value of “$\alpha = 0.00833$” which corresponds to a slow growing fire. The corridors are almost free of combustibles; therefore, a slow growing fire is an acceptable growth rate. As can be seen from Figure 8, the smoke layer will descend ($z(t)$) to approximately to 3 m from the floor when everyone has already evacuated (most conservative). This means that people and smoke will not interact.

Furthermore, the temperature of the smoke layer would have not reached 100°C by the time everyone has left the building. This is a smoke layer temperature that will still maintain safe conditions for occupants. This analysis demonstrates that the building design (i.e. geometry), while not compliant with building regulations, still provides a safe environment for occupants. It is important to note that this example is only presented to illustrate an alternative approach. In an analysis of this nature it is essential to demonstrate adequacy for numerous scenarios under different conditions. Furthermore, it is essential to take into account numerous variables including occupants with limited mobility, redundancies etc. Nevertheless, this example demonstrates that by taking advantage of the geometric characteristics of the building, it is possible to demonstrate that the building is safe while not being compliant.
In a similar manner, a fire dynamics analysis was conducted to demonstrate that flashover will not occur in any of the compartments. The ceiling height is sufficiently large that common furniture and contents of this building cannot generate sufficient heat to enable flashover to occur. This is of extreme importance because it shows that temperatures within the compartment will not reach values that will threaten the structure nor ignite timber. A compliant solution would require a fire resistance rating for all structural elements in red (Figure 6(a), 6(c) and 6(d)), this will have most likely implied encapsulation or replacement that might have include particularly valuable elements such as the vitreaux. The premise behind the fire resistance rating is the exposure of a structure to a post-flashover fire for a duration capable of consuming the integrity of the fuel content (i.e. time to burn-out) [10]. Given that the fire will not reach flashover, temperatures of the smoke layer can be estimated using a zone model and in this case indicate that they will never exceed 300°C. This is consistent with values presented in the literature [29]. A detailed heat transfer and structural analysis could have been performed to demonstrate that the building structure offers adequate strength, nevertheless the estimated temperatures rendered this analysis unnecessary. Instead, only a heat transfer analysis was performed to establish any areas where a temperature increase, even mild, could create potential structural problems. This analysis identified no areas of concern. The focus then became compartmentalizing the smoke, which implies a detailed inspection of any possible smoke migration paths. Filling these paths to avoid smoke migration is most definitely a much less intrusive intervention.

For the doors, an extremely conservative assessment was made to establish that the doors were thick enough even if extreme charring rates were used to calculate fire damage. Despite the fire not reaching flashover, a localized fire can require the doors to withstand an intense fire for periods much longer than the egress times. So no modifications to the structure are required nor the replacement of the doors. Given that occupants can exit
without any interaction with the smoke means that no intervention is necessary. The vitreaux can remain, the mirror doors are not necessary and the two proposed new means of escape can be omitted.

Identifying which compartments can attain flashover and establishing typical compartment temperatures allows to identify which sectors of the building are susceptible to significant damage. This is important because it allows to identify which areas of the building will put at risk valuable objects, thus will inform where valuable objects might have to be actively protected or displaced.

5. Conclusions

The solution to fire safety for historic buildings requires a performance assessment to explicitly demonstrate that the necessary fire safety objectives have been met. In the case of historic buildings, the fire safety objectives include life safety but also need to include adequate protection of the patrimony. Currently, the Fire Safety Engineering profession has adequate tools to conduct these analyses, allowing for unprecedented freedom in the manner in which adequate levels of safety are delivered. To be able to implement these tools it is necessary to understand that safety is not only attained by compliance and furthermore that compliance does not mean safety. Many historic buildings have features that make them inherently safe despite not being compliant with current codes. This paper has used an existing renovation as an example to illustrate this. This paper does not intend to question or analyze the approach used for the Bastions Building at the University of Geneva, but to use alternative analyses to demonstrate the options available towards a renovation that will be most respectful of the historical building.

6. Acknowledgments

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7. References


Scaling-Up Fire

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Abstract
The role of combustion research in fire safety is revisited through the process of Scaling-Up fire. Scaling-Up fire requires the adequate definition of all the building blocks and couplings associated with the construction of a fire model. The model then has to deliver predictions of the evolution of a fire and its environment with the precision, completeness and robustness relevant to fire safety. Areas of combustion research relevant to the development of fire models emerge from an assessment of methodology, complexity, incompatibility and uncertainty associated to the Scaling-Up process.

Relevance
The evolution of a fire in any realistic context (building, vehicle, forest, underground, etc.) is an extremely complex process where it could be suggested that predictions of accuracy, completeness and robustness relevant to fire safety are impossible. Relevant accuracy, completeness and robustness is defined as the ability to quantitatively predict all the variables necessary for design or performance assessment to a level of precision and robustness that justifies using these predictions. The value associated to knowledge gain is established by how this gain can be linked to a quantifiable improvement in the accuracy, completeness or robustness of the prediction.

The gain associated with an enhancement in knowledge can be easily established when the full process is completely described and the areas where the sub-processes that are coarsely represented have been clearly identified. This procedure starts with the more fundamental processes, linking them to generate more complex systems that in turn are further linked until the full process is described and an output can be obtained [1]. Refinement can then be punctually applied and clearly linked to an improved output. This building strategy will be defined here as Scaling-Up.

In extremely complex problems, the link between the sub-processes and the output is not always clear. The sub-processes and couplings between sub-processes tend to be coarsely modelled making it difficult to identify the consequences of a change. In this case, deterministic Scaling-Up is very difficult but probabilistic assessment can be an effective way to achieve the same objective. In probabilistic assessment, a refinement is introduced and the outcome is then monitored. If this is repeated a sufficient number of times, and if there is a consistent outcome, then the refinement can be deemed to result in a quantifiable gain without necessarily understanding the path followed. This approach is mostly statistical and therefore requires large populations to gain sufficient confidence. To obtain a large population, the process under study needs to remain stable until the link between a component and the outcome is established.

The most difficult category corresponds to complex systems where processes and their links are still coarsely described and where each system to be modelled has a very small population. These are systems that evolve fast or are unique therefore the population

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available for study at any specific moment is always small. A general overview of the issues associated to the statistical treatment of these complex systems is provided by Neyman [2].

It has been suggested that fire problems belong to the last category [3, 4]. Our understanding of the processes involved in fire is very coarse, nevertheless, the outcome is extremely sensitive to multiple variables resulting in many cases in drastic bifurcations (ignition, extinction, flashover, backdraught, etc.) therefore most fundamental processes need to be refined and coupled in precise and complex manners. Unfortunately, many of the links and couplings between these processes are unknown, thus it is currently not possible to relate improvements in the understanding of the fundamental processes to benefits for the outcome. Thus, it can be claimed that deterministic Scaling-Up of fires is currently not possible.

When addressing the problem via probabilistic tools, the evolution of our habitat (e.g. novel construction materials such as phase change insulation, discontinuation of fire retardants, new construction systems such as curtain walls, etc.) is much faster than the evolution of the fundamental science associated to fire [5, 6]. This is in contrast to other disciplines such as medical research where the evolution of the subject, the human, is in the order of thousands of years. Thus, the problem in question will drastically evolve before science has been able to mature. Within the evolving habitat there is an infinite variation of specific scenarios making each overall process to be modelled unique. So, from the perspective of predictive capabilities, it can be claimed that each fire scenario has a population of one and the conclusions of one event cannot be used for a general assessment of benefit. Thus, statistical analysis as a Scaling-up method for fire predictions will inevitably result in a low confidence output.

It is therefore clear that the relevance of research leading to the refinement of a specific component is linked to our capability to Scale-Up. Nevertheless, Scaling-up Fire appears as the insurmountable challenge of fire safety. Combustion is one of the fundamental processes within the description of a fire and a component that could be refined by means of research. But given the difficulties associated to Scaling-Up Fire, the relevance of combustion research for fire safety seems questionable. This paper will discuss the relevance of combustion research in fire safety through a better understanding of the process of Scaling-Up Fire.

**Scaling-Up Fire**

Fire safety involves a broad range of disciplines tied by a combustion process, “the fire” [7-14]. The combustion reaction will result in species and energy being released in an uncontrolled manner. The release of energy and species will negatively affect structures, people and the environment but will also activate countermeasures and result in human response (evacuation, intervention) intended to minimize the negative impact of the combustion process. A feedback loop exists by which the structure, people and countermeasures will also impact the combustion process. Therefore, fire safety can only be quantitatively assessed if the combustion process can be modelled within the context of its environment. The modelling of the combustion process within the context of its environment will be referred to here as “fire modelling.”

Currently we have many models that attempt the Scaling-Up of fire [12, 15]. These models can be deterministic, probabilistic and in some cases system models [16]. These models provide outputs with a specific level of precision, completeness and robustness and in all cases they include a representation of the combustion processes involved.

The simplest form of fire models are prescriptive regulations. For certain environments that share common characteristics a specific design form has been studied and
its performance established and deemed acceptable. Different tools are then used to establish to what extent the context can be changed without exceeding the acceptable outcomes. Among these tools many incorporate combustion principles (classification of flammable liquids in relationship to ignition, hazard classification in relation to fire spread, sprinkler classification in relation to burning rates and heat of combustion, etc.). Once the potential context variation is defined then a classification emerges that provides the context bounds to which the solution can be applied. Therefore, the core of prescriptive design is the classification. If a designer follows a set of prescriptive rules that create the context where a solution is known to yield and adequate outcome then, another set of rules that implements the predefined solution guarantees performance. **Scaling-Up** is simply the extrapolation process that enables the use of the same solution in a context that lies within the bounds of the classification.

Fire models can also be explicit representations of the event and their outputs can be physical parameters such as velocities, temperatures, concentrations, stresses, strains, displacements, heat release rates etc. **Scaling-Up** becomes the explicit integration of all the fundamental processes involved. There is a very large body of literature focusing in the development of explicit fire models, their predictive capabilities and different validation strategies for many relevant fire scenarios [7-14, 17]. This paper does not intend to be a review of this literature instead a systemic view of the issues associated to fire models is presented.

A final set of models are the system models [16]. In system models the fire is also represented in an explicit manner but is only a small component of a scenario analysis. The focus is on the interrelation of the different components with the components described in very simple terms. Nevertheless, system models still rely on an explicit representation of each of the components. **Scaling-Up** remains the explicit integration of all the fundamental processes involved.

Independent of the model, the model output is used for the purpose of designing or assessing the performance of a fire safety strategy. Therefore, it is necessary to establish if the outputs are precise enough, complete enough and robust enough. If they are not precise, complete or robust enough then a compensation strategy needs to be implemented. The most common compensation strategy is the safety factor. The safety factor implies that during implementation, the calculated outputs will be exceeded to compensate for lack in precision, completeness or robustness. The poorer the quality of the output the larger the necessary safety factor, the safety factor can therefore be seen as wasteful use of resources thus a motivation for research.

In prescriptive design, the safety factor is implicit and cannot be quantified. It is embedded in the constraints associated to the definition of the classification and in the implementation of the solution. The implemented solution is deemed to carry a significant safety factor because it has to be robust to the variations permitted within the bounds of the classification. While prescriptive solutions will not be discussed any further, it is clear that research supports the improvement of prescriptive rules. Rules are (in principle) derived from knowledge, thus more knowledge has the potential for better rules, therefore the discussion below will also apply to the potential gain associated to the improvement of prescriptive rules. The nature of prescriptive rules and classifications inevitably imply constraints and large safety factors. Thus the explicit assessment of performance is seen as an effective alternative that enables the reduction of safety factors. Explicit performance assessment enables to break with the constraints imposed by the classification and can refine the safety factor to the specific scenario studied. In a world where sustainability is paramount, waste is
unacceptable and explicit fire modelling represents the only viable option. The remaining sections of this paper will focus on explicit Scaling-Up Fire.

The Complexity of Explicit Fire Modelling

Explicit fire modelling is by nature of great complexity because of the unavoidable relationship between the combustion phenomenon and its environment [12, 14, 18, 19]. The relationship between the combustion reaction and its environment introduces two major complexities. First, the environment imposes length and time scales that bound the problem while the underlying physical and chemical processes (that have their own natural length and time scales) still need to be resolved. For example, forest fires are defined by weather and terrain phenomena of kilometre length scales and underground smouldering fires by diffusion rates characterized by century long time scales nevertheless, in both cases the resolution of the fluid mechanics, heat transfer and chemistry associated to the combustion reaction still requires nanometre length scale and microsecond time scale precision [20, 21]. Extensive range and incompatibility of scales is an unavoidable complexity of explicit fire modelling. Second, within a fire, the mass and heat transfer environments result from a self-defined and uncontrolled combustion process that can be deeply affected by the context in which it occurs. The fire will provide the necessary energy to sustain its growth via the degradation of further combustible materials but also the energy to induce buoyancy driven flows that in most cases dominate the nature of fuel and oxygen supply to the combustion reaction [11, 13, 22-24]. Buoyancy defines the location and geometry of the flames, the aerodynamic characteristics of the flow and the kinetic structure of the reactions. The flames will then affect the environment in which the fire develops, which in turn can affect the nature of the combustion process (i.e. heat feedback). Context variables such as the nature and quantity of the combustible materials, the failure modes of structural elements, human behaviour and the activation of the different countermeasures introduce local and/or global changes that will have an obvious and potentially dramatic impact on the fire.

When Scaling-Up fire, processes such as chemistry, heat and mass transfer, fluid and solid mechanics are brought together within the context of a model to predict in a quantitative way the evolution of a fire and its impact (interaction) on (with) its environment. Even in this context, Scaling-Up does not have to be purely deterministic. Deterministic modelling can always be modulated by different forms of statistical treatment that enable addressing issues of uncertainty [25]. Other elements such as human behaviour and the physiological and psychological reaction of people to the fire are also of great importance and can be incorporated but will not be addressed here. The focus here will be in the non-human related aspects of the problem.

Despite the complexity of the problem, explicit fire models with different levels of detail have been constructed. The simplest models tend to neglect (and thus avoid describing) many processes of lesser importance [12], thus tend to be robust and require simple inputs but have narrow ranges of application and carry significant error bars. Furthermore, they tend to focus on individual processes and scales ignoring (or simplifying) the couplings between processes and the interactions between different scales. Entrainment correlations, relative flammability tests, statistical flame spread models all belong to this category [11, 12]. The application of simple closed form models tends to be restricted and when used for design purposes, merit large factors of safety.

For more than five decades analytical formulations and empirically based correlations have been used to Scale-Up fire. In the last thirty years computer models have entered fire
safety, first as simple energy and mass conservation models (zone models), and later through different forms of computational fluid dynamics (CFD) [4, 18, 19]. The scientific literature is currently populated by studies that attempt to improve, verify or validate these models and the practise has made them of mainstream use. Notable to all these models is the Fire Dynamics Simulator (FDS) which currently is used, for the most diverse applications, by thousands of scientists and practitioners [26]. Other models that range from the general to the specific are also in use, both as alternative to FDS or for specific applications where their performance is deemed more relevant [15, 27-38].

More complex models incorporate a more complete description of the processes and the interactions involved. They tend to allow a broader utilization and a reduction of factors of safety. In contrast, complex models require more, and many times more complex, inputs and can only be as robust as the least robust process/interaction formulation. In fire, it is often the case that the complexity of the models to be used is not defined by the capability to mathematically formulate the process but by the impossibility to obtain the inputs required. The descriptions of combustible material degradation [39-45], soot formation [46] and radiative heat transfer [47-50] are among the most common processes where the complexity of the models used is limited by the availability of inputs.

Given the importance of the context in the modelling of fire, it is common to reach the conclusion that complex models are not justified because unavoidable scenario uncertainties lead to output variations much larger than those associated to errors induced by the simplifications introduced in simple models. Furthermore, countermeasures can be over-designed in a manner such that their effect on the combustion process is so overwhelming that detailed modelling of the interaction between the fire and the countermeasure can only be justified when seeking a reduction in the factor of safety [51].

When designing or assessing the performance of a fire safety strategy in an explicit manner, fire models are incorporated in tools intended to enable the quantification of safety. Combustion research, in the context of fire safety, is thus only justified if it can be demonstrated that enhancements in the understanding of relevant combustion process can lead to subsequent improvements in fire modelling and ultimately if the tools, in which fire models are embedded, can deliver a more effective fire safety strategy.

The Fire Safety Strategy

Despite the numerous fire modelling alternatives and the fact that there is always room for improvement, it is important to address if existing fire modelling tools can be improved to deliver a gain that justifies the investment. The gain has to be linked to a more effective fire safety strategy and has to remain even in the presence of the unavoidable scenario uncertainties. If safer environments can be demonstrated or current safety factors can be significantly reduced by gaining precision, completeness and robustness then improvement is justified.

A fire safety strategy consists of numerous components that deliver a fire safe environment. These components are structured around life safety, property protection and business continuity. People in contact with the fire event need to be protected or delivered to areas of safety (life safety), the impact of the fire on its environment needs to be minimized (property and environmental protection) and the fastest return to its original condition needs to be guaranteed (minimization of business interruption). For this purpose a fire safety strategy is put in place. This applies to public and industrial buildings as well as wild land or wild land urban interfaces (WUI). In the absence of a fire safety strategy, life loss will most likely occur and potentially unacceptable property losses and business interruption will result.
In explicit terms, the fire strategy intends to affect the evolution of the fire, reduce the interaction of people with the heat and combustion products and define the environment in a manner that the impact of the fire is reduced to a level where the integral cost of failure is much smaller than the investment on protection.

Fire growth can be controlled in a passive manner by compartmentalizing the space introducing physical barriers that can contain the fire and smoke. These barriers can be fire doors and windows, fire resistant walls and floors as well as non-flammable claddings. The fire can also be affected in an active manner by means of suppression systems (water, gas, powder, etc.) that introduce heat sinks and chemical inhibitors that will negatively impact the combustion processes. The fire service can be considered a mode of active fire suppression.

The interaction of people with the heat and products of combustion is also minimized by means of compartmentalization and fire suppression. The barriers will not only prevent the fire from migrating outside the compartment of origin but will also reduce the dispersion of smoke. Fire suppression will limit the size of the fire, thus the release of heat and combustion products. A complement to these elements of the fire strategy is detection and alarm. Heat, products of combustion, electromagnetic waves or visible images can be used to identify the presence of a fire and provide an alarm so that people can initiate displacement away from the fire. This applies to buildings as well as external environments where evacuation procedures associated to forest fires or large external fires can displace entire communities away from the event [52].

An effective way of managing the interactions between people, heat and products of combustion is by inducing flows that will prevent smoke from reaching certain areas (pressurization of stairwells, downward flow for clean rooms, smoke fans for tunnels, etc.) or by extracting the smoke away from occupied areas or areas to be protected.

Infrastructure can be designed in such a manner that its response to the fire is optimized. Structural systems can be designed and protected to minimize unwanted behaviour (large deformations, progressive collapse, connection failure, breach of compartmentalization, etc.) and building materials can be selected to prevent or reduce fire spread (wall linings, external cladding, roofing materials, etc.). In some cases, such as industrial facilities, structural systems can even be designed to fail prematurely to guarantee the evacuation of smoke and heat. The evacuation of the smoke minimizes the areas affected by the fire and facilitates fire fighting.

In summary, the Fire Safety Strategy is a compendium of measures that are designed to achieve a socially acceptable outcome in the event of any possible fire. The evolution of the fire, the behaviour of structural systems, the response of countermeasures and the migration of people will all evolve in time, thus the evaluation of a fire safety strategy needs to be done within the context of a timeline. Predictions therefore need to be made as a function of time and performance can be established as a relative function of time (Required Safe Egress Time (RSET) vs. Available Safe Egress Time (ASET), RSET vs. Structural Fire Resistance (SFR), detector activation times vs. time to flashover, etc.) [53]. Given that all the components of the strategy are either activated or affected by the fire, to be able to quantify the outcome in an explicit way, the first step is to be able to understand the time evolution of the fire within the context of its environment, thus the “Fire Dynamics” [11, 54].

A Short History of Fire Dynamics

When defining a fire strategy it is essential to be able to characterize the time evolution of the fire and the associated outputs that are to be used to assess performance. For example, to define detection it is necessary to establish the velocity profiles in the vicinity of
the detectors as well as the different species concentrations that are required to activate the detector [55, 56]. When addressing sprinkler performance, velocity and temperature distributions in the immediate region of the sprinkler head are required to calculate the activation time [12], the capability of a water spray to extinguish or control the fire is defined by the trajectory and evaporation rates of the droplets [57-59], the interaction between the droplets and combustible and non-combustible surfaces is necessary to quantify the heat exchange that enables flame spread and the interaction between the water droplets, pyrolyzing surfaces and flames is required to assess the fate of the combustion process. To establish the evolution of structural components detailed heat transfer calculations between the gas and solid phase are necessary. All the parameters associated with convective and radiative heat transfer are required to establish the thermal boundary condition used by structural engineers as input to conduction heat transfer and solid mechanics models [14, 60, 61]. It is clear that none of these outputs can be obtained if the fire cannot be modelled with enough precision and robustness and in a manner that delivers the complete set of data required.

As seen through the examples, for each aspect of the fire strategy there are a multiplicity of aspects that need to be evaluated to establish if the modelling outputs have the required precision, completeness and robustness. In general, transport processes, combustion chemistry and the technology used as a countermeasure are all intimately coupled thus it is impossible to look at each aspect in isolation. Nevertheless, for the purpose of illustration, it is useful to concentrate on some specific aspects of the problem. This paper will only focus on the modelling of the fire.

The Standard Fire

The history of explicit fire modelling is not very old with the first attempts done at the beginning of the 20th century but only formalized in the 1960’s and 70’s [62]. Probably the first descriptions of the fire are associated to fire resistance and attempts to guarantee adequate structural behaviour. In the absence of most of the fundamental knowledge of combustion, heat and mass transfer, the fire was modelled by attempting to reproduce reality within a furnace [63]. A combustion reaction was sustained within a realistic scale compartment in which the structural element was introduced. Heat transfer was bypassed by measuring directly the temperature of the structural element and the fire was generalized by attempting a “worst case” condition. The worst case condition was generated by reproducing the fastest possible temperature rise to the highest possible temperature. This “worst case” fire was formalized as the “standard fire” and the “standard fire” gave birth to the “structural temperature vs. time” concept. The “standard fire” could then be reproduced in a furnace according to a pre-defined “temperature vs. time” and structural systems tested within that furnace. No real fire could produce a faster temperature rise nor attain the temperatures obtained in the furnace. The exposure time was defined on the basis of attaining burn-out of the estimated fuel load, thus no real fire could last longer. The time required for burn-out was labelled the required structural fire resistance rating. While this “worst case” scenario allowed for confident extrapolation, it is clear that an important safety factor was embedded in this primitive form of fire modelling.

Understanding of structural behaviour at high temperatures was limited to the characterization of the material properties as a function of temperature. Typical safety factors for structural design established how far the loss of mechanical properties could be tolerated. This loss of mechanical properties was then correlated with a temperature resulting in a failure temperature criterion. The time necessary for the structural element to attain this critical temperature in the furnace was then established as the failure time. If the failure time
was greater than the required fire resistance rating then the structural element could be used without any thermal protection, if not, thermal protection should be added in quantities that enabled the time to attain the failure temperature to exceed the required fire resistance rating [9, 12].

An important concept associated to the extrapolation between thermal behaviour in the furnace and real fire behaviour was the compartment size. While there was no clear understanding of the role of compartmentalization, it was inferred that extrapolation could only be robust if the conditions of burning were similar. Furthermore, accepting that single element behaviour, based only on material properties, could be extrapolated to real scale structural behaviour could only be tolerated heating was localized. If a zone of comparable size to the furnace was the only heated area, then the surrounding structure will remain cold and maintain its strength. Any stresses generated in the heated area could then be transferred (redistributed) to the rest of the building and will be of lesser magnitude than those tolerable by the cold structure. In modern terms this represents a requirement of mechanical restraint that is guaranteed by effective compartmentalization. As a consequence, very restrictive compartmentalization requirements were imposed by building codes of the time.

A similar analysis can be done with life safety, where compartmentalization was used to restrict the progress of the fire and combustion products to guarantee the safe egress of occupants. Sprinklers were introduced at the end of the 19th century using a modelling approach very similar to the standard fire. Sprinkler performance was tested using a “worst case” fire within a compartment consistent with the application. Complex industrial conditions where compartmentalization was not possible were addressed by reproducing the environment in a laboratory and testing the sprinklers at the real scale. When the water supply was sufficient to control the fire and maintain it at a manageable size the sprinklers were deemed to perform adequately [64]. For sprinkler and structural performance fire modelling was mostly a trial and error process.

Combustion science progressed through the 20th century nevertheless these issues will not be revisited until the 1960’s. Advancement in the understanding of fluid mechanics, heat transfer and combustion did not permeate into fire modelling because the complex problem of fire could not be effectively linked to fundamental knowledge in any of these areas. Scaling-Up fire from fundamental principles was not possible, the gain was not evident and the existing design methods seemed to provide satisfactory results. At the time excessive safety factors were not a matter of consideration.

**Compartment Fire Dynamics**

The 1960’s brought two fundamental changes to the construction industry, (1) the relaxation of compartmentalization and (2) the introduction of plastic materials. In the past, “worst case” fires were defined on the basis of burning wood and were limited to a compartment of a size and characteristics regulated by building codes. As buildings became more complex and features such as ventilation ducts and false ceilings were introduced, it became unclear how to maintain compartmentalization. Given that the link between compartmentalization and fire safety performance had not been established on the basis of fundamental principles, it was difficult to establish the implications of the changes associated to new forms of construction. The loss of some level of compartmentalization occurred unnoticed. The consequences of losing compartmentalization were made evident in several tragic fires [64]. In a similar manner, the migration towards plastics introduced novel failure modes induced by physical phenomena such as melting or dripping. These failure modes resulted in burning conditions that were different to those defined by the burning of cellulosic materials (e.g. wood). The need to better Scale-Up fire by incorporating these new features
became the driver to a significant research effort that for the first time brought combustion knowledge into fire safety [64].

In an attempt to describe the complexity of the fire in combustion terms, the problem was broken down into numerous components. The interaction between the compartment and the combustion reaction was named compartment/enclosure fire dynamics [65]. The link between the fire and stoichiometry was established by quantifying buoyant flows that serve to supply oxygen to the pyrolyzing fuel (entrainment). The compartment itself was also linked to stoichiometry by quantifying heat transfer from the fire to the walls and from the walls to the fire (feedback). As the fire heats the walls, radiative feedback to the fuel increases leading to an increasing supply of gaseous fuel to the compartment. The global stoichiometry of the compartment then drifts from the lean to the rich and the transition results in the migration of the flames from the interior of the compartments towards the openings. Terminology such as flashover, oxygen limited and fuel limited fires were introduced to describe these phenomena [66-72].

Smoke Management

Through the study of compartment fires it was observed that in the fuel limited regime (early stages of the fire) the energy produced by the fire is controlled by the amount of fuel produced. Buoyant entrainment can deliver enough oxygen to the flames to maintain the global stoichiometry lean. The energy released and the mass of combustion products is controlled by the fuel supply [66] but the amount of smoke produced by buoyant entrainment of air [12, 13, 73-75]. In the fuel limited regime the objective is to establish how long would it take for the compartment to fill with smoke and how much smoke will be spilled into areas surrounding the burning compartment. Simple two zone models [65] were developed for this purpose computing variables such as smoke temperature and time to flashover. After flashover the compartment, and not the fire, becomes the source for buoyant entrainment and heat feedback from the hot gases to the fuel determines the burning rate. Similar expressions for temperatures, air and smoke flows were developed [66-73]. The qualitative nature of the fuel rich post-flashover combustion could not be resolved by these models, thus empirical yields were used to Scale-Up species production. With this information, the absence of compartmentalization could be quantitatively addressed. Buoyant entrainment, energy release rate and species yields became the sub-processes introduced into models and used to Scale-Up the fire and deliver temperatures and the quantity and composition of the smoke. With these tools smoke management was introduced as a strategy to increase the available egress time (ASET) in non-compartmentalized environments. Smoke management enabled the construction of modern shopping centres, hotel atria and numerous other architectural features that are now common. Furthermore, it allowed improving building codes to enforce compartmentalization when smoke could not be managed. The acquired knowledge resulted in a clear gain that could be directly linked to the understanding brought by the application of combustion principles [76].

Material Flammability

An even more important gain was established when quantifying the energy released by the pyrolyzing fuel. In the lean regime, energy release is associated to the consumption of the fuel. Thus the nature of the fuel is of preeminent importance. The introduction of plastic materials required a better understanding of the differences associated to different materials used in the built environment. Flammability tests had existed for many years nevertheless they were only simplified and reduced representations of reality [12]. Combustion principles allowed to separate the different processes involved in the production of fuel and the release of energy. The formalization of the transport mechanisms by which the flame transfers heat
to non-burning fuel lead to the first definitions of flame spread. Numerous studies established the nature of flame spread and linked it to concepts such as gas phase ignition and extinction [77]. It was identified that flame spread was strongly dependent on the magnitude and nature of the buoyantly induced air flows, therefore, the understanding of the role of complex buoyancy induced flows and turbulence in heat transfer, completeness of combustion, soot production and extinction set hard limits to the Scale-Up process. The size of the fire could only be established if the effect of buoyancy could be incorporated into fire models [78]. At this stage, two fundamental approaches were followed, the first was to introduce buoyancy induced flows by means of empirical correlations and the second was the development of computational fluid dynamics models.

It is at this stage that flammability tests acquire a different meaning. Before combustion principles were introduced, flammability tests were simplified representations of reality that allow to rank materials of very similar nature (mostly cellulosic) on the basis of variables that were explicitly related to the application scenarios. Once combustion principles were incorporated, flammability tests could be used to extract “global material properties” that could be incorporated in fire models to define the size of a fire and the energy being released. For example, the Lateral Ignition and Flame Spread Test provided a thermal inertia ($k \rho C_p$), and ignition temperature ($T_{ig}$) and a flame spread parameter ($\phi$) describing heat transfer from the flame to the fuel that could be directly incorporated into a mathematical formulation that allowed the calculation of flames spread velocities [79, 80]. While this formulation can be seen as oversimplified, it appeared consistent with more fundamental studies on flame spread that serve to support the simplifications embedded in the flammability tests [81]. Oxygen consumption calorimetry [82, 83] was derived from the fundamental fuel oxidation principles developed by Thornton [84] and adapted by Hugget [85] delivering from a test the energy release rate per unit area of burning fuel (mostly known as the Heat Release Rate per Unit Area ($\dot{Q}''$)) that could then be incorporated directly into entrainment models to deliver the mass of smoke produced. These tests were directed to deliver the parameters that could feed empirical correlations and zone models.

Equation (1) summarizes the process by which the Heat Release Rate ($\dot{Q}$) is defined on the basis of properties extracted from flammability tests.

$$\dot{Q} = A.\dot{Q}''$$

The heat release rate per unit area is obtained directly from oxygen consumption calorimetry and multiplied by the burning area ($A$). The burning area is a function of the flame spread rate ($V_s$), thus it can be represented as a function of the flame spread rate and time ($t$). While this function is complex and dependent on fuel geometry and flow field it can be argued that a worst case scenario could be represented by radial spread over a fuel surface where the area is equal to the area of a circle of radius $r$ ($A=\pi r^2$). Then the radius is a linear function of the flame spread velocity and time ($r=V_st$) that when substituted into Equation (1) results in a simple expression for the heat release rate

$$\dot{Q} = A.\dot{Q}'' = \pi V_s^2 t^2 \dot{Q}'' = \alpha t^2$$

(2)
where the parameter $\alpha = \pi V_d^2 \dot{Q}^*$ and the flame spread velocity ($V_d$) and energy release rate per unit area ($\dot{Q}^*$) could be obtained from the flammability tests. Thus the tests could be summarized into a single criterion ($\alpha$) that within Equation (2) provides the evolution in time of the heat release rate. This is a practical means by which designers could incorporate the heat release rates into fire models and smoke management calculations [12].

The formalization of material flammability fed smoke management models but also allowed a more comprehensive classification of materials that enable capturing specific features of complex materials such as plastics. The plastics industry adopted the heat release rate per unit area ($\dot{Q}^*$) as a direct target for the design of fire retardant formulations opening the market to numerous products [86]. While the gain is evident, once again, the full resolution of the induced buoyant flow disabled the Scale-Up process by which the fire models, with inputs from the test, could be used to predict the behaviour of the real event.

Using test results as inputs for fire models is complex because the test themselves are influenced by buoyant flows, thus the interpretation of the tests required detailed modelling of the gas phase. This was not recognized at the time and tests were only conceived on the basis of providing realistic, reproducible, simplified and standardized conditions. Flammability tests were not analyzed or instrumented to truly separate the solid and the gas phase. As a result, all properties extracted from the tests remain hybrids that blend flow and material characteristics. While many attempts have been made to use test properties to Scale-Up fire from first principles [87, 88], success has never been truly achieved and the potential gain associated to this effort remains uncertain.

**Fully-Developed Compartment Fire**

In the oxygen limited regime, the stoichiometry is rich, thus excess fuel is being produced and combustion is limited by the oxygen supply induced by buoyancy through the compartment openings. Buoyancy induced flows are displaced from the fire and calculated at the vents and the energy source is directly linked to the consumption of the available oxygen. The temperature of the compartment is then established by balancing the energy generated by combustion of the incoming buoyant flow, the energy lost by the combustion products leaving the compartment and heat transfer through the compartment boundaries [67-72].

The focus of the oxygen limited regime was to calculate the gas phase temperatures of the compartment and the duration of the fire. The objective was twofold, (1) to calculate the mass of smoke spilling into the adjacent compartments once the fire had reached the oxygen limited condition in the compartment of origin, (2) it aimed to establish a set of more realistic conditions (temperature vs. time) curves that could allow the assessment of structural behaviour in fire [89]. While the first objective had a clear gain associated to smoke management and was almost immediately formulated to engineer smoke extraction systems, the second was of restricted application [76].

The determination of more realistic temperature vs. time fire curves seems to be a very direct way of reducing unrealistic safety factors without violating the principles of a “worst case” scenario and design for fuel burnout. Nevertheless, the acceptance of this approach encountered much resistance. The bridge between structural and fire safety engineering is the standard furnace [90]. Structural engineers were not educated to understand – or even be aware of- the differences between the standard fires and the more realistic descriptions of the fire. Nor are architects who are typically the people assigned to prescribe the required insulation.

The first attempt to compare the standard fire with a realistic fire dates as early as Ingberg [63] who defined the concept of time equivalency. Time equivalency is based on a
simplified linearization of heat transfer that allows defining the “fire load” as the integral of the temperature vs. time curve. The concept of equal areas under the temperature vs. time curve implying equal fires builds a bridge between the furnace test and real fires. Nevertheless, the first true application of this concept dates only to the design of the Georges Pompidou Centre in Paris where Margaret Law demonstrated that the external structure could be designed without any fire proofing [76]. The energy transferred from the fire to the external steel structure until burnout of the fuel was much less than the energy transferred by the furnace for the required rating therefore fireproofing could be eliminated exposing the structure as requested by the architects. Following this application, the realistic curves developed by Pettersson et al [89] where formalized in the Eurocodes [91] as the “parametric curves.” These curves offer an array of temperature vs. time curves obtained for different fuel loads and ventilation conditions that define a more realistic temperature vs. time formulation.

There are several weaknesses to the “parametric curves” approach: (1) while the “parametric curves” are extracted from experimental data and the gas phase temperatures can be deemed as realistic, the heat transfer between the fire and the structures is not fully resolved, (2) the “parametric curves” represent a fire within a specific compartment size and are not easy to extrapolate to spaces with different dimensions [92] and (3) the critical structural temperature (resulting from a material property) concept depends on the unrealistic assumption that compartmentalization and load transfer to adjacent cold structural elements allow to extrapolate global structural behaviour from single element behaviour [9, 93]. Time equivalency, as a methodology to Scale-Up the influence of the fire on the structure, remained incomplete. Robustness, precision and completeness of the model could not be demonstrated and therefore the value of the refinement remained questionable.

Despite the limitations of the tools conceived in this period, it was clear that the calculation methods developed made possible a significant reduction of safety factors and enabled many architectural solutions that would not otherwise be permitted by the existing prescriptive framework. The understanding of fire dynamics established how context variables affected the combustion processes making every environment unique. The result was not only the continuous evolution of building codes, but more fundamentally, the breakdown of the classification framework. Infrastructure did not have to be classified so that a standardized solution could be prescribed by a building code, but it could be treated as a unique problem whose performance could be quantitatively assessed. As a result many building codes incorporated a performance based design clause that enabled the use of engineering tools to demonstrate if a design met an acceptable level of performance [94].

In parallel to the development of tools directly linked to the application, a better understanding of many combustion processes associated to fire was achieved. But despite the quality and fundamental nature of most of this work it has found very little relevance within the context of the definition of a fire safety strategy. Eventually, it was impossible to demonstrate the gain associated with these fundamental combustion studies and the links between combustion and fire modelling weakened bringing us to ask if a better understanding of combustion still has a place in the Scaling-up of fire?

Computational Models

The last decade has seen how traditional fire tools such as empirical correlations, experimental data, zone models, etc. have been substituted by Computational Fluid Dynamics (CFD). Tools of general use such as smoke management calculations and large scale experiments are being replaced by CFD. Classic smoke management calculations are based on entrainment correlations that are limited by simple geometries and tend to use worst case entrainment scenarios. The result is very large extraction flows and significant questions on
the universality of the results. In contrast CFD can deliver computations for specific scenarios that can potentially optimize smoke extraction rates. In a similar manner, sprinkler performance is commonly established on the basis of large scale testing but these tests are an expensive and inefficient process that will always leave the question of how far the tests can be extrapolated. Computational tools have the potential to provide this assessment in a cost effective and efficient way, but most important, they allow an explicit extrapolation of a much reduced number of test results to any scenario that is deemed within the bounds of validity of the models. A similar case can be made for most elements of the fire strategy, where three dimensional and temporal resolution of the transport equations can quantify all the variables required to assess the performance of complex scenarios or novel technologies in a manner that no other tool can achieve.

One of the most dramatic shifts in the methods used to establish a fire safety strategy is the evolution of the performance assessment of structural systems. The last decade has seen a dramatic evolution of our understanding of the behaviour of structures in fire [9, 93, 95]. The evolution of Finite Element Modelling (FEM) has allowed the analysis of complex structural systems showing that critical structural failure temperatures cannot be established simply on the basis of material properties. For most real building systems, the failure temperatures depend much more on the interaction of the different structural systems within a full structure than on the specific material properties of the building’s constituents. For a given structural system, features such as restraint and load redistribution can deliver considerable additional load carrying capacity even at very high temperatures [60, 93, 95]. Thermal expansion results in deformations that enable the use of the compressive and/or tensile membrane action established in composite slabs resulting in failure temperatures that far exceed those linked to the degradation of material properties or to the performance of similar elements tested in furnaces. Other structural systems such as long span beams or light weight trusses can potentially introduce failure mechanisms that appear at temperatures significantly below those established from the decay of the material properties. Furthermore, temperature gradients and heating rates have significant impact on composite systems, where high thermal conductivity materials such as steel work in a composite manner with low thermal conductivity materials such as concrete and thermal insulation. Given the evolution of the heat transfer within the structural systems, deformations will change resulting in different load distributions and thus different failure mechanisms. The refinement of structural modelling for fire requires a higher resolution of the fire and the heat transfer that cannot be delivered by any of the conventional “temperature vs. time curves.” CFD is the only mechanism by which temporal and spatial resolution of the heat flow from the fire to the structure can be attained, thus the gain associated to using these methods to Scale-Up seems significant [14, 61]. This paper will not discuss FEM models because the combustion relevance to these models relies within the definition of the thermal boundary condition provided by the CFD models.

As defined above, the use of CFD as a basis for the Scaling-up of fire has a very clear gain and therefore there is a strong motivation for the development and improvement of these tools. Classic tools, while still relevant, will be limited to the simpler and more conventional applications leaving little motivation for further refinement. There are numerous CFD tools available, some of general use and some specific to fire. They all have advantages and disadvantages and a detail discussion of the tools is not the subject of this paper. What is central to this paper is establishing if there is a gain in the further refinement of existing CFD tools. CFD tools are broadly used in the practise of fire safety thus there is a clear perception of their adequacy and a sentiment that further refinement will deliver little to no gain.
Nevertheless, it is not clear that our current CFD tools provide a set of outputs that is precise, robust and complete enough.

**Performance Assessment of CFD Fire Models**

The fundamental premise behind the development of fire related CFD tools is to be able to reproduce reactive flow fields where buoyancy plays a significant (and many times dominant) role. Furthermore, the models need to be able to include interactions between the combustion process and its environment; the environment being a test, a building, terrain or weather conditions. CFD fire model development focused initially on the gas phase, first as a means to calculate transport of heat and species with an imposed energy source term and only later resolving combustion. These first generation models incorporated extensive knowledge on turbulent flow formulations as well as effective numerical schemes but treated the environmental context only as an imposed boundary condition. It was only much later that CFD models begun to incorporate reactive condensed phase boundaries and to carefully resolve heat and mass transfer at the boundaries. These developments attempted to provide a better definition of the fuel generating boundaries for the CFD. With the incorporation the implementation of turbulent combustion formulations, pyrolysis models, and the refinement of heat transfer within the gas phase and with the boundaries that CFD evolved to become a fire model.

Many exercises of validation and verification have been presented showing different levels of agreement between experimental data and model predictions for many of the variables required as inputs for a fire safety strategy [17, 26]. Despite the extensive effort devoted to these exercises, in most cases, it has been difficult to establish, from the experimental data, the elements of the CFD models that were providing precise enough computations and those who were introducing observed output errors. An exhaustive analysis of all verification and validation studies that establishes the achievements and limitations of individual fire models is yet not available. While the NRC-NIST [17] study is the closest attempt to do this, it still does not analyze in sufficient detail the experiments used and the model output to establish the link between output and model component that will allow establishing where refinement will lead to gain. This is not a criticism to the work because there are two fundamental reasons that disable these verification and validation studies to achieve the full objective, them being:

- Most of the experimental data base used was not developed for the purpose of validation and verification of CFD models. Experiments used were mostly developed to either validate analytical formulations or zone models [96] or as forensic representations of particular scenarios [60]. Thus the resolution and type of data obtained is not targeted for the purpose and in general is too coarse or incomplete to conduct an analysis with the required level of detail.
- Given that a fire model needs to be assessed within the context of its environment, the experimental and numerical burden is very high, thus concessions on grid resolution, modelling detail, experimental control, repeatability and measurements need to be made, creating unavoidable limits to what can be concluded.

Once more the issue of relevance appears. Fire tests that are specifically designed for the validation and verification of CFD fire models that are of a scale and complexity that enables an adequate assessment of the performance of the model within the context of its environment seem necessary. Nevertheless, it is not clear if it is relevant to conduct large scale tests. Large scale tests introduce several complex issues: (1) the number of tests
required to ensure repeatability, (2) the implementation of diagnostics that can produce the necessary data and (3) the magnitude of the test that guarantees that all necessary model/environmental context interactions required are present. Large scale fire tests are only relevant to the validation and verification of CFD models if they can deliver adequate repeatability, the correct data at the correct level of precision and if they can test a scenario that includes the necessary level of interaction between the reactive flow and the environment. Otherwise, the tests will remain simply demonstrations where repeatability, data and scenario can always be questioned. Currently, it can be said with confidence that no large scale fire test has fully delivered a set of data that satisfies all these three conditions. A striking contrast can be established when comparing the needs of fire models with turbulent combustion models where experimental studies such as the Sandia flames [97, 98] provided the correct experiments for the validation and verification of combustion turbulence and chemistry models [99, 100].

In parallel to the development of the CFD framework there has been extensive work within the combustion community to understand specific components of fire models. These studies have targeted the development of sub-components for fire models but also used combustion CFD models for the better understanding of the different sub-processes present in a fire model. Extensive work has focused on specific scenarios where idealized conditions have been defined to understand the key phenomenological features of some individual sub-components of fire models without the complexity introduced when incorporating the full context. An excellent example of these type of studies is the work conducted in micro-gravity combustion and that is summarized by Ross [101]. Here buoyancy was removed allowing analysing fire related processes with a flow field that could be varied in a controlled manner. It is difficult to establish how much of that work has permeated into fire models, but it is clear that the development of fire models is strongly influenced by some of that work. What is not clear is how much more of this detailed work can ever make its way into fire models once the extensive constraints of the environmental context are incorporated. The issue of relevance becomes once more an important aspect that needs to be understood. Is it relevant to further develop the understanding of fundamental processes if these understanding can never be transported in to a fire model? Is it relevant to extrapolate idealized scenarios to a fire model if the added complexity invalidates the extrapolation?

A final issue that needs to be addressed is the robustness of the model. Robust models will deliver results that are invariant when aspects of the modelling process that are extrinsic are changed. This statement can generally be directed towards the user of the model but it could also refer to the computational hardware and software (compilation, platform, etc.). Issues such as robustness to computational hardware and software are generally simple to address and are part of the standard model development procedures, issues associated with the user are more complex. In the case of the user, with a robust model competent users will always reach the same conclusion regarding the manner in which a specific scenario should be addressed (i.e. grid resolution to obtain a grid independent result, input values such as heats of combustion, heats of pyrolysis, thermal properties, etc., constants such as turbulent invariants, laws of the wall, etc. or boundaries). At the end it will be expected that outputs obtained varying these extrinsic aspects should be similar and their variance will define the robustness of the model. As models evolve, a continuous assessment of robustness is always relevant because it directly establishes the validity of the output.

The Dalmarnock Fire Tests

The previous section discusses in general terms the relevance of large scale tests and sub-process analysis to the development, validation and verification of CFD fire models. This
section considers a specific scenario to illustrate the different issues that emerge when attempting to create a scenario that fulfils all of the necessary requirements for repeatability, data quality and density and environmental context.

The minimum cell that provides a realistic context for a fire model is the compartment. Here, the classic definition of compartment used in most classical studies is used. The compartment represents a small (approximately 100 m$^3$), quasi-cubic space surrounded by non-flammable boundaries (walls) and with a small number of openings (i.e. doors, windows). While the classic compartment might be perceived as an over simplification it does provide the minimum level of complexity that a fire model should be able to reproduce, thus an ideal place to start. Other real scenarios such as large industrial volumes or atria might provide less (or more) of a challenge to the models; nevertheless, in the immediacy of the fire it is most likely that all the features of a compartment fire will be present. It is clear that many real scenarios will result in further challenges to the fire model, thus the compartment can only be treated as a minimum representation of the problem.

The issue of repeatability is a major concern because tests of this magnitude can only be conducted in a reduced number. Thus the luxury of repeating the test until the same result can be attained in a consistent manner is one that will never exist. For fire models a different approach is necessary. An alternative way of attaining repeatability is by designing a scenario where the importance of the dominant sub-process is emphasized. This process is then meticulously controlled in a manner that when tested independently (much smaller test) the results are consistent. As a means of establishing repeatability, the sub-process next in importance is then varied within an extreme range to establish the magnitude of the impact of this variation. While not ideal, this approach allows reducing the number of large scale tests to a minimum of two (extreme bounds of the secondary sub-process) but it is restricted to serve as a scenario that only validates or verifies the performance of the fire models when the specific sub-process dominates. It is obvious that more tests will always deliver a better sense of repeatability, nevertheless, under these conditions two tests does attain the objective of establishing consistency among the results.

Finally, there is the issue of quality and quantity of the data. Complex diagnostics in a fire environment are extremely difficult to implement. While there are excellent examples of the state of the art measurements made under difficult fire conditions, these examples are always limited to very specific scenarios. The problem is one of extracting the minimum amount of useful data relying on diagnostics that are viable within the context of the particular environment.

The Dalmarnock fire tests [102, 103] are probably one of the few scenarios that explicitly attempted to follow this strategy. Other tests have probably delivered the same results nevertheless they were not explicitly structured for this purpose. The detailed discussion of the large experimental data base available is avoided here only on the basis that the Dalmarnock fire tests explicitly acknowledge the purpose of their design and thus can be used as an example that helps illustrate the challenges associated to validation and verification of CFD fire models.

Description of the Tests

Two tests were conducted in a derelict building in Dalmarnock (Glasgow, UK) in identical compartments. The tests were designed to the constraints typical of a classic compartment. The dimensions of the room were 2.45m high, 3.50m by 4.75m and the compartment included three vents; a window and two doors. The fuel corresponded to realistic office furniture and objects in quantities that would be typically found in any modern work environment. The most important features of the test were the sensor density and the fire that was designed for the test. Figure 1 shows two views of the compartment and Figure 2
a detailed legend for all sensors displayed within the compartment. The Dalmarnock fire tests are described in some detail by Rein et al. [104] and in greater detail in Abecassis-Empis et al. [102] and Rein et al. [103]. Here only a brief description that highlights the aspects best linked to the discussion will be presented.

Given that the objective of the test was to provide a data set that could be used for the purpose of validation, verification and improvement of CFD models it was considered that the type and resolution of the data had to be consistent with standard CFD model outputs and resolution. For this purpose four outputs were selected, temperatures, heat fluxes, light obscuration and velocity. Within the compartment 240 thermocouples were distributed (Figure 2) in as homogeneous a manner as possible. Similarly, 80 thermocouples were placed outside the window to reconstruct the fire plume. Nine thin-skin calorimeters were used to measure heat flux to the compartment ceiling and 16 heat flux gauges were mounted on the partition wall shared with the kitchen. Eight lasers used to measure light obscuration were set in emitter-receiver pairs, such that five were horizontally aligned and three were vertically aligned. Three bidirectional velocity flow probes, were placed in both the doorway leading to the flat corridor and in the doorway to the kitchen and a further eight probes were placed outside the compartment window. Six web-cameras were also used to monitor the fire growth and all data collected was time stamped, both camera and data logger clocks (for all other measurements) having been synchronised prior to ignition.

The thermocouples allowed producing three-dimensional isotherms as a function of time that could be directly compared to a CFD model at equal level of precision and resolution. The heat fluxes to a wall and the ceiling also provided two-dimensional contours of the heat flux as a function of time with a resolution and precision consistent with a CFD model. Light obscuration measurements could only be collected for a few points therefore only characteristic measurements were expected. Also, light obscuration is not a direct output from the model therefore path integration of the model output had to be conducted for comparison. The velocity measurements were a different form of compromise in that only one component of the velocity vector could be obtained for a much reduced number of locations all at the compartment boundaries. The choice of location was given by the performance of the probes but also because it was deemed important to be able to reconstruct a mass balance that established the global heat release rate of the fire. Here, a further assumption needed to be made, which is total consumption of all the oxygen entering the compartment. The global heat release rate is no longer a variable that is directly related to the CFD output, but CFD models are expected to be able to reproduce the time evolution of this variable. The most important limitation of the data was the absence of any gas analysis. This represents a real limitation that could not be resolved given the budget available and the constraints imposed by the test environment. As can be seen, the complexity of the environment not only limits the nature and quantity of the sensors but also introduces compromises on the nature of the measurements.
Figure 1  Photographs of the Dalmarnock compartment (a) view of the front of the compartment towards the only window (b) view of the back of the compartment. (c) a view of the back of the compartment showing the two doors at the right hand side of the compartment. Figure 2 indicates the direction of the three views.
A typical set of thermocouple data for a plane perpendicular to the window wall (3.10 m from the Bedroom 1 wall) is presented in Figure 3 showing the spatial distribution of isotherms for an individual plane at a specific point in time. As shown in Figure 3 these isotherms provided a level of resolution consistent with typical CFD fire models that resolve the combustion and smoke regions. Similar sets of data were constructed for other planes as well as for other times. Data sets for all other measured variables were also obtained with resolutions consistent to the limitations of each measurement. This resolution not only enables a clear understanding of the evolution of the fire but also allows a more detailed comparison with the CFD fire models. More complete sets of data can be found in Abecassis-Empis et al [102] and Rein et al [103, 104].

The boundaries of the compartment (walls and ceiling) were instrumented with thermocouples embedded in the concrete structure as well as strain gauges and displacement sensors. These measurements were intended for comparison with FEM models of heat transfer through the solid boundaries and of structural evolution. Furthermore, the measurements allowed establishing the integrity of the compartment so that the boundary conditions for a CFD model could be specified with certainty.

Repeatability

The repeatability of the test was established by designing the fire in a manner that enabled as consistent of an outcome as possible. The principle behind the design of the fire was to address all major sources of uncertainty. The first source of uncertainty is the ignition protocol. The evolution of a fire can be defined by ignition, especially for a fuel of complex nature, such as furniture. Modern furniture is designed to minimize the potential for ignition, thus barriers are placed on the sides of the furniture protecting the cushions that are generally made of polyurethane covered with fire retarded fabric. Common ignition sources such as waste paper baskets will burn-out before penetrating the barriers thus preventing the flames from propagating towards the polyurethane cushions. Several tests were conducted prior to the test with identical pieces of furniture that allowed a consistent and repeatable ignition protocol that bypassed the barriers and resulted in an almost instantaneous ignition of the polyurethane [102, 103]. Under these conditions, the ignition delay time could be assumed as zero and the magnitude of the fire was large enough from the onset so that the subsequent propagation was observed to be repeatable.

The main piece of fuel was the sofa (Figure 1) which is labelled (i) in Figure 2. Ignition was induced on a waste paper basket filled with paper and a predefined quantity of heptane (labelled (vii) in Figure 2). While burning of the sofa had the potential to induce flashover within the compartment, spread rates will be dominated by many variables of which the inclination of the flame and heat feedback from the smoke and the ceiling were deemed to be the most important. Both variables introduce significant uncertainty given that they will be the result of the balance between the energy generated by the fire and the nature of the ventilation. By igniting the sofa on one end, the leading edge of the flame controlled flame spread (opposed flame spread), thus the influence of the inclination of the flame on propagation rates was minimized. The influence of heat feedback was reduced by inducing flashover before the upper layer temperature increased to a level where radiative feedback became significant. This was achieved by guaranteeing that the flames from the sofa tilted towards a second fuel package that could sustain fast upward flame spread.
Figure 2  Sensors distributed within the main compartment. The red arrow indicates the view corresponding to the image of Figure 1(a), the blue arrow corresponds to the image of Figure 1(b) and the green arrow to the image of Figure 1(c). The sensor key indicates the type of sensor and the symbol next to it corresponds to the nomenclature used.

SENSOR KEY
- E Thermocouple Tree
- E External Thermocouple Tree
- E Heat Flux Gauge
- Horizontal Obscuration Sensor
- Vertical Obscuration Sensor
- Air Velocity Probe
- Camera

FURNITURE KEY
- i Sofa
- ii Desk, Computer and Chair
- iii Bookcase
- iv Cabinet
- v Coffee Table
- vi Tall Plastic Lamp
- vii Waste-paper Basket
Three bookshelves filled with loose paper and cardboard were used as the second fuel package. The bookshelves were placed strategically in a corner of the room (labelled (iii) in Figure 2 and visible in Figures 1(b) and 1(c)) with the sofa between the vents and the bookshelves. Individual testing of the bookshelves established that once ignited upward flame spread will engulf the entire bookshelf in a very short period of time (~10 seconds) generating sufficient energy to induce flashover in the compartment (>0.5 MW). So once the length of the sofa flame was enough to ignite the bookshelves flashover will be induced instantaneously and the fire will progress to a fully developed fire. It is clear that the present scenario emphasizes the sub-processes associated to secondary ignition (i.e. material properties of the fuel in the shelves, radiative and convective heat transfer from the primary flame, etc.).

![Temperature isotherm for a plane parallel to the side wall where x=0 is the plane of the window and x=4,750 mm the plane of the back wall. The plane is 400 mm away from the side wall and the data was taken 251 seconds after ignition. Data used for the plot was adapted from reference [103].](image)

Once the fire had attained flashover and entered the fully developed phase ventilation becomes the controlling parameter. The two doors were left open and the window was broken at a pre-specified time eliminating the uncertainty of window breakage [103]. The doors were buffered from the environment by other rooms (kitchen and bedroom in Figure 2) and the widows were left open in both adjacent compartments. This allowed enough air to flow into the compartment but sufficient pressure drop to minimize the influence of outside flows. Figure 4 shows a sequence of events using an average compartment temperature as a reference. It can be seen that temperatures before flashover are very low (<150°C) minimizing radiative feedback, flashover occurs almost instantaneously and once the compartment reaches fully-developed conditions it attains an almost steady state until the window is broken (800 sec). After the window is broken, a second steady-state period is observed that eventually is terminated by the fire-fighters. It is important to note that the fire had almost consumed all the available fuel at this point.
A second test was conducted to verify the repeatability of the results. The criteria chosen to establish consistency was time to flashover and the parameter varied was the ventilation. Ventilation will control the inclination of the flame and the temperature of the compartment, thus the radiative feedback. To enhance the ventilation the window was opened early in the test and a large perforation (1.2 m by 1.2 m) was made between the compartment and the bedroom allowing direct access of air from the window in the bedroom to the compartment. This represented a drastic departure from the first test imposing the greatest possible challenge to the repeatability of the test. Given the specific characteristics of the compartment there was no other change that could have a bigger impact. Establishing repeatability for the post flashover stage was not possible given the significant differences in ventilation, nevertheless it was considered that post-flashover conditions are more consistent if the fuel load, type and distribution remains the same. Thus Test 2 was extinguished after flashover was attained. It is clear that further tests could have been carried to guarantee repeatability of the post-flashover scenario. These would have fixed ventilation and vary fuel load and distribution. Nevertheless, once again constraints associated to large scale experimentation limited the number of tests possible. Figure 5 shows the comparison between the two tests. As expected, Test 2 shows lower temperatures throughout the entire pre-flashover period nevertheless flashover occurs almost at exactly the same time and following very similar characteristics. Comparison of video images shows that the evolution of the sofa flame in both tests is very similar and that flashover is, in both cases, induced by the ignition and rapid upwards flame spread of the bookshelf.
Summary

The Dalmarnock fire tests represent a good example of the different measures necessary to achieve large scale tests that can be deemed as relevant to the validation and verification of CFD models. While in its minimum expression, these tests are of a scale and complexity that enables an adequate assessment of the performance of the model within the context of its environment. Every effort was made, within unavoidable limitations, to deliver the correct data at the correct level of precision and density. Finally, an adequate scheme was developed to deliver confidence on the repeatability of the tests. While many things could have been improved, and many criticisms can be made to many of the choices, these tests are important in that they represent an explicit attempt to provide data that is relevant to the validation and verification of CFD models.

![Comparison of the experimental average room temperature (°C) variation in time (s) of Test One and Test Two. Data is only presented until extinction of Test Two (400 seconds). Data for the plot adapted from reference [103].](image)

Figure 5

Modelling Study

Validation, verification and improvement of fire models require experiments and model output to be compared at many levels. Components of the fire model can be studied by conducting idealized experiments where individual processes or couplings are tested. Several studies of this nature are present in the literature; i.e. The capability of the numerical model to resolve the transport of energy and species can be studied by means of well defined burners where the flames are consistent in nature and buoyant entrainment can be modelled free of any other influences [105-108]; flame spread models can be studied by means of wind tunnels that establish well defined boundary layers where buoyancy is subdued to a forced
flow [109-112] or the accuracy of pyrolysis models can be explored by means degradation experiments where combustion is prevented and substituted by a fixed heat flux [113-116].

The study of the coupling between the sub-processes and their interaction with their environment is then necessary to truly address the validity of a fire model. To achieve this, several approaches need to be explored. A first strategy consists to attempt reproducing existing data to identify sub-process or couplings that are properly modelled or that introduce significant departures from the model output, this is generally referred to as *a posteriori* modelling. This can be difficult given the numerous sub-processes and couplings and it can therefore require several experiments. Experiments need to be designed with a clear objective and simplifications have to be introduced in a manner such that the effect of the sub-process or coupling on the output can be isolated. The literature has very few examples of fire experiments specifically designed for this purpose. The study of fire models has been conducted mostly using experimental data obtained in the past with very different objectives [26], thus the identification of target sub-processes and couplings is rarely possible. Instead, most studies of this nature conform themselves with establishing acceptable agreement but are not capable of addressing the reasons for the agreement or the weaknesses in the sub-processes or couplings that result in departures. With a problem that has such a large and complex parameter space, this exercise is like shooting in the dark where even if the target is reached it is impossible to define why.

A final exercise relates to the validation of the model and its robustness. Once sub-processes and couplings have been refined to a sufficient level it is important to conduct blind or *a priori* comparisons. The output of the model is obtained first and then the experiment is conducted to establish by means of a comparison of the relevant parameters the level of precision of the model output and the confidence on the modelling results. On a first instance a single model user should conduct the calculations followed by a Round Robin. The two studies will separate the model capabilities from the robustness of the model to the user. These protocols for validation, verification and improvement have been standardized and are presented in a much more rigorous manner in many publications [117], nevertheless it is important to reformulate them here in the context of fire models and the example presented.

*The “A Priori” Round Robin*

A Round Robin study was organized in conjunction with the Dalmarnock fire tests [104]. The tests, as explained above, were deemed to be appropriate for this objective, nevertheless assumed that the models to be used already incorporated in an adequate manner all sub-processes required, all necessary couplings among the different sub-processes and with the environmental context and that single user validation had established that the models were capable to provide an output of relevant precision. In other words, the exercise assumed that fire models were ready to be used for their intended application. The fundamental driver behind this study was the verification that existing fire models were extensively used for scenarios very similar to the Dalmarnock fire tests (in most cases much more complex). Thus, the objective was simply to establish the robustness of the models to the user.
The details of the Round Robin and the comparisons between the different submissions and the experimental results can be found in Rein et al. [104]. As an example the comparison corresponding to the heat release rate (HRR) is presented in Figure 6. The heat release rate is a global variable that fire models are expected to be able to predict, because it represents the source term to be used for any interaction between the compartment and the environment external to it. As can be seen in Figure 6, notable are the differences between experimental data and the model output, the differences between different model outputs and the fact that the output from CFD models blends with that of much simpler models (zone models). These observations are consistent among all variables measured with no specific model output being systematically better. While Figure 6 shows E1 as the result closest to the experiment, for other data a different set of predictions will take this role [104].

While the exercise is of great importance, it is not the results that matter, but what can be inferred from the results. Clearly, the objectives were not met and the model outputs did not deliver adequate predictions of the different variables relevant to fire safety. The authors of the Round Robin argue that the scatter and randomness in the outputs originated in the different assumptions introduced in the input parameters indicating that the large number of inputs and the variability observed in literature values associated to this inputs can lead to a large variance in the results. This is clearly a possibility but not the only one. It is also
possible that the sub-processes emphasized in the Dalmarnock fire tests are not well described in existing fire models or that the couplings between these sub-processes have not been properly modelled. The model outputs and the comparison between the different submissions do not shed light on this issue because the modelling study was not designed for that purpose. It assumed that these sub-processes and couplings were properly included in the fire model and that they were robust to the user. Finally, the experiments can be questioned. As indicated in the previous section, the experiments were deemed, within the scale and complexity, to be repeatable and the data was deemed sufficient and precise enough. Nevertheless, the experiments were limited in that they over emphasized a specific sub-process (the secondary ignition of the bookshelf) thus were designed with only two possible objectives, to establish the accuracy of the sub-processes and couplings involved in the secondary ignition of the bookshelf or to establish a realistic and repeatable scenario to test the robustness of the overall fire modelling process to the user. The later was explored unsuccessfully by the \textit{a priori} Round Robin but the former needs to be explored by means of an \textit{a posteriori} modelling analysis that focuses on the secondary ignition process.

\textbf{The “A Posteriori” Modelling Study}

Several studies have been reported where the scenario of the Dalmarnock tests were modelled after the event and with the data available [19, 118-120]. These studies explore, in more or less detail, the different variables influencing the computational outcome. In all cases some level of agreement between model output and data is demonstrated. The agreement observed, while still showing departures, is to a level much greater than that obtained for any of the models in the \textit{a priori} study. The studies concluded that:

- Reducing the qualitative and quantitative disagreement between experiments and model outputs requires significant effort beyond the standard grid sensitivity and parameter selection process. Some of the inputs need to be explored in greater detail and with the information available parameters need to be tailored to the specific application. A typical set of data is presented in Figure 7 showing the comparison between two modelling scenarios for bounding conditions that could possibly represent the test and the experimental data.

- The common practise of prescribing the heat release rate as the source term that enables the introduction of fuel is not sufficient. For the particular scenario it is necessary to correctly specify the area through which the fuel is incorporated. If this is not done with precision then the flame height is not predicted correctly and heat transfer to the bookshelf is misrepresented and secondary ignition is not predicted adequately. Given that this is the dominant sub-process for the particular scenario, changes in this specific output result in drastic changes in the overall outcome. Thus, for the Dalmarnock scenario it is essential to be able to properly predict flame spread. In the simulation by Jahn et al. [120] the burning area was established from video images, thus an effective correction was introduced on the basis of sensor data.

- Very small scenario changes (e.g. a blanket) can result in a significant difference in the overall results [120].

- Discrepancies were of a quantitative and qualitative manner. When field comparisons were made it was established that energy distribution within the compartment was not necessarily correct. Some of the values were within acceptable error bars others were not. Figure 7 shows how the upper layer temperatures were within the bounds of the models while the lower layer temperatures were not. Field comparisons
provided an added value to the study because they allowed identifying detailed discrepancies.

- It was not possible to identify the sources of error because of the many variables with direct impact on the outcome and the untraceable link between the sub-processes and the outcome. Reference [26] establishes that in this context simulation of fire growth was significantly sensitive to location of the heat release rate, fire area, flame radiative fraction, and material thermal and ignition properties, but these are just a few of the possible sensitivities of the models.

While the a posteriori exercise remains of value and it is worth reporting, it highlights a fundamental problem that is the essence of the point being made here, validation, verification and improvement experiments need to be defined for a specific purpose that is consistent with the state of the art of the models. The Dalmarnock fire tests, even with all the precautions taken and the extensive data collected, were not designed for the purpose of learning about the model. The tests were designed for a scenario that assumed that all the model sub-processes, input data and couplings were formulated to a level of precision that was relevant to fire safety. Thus, fuel packages introduced too much input data uncertainty and the many sub-processes and couplings included in the scenario made it impossible for the modeller to trace back the sources of error. The a posteriori modelling study only served to highlight the sensitivity of the outcome to several sub-processes (e.g. flame spread) and the fact that small uncertainties in the definition of the scenario can result in major discrepancies in the output. From the perspective of the modeller, this was probably already known and of little help, from the perspective of Fire Safety, it is a reminder that much work still needs to be done in fire modelling.

A final issue of importance is the scenario uncertainty. Fire safety carries, by nature, a significant scenario uncertainty, thus from the present study it can be concluded that detailed CFD modelling is of no relevance to fire safety and that further improvements in the sub-processes will always be overruled by the inherent uncertainties of the scenarios studied. From the perspective of the author, this is an incorrect interpretation of the results of this study. What this exercise demonstrates is that variations in the scenario introduce such differences to the outcome that they need to be incorporated in the modelling process. As an example, if the surface area covered by the flames is not predicted correctly, the outcome is drastically different and the potential consequences for fire safety are extraordinary. As clearly demonstrated in Figure 6 where the predictions of the heat release rate (relevant variable) cover several orders of magnitude. Thus, being able to establish accurate flame spread rates is essential. Furthermore, the study showed that sensor data (such as video recordings) can be used effectively for this purpose.

**Predictive Modelling or Inverse Modelling for the Scaling-Up of Fire**

Most current modelling efforts are directed towards predictive modelling. Thus the focus is on improving the models to achieve more robust and precise predictions of a fire event. While this is clearly a necessary approach it does not always lead to results that can be deemed of direct relevance to fire safety. The entire process of fire model development, validation, verification and improvement is a tedious, long and expensive process that can only be justified if the improved results lead to a more effective definition of fire safety. This is clearly not the case where variability in the scenario can create errors much greater than the errors associated to the pure modelling exercise. Fire is not the only field where this is a possibility. Other fields such as weather predictions [121] or biological flows [122] also...
encounter similar problems because the changes in the initial or boundary conditions can generate massive changes in the outcome. Thus the impact of model refinements is negligible when compared to that of scenario changes. It is therefore essential to be able to incorporate the particular characteristics of the scenario into the model. Given that the scenario can evolve in time it is necessary to be able to capture the scenario at the onset of the model and through the time period that the model is trying to predict.

Predictive modelling has yet another problem, gas phase (combustion chemistry, heat transfer and fluid mechanics) and solid phase processes (pyrolysis chemistry, phase change, heat transfer, solid mechanics) can have very different characteristic length and time scales, thus fully resolving and coupling all the processes can represent an insurmountable computational burden that requires input parameters that in many cases cannot be obtained. Thus comprehensive fire modelling cannot be justified as relevant to fire safety. The common solution to this problem is to simplify certain components of the model. Some simplifications are simple filters that generate compatibility between otherwise incompatible length and time scales (e.g. LES models, Favre Averages, PDF’s, etc.[18-21]), some simplifications are physically based and rely on some of the sub-processes being established as negligible (e.g. Low Mach number formulations [18,19], Laminar Smoke Point [123], infinite chemistry [18, 19], etc.), some of them are mathematical leading to solvers that allow coarse grid resolution [29, 35] and some of them simply substitute entire processes by empirical formulations (source terms as empirical burning rates or heat release rates, laws of the wall, etc.[18,19]). An excellent example of the range of simplifications possible is the comparison between the mathematical representation of the problem derived through the development of the Fire Dynamics Simulator [26] (and WFDS [33]), the fire variant of openFOAM [27], the Utah C-SAFE modelling effort [32] or any of the other available
computational tools. Each model incorporates numerous simplifications of different nature leading to models with very different limitations, versatility and application prospects.

The author does not intend to state that comprehensive modelling of the type commonly done in the study of combustion (DNS studies, high level combustion chemistry studies, detailed local heat transfer analysis for flame quenching, etc. [20, 21]) has no place in fire safety, nevertheless its role is primarily to inform fire models and not to be fire models. Fire models should introduce simplified sub-processes that are developed from a combination of canonical experiments and detailed models. Only the combination of both will deliver sufficient understanding of the sub-process, provide direct validation and verification of the model and enable the reformulation of sub-process in a simplified manner that is amenable for introduction in the broader framework of a fire model. Important examples of the detailed analysis of these sub-processes abound in the micro-gravity combustion literature [101] and are of great value to the understanding of the sub-processes nevertheless very few of these studies have aimed to deliver a simplified formulation that then can be introduced into a fire model. Removing the dominant role of buoyancy delivered the canonical experiment that enabled to explore in great detail numerous fundamental processes that are masked in a buoyantly dominated fire model. These processes, while masked by buoyancy, still have an important influence on the overall progression of the fire.

When exploring the literature on the advances of chemical kinetics and their contributions to combustion modelling, the use of canonical experiments like the perfectly stirred reactors allowed the development of combustion chemistry under constant turbulence conditions [124]. These studies delivered simplified chemical kinetic models and constants that then could be introduced into detailed combustion models to study the role of turbulence in combustion [125, 126]. Subsequently, reduced mechanisms and turbulent models were applied successfully to realistic problems such as turbine engine combustion [127]. This approach is not only less frequent in fire, but it is less comprehensive, when a simplified model is developed from a combination of a canonical experiment and detailed modelling, it rarely makes its way to the fire model.

With the exception of a few notable cases, much of the knowledge acquired has not managed to migrate into fire models. This is not because the knowledge acquired is not good or relevant but because it has not been possible to demonstrate its relevance to fire safety. The argument is simple, what is the point to further understand these sub-processes or their couplings to deliver a better fire model if at the end, scenario variables will introduce variants that will completely overrule the improvements associated to a better definition of the sub-process? As a result fire models continue to rely on simplifications that were developed on the basis of very strong, scenario specific or unverified assumptions. These simplifications (and their coarse nature) were introduced for models with a different level of resolution, where the framework did not merit the detail (e.g. analytical or zone models). Decades of research have demonstrated that more detailed and better defined models cannot produce results that are more relevant to fire safety. Scenario uncertainty has always overruled the need for more understanding or better resolution of the sub-processes and their couplings.

Given that fire modelling is no different than any other complex process, predictive modelling requires understanding of the fundamental sub-processes and their couplings. With this understanding, simplifications can be introduced to enable modelling of the combustion process within the context of its environment [128]. It is the fundamental understanding that will deliver the required robustness and will enable linking the sub-processes and couplings to the outcome. Nevertheless, this fundamental scientific path can only be deemed relevant
to fire safety if the impact of scenario uncertainty is reduced to a level smaller than the uncertainty of the model.

The answer to the problem of scenario uncertainty was first established within the weather forecast community several decades ago. Weather data from all over the world is used to initialize (data assimilation) a model prediction. The model then extrapolates the evolution in time of the weather patterns. As new data is collected, a new model is launched with a new set of initial conditions and a new extrapolation is derived. Most modern weather prediction models assimilate observations during a certain period of time (assimilation window) before starting the forecast. This is done in order to account for the dynamic coupling of the involved processes [129]. When consistency between predictions and acquired data is obtained, then it can be deemed that there is a period of time where the model can effectively reproduce reality with a relevant precision (lead time). While this approach is consistent with the needs of fire modelling, the extrapolation from one field to another is not straightforward. In fire, like in weather, conditions evolve in time, thus initializing the simulation by means of data is necessary but not sufficient. The scenario uncertainties are embedded in the boundary conditions but also the fire influences the time evolution of the boundary conditions. Thus, the data being assimilated needs to be sufficient to recreate initial and boundary conditions at a relevant level of precision. In this manner the breakage of a window or the presence of a blanket (boundary conditions) can be deducted from the combination of data and modelling.

Several inverse modelling studies have been undertaken in the last few years. Richards et al. [130, 131] used a zone-type model and experimental ceiling jet temperatures to estimate the location of a fire and the coefficient of a quadratic fire growth function such as that presented in Equation (2). The experimental data was obtained from the literature and by using temperature sensitive plates and cameras. The model used an axis-symmetric plume as source term, ceiling jet correlations to establish the spatial decay of the smoke temperature and an optimization algorithm to establish a best fit between sensor data and a library of solutions to the zone model. This data allowed using the model to determine a unique fire size and location at the moment when a detector was activated (temperature criterion). The authors found that the accuracy of the fire growth estimations was very sensitive to the nature of the physical model but that the location of the fire could be established in a much more robust manner. While the study discusses numerous ways to quantify errors they do not establish how the limitations of the physical model, the different sub-models (plume, ceiling jet, etc.) and the nature of the data assimilated affected the potential for the combined data and model to deliver predictions.

Similar zone models were used by Leblanc and Trouvé [132] and by Koo et al. [133] In the former study pre-runs were fed to the model to extract successful estimations of the heat release rate evolution while the latter used experimental data to progressively steer the fire simulations towards the experimentally measured temperatures. Koo et al [132] use a Monte Carlo approach where a set of initial parameters was used for random generation of scenarios. In both cases the data (real or simulated) was used to quantify a series of constants that allow to reproduce the variables of interest but it was not established if these constants were invariant, thus providing a data calibrated model that could deliver a prediction. This final point is of critical importance because, if the physical processes are described with sufficient accuracy and completeness, then the calibrating parameters should attain a constant value after sufficient data has been assimilated. Jahn et al. [134] follow a similar approach but described in an explicit manner three invariants, “α” as per Equation (2), an entrainment constant (C) and a time delay intended to displace the onset of the fire growth curve (Equation (2)). The data used for assimilation was obtained from the results of a CFD
simulation for a very simple scenario of a small compartment with homogeneous fuel distribution where the fire spread in a radial manner at a pre-specified rate. Even with a simple formulation, such as a zone model, Jahn et al. [134] managed to establish that convergence of the constants could be achieved. It is clear that the simple nature of the scenario is best fitted for the zone model, thus these results do not necessarily demonstrate that a zone model provides all the necessary physical complexity required for a case such as the Dalmarnock tests. A follow-up to this work used a similar approach but instead of a zone model used a CFD model with a coarse grid resolution [135]. The description of the fire source was initially similar to that presented in the earlier work and the data to be assimilated was generated by a more refined CFD computation. The assimilation process delivered more precise resolution of the different variables albeit at a much higher computational cost. In a final study the same authors use the same model with the Dalmarnock fire data to deliver accurate predictions of all relevant variables with an effective lead time [136]. In this latter scenario it is necessary to introduce a more detailed fire growth formulation that incorporates geometrical features and a flame spread velocity. The flame spread velocity is then addressed independently [137] to demonstrate that a simple model [13, 81] can be used with relevant data to predict the spread of a flame. Only when these components are introduced the invariants converge indicating that the physical processes used suffice to deliver adequate predictions of all relevant outputs.

These initial studies have demonstrated that by assimilating sensor data into models it is possible to account for scenario induced uncertainties, but only if the processes and couplings involved are described with sufficient level of detail. Furthermore, the assimilation of data into models enables a better interpretation of tests results, identification of controlling mechanisms and improvement of the sub-processes involved and the couplings that eventually lead to a fire model.

Conclusion

Fire Safety can only be Scaled-Up if the combustion process involved can be modelled within the context of their environment (fire modelling). Many forms of fire models exist but only the use of explicit fire models is acceptable in a world that strives for sustainability. Being combustion one of the fundamental processes within fire modelling and a component that could be refined by means of research. The relevance of combustion research to Fire Safety is defined by the transparency by which this research can be linked to the precision, completeness and robustness associated to the Scaling-Up of Fire.

The link between refinements in the combustion processes involved in fire modelling and the potential improvements in a fire safety strategy is generally blurred by the complexity of the processes involved, the natural incompatibility of time and length scales and the unavoidable scenario uncertainty. In this context the use of CFD as a basis for the Scaling-up of fire has a very clear gain. Classic tools, while still relevant, will be limited to the simpler and more conventional applications leaving little motivation for further refinement.

Predictive modelling requires understanding of the fundamental sub-processes and their couplings. With this understanding, simplifications can be introduced to enable modelling of the combustion process within the context of its environment.

Adequate experimentation is critical not only to develop the necessary understanding but also for validation, verification and improvement of fire models. Combined use of models and experiments requires multiple strategies:
• The study of sub-processes in isolation.
• The study of the coupling between the sub-processes and their interaction with their environment using experimental data obtained specifically for the purpose of model validation and of a scale that incorporates relevant complexity and captures all couplings and interactions
• _A priori_ studies with a single user should be conducted to assess model capabilities and a Round Robin to establish the robustness of the model to the user
• _A posteriori_ studies should be conducted to identify sub-process or couplings that are either properly modelled or that introduce significant errors
• Validation, verification and improvement experiments need to be defined for a specific purpose that is consistent with the state of the art of the models.

Currently, fire models have not been tested following this level of rigour and available experiments have not been defined with this methodology in mind.

In the last 20 years many fundamental studies have been conducted to achieve a better understanding of the sub-processes involved in fire modelling. Nevertheless, most of this knowledge has never been transferred to fire models because its _relevance_ has been challenged by the overwhelming impact of scenario uncertainty. Thus, scenario uncertainty represents a major challenge to the _relevance_ of combustion research for Fire Safety applications.

An effective means of tackling scenario uncertainty is data driven inverse modelling. Data driven inverse modelling requires the assimilation of adequate input data but also fire models that are specifically designed for that purpose. Through the assimilation of _relevant_ data the output will be no longer subdued to scenario uncertainty.

It is at the level of the fundamental processes that predictive fire modelling and data driven inverse modelling meet. A fundamental understanding of the combustion processes enables the introduction of all the necessary variables that affect the outcome of a specific sub-process as well as the couplings between the sub-processes. It is this understanding that then enables confident reformulation of the model in a manner that provides the resolution required by a fire model or in a form that is amenable for data assimilation. The link between the sub-processes, their couplings and the output can then be established through a fire model and any improvements or refinements can be directly linked to an improved output. The improved output can then be used for a better definition or assessment of a fire safety strategy establishing the _relevance_ of combustion research in Fire Safety. It is by means of this approach that _Scaling-Up_ of fire can be achieved.

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References


Applications of Heat Transfer Fundamentals to Fire Modeling
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Abstract
The fire industry relies on fire engineers and scientists to develop materials and technologies used to either resist, detect, or suppress fire. While combustion processes are the drivers for what might be considered to be fire phenomena, it is heat transfer physics that mediate how fire spreads. Much of the knowledge of fire phenomena has been encapsulated and exercised in fire modeling software tools. Over the past 30 years, participants in the fire industry have begun to use fire modeling tools to aid in decision making associated with design and analysis. In the rest of this paper we will discuss what the drivers have been for the growth of fire modeling tools, the types of submodels incorporated into such tools, the role of model verification, validation, and uncertainty propagation in these tools, and possible futures for these types of tools to best meet the requirements of the user community. Throughout this discussion, we identify how heat transfer research has supported and aided the advancement of fire modeling.

Introduction
On this occasion of the 75th anniversary of the ASME Heat Transfer Division, we provide an overview of the fire industry and discuss how heat and mass transfer fundamentals are applied in fire modeling. The fire industry, which will be discussed shortly, relies on fire engineers and fire scientists to advance materials and technologies used to either resist, detect, or suppress fire. Fire, as a phenomenon, might be considered wild and untamed combustion. So, while combustion processes are the drivers for fire phenomena, the engineering of systems to address the fire’s development is central to fire engineering. The fire industry is a vast enterprise that touches on many aspects of the economy. Starting with manufacturing companies, one finds that there is a supply chain that continuously evaluates how fire impacts their products. Chemicals and materials companies form one group of companies in the fire economy. These enterprises seek to deliver materials that are more resistant to thermal degradation and subsequent ignition. Manufacturers of finished products, whether consumer goods or industrial goods, are constrained in their choices of designs and materials by the effect that these choices might have on the ignition and burning characteristics of the delivered product. The construction
industry, both for residential and commercial structures, is strongly constrained through building
codes to produce structures that meet underlying life safety requirements. To make the built
environment safer, there are product companies that continue to innovate in fire detection, alarm,
and suppression systems. While many of these technologies are intended to operate autonomously, there are also fire mitigation technologies intended for use by the fire service. In
the United States alone there are over one million fire fighters who use continually improved
tools and equipment to fight fire. The service component of the fire industry includes public
safety personnel, research and testing organizations, standards organizations, insurance firms,
legal firms, and others. For the various stakeholders in the fire economy, answers are sought on
how fire affects the particular issues that they deal with.

Much of the knowledge of fire phenomena has been encapsulated and exercised in fire
modeling software tools. Over the past 30 years, participants in the fire industry have begun to
use fire modeling tools to aid in decision making associated with design and analysis. In the rest
of this paper we will discuss what the drivers have been for the growth of fire modeling tools, the
types of submodels incorporated into such tools, the role of model verification, validation, and
uncertainty propagation in these tools, and possible futures for these types of tools to best meet
the requirements of the user community.

Why Model Fires?
One of the primary drivers for development and use of fire models has been the growth of the
fire protection engineering field. Fire protection engineering - the design of buildings to protect
people and property from fire - is at the beginning of a major evolution. This evolution is
moving away from designing buildings based on specific rules and towards designing based on
predictions of what would happen in the event of a fire. This evolution is changing the codes
and standards used to regulate building construction from "prescriptive" to "performance based."
Advances in fire modeling capabilities plays a key role in enabling and facilitating this change.
This evolution is not unique to fire protection engineering. Other engineering disciplines
evolved in response to advances in understanding of their underpinning science. Over the past
century, fields like mechanical engineering and structural engineering have evolved as new
materials, manufacturing processes, and engineered systems pushed the boundaries of existing
knowledge and technical capabilities. These changes facilitated innovation in those disciplines.
Similarly, fire protection engineering has been influenced by improvements in the understanding
of fire science and societal desire for new, cost effective, and innovative building designs.

Almost all buildings today are designed and constructed to meet the provisions of
prescriptive codes and standards. These prescriptive codes and standards describe what is
acceptable or not acceptable in specific terms. Fire safety provisions include what types of fire
safety systems should be installed in buildings and acceptable building geometries. Most
engineering design resources are expended on commercial properties, and commercial properties
perform very well in fire. For example, in 2011, there were 3,005 civilian fire deaths in the
United States. Of these deaths, 2,520 (84%) occurred in a home (Karter, 2012). Fire protection
engineering is generally not applied in the design of residential buildings, but is used in the development of tests for characterizing the construction materials and finished products used in a house. The economics of the fire industry are staggering. In the United States alone, direct and indirect fire costs represent approximately 2% of the GDP (Hall, 2012). These costs range from the cost of fire protection and mitigation to the additional costs of construction associated with adherence to fire safety provisions to the cost of fire losses.

Blind adherence to fire provisions that have not necessarily evolved with changes in materials, technologies, and knowledge has negative consequences. One fundamental tenet of engineering is providing the necessary level of safety at the most reasonable cost. While the buildings to which engineering has traditionally been applied have an excellent history of fire performance, they also have an unknown safety margin. Ideally, model-based fire design would be useful to assessing the marginal cost for a specified level of safety. The use of performance-based design and fire models would allow the fire protection that is provided in a building to be tailored to the characteristics of the building, the items stored within the building, and the people that would use the building.

Another fundamental tenet of engineering is to incorporate the best available scientific knowledge into tools and processes. Application of prescriptive design typically is accomplished with minimal reference to the engineering and scientific literature. This results in an unknown and inconsistent level of safety. Structural fire resistance can be used as a case study. Consider three relatively recent fires that occurred in the United States – One Meridian Plaza, Philadelphia, 1991 (Routley et al., 1991); First Interstate Bank, Los Angeles, 1988 (Routley, 1988); and the World Trade Center towers, New York City, 2001. In the case of One Meridian Plaza and the First Interstate Bank, both buildings withstood fires of very long duration. However, the World Trade Center towers collapsed after 102 minutes and 57 minutes of fire exposure, respectively (Milke, 2003). While the fires in World Trade Center were ignited by aircraft collisions, the bulk of the fire exposure resulted from ordinary combustible material and not jet fuel (Milke 2003). Although the fires did not start in the same manner, each of the fires in these buildings was similar in magnitude, but may have provided a different thermal load to the structural components. Regardless of the performance intended by compliance with prescriptive codes, these buildings did not all perform in a similar manner. Heat transfer processes couple the fire to the structure and should be modeled in a meaningful way for inclusion in structural performance-based design. Through a validated performance-based design process, structures could be designed such that structural fire performance would meet the needs of the community and the building owner in the most efficient means possible.

Early (pre-1900’s) fire protection requirements were generally prescriptive, with such requirements as the permissible materials from which building exteriors could be constructed or the minimum acceptable spacing between buildings. It is notable that while not explicitly identified, the choice of building materials and the spacing requirements were associated with underlying heat transfer processes. Most modern building and fire code requirements more explicitly have some element of performance associated with them, which can enable the use of
Performance-based approaches for designing building fire protection can be traced to the early 1970’s, when the Goal-Oriented Approach to Building Fire Safety was developed by the United States General Services Administration (Custer and Meacham, 1997). The GSA approach was developed to help the United States government evaluate fire safety in high-rise buildings. Over the 1970’s, the GSA work continued to evolve, spawning the Fire Safety Evaluation System (ultimately published as NFPA 101A), the Building Fire Safety Engineering Methodology, and the Fire Safety Concepts Tree (NFPA 550).

The GSA and subsequent works were published as guidelines, meaning that they could be used as a voluntary alternative to strict compliance with prescriptive codes. In 1985, the first performance-based code was published – the performance-based British Regulations. New Zealand published a performance-based building code in 1992, and Australia followed suit in 1995. Other major developments in performance-based design include the following publications:

- Performance Requirements for Fire Safety and Technical Guide for Verification by Calculation by the Nordic Committee on Building Regulations in 1995
- Performance option in the NFPA Building Code in 2003

Each of these published documents facilitated the use of fire models in the design of buildings.

Beyond the design of structures, fire models are increasingly used in forensic analyses. A fire loss may be analyzed to determine the cause and origin and contributing factors. Fire models allow the analyst to hypothesize a scenario and determine if the modeled results of the scenario are consistent with observations from the fire. Forensic analysis in fires is an extremely challenging inverse analysis process since the fire destroys much of the evidence of the factors that created it. Nevertheless, the fire leaves signatures even after consuming many parts of the structure. The National Fire Protection Association’s Guide for Fire and Explosion Investigations (NFPA 921) provides guidance to fire investigation professionals to improve the overall quality of the fire investigation process. The fire investigation process is used to assess if improvements can be made in codes and standards after major losses have occurred. The process is also used in civil litigation and criminal prosecution to determine culpability when fire has caused damage, injury, or death. In the civil litigation context in the US, while insurance companies will likely issue some initial settlements, the subrogation process is used to assess
responsibility to the various parties involved in the litigation. In the litigation, fire investigators, fire engineers, and fire scientists serve as expert witnesses using their expertise in fire evolution to propose or refute various hypotheses on how some aspect of the fire took place. Experts serve in similar capacity in criminal prosecution in the US, but unlike in civil cases, a defendant in a criminal case could be given a death sentence based on evidence and witness testimony. The gravity of this consequence should require a process and standard for hypothesis testing that is as stringent as can possibly be devised. Fire models are more routinely being used in both civil litigation and criminal prosecution. There should be a path forward on how to incorporate the uncertainty inherent in any given model into a hypothesis testing standard.

Physics and Submodels
The typical structure fire in the United States takes place in a single family residence. While the most likely room for a fire to start is the kitchen, these fires tend to be more monitored than fires that begin in other parts of the home. Undetected fires often begin when a heat source such as a compromised electrical connection, unmonitored candle, or improperly discarded cigarette heats up some organic mass of material. The heat source heats the material until the material begins to pyrolyze wherein volatile material is released from it. Depending on the local flow conditions, type and arrangement of the material, and intensity of the heat source, the pyrolysis process could lead to smoldering combustion or transition into gas phase flaming combustion. If a flame develops, the flame spreads over the fuel surface in what is essentially a continuous ignition process. With increased flame spread and as more of the fuel material is consumed by the fire, the fire products and plume can begin to accumulate in sufficient concentration in the upper regions of the room that the heat transfer from this region begins to affect the overall heating rate of all fuel material within the compartment. The upper layer radiative heating increases the burning rate dramatically, if there is enough oxygen within the room. Fire models have been developed to predict the evolution of any given fire scenario. Deterministic fire models have evolved over the past 40 years to the point where there are three basic types: empirical correlations, zone models, and computational fluid dynamics (CFD) models. The correlations were developed in the 1970s and 1980s as a combination of classical buoyant plume theory and well-stirred reactor concepts. Using estimates of the fire’s heat release rate and the basic compartment dimensions and material properties, it became possible to predict average hot gas layer temperatures, sprinkler activation times, and the time to flashover (where the compartment becomes oxygen limited and engulfed in flames). These correlations are simple, robust, and remain to this day a primary component of any fire protection engineering design. However, the correlations were limited to single compartments and very simple geometries, and there soon became a need to model a series of compartments or even an entire building. Thus, in the 1980s, the two-zone models were developed. The basic idea of these models is that a fire creates two distinct thermal layers in a compartment, and pressure differences between compartments drive heat and smoke from one to the other. A zone model is essentially a stiff system of ordinary differential equations that can be solved in seconds to simulate the spread of
smoke and heat throughout a building. As zone models became widely used through the 1990s, geometrical limitations once again drove the profession towards more complex modeling tools. Computational fluid dynamics (CFD) codes were soon being developed for fire specific problems. An overview of the issues in CFD modeling of fire is provided by McGrattan (2005). With CFD, there is no need to limit the computational domain to conform to the basic two layer concept, and, thus, a much wider array of applications opened up, coinciding with the architectural trend towards unconventional building design.

Regardless of type, what distinguishes a fire model from any other type of simulation tool is the source term in the energy conservation equation; namely the fire. The fundamental physical process that drives fire phenomena is the combustion process which can occur either in the gas phase, or within a porous medium, or on the surface of a material. In the overall evolution of a fire, the gas phase flaming reaction represents only one part of the overall dynamic. Torero (2012) detailed the role of combustion science in fire safety engineering. The following discussions consider the same physical processes noted by Torero, but more narrowly discuss the roles of heat and mass transfer analysis to the overall system level modeling. The discussion also identifies the role of data reduction models, many of which require heat and mass transfer models, in advancing the theoretical bases used in fire modeling.

Pyrolysis
In fire applications, the fuel is often an inhomogeneous condensed phase material. A significant part of fire modeling is characterizing the thermophysical and chemical properties of arbitrary engineered materials. One requirement of the modeling process is to be able to describe solid thermo-chemical pyrolysis. While the chemistry and the mechanical evolution of the materials have a significant effect on pyrolysis, the amount of fuel produced is also strongly coupled to complex heat and mass transfer processes. The temperature of the material, initially at ambient, increases with convective and/or radiative heating of the material’s surface. Because the radiative heat flux in fire scenarios is often larger than the convective flux, it can be important in some scenarios to properly couple the details of the radiative heat flux to the condensed phase fuel. The evolved pyrolysis products from the condensed phase decomposition may modulate the incident radiative field near the condensed phase interface. Typically, the highest temperatures will be achieved close to the surface, but energy transfer in-depth will result in a spatially and temporally varying internal temperature distribution. For some scenarios, it is important to characterize the radiative field coupling within the condensed phase. In general, however, for a decoupled analysis of solid pyrolysis, the evolution of the in-depth temperature field is modeled using an energy balance in a control volume limited by the surface of the material for which the surface energy balance sets a boundary condition.

Pyrolysis tends to be an endothermic process controlled by many chemical reactions which are strong functions of the temperature. Most pyrolysis reaction rates tend to be described by Arrhenius type dependence on the temperature. Depending on the fuel, heating characteristics, and local gas phase species constituents, the pyrolysis process can follow
distinctively different paths. Because it is difficult to in-situ sample pyrolysing materials in the
same way that one can probe gas phase systems, a much less resolved picture exists of the
chemical pathways. These paths can be a compendium of numerous reactions that could be
sequential or compete against each other. Furthermore, the chemical pathways can be strongly
influenced by the presence of oxygen (Hirata et al. 1985, DiBlasi et al, 1993). The effect of
oxygen on the degradation kinetics emphasizes the importance of mass transfer effects within the
material. In-depth oxygen diffusion is controlled by the structure of the solid. Some materials are
highly permeable and allow unrestricted transport of species in and out of the solid. The
permeability of the fuel can be a function of many variables including the degradation and
consumption of the material and has deserved very little attention in the fire literature. Oxygen
concentrations will be controlled by the local permeability and by production/consumption rates,
thus indirectly by the temperature distribution. The effects of permeability and pressure are
combined in a complex manner to define the flow within the porous fuel medium. This remains
an unresolved problem.

For charring materials, pyrolysis leads to the production of gaseous fuel (pyrolyzate) and
a residual solid phase char. The char is mainly a carbonaceous solid that could be further
decomposed. The secondary decomposition could be complete, leading to an inert ash or to a
secondary char that can be further decomposed in a single or multiple steps. Non-charring
materials decompose leaving no residue behind. One approach to providing global
characterization of the pyrolysis process is to apply thermal analytical methods to thermally
decomposing materials.

Often, the kinetics of degradation are parameterized using experiments like
thermogravimetric analysis (TGA). In TGA a sample of a material is subjected to a heating
history while the mass of the sample is measured as the sample thermally decomposes.
Typically, sample sizes for these materials are considered to be sufficiently small that transport
time scales are fast relative to chemical decomposition time scales. Hence, the samples can be
considered to be thermally and chemically lumped. By assuming that heat and mass transfer
processes within the sample are fast relative to the chemical time scales, the mass loss rate is
then controlled by the decomposition kinetics. Rate parameters can then be derived from the
mass loss rate data, but there are concerns that such data do not adequately represent the true
decomposition processes associated with heating rates associated with fires (Conesa, 1996;
Burnham and Weese, 2004; Bruns and Ezekoye 2009). Additionally, as research progresses on
the effects of inorganic micro and nanoscale additives on flammability, questions are being
raised on the role of heat and mass transfer physics on experimental observations (Kashiwagi et
al., 2005).

Other details of the decomposition process can be found from tests like differential
scanning calorimetry (DSC) (Höhne et al., 2003, Stoliarov, 2008). In DSC two cells, one with a
reference material and the other with the sample under consideration are heated with a prescribed
temperature time history. Differences in the amount of heating required between the two
samples is used to infer the effective thermodynamic parameters of the sample in question. The
data reduction model for the DSC could either be limited to the sample model or could include
the furnace and reference material models. Both TGA and DSC based studies tend to produce
the relevant constants for reduced chemical mechanisms that represent the complex degradation
process. Given that the reaction rate is a strong function of temperature, it is clear that the
adequate resolution of the energy equation is paramount in defining the degradation rates.

Prediction of evolved species from the degrading material is important in the ignition
phase of a material and may be important in describing the products of flaming combustion. As
in other heat and mass transfer applications, computations and models at atomic and molecular
scales have begun to play an ever increasing role in characterizing physical processes. The
connection between macroscopic and continuum descriptions of material evolution and atomistic
descriptions has been made using modified classical molecular dynamics simulation concepts.
Various flavors of reactive molecular dynamics (MD) simulation tools and techniques have
evolved wherein the electronic and atomic potential energy surface modifications are included in
classical MD models as submodels to describe bond breakage steps (Stoliarov et al., 2003;
Nyden et al., 2004; Smith et al., 2011). Quantum chemistry calculations are performed offline
using either ab-initio tools or hybrid approaches like density function theory to inform the
reaction chemistry of the models (Car and Parrinello, 1985).

Because the chemical pathways leading to the pyrolysis of most solid fuels of interest in
fire are unknown, many studies have sought to develop reduced chemical mechanisms for the
pyrolysis of specific solids following the initial approach of Rein et al. (2006) and Lautenberger
et al. (2006). Even for reduced mechanisms, there is still great uncertainty on the chemical
pathways, the number of reaction steps required and the parameters associated with them. Data
reduction models, used to test these mechanisms and fit the parameters, rely on complex heat and
mass transfer models that are coupled with the reduced chemical degradation models containing
the unknown parameters. Because of the large number of parameters and degrees of freedom
that need to be explored by the optimization process, the required amount of experimental data
required in the optimization process (TGA, DSC, cone calorimeter) often becomes infeasible.
Even the nature of these experiments and associated uncertainty in the data propagates further
uncertainty into the calibrated parameters (Carvel et al., 2011 and Rogaume et al., 2011).

At the continuum scale, fuel decomposition models should also be able to describe heat
and mass transfer processes within arbitrary condensed phase materials undergoing thermal
degradation. While a framework exists to model such processes using, as an example, the
formalism developed for porous media heat and mass transfer (Kaviany, 1991), the details
associated with characterization of thermophysical and transport properties remain a challenge.
Further, it is generally unclear how to properly specify the appropriate level of complexity
required in any particular analysis of a complex composite system in which there are synergistic
effects between the materials due to manufacturing features etc. The coupled effects of
decomposition and transport are evident when one considers the range of actual degradation
behavior that potentially exists in fire scenarios. Common polymeric materials in fire
environments range from thermoplastics to thermosets. There are materials that melt and drip,
while others form a char layer. These gross changes to physical configuration of the material often affect the overall evolution of the fire (Ohlemiller, 2000). At the fundamental level, melt flow depends on the temperature, morphology, and molecular weight distribution of the polymeric system (Berry and Fox, 1968). The fluid mechanics, heat transfer and materials processing literature has developed various ways to model melting and flowing polymeric systems (Denn, 1990; Jaluria, 2001). Because of melting and melt flow, a localized fire could spread by burning droplets or a flowing melt stream to other adjacent fuel packets.

**Ignition**

Ignition is a competition between the exothermic energy release rate and heat losses from the reacting gases to unreacted gas and to the condensed phase fuel. Obviously, a flammable mixture is required before flaming ignition can occur. Before flaming ignition can occur, a sufficient concentration of fuel vapor needs to be available in the gas phase. The solid decomposition products in the gas phase depend on many factors and might be a combination of solid phase pyrolysis and oxidation products. Thus, the product composition might include fully oxidized compounds such as carbon dioxide ($CO_2$), partially oxidized gases such as carbon monoxide ($CO$) and other molecules that can have varying levels of partial oxidation. As an example, Kashiwagi and Nambu (1992) studied the degradation products of cellulosic paper showing that there is a significant presence of inert gases like water vapor, fully oxidized gases like $CO_2$, partially oxidized products like $CO$ and unoxidized species like $CH_4$ and $H_2$. There is very little data available on the degradation products of most materials relevant to fire, therefore, the mass fraction of flammable gases present in the local products of degradation is generally described by means of a global contribution of all compounds that can be further oxidized. This suggests that together with the gas phase reaction rates, the decomposition products concentration must be known to model ignition.

After pyrolysis gas begins to emerge from the fuel surface, the emerging fuel will encounter the ambient oxidizer and possibly produce a flammable mixture. Given that a complex fuel flow is migrating into the oxidizer flow, the definition of a flammable mixture region is not a simple one. In standard test methods the ambient flow is well defined but in real fires, flow fields are defined by the flames themselves and by the geometry of the environment (obstacles, fuel geometry, etc.) with the possibility of complex flow patterns. After a flammable mixture has been attained, this mixture needs to increase in temperature until a combustion reaction can occur. This process is described in great detail by Fernandez-Pello (1995). Nioka et al (1981) identify an induction time and a pyrolysis time. The pyrolysis time corresponds to the time required to attain a flammable mixture while the induction time is the time for the mixture to reach a temperature at which ignition can occur.

The amount of energy required for ignition can be associated to a Damköhler number (Williams, 1985). The Damköhler number corresponds to the ratio between local residence and chemical times. The chemical time represents the necessary time for the reaction chemistry to occur and is expressed as the inverse of the reaction rate. A critical Damköhler number for
ignition can then be established, above which a combustion reaction can proceed. This is probably the most precise way to describe ignition but it requires the full resolution of the flow and temperature fields as well as comprehensive knowledge of the kinetic constants associated to the combustion reaction. While the flow field can be resolved by means of Computational Fluid Dynamics (CFD) the chemistry of most fire related fuels still remains uncertain. Qualitative assessment of the Damköhler number for ignition has only been achieved for a few very well defined experimental conditions such as stagnation flows or boundary layers (Quintiere, 2006).

Auto-ignition in its simplest form is a competition between the exothermic energy release rate associated with oxidation and heat losses from premixed fuel charge. Data on auto-ignition is generally reported as Auto-Ignition Temperatures (AIT) which corresponds to a recorded temperature at the moment where ignition of a flame is first observed. A summary of much of the data available is presented by Babrauskas (2003). Given the complexity of the processes leading to auto-ignition, these values can only be taken as reference values that are a direct function of the specific test conditions. Generally, significant discrepancy is found in the literature with reported Auto-Ignition Temperatures varying more than 150 °C for a given material.

In practice, ignition is initiated by a pilot flame, hot gases, or hot element. From the perspective of ignition, the exposed solid surface represents not only a boundary between the gas and the solid, but also a potential ignition site. While regression rates can be very different between charring and non-charring materials, at the surface, the main difference between the two material types is the temperatures that can be achieved during pyrolysis. Carbonaceous chars in ambient oxygen environments can reach much higher temperatures than non-charring surfaces. In many cases, vigorous oxidation often termed surface glowing, can initiate gas phase ignition. The actual temperatures reached by the oxidizing char are controlled by heat transfer through the char, transpiration cooling by the fuel produced in-depth, and radiative losses from the glowing surface char.

The presence of a pilot can simplify modeling of the gas phase ignition processes and somewhat reduces the influence of environmental variables. Characterization of the flow field is still required to establish the presence of a flammable mixture and heat transfer between the hot element and adjacent premixed fuel mixture. For some global models, ignition can be assumed to occur at the moment where the lean flammability limit (LFL) is attained at the location of the pilot. To attain the LFL at the pilot location it is necessary to resolve the momentum and mass transport equations simultaneously with the surface boundary conditions.

Given a flammable mixture and an ignition source, the pyrolysis rates at the moment when the flame is established will determine if a flame can continue to exist or if the combustion reaction will cease after the premixed gas mixture is consumed. The feedback from the ignited flame will enhance pyrolysis, but usually, the relatively large thermal inertia of the solid will result in a slow response, therefore it will be necessary for pyrolysis rates to already be sufficiently large even in the absence of the flame heat feedback. If pyrolysis rates are not sufficient, the flame will extinguish and continuous pyrolysis will lead once again to the
formation of a flammable mixture and subsequent ignition. This manifests itself as a sequence of flashes that precede the establishment of a flame over the combustible solid. This process is identical to the “flash point” generally associated to liquid fuels and for solid fuels has been described in detail by Atreya (1998).

The transition between the “flash point” ignition and the established flame, which could also be named the “fire point” in an analogy with liquid fuels, deserves especial attention. The characteristics of the diffusion flame established on a solid fuel surface are defined by the flow field and the supply of fuel. The rate at which both reactants reach the flame zone defines the flame temperature and thus the characteristic chemical time. If the amount of fuel reaching the flame is small, then the flame temperature will be low and the chemical time will be long. As described above, the flow field defines the residence time. A second critical Damköhler number appears, but this time is one of extinction. This concept has been described many times explicitly in the combustion literature (Williams, 1985) but only implicitly in the fire literature. In most discussions simplifications have been assumed leading to simpler parameters that can serve as surrogates for the Damköhler number. Williams (1985) discusses a critical gas phase temperature below which extinction will occur. If the residence time remains unchanged, then extinction is only associated to the chemical time, thus can be directly linked to a critical gas phase temperature. It can be further argued that extinction is much more sensitive to temperature than to flow, thus only radical changes in the residence time need to be addressed making this criterion a robust one. A more practical surrogate to the Damköhler number is a critical fuel mass flux criterion. The concept of critical fuel vapor mass flux for ignition resembles elements of premixed flame quenching. The attainment of a critical mass flux of fuel will be the single parameter defining the flame temperature and thus the Damköhler number (Rasbash et al, 1986). Furthermore, under more restrictive conditions the critical mass flux can be associated to a critical solid phase temperature (Thomson et al., 1988).

Combustion

Once gas phase ignition has occurred heat and mass transfer processes allow the flame to creep across the fuel, this process is referred as flame spread and has been the subject of many studies in the literature. Flame spread is effectively a sequence of ignitions, therefore will not be described here. A summary of the different flame spread studies is provided by Drysdale (2011).

A flame is described by thermal and diffusive balances with extremely sensitive temperature dependent reaction terms. The characteristic length scales in flames defined only once one appropriately characterizes the thermal and mass transport thermophysical properties. Because of the disparate length scales in a practical fire scenario, the length scale ratio between a typical flame thickness and the compartment geometry typically preclude the ability to describe the flame with adequate resolution. There are many issues to address when describing the gas phase chemistry evolution in fire models. More important than the details of the flame is that a model should be able to describe the gross heat release rate which produces the density change and dilatation in the velocity field. Depending on the quantity of interest from the fire model,
this may not be the most important chemistry issue to address. Much of the hazard posed by fires is associated with the toxicity of incomplete products of combustion such as carbon monoxide, hydrogen cyanide, and soot coated with hydrocarbons (Pitts, 1995). Unlike many scenarios studied in combustion science, in fire modeling, the incomplete products of combustion, particularly CO, are non-negligible in their impact on the overall heat release rate of the combustion process. Significant amounts of carbon monoxide are produced in a typical compartment fire because of the relatively large global fuel to air ratio. Once a condensed phase fuel has ignited, the inefficient mixing of air and fuel in the fire produces copious amounts of incomplete products. Proper description of the evolving product soup requires knowledge of the chemical composition of the condensed phase fuel and its pyrolysis products. These are typically relatively large hydrocarbons that may be also bound to various trace chemicals used as flame retardants etc. Because gas phase combustion in fire is predominantly in non-premixed flames, the pyrolysis gases evolve in high temperature environments and begin to form soot. The kinetic description of soot evolution is extremely complex even for very simple fuels. One description is that polycyclic aromatic hydrocarbon molecules, formed in the pyrolysis gas mixture, coagulate to form nascent soot particles that then grow by surface addition of smaller hydrocarbon molecules and polycyclic aromatic hydrocarbons (PAHs) and by agglomeration (Frenklach, 2002; Öktem, et al., 2005). Predicting soot evolution is extremely important in fire modeling because the radiation heat transfer in fire is primarily associated with the soot species and because soot impacts sensor activation, human visibility, and respiratory irritation. Even for relatively simple and lower molecular weight fuels, it is very difficult to predict soot volume fractions in a flame to within a factor of two (Mehta et al, 2009, Saffaripour et al, 2011). In-situ measurements have been useful in better characterization of soot evolution.

**Thermal Radiation and Soot**

Fire evolution and spread is mediated by heat transfer rates. In practical fire modeling scenarios, radiation is the dominant mode of heat transfer (Sacadura, 2005). If one assumes a gray gas model for the gas mixture, and uses a Planck mean absorption coefficient for typical combustion product gases, one can easily show that when the soot volume fraction exceeds approximately 1 ppm, the soot absorption coefficient is larger than the gas absorption coefficient. In most practical fire conditions the soot volume fraction is much larger than 1 ppm in most of the fire. An exception to this rule is very near the surface of a liquid fuel pool. Because the fuel vapor has not necessarily had time to breakdown into soot, there is an abundance of fuel vapor that participates with the incident radiation. It is in this near surface region that a gray gas model might be most limited. Work in the heat transfer literature has been useful in parameterizing fuel spectral absorption coefficient models (Fuss et al, 1997). The spectral details of the absorption coefficient and its modification of the radiative intensity determine the true incident flux on the fuel surface. Depending on the interface’s radiative properties, these spectral effects could be important.
Typical measurements used to characterize the soot properties are laser based extinction experiments and laser induced incandescence experiments. Both extinction and LII measurements are grounded in heat and mass transfer fundamentals. Considerable effort has gone into developing detailed descriptions of soot morphology with a goal of better characterization of the soot radiation properties and soot transport physics. Sorensen and co-workers (e.g., Cai et al., 1995), Faeth and coworkers (e.g., Köylü and Faeth, 1994), and Mulholland and coworkers (Zhu et al., 2000) characterized the mass fractal and optical properties of soot aggregates. The morphological characteristics of soot aggregates somewhat modify their radiative emission properties but do not markedly change the absorption properties if reasonable approximations are made about the soot primary particle size and volume fraction. These changes in radiative properties are neither significant for measuring soot volume fraction by extinction nor for simulations of most compartment fires. Where these morphological effects do matter is in models for smoke detection systems. Smoke detectors sense smoke using either optoelectronic or mobility principles. In both cases, the morphological properties of the smoke play a role in the detection sensitivity. A model for the radiative scattering processes in smoke detector activation was reported by Upadhyay and Ezekoye (2005), and the role of soot fractal dimension on detector processes was discussed. For LII, Knudsen number effects on the cooling rates and subsequent interpretation of LII signal outputs have been useful in validating experimental techniques (Daun et al., 2007).

While soot primarily absorbs thermal radiation, water droplets from sprinkler and mist fire suppression systems scatter radiation. From a fire design perspective, water sprays/curtains are sometimes used as radiation shields. The heat transfer submodel in a fire model should be able to model droplet scattering physics (Dembele et al., 1997). Depending on the characteristic length scales of the droplet cloud, particles can either be modeled using either a Rayleigh limit or a geometrical optics limit. For intermediate scales, full Mie analysis may be required, but approximations are often made in the specification of the phase function. Additionally, the effects of both water vapor and water droplet size distribution may be included in the analysis as was done by Dembele et al.

Turbulence radiation interactions have been investigated in the literature to determine if including improved estimates of temporal and spatial temperature fluctuations affects radiative heat transfer predictions (Li and Modest, 2002). The nonlinear dependence of radiative intensity on temperature implies that for some applications, there will be significant deviation between the temporally and spatially averaged radiative emission relative to estimates based on the temporally and spatially averaged temperature.

In depth radiative transfer in some materials, particularly many polymer systems, has been shown to affect the thermal degradation and ignition characteristics of the material. As an example, Bal and Rein (2011) recently noted the importance of including in-depth radiation modeling to properly predict the ignition time of polymethylmethacrylate using a thermal ignition model. Thermal radiation induced damage and heating has also been important to characterize and analyze in the development of increasingly burn resistant protective garments.
for firefighters and warfighters. Mell and Lawson (2000) applied heat transfer fundamentals to characterize the mechanisms controlling the protective properties of firefighter personal protective equipment.

**Smoke and Convective Heat Transport**

Fire modeling has contributed to and borrowed from developments in computational fluid dynamics in developing gas phase flow models (McGrattan, 2005). In many respects, this is one area in which fire modeling has the strongest validation. While the turbulent flow processes can be quite complex and involve variable density and composition, there is an underlying physical model (i.e., Navier Stokes) that describes the flow evolution over a range of scales. The challenge in this area of modeling is in developing submodels for physics that occur at scales smaller than the computational grid. Fire gas phase flow modeling typically takes place in compartments with characteristic length scales on the order of meters. Dissipative length scales (whether Batchelor or Kolmogorov) are often millimeter or sub-millimeter for the velocities encountered in compartment fires. It is currently infeasible to simulate processes across the range of scales. There are many approaches to modeling subgrid scale mixing in CFD, but fire modeling has traditionally looked to the meteorological literature because of its emphasis on low speed, buoyancy-driven flow (Smagorinsky, 1963; Deardorff, 1972; Germano et al., 1991).

**Structural Response**

Structural components can be compromised either by high heat fluxes or by oxidative damage. It is necessary to be able to couple the combustion evolution with descriptors of structural evolution. The overall time scales over which structures evolve are considerably longer than the time scales associated with the flow processes. On the other hand, the spatial resolution required to model structural component thermomechanical evolution is at much more resolved scales than what is typically available from fire simulation. As such, sensible ways of coupling the fire flow evolution to the structural evolution are necessary. For many scenarios, the structural evolution can be decoupled from the fire flow evolution. There are, however, scenarios in which fire induced changes in the structure strongly modify the evolution of the fire. One obvious case in which the fire affects the structure which in turn affects the fire is window glass failure. As already noted, fuel loads for typical fire compartment scenarios are globally rich. In the fire literature, the resulting fires in such compartments are said to be ventilation limited. For ventilation limited fires, the heat release rate within a compartment is controlled by the oxygen mass flow rate into the compartment. Thus, a change in the availability of oxygen entering the compartment associated with a window breaking or a door being opened dramatically impacts the fire evolution. Time scales over which a door might be breached by a fire are considerably longer than the times required to fail a window. Simple models are available for window breakage that rely on the heat transfer rates to the window, the geometry and constraints on the glass (Cuzillo & Pagni, 1998). Given the variability in window types, age, and condition, one can perhaps only view such models as being statistically descriptive. Glass breakage models rely
on thermomechanical models for the glass and window system. Glass heating by convection and radiation is important to the overall model. Details like the insulating properties of the window cladding strongly affect the crack growth and propagation. Initial microscale features of any particular glass sample provide a state of stress on the boundaries (e.g., associated with the glass being cut) and in the interior that affect breakage. In spite of this complexity, it is extremely important to provide a means for implementing window/glass breakage into fire models because of how dramatically such failures affect the subsequent fire evolution.

A slightly simpler problem is the modeling of the behavior of structural systems in fire. In this case, the potential of a structural system to affect the nature of the fire is only as a thermal boundary condition until major structural collapse (usually late in the fire evolution) occurs. By exploiting the time scale differences, one can decouple the gas phase evolution and the solid phase and the fire becomes only the forcing for the heat transfer to the solid mechanics models (generally finite element models) that are normally used to establish the evolution of a structure (Usmani et al. 2001). Interestingly, the detailed mechanical properties of common building materials are not well known at elevated temperatures associated with fire (Hu et al, 2009).

To be able to define the temporal and spatial evolution of a structure during the event of a fire, the following issues need to be resolved:

1. The temporal and spatial evolution of the gas phase fire thermal, flow, and species fields should be known.
2. The evolution of the gas phase fields determines the temporal and spatial evolution of the heat exchange between the structural elements and the gases.
3. With thermal boundary conditions defined on the structural elements, detailed analysis can then take place for the structural elements. For materials like steel the transient energy equation consists only of heat conduction and enthalpy terms with variable thermal properties, but for other more complex materials such as concrete or plaster board, complex mass transfer equations need to be resolved to account for the vaporization enthalpy as well as moisture migration.
4. The spatial and temporal evolution of the temperature of the structural elements affects the material and mechanical properties of the solid which determine stresses and deformations within the structure.
5. The results of these calculations can be used to establish quantitative failure thresholds.

The comprehensive formulation of the problem requires the coupling of the gas and solid phases. Explicit finite element models coupled with transient CFD models become a necessity if the complete interaction is to be resolved. Despite many attempts to do this, there is currently no combination of models that solves the coupled effects of fire and structure. Furthermore, there is currently no CFD model that comprehensively resolves the fire at the necessary scale and with full detail. Finite element models are more advanced but many of the mechanical and thermal properties that serve as inputs are still unavailable.
Numerous alternative approaches can be found in the literature, some of them are well argued simplifications that use the characteristics of the problem to either relax the coupling between gas and solid phase or simplify certain terms of the equations. Among these simplifications are simplified connection models, constitutive property models, total heat transfer coefficients and spatial and temporal averaging of the gas phase. These simplifications take advantage of the very different time and length scales of the solid and gas phase problems to decouple and simplify many of the processes. When correctly argued these approaches are perfectly valid and provide a true assessment of the performance of the structure as well as quantified error bars linked to uncertainties and simplifications (Buchanan, 2002).

The equations used in simple numerical methods are derived from simplified heat transfer approaches. For example, a quasi-steady-state, lumped heat capacity analysis can provide the temperature rise of unprotected steel members, while for protected steel members, the thermal resistance provided by the insulating material can be accommodated by empirically derived correlations (c.f. the Structural Eurocodes methodology (CEN, 2005)). These approximate methods allow the designer to use any appropriate gas-phase temperature-time curve, but their generality remains uncertain.

Advanced models based on numerical heat transfer methods provide a more general approach and are becoming increasingly popular both in a research and industrial context (Cox and Kumar, 2002). Their advantages lie in the ability to define an arbitrary gas-phase boundary condition and to perform conjugate heat transfer calculations in which the surface temperature is obtained from the balance of the gas- and solid-phase thermal conditions (Patankar, 1980). The analysis is typically performed in three-dimensions, thereby overcoming the limitations of simpler approaches which consider only the in-depth direction. There is a significant challenge in achieving sufficient grid resolution within the solid, where much smaller cells are normally required due to the steep thermal gradients, especially when structured meshes are adopted (which may demand a similar cell size in the gas and solid phases) (Kumar et al., 2005); this can be overcome using unstructured meshes, or by coupling to an independent high resolution mesh within the solid, though in the latter case there will still be limitations associated with the resolution of the surface cells, e.g. where these are not able to fully resolve the details of the geometry, such as an I beam. In addition, temperature-dependent properties can easily be incorporated into the calculations for greater accuracy.

The resolution of the thermal gradients is necessary to model structural behavior in fire. Without precise thermal gradients phenomena such as connection behavior, thermal expansion, thermal bowing or tensile membrane action cannot be reproduced. These phenomena determine the evolution of the structure as it is being heated and allow identifying potential forms of failure (Usmani et al, 2001). Furthermore, the potential for concrete spalling is strongly defined by temperature gradients.

A second approach that is equally valid is that of establishing a series of constraints in the form of codes and standards. These constraints guarantee a simplified environment that can be quantified by means of a simple representation. The most common of these code based
constraints are the requirements for compartmentalization. By reducing all buildings to a summation of standardized compartments, the evolution of the fire can be reduced to an energy balance and thus both gas and solid phase behavior can be deeply simplified. This particular approach still provides a true assessment of performance. The error bars, in this case, are linked to the simplifications of the physical models defining the gas and solids but also to the deviation of the real compartments from the standardized ones (Thomas and Nilsson, 1973, Harmathy, 1981)

An approach that is acquiring popularity is that of using simplified models coupled with probabilistic estimations of error. These methods, based on theories of risk and reliability, are only valid if the representation of the physical phenomena incorporates in a correct manner all the necessary variables and couplings and the probabilistic distributions for all poorly defined properties are available. In this case a probabilistic distribution of true performance can be established.

A final method is the relative assessment of performance. This method creates a realistic scenario and assesses the performance of a system against it. The realistic scenario can be a standardized temperature vs. time curve, a parametric temperature vs. time curve to provide a relative performance of a structural component or system but also a standardized compartment to assess the relative severity of a fire given different fuels. While this approach can be used for the purpose of understanding or for classification, it will never provide true performance assessment.

**Human Behavior and Egress**

Modeling human activity in fires has primarily considered the effects of fire on civilian occupants within structures. The type of civilian action in fires that has been most examined has been egress modeling, where the time necessary to evacuate a building is predicted (Gwynne, 2001). One of two different approaches is used in an egress model: either (1) predicting occupant movement speed by using a hydraulic analogy, or (2) assigning each occupant its own behavioral characteristics. The hydraulic analogy predicts movements speeds based on the width of the egress component and the density of occupants within that component. Behavioral models rely simple rules based upon the location of exits, amount of heat or smoke, and assumed mobility data to characterize the evacuation of a structure. Building occupants can affect the fire conditions in a building by actions such as opening doors, windows etc. Similarly, firefighters affect the fire by changing the ventilation in the structure and also by application of water and other suppressants to the fire. However, the effects of occupants or the fire service on the progression of fire are generally not modeled. There is an opportunity for coupling egress models with fire simulations to improve the quality of simulation and support firefighting training and post incident reviews.

**Modeling Engineering Subsystems**

The range of engineered systems that are frequently encountered in compartment fires has motivated the development of submodels for heating ventilation and air conditioning systems
(Gaunt, 2000), sprinkler activation (Heskestad and Bill, 1988), and smoke detection (Cleary et al., 1999). Typically, these submodels are in the form of an ordinary differential equation involving a handful of empirical parameters. Ideally, these parameters are obtained via a standard test, like the RTI (Response Time Index) of a sprinkler.

In addition to fire protection and building systems, models of measurement devices are commonly added to fire models. For example, gas temperatures are typically measured with bare-bead thermocouples which do not actually measure the true gas temperature but rather the small bead of metal itself. A fire model can easily incorporate simple models of a thermocouple (Welsh and Rubini, 1997) so that model predictions can be compared directly with measurements for validation purposes. Another useful measurement device that can be easily modeled is a plate thermometer, a thin, insulated inconel plate useful for monitoring standard furnace tests (Wickström et al., 2007). These simple models of measurement devices help the model user to report the computed quantity in a way that an experimentalist would so that there is less confusion when comparing model and experimental results.

Model Verification and Validation

The use of fire models currently extends beyond the fire research laboratories and into the engineering, fire service, and legal communities. Sufficient evaluation of a model is necessary to ensure that users and regulatory authorities can judge the adequacy of its technical basis, appropriateness of its use, and confidence level of its predictions. This is ever more true due to the emergence of performance-based design as an alternative to prescriptive regulations.

The model evaluation process consists of two main components: verification and validation [ASTM E 1355]. Verification is a process to check the correctness of the solution of the governing equations. Verification does not imply that the governing equations are appropriate, only that the equations are being solved correctly. Validation is a process to determine the appropriateness of the governing equations as a mathematical model of the physical phenomena of interest. Typically, validation involves comparing model results with experimental measurement. Differences that cannot be attributed to uncertainty in the experimental measurements are attributed to the assumptions and simplifications of the physical model.

Consider in turn the three basic classes of fire models. Empirical correlations are typically presented in the form of simple formulae or equations that require, at most, a spreadsheet program to calculate a result. Verification of such models is trivial. Validation is often assumed, given that the models are typically based on full-scale experiments. However, there have been efforts in recent years to compare classic empirical correlations with experiments that were not used in their original development. One study, sponsored by the United States Nuclear Regulatory Commission and the Electrical Power Research Institute [Hill et al. 2007], considered a number of classic compartment fire correlations and found that these correlations tend to over-predict compartment temperatures. This result is looked upon favorably by regulatory agencies who prefer that these simple models err “on the conservative side.”
Next, consider two-zone models. These models are essentially a set of ordinary
differential equations for the average upper and lower temperatures and pressures within a set of
compartments. Again, verification of the governing equation solver is straightforward, and this
procedure is supplemented by global checks of mass and energy conservation within each
“control volume.” Validation of zone models has traditionally consisted of comparing model
predictions with the results of full-scale experiments in compartments that conformed to the
basic assumptions of the model; that is, relatively flat, unobstructed ceilings and simple
geometries. More recent validation work [Hill et al. 2007], however, has documented more
challenging fire scenarios that highlight the strengths and weaknesses of these models.

Finally, verification and validation of CFD fire models has dominated this area in the past
decade. Neither is trivial. Verification of these models takes on many forms, from grid resolution
(convergence) studies to checks of the conservation laws of mass, energy and momentum.
Validation of CFD models is similar to that of the simpler models -- comparisons with full-scale
experiments. Given the abundance of fire test data, it is more practical to compare model and
experiment rather than to dissect the model into its constituent parts and evaluate each separately
using various analytical techniques. For other fields of CFD, this is unavoidable, but for obvious
reasons fire science has yielded a wealth of test data with which to evaluate the models. In
addition, regulatory authorities are typically not experts in CFD and prefer simple comparisons
of model predictions with experimental measurements as a means of assessing the accuracy of
the model.

So what are the challenges associated with fire model V&V?

1. Even though there is an abundance of fire test data, many of these past experiments were
not intended for model validation. This means that the experiments are not well-documented,
experimental uncertainties are not reported, and the test results are often presented as simple
pass/fail judgments with limited data to use for model validation.
2. Experiments conducted prior to the advent of oxygen consumption calorimetry do not
provide accurate measurements of the fire’s heat release rate. Without this key input parameter,
these experiments can only serve as a rough qualitative check of the model.
3. Model validation cannot be static; that is, with each new version of the model, developers
need to re-run and re-document the results of the V&V studies. From a regulatory standpoint, if a
particular version of the model has been validated, this is the version that shall be used until a
new validation study is performed. To address this problem, a substantial repository of validation
data is being collected and archived at NIST and an automated procedure has been developed to
continually re-run a suite of V&V cases so that model users can cite up to date estimates of
model uncertainty.
4. Standards like ASTM E 1355 do not explicitly state how the results of model V&V
studies are to be reported, and it does not specify what level of accuracy constitutes “validation.”
It is left to the model user to decide how to report the results of the study, and it is up to the AHJ
(Authority Having Jurisdiction) to decide if the model is appropriate for the given application. In the NRC/EPRI fire model validation study [Hill et al. 2007], the NRC and interested industry and research collaborators developed a relatively simple methodology for reporting model uncertainty. In brief, for a given model and given predicted output quantity, there is a reported relative bias and relative standard deviation that is based on comparisons to a wide range of full-scale experiments. This methodology has been applied in various ways over the years and it is now typical for a validation study to conclude that Model X over or under-predicts Quantity Y, on average, by Z %, with a relative standard deviation of sigma %.

5. From the discussion above, it is apparent that there are fairly well accepted methods for performing model V&V. These methods, however, only quantify model uncertainty; that is, the uncertainty in the model prediction due to assumptions and simplifications of the model itself. The issue of parameter uncertainty, the uncertainty related to the input parameters, is receiving more attention for two reasons: First, as models become more accurate, the relative contribution of parameter uncertainty to the overall uncertainty increases. Second, the increased use of CFD means that conventional techniques for propagating parameter uncertainty are now much more difficult to apply. Empirical correlations and to some extent zone models lend themselves nicely to the various analytical methods to assess the influence of input parameters on the resulting prediction. CFD does not because these models incorporate more detailed physics and require hours or days of computational time. Adjoint based models are gaining acceptance in many areas of CFD, and such models are likely to be incorporated into fire modeling such that sensitivities can be extracted in computationally efficient ways. In evaluating the uncertainties in model parameters, there are many ways that parameter inference can be performed. One approach gaining favor is the use of Bayesian inference in parameter estimation (Tarantola, 2005). The Bayesian formulation naturally leads to the specification of a probability density function in the parameter being evaluated (Upadhyay et al., 2011). Knowledge of the statistical distributions of the uncertain parameters provides a basis for propagating said uncertainties through the fire model to determine a risk informed quantity of interest (Upadhyay and Ezekoye, 2008).

Based on this list of challenges, there are a number of potential areas for future research. First, consider the need for experiments. There exists a considerable number of experimental data sets in which the temperature, heat flux, species concentrations, and other quantities are measured within a compartment with a controlled fire, usually a gas or liquid fuel spray burner whose heat release rate is accurately measured. These experiments are ideal for assessing the capability of the models to transport and distribute the heat from the fire throughout the compartment. What is lacking are carefully designed experiments in which the fire’s heat release rate is not a specified input parameter, but rather a predicted output quantity. The most obvious example is a room filled with furniture, and certainly many experiments of this type have been conducted for various reasons, but the results of these experiments are not particularly useful for model validation because the material properties are typically not measured. Even if they are measured, to some extent, the uncertainty related to the prediction of the heat release rate of a growing, spreading fire overwhelms all other sources of uncertainty to the point where the model
at best makes a very rough qualitative prediction of the outcome. What is needed are a series of experiments of increasing complexity that can be used to assess the model capabilities step by step -- first, how well the model predicts the burning rate of a given object, second, how well the model predicts the spread of the fire from object to object, and finally, how well the model predicts the transition from small fire to flashover and beyond. Combining all of these phenomena into a single experiment does not allow for a systematic assessment of the sub-models that are adequate and those that are not and need improvement. A key component of this analysis is the propagation of parameter uncertainty. The rate of fire growth and spread is very sensitive to the material properties -- temperature-dependent thermal conductivity, specific heat and density; the choice of reaction mechanism and associated parameters; geometric complexity of the burning object.

**Inverse Analysis**

Inverse analysis generally refers to analysis in which the usual ideas of causality are reversed. In the heat transfer literature there has been a large body of work on development of computational techniques for inverse analysis (Beck et al., 1985; Ozisik, 2000). These approaches have been applied to parameter estimation, boundary condition estimation, and source estimation. One can arrive at an inverse solution either through an optimization process in which one seeks to minimize an objective function, defined as the difference between a forward model and some measured or desired. Alternatively, one can formulate a model in an inverse sense and use one of many approaches in the literature to generate the solution. Typically, problems formulated in an inverse sense are mathematically ill-conditioned. For problems developed as a system of equations as might be generated from differential operators or from Fredholm integral equations, an ill conditioned system is identified by the ratio of the largest to smallest singular value for the system (Hansen, 1987). Hansen discusses several approaches to regularization of the system of equations such that meaningful solutions that are less sensitive to measurement noise can be computed. Optimization based inverse analysis has been applied to problems of interest in fire scenarios (Richards et al, 1997, Jahn et al, 2011, Overholt and Ezekoye, 2012). In each of these studies, the authors used forward models for fire evolution to predict compartment fire behavior. Fire researchers at the National Institute of Standards and Technology, among others, have begun to frame a discussion on the use of building fire sensors with very fast computational models for fire growth modeling for firefighter operations (Evans, 2003; Jones et al., 2001).

measurement systems for fire systems have also benefitted from inverse analysis techniques. Boundary condition estimation techniques for conduction analysis have been useful in development of heat flux measurement gauges in fires (Lam and Weckman, 2009). In the heat transfer literature, much of the source estimation and boundary condition estimation analysis has occurred for temporally evolving physical systems. Approaches like that of Erturk et al (2002) may be useful in better characterization of furnaces used to characterize material fire resistance and in development of fire detection analysis.
Forensic analysis in fire scenarios challenges the limits of inverse analysis techniques. For such problems, the fire often has destroyed much of the evidence associated with its evolution. The National Fire Protection Association’s fire investigation reference document (NFPA 921) details the types of signatures that fire forensic analysts should consider in determining the cause and origin of a fire. These so-called fire-patterns include burn patterns on walls, depth of char on wood, spalling of concrete or masonry, glass breakage location, and other damage indicators. Many of these damage processes are thermally mediated, and any model based reconstruction of the fire should be able to predict the observed damage. The implication is that there should be available submodels to predict fire damage assessment as part of the hypothesis validation steps in forensic reconstruction.

Conclusions
Fire modeling represents a broad set of tools at various scales, with different underlying physical models used to design materials resistant to fire, model fire testing equipment, and predict fire ignition, spread, and damage in the built environment. Proper characterization of heat and mass transfer processes is critical to the predictive capability of these tools. In this paper, we have outlined different ways in which ongoing heat and mass transfer research plays a role in advancing fire models.

Several critical areas of research are evident to advance fire models. Perhaps the greatest current need in fire modeling is the need to be able to reliably predict burning rates of real materials. To do so is an interdisciplinary endeavor that requires a more nuanced view of the coupling of experiments and testing with modeling. At the heart of this endeavor is the need for improvements in condensed phase materials evolution models. Such improvements have many possible side benefits including closer integration in use of tests and models for product design. Translation of inverse modeling approaches to fire scenarios could revolutionize fire arson investigation. Fire investigation had traditionally been conducted by nontechnical investigators. Given the potential disastrous impact of an incorrect fire evolution hypothesis being accepted, the need to improve this capability is evident. Development of a fire inverse analysis framework is another interdisciplinary endeavor that will require closer coordination between experimental and computational research. On the computational and modeling side, the largest computational effort for smoke and heat transport or forensic analysis or any compartment scale analysis is the computational fluid dynamics model. Development of low dimensional models for fire flow processes would significantly improve the ability to make multiple runs for either design or forensics applications. As the overall predictive reliability of fire models improve and computing power increases, one envisions routine use of fire models to aid evacuation and firefighting operations during fire hazards.
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Revisiting the Compartment Fire

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ABSTRACT
Understanding the relevant behaviour of fire in buildings is critical for the continued provision of fire safety solutions as infrastructure continually evolves. Traditionally, new and improved understanding has helped define more accurate classifications and correspondingly, better prescriptive solutions. Among all the different concepts emerging from research into fire behaviour, the “compartment fire” is probably the one that has most influenced the evolution of the built environment. Initially, compartmentalization was exploited as a means of reducing the rate of fire spread in buildings. Through the observations acquired in fires, it was concluded that reducing spread rates enabled safe egress and a more effective intervention by the fire service. Thus, different forms of compartmentalization permeated through most prescriptive codes. Once fire behaviour within a compartment was conceptualized on the basis of scientific principles, the “compartment fire” framework became a means to establish, under certain specific circumstances, temperatures and thermal loads imposed by a fire to a building. This resulted not only in improved codes but also in a scientifically based methodology for the assessment of structural performance. The last three decades have however seen an evolution of the built environment away from compartmentalization while the “compartment fire” framework has remained. It is therefore necessary to revisit the knowledge underpinning this seminal approach to initiate discussion of its continued relevance and applicability to an increasingly non-compartmentalised built environment. This paper, through a review of classic literature and the description of some recent experimentation, aims to inform and encourage such discussion.

KEYWORDS: compartment fires; fire dynamics; design fires.

INTRODUCTION
Predicting the progression of a fire is inevitably the starting step of any form of performance based design. Defining the time evolution of all relevant variables (temperatures, velocities, species, etc.) is the initial challenge that a Fire Engineer faces when attempting to quantify the performance of a system and all countermeasures introduced to mitigate the impact of a fire. Decades of research have focused on the different processes linked to the characterization of a fire environment and numerous engineering methods have been developed to enable engineers to quantify the performance of a design. This is particularly true when focusing on the evolution of a fire within buildings.

The evolution of a fire within a building is characterized by the coupling between the building and the combustion process. The environment resulting from the interaction of building and combustion can then be used to establish its influence on egress, countermeasures (detection and suppression) or on structural behaviour. Each component of a fire safety strategy is drastically different from the others therefore the evaluation of the performance of each component needs to be done in a manner consistent with the specific processes involved. A comprehensive assessment of the evolution of a fire and its interactions with people and buildings has long been recognized as an intractable problem. And while in recent years complex computational tools have been developed for all aspects of a fire strategy, it is still necessary, for the purpose of design, to develop simplified methods that allows an effective but manageable design process.

A common mechanism to simplify the design process is to separate the different components of the problem by linking specific processes to specific characteristic times within a fire timeline. For example, the characteristic timescales associated to egress and the activation of countermeasures are relatively small, therefore the assessment of their performance will emphasize the understanding of the earlier phases of a
fire, i.e. fire growth time and time to flashover. In contrast, when addressing structural behaviour, growth and flashover occur within time scales that are much smaller than those required to significantly affect the mechanical strength of structural systems, thus the focus has been on fully developed fires. While a similar analysis could be done for each process, this paper focuses on the interaction between a fire and the structure. The simplified framework of a fully developed fire will be used to initiate the discussion. That being said, it is important to accept that this is already a simplification that excludes scenarios where the concept of a fully developed fire is not relevant.

The understanding of the thermal interaction between a fire and a structure has been explored since the late 19th century. Bisby et al [1] provide a comprehensive review of the associated literature. The main achievement of the earlier stages of research was the definition of the standard temperature vs time curve as a general description of the fire environment [2]. This definition enabled structural engineers to establish methods to protect structural systems from a fire. The recognition that further understanding of the fire environment is necessary to quantify structural behaviour only emerges through 30 years of research encompassing the period from 1960-1990. In this period, a series of seminal studies authored by the fathers of fire safety science provided the foundations for our current engineering methods. Kawagoe questions the physical basis of the standard temperature vs time curve and is the first to intuitively establish the concept of the compartment fire [3]. Through experimental observations he defines the link between ventilation, gas phase temperatures and burning rate. Thomas and co-workers [4, 5] extend and formalize the experimental database into a series of engineering expressions that characterize the maximum temperature within a compartment and, given a fuel load, the potential duration of the a fully developed fire. Thomas’s formulation de-emphasizes time and provides a worst case time invariant temperature regime for the fire until total burn-out of the fuel. At this point research bifurcates, while Petterson et al [6] extend the empirical data base by re-emphasizing the time evolution of the fire, Emmons et al [7] and McCaffrey et al [8] refine Thomas’s formulation by further describing the different processes and adding more experimental data. It is important to note that only Petterson et al [6] emphasize the time evolution of the fire while all others focus on the worst case condition. Of notable importance are the studies by Harmathy et al [9], Law et al [10-12] and Tanaka et al [13-17] who attempted to translate the acquired knowledge into design methodologies with an emphasis on structural performance. Numerous complementary studies were conducted in this period providing refinements and extensions to the existing methods but emphasizing the validity of the fundamental approach initiated by Kawagoe [3].

In 1998 the SFPE Task Group on Fire Exposures to Structural Elements chaired by Prof. J.G. Quintiere started to develop the SFPE Engineering Guide for Fire Exposure to Structural Elements that was finally published in 2004 [18]. This guide provides a comprehensive review of the different methods used in the calculation of how fires thermally affect structures. This guide was followed in 2011 with the SFPE Engineering Standard on Calculating Fire Exposures to Structures [19] developed by SFPE Standards-Making Committee on Calculating Fire Exposures to Structures chaired by J. K. Richardson. The SFPE Engineering Standard draws on the information of SFPE Engineering Guide to provide a method that enables the engineer to establish the evolution of the thermal boundary condition for a structure subject to a fire. Given a well-defined set of boundary conditions, the evolution of the transient temperature distribution of a structure can be established by means of a heat conduction analysis [4, 5, 9, 19-23]. These temperature distributions are then used as inputs for a structural analysis that determines the performance of a structural system in fire [23, 24]. There are other methods available in the literature [25-29] nevertheless, the comprehensive nature of the SFPE Guide and Standard make it a good starting point for this paper.

In parallel to the development of design methods, significant advances in the development of Computational Fluid Dynamics (CFD) models for fire applications have been reported. These models allow a significant level of refinement that enables a much more detailed treatment of the thermal boundary conditions for the structure. Successful applications have populated the literature in the last 10 years [30, 31]. CFD has a fundamental role in enabling better understanding of the physical processes [32] but it is recognized that there are still many uncertainties in the models. In what concerns the use of CFD for design, the utilization of the models can be too complex to be practical for main stream design and the drastic differences between solid and gas phase time scales do not necessarily justify the level of precision
brought by the utilization of CFD [33]. This paper will not address further the use of CFD, this is a subject of enough complexity to merit its own individual work.

It could appear as if by 2011, date of the publication of the SFPE Engineering Standard on Calculating Fire Exposures to Structures [19], that research had matured to a level where the thermal boundary condition for a structure was fully defined. Existing design methodologies, albeit conservative, provided a robust solution to the thermal boundary condition for performance assessment of a structure in fire.

A review of the classical studies on which existing design methodologies are based serves to clarify the limitations of existing design methods and the areas where further research is necessary. Some new experiments will be presented to provide evidence towards the need for further research.

THE COMPARTMENT FIRE FRAMEWORK

The temperature evolution within a building enclosure is defined by a compendium of complex processes occurring simultaneously. Fuel is pyrolyzed at a rate determined by the characteristics of the material and the net heat exchange between the fuel, the fire, the enclosure, the exterior environment and gas phase (hot and cold). The fuel mixes with oxidizer flowing through the compartment leading to a combustion reaction whose characteristics are defined by the relative quantities of fuel and oxidizer (local stoichiometry) as well by heat exchange with the enclosure and the exterior environment. The heat generated by the combustion reaction is partially lost at the openings, partially transferred to the enclosure and to a minor extent fed back to the fuel. The relative importance of all these terms defines the energy accumulated in the compartment and thus its temperature evolution. The resulting gas phase temperature will most likely be a function of all three spatial coordinates and time ($T_g(x,y,z,t)$) and the consequence of complex heat and mass transfer processes. The characteristic time scales of combustion, flow and heat transfer can be very different, thus significant simplifications are potentially possible. Given the complexity of the processes an a priori assessment of the possible simplifications is not possible without a detailed quantification of each term.

![The “Compartment Fire” framework.](image)

The “Compartment Fire” framework is based on a series of observations that emerged from numerous experiments conducted by Kawagoe [3] and later by Thomas et al. [5]. These experiments were then complemented by results of Harmathy [9]. The principle behind the method is that characteristic time scales for combustion are very short thus energy is assumed to be released as a function of reactant supply,
i.e. oxygen in the case of an oxygen-limited reaction and fuel in the case of a fuel-limited reaction. The characteristic time for heating of the enclosure is extremely long compared to all gas phase processes, therefore the gas phase can be assumed to be quasi-steady. The characteristic time for fuel pyrolysis is comparable to that of solid heating therefore a single characteristic time describes both. The burning rate will attain steady state conditions at the same time as the enclosure reaches thermal equilibrium with the gas phase. Under those circumstances a maximum gas phase temperature will be achieved (and maintained) beyond the transient heating of the enclosure. The steady state condition implies a constant heat transfer to the walls, a constant generation of heat, and a constant flow of heat out of the enclosure. The main consequence of this approach is that the geometry of the enclosure (dimensions, aspect ratio and openings) defines the relative importance of each term and therefore the value of the equilibrium gas phase temperature ($T_{g,\text{max}}(x,y,z)$). Thomas explores all three parameter spaces emphasizing the role of each of them [4, 5].

As explained above, depending on the availability of air the generation of heat is either controlled by fuel supply (fuel limited) or air supply (oxygen limited). This distinction is important in that it determines the form the energy source takes when introduced in the energy equation. Nevertheless, it does not eliminate the need to resolve the transport processes that bring fuel and oxidizer towards the reaction zone. Thomas et al. [4] describe the role of transport by establishing two limit regimes, Regime I and Regime II. Harmathy [9], offers a similar discussion using a different terminology (“ventilation controlled,” “fuel-surface-controlled”) but identical concepts.

Thomas et al. [4] describe Regime I as the case where the vents are small enough that they allow for the compartment to fill with smoke. In this case, at steady-state oxygen supply is limited, combustion is rich and soot concentrations are high. A significant amount of the energy released by combustion occurs outside the compartment and the flow field within the enclosure is dominated by thermal expansion of the gases allowing the assumption that momentum within the enclosure is negligible. Momentum and mass is only exchanged at the openings therefore it can be characterized by static pressure differentials across the openings. If a fixed fraction of the energy released is lost through the openings then the maximum temperature distribution ($T_{g,\text{max}}(x,y,z)$) will only be a function of the equilibrium heat exchange with the enclosure and the heat generated, where the heat generated is directly related to the mass flow of oxygen through the vents. Given the high soot concentrations (the optical depth is very small) and low velocities a linearized approximation for total heat transfer is acceptable. This enables not only the formulation of heat exchange through the walls by simple expressions [18, 33] but also the expression of the burning rate as a direct function of the gas phase temperature. As Thomas et al. [4] and Harmathy [9] point out, the equilibrium temperature, and consequently all other characteristic values, are defined by the relative magnitude of the three main terms of the energy equation, heat generation, heat transfer to the enclosure and heat losses through the vents. The relative values are therefore strongly dependent on the geometry of the compartment. While the validity of the framework extends to all geometries that comply with the assumptions, the resulting values are defined by the complex heat and mass transfer processes that remained unresolved. All unresolved processes are substituted by experimental values therefore the quantitative values extracted from experimentation are only applicable for the characteristic geometries reported in the tests.

In the case where the vents are sufficiently large, the smoke evacuates the enclosure with little resistance allowing for the fire to draw air. If the pressure differentials generated by the fire dominate over the static pressure differentials, the combustion products are expelled from the enclosure as fast as air is drawn into the enclosure. Complex heat and mass transfer processes dominate over this regime that Thomas et al. [4] label Regime II. No simple theoretical analysis can be defined for Regime II. Characteristic heat transfer times are short, soot concentrations are low therefore heat exchange from the fire to the structure was deemed to be less severe than for Regime I [4]. Harmathy [20] argues theoretically the lower severity of Regime II showing that the large velocities and vent size result in a major fraction of the heat being expelled through the vents, a decreased net heat accumulation in the enclosure and lower gas phase temperatures. Quantification of the actual heat transfer to the structure and the fuel is highly dependent on the geometry of the enclosure and extrapolation is extremely difficult under these circumstances. If quantification of the environment is desired, Regime II needs to be avoided.
From a design perspective different approaches can be followed. Code based restrictions on vent and compartment size can be imposed to avoid either regime. Through Thomas’s work it is generally implied that Regime I is more severe than Regime II (albeit never truly quantified) therefore building design can be done under the quantifiable worst case conditions of Regime I. In other words, the building geometry can be restricted so that only Regime I fires are possible and structural design can be done to withstand the thermal load of such fires. Alternatively, an even more conservative approach can be followed which is to quantify Regime I as a worst case condition but require building characteristics consistent with Regime II. A final approach was strongly advocated by Harmathy [20-22] who embraced Thomas’s conclusion on the greater severity of Regime I and encouraged designers to increase venting as an effective means to reduce fire proofing. The following quote is extracted from Reference [21]: “The simplest way of improving fire safety is to reduce its destructive potential in the “fire cell” (space on fire) by ensuring that the fire, if it occurs, will be fuel-surface-controlled (i.e. Regime II), in other words, by using large window areas, whenever possible, it becomes possible to replace fire resistance requirements with ventilation requirements. This means that the designer is entitled to decide whether to choose between buildings built with small windows and heavy fire-rated walls and floors, and buildings with large windows and lighter non-combustible, non-fire-rated elements.” Whatever approach is followed, it was recognized that this is only valid within the context of the specific geometries studied [5, 9].

An important point regarding the differences between Regime I and Regime II is highlighted by Harmathy [20]. The mechanisms linking compartment temperature and burning rate are only valid for Regime I and not for Regime II, in particular, the inverse relationship between the maximum average gas phase temperature ($T_{g,\text{max}}$) and the duration of the fire. In Reference [20] Harmathy indicates: “The conclusion reached so far is that well-ventilated fires, i.e., fuel-surface controlled fires, not only burn at lower temperatures (in general), but also are very short. The common belief that compartment fires are either short and hot or long and relatively cool is, therefore, completely wrong.” This observation seems to have been forgotten and it has become common to describe both regimes as being defined by the same interaction of physical processes [34] without remembering that Regimes I and II are two limit forms of behaviour that are the result of neglecting different processes and having the remaining ones interacting in a very specific manner.

In summary, the “Compartment Fire” framework is a robust representation of the behaviour of a fire in an enclosure. There is no fundamental weakness in the approach but the quantitative results are intimately linked to the geometry of the compartment (size, vent size, aspect ratio). The geometry will define if the conditions are consistent with the assumptions of the analysis but most importantly, it will establish the relative magnitude of the heat flow in and out of the enclosure (terms in Figure 1), which in turn defines the equilibrium temperature. Currently, the relative distribution is not defined in an analytic way but by means of experimental values. Extrapolation of these experimental values requires geometrical consistency. The SFPE Engineering Guide for Fire Exposure to Structural Elements [18] addresses this issue as early as the Executive Summary, nevertheless it addresses the influence of the geometry on the validity of the different methodologies employed in terms that are relevant only to Regime I fires, in other words as a function of the Opening Factor ($A/A_0\sqrt{H_0}$). The following section will define this terminology and address the fundamental differences between both regimes.

**Energy Balance in a Compartment Fire**

A compartment will be used as a control volume to describe the mechanisms by which energy can be transferred in and out of the control volume resulting in temperature distributions within the compartment. Friction work will be neglected and the volume of the compartment will be assumed constant. The energy conservation equation for the fixed control volume of Figure 1 can be represented as:

$$\frac{dQ_{cv}}{dt} = \dot{Q}_{in} - \dot{Q}_{out} + \dot{Q} - \dot{Q}_w$$

(1)

Where $\dot{Q}_{in}$ is the enthalpy entering the control volume with the reactants per unit time, $\dot{Q}_{out}$ is the enthalpy leaving the control volume with the products per unit time, $\dot{Q}_w$ represents the heat losses to the enclosure
boundaries and $\dot{Q}$ the total heat release rate within the enclosure by the fire. To understand better the role of each term it is useful to normalize the Equation (1) by the heat release rate.

$$\frac{1}{Q} \frac{dQ_{CV}}{dt} = 1 + \frac{\dot{Q}_{in}}{Q} - \frac{\dot{Q}_{out}}{Q} - \frac{\dot{Q}_{w}}{Q}$$

(2)

Given that the addition of mass into the enclosure associated to the fuel’s mass loss rate is negligible in comparison to the air mass inflow and gas mass outflow rates (estimated between 16% [9] and 18%[4]), the rate of change of mass within the control volume can be considered close to zero (i.e. $\frac{dm_{CV}}{dt} \approx 0$), therefore the transient term of the conservation of mass equation can be neglected resulting in:

$$\bar{m}_{in} = \bar{m}_{out} = \bar{m}$$

(3)

Given the significant temperature differences between the reactants and products it is possible to establish that $\bar{\dot{Q}}_{in} \ll \bar{\dot{Q}}_{out}$. This simplification is not necessary for the rest of the analysis but it will be retained here for consistency with the original presentation. Simple scaling analysis establishes that the characteristic heating times for the solid walls is at least two orders of magnitude longer than that of the combustion products allowing to assume quasi-steady conditions, i.e. $\frac{1}{Q} \frac{dQ_{CV}}{dt} \approx 0$. On the basis of these simplifications equation (3) can be rewritten as

$$1 = \frac{\dot{Q}_{out}}{Q} + \frac{\dot{Q}_{w}}{Q}$$

(4)

It is important to note that until this point no strong assumptions have been made and Equation (4) can be satisfied by any enclosure subject to a fire. What follows is a series of assumptions that enable the transformation of Equation (4) into a set of very simple expressions that serve to characterize the enclosure fire under Regime I conditions. The assumptions are:

(a) The heat release rate is defined by the complete consumption of all oxygen entering the compartment and its subsequent transformation into energy, $\dot{Q} = \bar{m}Y_{O_2,\infty}\Delta Hc_{O_2}$. Where the ambient oxygen concentration is given by $Y_{O_2,\infty}$ and the heat of combustion per kilogram of oxygen consumed is given by $\Delta Hc_{O_2}$. This assumption not only eliminates the need to define the oxygen concentration in the outgoing combustion products but also eliminates the need to resolve the oxygen transport equation within the compartment. Implicitly this assumption limits the analysis to scenarios where there is excess fuel availability, chemistry is fast enough to consume all oxygen transported to the reaction zone and the control volume acts as a perfectly stirred reactor. It is important to add that if the heat of combustion is assumed to be an invariant then the level of completeness of the combustion process is assumed to be independent of the compartment.

(b) Radiative losses through the openings are assumed to be negligible [4] therefore $\dot{Q}_{out}$ is treated as an advection term. Harmathy [9] provides an estimate for the radiative losses of approximately 3% of the total energy released.

(c) There are no gas or solid phase temperature spatial distributions within the compartment. The gas phase equilibrium temperature is therefore defined by a single value, $T_{g,max}$ and the equilibrium surface temperature of all solid surfaces also by a single value, $T_{w}$. $\dot{Q}_{out}$ and $\dot{Q}_{w}$ can then be strongly simplified. If the specific heat is assumed to be a constant then $\dot{Q}_{out} = \bar{m}C_{p}T_{g,max} \cdot \dot{Q}_{w}$
can be simplified in several manners depending on the objectives of the simplification. The simplifications associated to \( \dot{Q}_w \) require more detail and are addressed later.

(d) Mass transfer through the openings is governed by static pressure differences therefore a simple orifice plate expression can be used to evaluate the mass flow of air through the openings, \( \dot{m} = C A_O \sqrt{H_O} \), where \( A_O \) and \( H_O \) are the opening area and height respectively and \( C \) is a constant that amalgamates all other constants including the orifice plate coefficient and gravity. It is important to note that this assumption requires all velocities within the compartment to be negligible. Different values of the constant were derived by Harmathy [9] and calculated by Thomas [5] for different experimental conditions.

The classical approach is to define \( \dot{Q}_w \) as conduction losses through the boundaries of the compartment. While more complex formulations are possible, a simple steady state approximation will be used to quantify conductive losses:

\[
\dot{Q}_w = A k \frac{(T_{g,max} - T_\infty)}{\delta}
\]

(5)

Where \( A \) is the area through which heat is being transferred, \( k \) an effective thermal conductivity of the compartment boundaries, \( \delta \) a characteristic thickness of the boundaries and \( T_\infty \) the ambient temperature. It is important to note that this approximation is quite coarse in that it assumes the temperature difference between the interior and the exterior of the compartment boundaries \( (T_{g,max} - T_\infty) \) as the maximum possible value i.e. \( T_\infty \) does not rise due to heat transfer through the walls, therefore the resulting heat transfer to the boundaries is maximized and the compartment temperature is minimized as a consequence of these maximal heat losses. While this approximation might not be conservative it is useful to establish the relationship between the gas phase temperature, the air intake and the compartment geometry. Substituting equation (5) into equation (4) and solving for the steady state gas phase temperature the following expression is obtained:

\[
T_{g,max} = \left( \frac{1 + \frac{T_\infty}{T_{CD}}}{1 + \frac{T_F}{T_{CD}}} \right) T_F
\]

(6)

Where \( T_F = Y_{O_2,\infty} \Delta H c_{O_2}/C_p \) is a characteristic flame temperature and \( T_{CD} = \frac{C Y_{O_2,\infty} \Delta H c_{O_2}}{(k/\delta)} \left( \frac{A_O \sqrt{H_O}}{A} \right) \) is a characteristic conduction temperature. It is important to note that under the present assumptions all terms of equation (6) are constant with the exception of the classic opening factor \( \left( \frac{A_O \sqrt{H_O}}{A} \right) \) and the thermal conduction heat transfer coefficient \( (k/\delta) \) both properties of the compartment.

An alternative approach to define the heat transfer through the walls is by means of a convective boundary condition. In this case heat transfer through the walls can be described by

\[
\dot{Q}_w = A h_T (T_{g,max} - T_W)
\]

(7)

Where \( h_T \) is a total heat transfer coefficient and \( T_W \) the interior surface temperature of the compartment boundaries. Once again, this is a very simple expression that establishes a different form of the steady state gas phase temperature:
$T_{g,\text{max}} = \left(1 + \frac{T_W}{T_{CV}}\right) T_F$ \hfill (8)

Where $T_{CV} = \frac{C V_0 A H \phi_2}{h_T} \left(\frac{A D \sqrt{H_D}}{A}\right)$ is a characteristic convection temperature. While both expressions (equations (6) and (8)) are very similar and depend on the opening factor $\left(\frac{A D \sqrt{H_D}}{A}\right)$, equation (8) also depends on a gas phase parameter which is the total heat transfer coefficient. This only becomes interesting when the asymptotic conditions are attained.

If $\frac{T_\infty}{T_{CD}} \ll 1$ and $\frac{T_F}{T_{CD}} \ll 1$ (i.e. large opening factor and insulating walls) then equation (6) results in

$T_{g,\text{max}} = T_F$ \hfill (9)

If $\frac{T_\infty}{T_{CD}} \gg 1$ and $\frac{T_F}{T_{CD}} \gg 1$ (i.e. small opening factor and non-insulating walls) then equation (6) results in

$T_{g,\text{max}} = T_\infty$ \hfill (10)

Similarly, if $\frac{T_\infty}{T_{CV}} \ll 1$ and $\frac{T_F}{T_{CV}} \ll 1$ (i.e. very large opening factor and weak total heat transfer) then equation (8) results in

$T_{g,\text{max}} = T_F$ \hfill (11)

But if $\frac{T_\infty}{T_{CV}} \gg 1$ and $\frac{T_F}{T_{CV}} \gg 1$ (i.e. very small opening factor and strong total heat transfer) then equation (8) results in

$T_{g,\text{max}} = T_W$ \hfill (12)

Fig. 2. Average compartment temperature for the CIB Tests, extracted from [5].

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The diagram shows the relationship between $A_l / A_w H^{1/2} m^{-1/2}$ and the number of tests, indicating how the temperature changes with different conditions.
It is important to note that the asymptotic values associated with equation (6) (i.e. equations (9) and (10)) directly relate the gas phase temperature to the two hard limits, the ambient and characteristic flame temperatures. Therefore, this equation is very useful when addressing the evolution of the gas phase temperature as a function of the opening factor. In the work by Thomas et al [4] it is stated that the quantitative values of $T_{g,max}$ will be dependent on the conduction heat transfer coefficient $(k/\delta)$ and that a conservative characteristic value can be taken for testing leading to a conservative empirical evolution of $T_{g,max}$ as a function of only the opening factor. Figure 2 shows the plot extracted from reference [5] where the right hand side of the curve shows the evolution of $T_{g,max}$ as a function of the inverse of the opening factor. Extrapolation of the trend in this region in both directions will lead towards the asymptotic values defined by equations (9) and (10). The asymptotic limit defined by equation (9) will not be attained. Towards the left of the maximum temperature (Figure 5) the conditions are representative of Regime II which does not comply with the assumptions of this analysis and therefore deviates from the trends defined by equation (6) and the asymptotic limit defined by equation (9).

Finally, Kawagoe [3] establishes that from equation (5) and from the fact that the burning rate is proportional to the heat transfer rate to any of the boundaries of the compartment, that the burning rate is proportional to $A_0\sqrt{H_0}$. In contrast to equation (6), equation (8) has a different asymptotic term for the case where heat transfer between the gas and compartment is high. In this case the gas phase and wall temperatures are the same (as represented by equation (12)). This observation is significant in that it focuses on the temperature of the structure and indicates that given the right heat transfer conditions, the thermal characteristics of the structure can dominate the minimum temperature of the gas phase and the balance of the two right hand terms of equation (4).

In summary, the compartment fire framework allows, by means of several strong assumptions, a representation of the maximum steady state temperature, $T_{g,max}$ of a compartment simply as a function of the opening factor $\left(\frac{A_0\sqrt{H_0}}{A}\right)$ and the burning rate, $R$, as proportional to the ventilation factor $A_0\sqrt{H_0}$. Those assumptions are consistent with Regime I, and while remaining within these assumptions, simple expressions (equations (6) and (8)) can be used to link $T_{g,max}$ to the opening factor. Outside the validity of the fundamental assumptions the theoretical link between temperature, burning rate and opening factor does not exist.

THE RANGE OF VALIDITY OF THE COMPARTMENT FIRE FRAMEWORK

The Original Experiments

To understand the range of validity of the expressions presented above it is important to discuss the experiments that led to this analysis. Two series of large scale experiments provide the initial set of data used to develop the Compartment Fire framework: those by Kawagoe [3] and those of the CIB study [4, 5]. The CIB programme summarizes Kawagoe’s experiments therefore will be used to describe the nature of the tests. The shape of the compartments used in the CIB Programme was rectangular, designated by a three figure code representing the three principal dimensions of width, depth and height (where all dimensions are normalized by the height). Thus, a 211 compartment measured 2 units wide, 1 unit depth and 1 unit height. The four shapes of compartment examined were 211, 121, 221, and 441. The overall scale of the compartment was taken as the compartment height, and scales of 0.5, 1, and 1.5 meter were employed. Therefore, the larger compartment size was 6 m x 6 m x 1.5 m height.

The data obtained through these experiments are mainly burning rates and average compartment temperatures ($T_{g,max}$). The weight of the fuel was obtained throughout each test either by weighing the whole compartment or by weighing the floor separately. The temperatures were recorded by only two thermocouples placed at ¼ and ¾ of the compartment height above the centre of the floor. As pointed out by Thomas and Heselden [5], in some cases, the lower thermocouple was laid inside the wood cribs that were used as fuel resulting in a measurement bias for the average temperature.

Although the CIB data for average temperatures vs. the inverse opening factor presented significant scatter, Thomas and Heselden [5] drew a best-fit line through one of the fuel configuration data sets (i.e. the (2,1)
 crib configuration, meaning 20 mm thick sticks spaced 20 mm apart) obtaining as a result the very well-known plot presented in Figure 2.

Similar graphs for other fuel crib configurations were presented by Thomas and Heselden [5] but because the (2,1) configuration resulted in higher average temperatures, the data of Figure 2 are generally used for design analysis. It is important to emphasize that the data shows reasonable scatter for Regime I conditions but the scatter is very large for Regime II. In the case of Regime II, factors such as aspect ratio, nature of the fuel and scale were shown by the authors to have a significant effect on the resulting temperatures.

An important finding in the CIB Programme was that high values of the enclosure’s depth to height ratio produced non-uniform temperatures horizontally and large windows non-uniformity vertically, with the ceiling temperatures typically being the maximum temperatures found in an enclosure fire.

**Non-Uniformity and the “Natural Fire”**

Following the observations of the CIB studies, Stern-Gottfried et al. [35] reviews the test literature in an attempt to establish if the assumption of homogeneous temperature distribution within the compartment is valid through the available data. The compiled data showed that for smaller, cubic compartments the assumption of a homogeneous temperature distribution is valid but it breaks down with the size of the compartment and in particular when the aspect ratio deviates from the cubic compartment.

Additionally, Drysdale [36] explains that most of our knowledge of the behaviour of compartment fires comes from experiments with near-cubical compartments, with characteristic dimensions ranging from 0.5 m to 3 m which of course are very different in shape and size compared with typical spaces in modern commercial buildings [37].

In 1999, the Natural Fire Safety Concept 2 test series at Cardington [38] included a much greater spatial resolution of instrumentation. The eight Cardington tests were conducted in a room 12 m x 12 m x 3 m with uniformly spaced fuel load packages distributed across the floor. Sixteen thermocouple trees containing four thermocouples each were placed on a uniform grid in the compartment to record the gas temperatures, shown in Figure 3. The tests were conducted with various combinations of fuel type, ventilation distribution, and interior lining material. The tests had liquid fuel channels connecting the fuel packages so that ignition and the subsequent burning could be as uniform as possible.

The Cardington experiments intended to test two types of compartment insulation; “insulating” and “highly insulating”. However, after Test 1, the “highly insulating” material was placed on the ceiling for all remaining tests, creating an intermediate level of insulation. The fuel packages were either just wood cribs or a combination of wood and plastic cribs. The ventilation openings were either fully open on the front of the enclosure or fully open on the front and back. As shown in Figure 3 there is a significant evolution in space and time of the temperature. The evolution in time is mostly related to the time lag between heating in the gas phase and the heating of the compartment, thus is related to the level of insulation. This had been
previously extensively studied by Pettersson et al [6] when developing the parametric fire curves, nevertheless the Natural Fire Concept tests were the first where the insulation was systematically varied. The evolution in space was observed but not studied in detail due to the restricted amount of instrumentation.

A different form of temperature distribution was reviewed and reported by Clifton [39] who describes fires that spread through a large compartment generating spatial and temporal distributions as a consequence not only of stratification but also of the progression of the fire through the compartment. Clifton [39] emphasizes a simple methodology to model these fires and only presents a limited set of experimental data to validate the analytical approach. While the data are coarse and limited, it does indicate drastic spatial and temperature evolutions throughout the compartment. An earlier study concerning the St. Lawrence Burn project [40] was recently reported by Gales [41] where compartments of dimensions 11.2 m x 12.8 m and 13 m x 9 m respectively were exposed to a propagating fire showing once again significant spatial and temporal distributions.

The Dalmarnock Fire Tests

The Dalmarnock Fire Tests, which provide the greatest instrumentation density to date, were conducted in a real high-rise apartment building in Glasgow, UK [42]. The two tests conducted had a realistic fuel load of typical furnishings. The compartment was 4.75 m x 3.50 m x 2.45 m, containing 20 thermocouple trees, each with 12 thermocouples (placed 0, 0.05, 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, 1.0, 1.3, 1.6 and 2 m from the ceiling). Ignition occurred in the waste-paper basket adjacent to the sofa. Two tests were conducted, Test One was allowed to progress to burn-out while the second test was manually suppressed immediately after flashover. Thus only Test One is of interest here.

![Fig. 4. Experimental results of Dalmarnock Test One [42] showing the compartment average, maximum and minimum temperatures, the standard deviation and the prediction from Figure 2. Flashover occurred at 5 min and the fully developed stage lasted until suppression at 19 min.](image)

The Dalmarnock Test One shows that the temperature distributions, even for a small compartment corresponding to Regime I, are lower than the predictions of the CIB and present very large variations in space and time. All it takes is to provide sufficient instrumentation density to spatially resolve the temperature fields. In the Natural Fire Concept tests the compartment was large but all fires were ignited simultaneously, in the Dalmarnock tests the fire was allowed to propagate, but the compartment was small. In the study by Clifton [39] one series of experiments was reported where the compartment was large (44 m x 34 m) and the fire was allowed to propagate, nevertheless, the data has poor resolution and only a single experimental condition is reported. A similar situation occurs with the St. Lawrence Burns Project where only two tests were reported and limited data is available.

Summary of Existing Evidence

The available experimental data confirm that the observations and analysis first developed by Kawagoe [3] and then by Thomas et al [4, 5] can provide a simple yet fundamentally adequate way to describe the
maximum average temperature, $T_{g,max}$, and burning rate as a function of a single parameter, the ventilation factor $\left(\frac{A_0 H}{A}\right)$. The SFPE Engineering Guide - Fire Exposures to Structural Elements [18] reviews a large amount of data that validates this approach. The data and analysis is presented in the context of the of the same methodology and while it explores the limits of validity of the approach it does not extended beyond the “Compartment Fire Framework” first formulated by Thomas et al [4]. Following on from Thomas et al [4], this paper highlights the main assumptions involved in the formulation that leads to the definition of the ventilation factor $\left(\frac{A_0 H}{A}\right)$ as the single parameter that characterizes the compartment fire and establishes through a brief review of some experimental data that there is a large body of evidence that demonstrates that the conditions necessary for a Regime I fire are not necessarily met in modern building enclosures. Furthermore, the available data is not sufficient to characterize the different forms of behaviour that fires can have in the multiplicity of compartment geometries now common in the built environment. The next section briefly summarizes a series of tests designed to start filling these gaps of knowledge.

THE “TALL BUILDING” TESTS

To respond to the need to better describe the special and temporal evolution of a fire that is allowed to progress in a large compartment a series of tests were conducted in 2013 at the Building Research Establishment in the UK. These tests are inscribed within a larger programme that looks to address fire scenarios for tall buildings, thus will be labelled the “Tall Building Tests.”

Fig. 5. (a) Schematic of the BRE large compartment constructed and (b), a photograph of a characteristic gas burner test.

A compartment of dimensions 5 m x 18 m x 2 m (Figure 5(a)) was constructed and included 15 openings along the front (1.5 m high by about 1 m wide each) that can be open and closed to allow varying ventilation in a systematic way. The tests are heavily instrumented including internal thermocouple trees spaced at 0.7 m in the x-direction, 0.6 m in the y-direction, and at 0.3, 0.6, 0.9, 1.2, 1.4, 1.6, 1.8, and 1.95m in the z-direction. There is also a thermocouple tree in the centre of each opening at $z = 0.25, 0.5, 0.75, 1.0,$ and 1.25m. Outside there is also a thermocouple tree at around 0.4 m from the compartment and aligned with the centre of each opening. These trees have 12 thermocouples each which are spaced as follows: 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75 and 3.0m. 100 thermocouples provide in-depth temperatures (at different depths) along a 3 m wide section of the back wall which is in-filled with non-flammable insulation. Heat flux gauges were placed on all 5 surfaces of the compartment evenly distributed. There are 45 on the floor (3 in x-direction, 15 in y-direction), 45 on the ceiling, 45 along the back wall (15 in y-direction, 3 in z-direction) and 15 (5 in the x-direction, 3 in the z-direction) along each of the side walls. There are also heat flux gauges outside, opposite the centre of each opening, at different distances away from the compartment (in x-direction). Smoke obscuration is measured with 5 laser-receiver pairs in total evenly spaced along the centre of the compartment. Bi-directional velocity probes allow characterizing the in-flow and out-flow of the compartment. There are 2 probes per opening ($z =$
0.225 m and \( z = 1.275 \) m of the opening height, respectively). There are 5 gas-sampling points evenly spaced along the ceiling of the compartment. The gas probes sample \( O_2 \), \( CO_2 \) and CO to establish completeness of combustion. Five cameras were used to film the compartment from different angles, including one camera at the centre of each of the side walls. An InfraRed camera was also used to film the compartment from the outside.

Two series of tests were conducted, a first series where a sequence of gas burners (12 propane burners, of \( 0.5 \) m \( \times 0.5 \) m trays full of gravel, evenly spaced throughout the compartment in pairs of 2) was ignited progressing from one end of the compartment to the other. Ventilation and fire spread were varied to cover a range that allowed for spread much faster than ventilation opening to spread much slower than ventilation opening. The second series of tests was conducted with wood cribs covering the entire floor and ignited at one end. The ventilation was again varied. For the wood crib tests, the central staging area has been divided into 8 sections that can move up and down independently. These sat on load cell systems that enabled the measurement of mass loss. A photograph of a typical test is presented in Figure 5(b).

While the description of the experimental data is beyond the scope of this paper, it is important to emphasize that the scale and data variety and resolution result in different observed behaviour that not only deviate from the compartment fire framework but that could potentially have a significant impact on the thermal boundary condition used to analyse structural behaviour. Furthermore, current detailed structural analysis requires a level of resolution that cannot be provided by the simple formulation of the compartment fire framework [34, 44]. These tests provide a level of resolution that is more consistent with the needs of such analysis.

Fig. 6. Temperature distributions along a plane 1800 mm deep and parallel to the open face (in between burners) – the openings were fully open allowing for the maximum evacuation of smoke.
Figure 6 shows a series of representative data for an experiment using gas burners ignited in a sequential manner while the panels allowing air were opened fully. The fire is initiated with two burners (front and back – Figure 5(b)) at the right hand side of the compartment. Initially, the ceiling jet propagates across the compartment with no significant accumulation of smoke but very rapidly it covers the entire compartment (<130 sec – Figure 6(a)). The smoke produced by the fire is fully evacuated allowing for the establishment of steady state conditions. The initial burners are turned-off as the next set is ignited and the temperatures once again reach steady-state conditions rapidly. A clear smoke layer can be seen in Figure 6(b). The smoke layer shows very similar temperatures to the ones observed in Figure 6(a).

![Temperature distributions along a plane 1800 mm deep and parallel to the open face – the openings were fully open allowing for the maximum evacuation of smoke and the fuel were wood cribs.](image)

This series of tests shows at each stage conditions very similar to those described by Regime II. These conditions reproduce themselves at each stage of the burning process and the characteristic times scales in the gas phase are short enough that quasi-steady conditions can be established at each stage of the propagation. The burners were ignited at rates consistent with spread rates of typical building fuels, therefore these observations could potentially be extrapolated to fires with realistic materials. While the conditions are similar to those of Regime II fires, the size of the compartment allows for the formation of gradients of temperature not only in the vertical direction but also in the directions parallel to the floor. The data has enough resolution to be able to provide an appropriate boundary condition for structures whose analysis requires spatial distribution.
The rate of ignition of the gas burners as well as the size and location of the openings were varied to establish other potential regimes. The rate of ignition of the burners as well as the size of the fire (i.e. number of burners) did not have a major impact on the nature of the fire in the compartment within the range of conditions studied. A clear smoke layer was rapidly established with the interface dependent mostly on the size of the fire indicating that the capacity of the open face to evacuate smoke exceeded the differences introduced by the changes to the fire. In contrast, as the vents were diminished in size or in number, smoke could not be evacuated and the quasi-steady nature of the process was lost leading to a complex and dynamic interaction between burners and smoke.

An experiment with wood cribs can be used as an example as it encompasses the full potential complexity of the dynamic interaction between the fire, the smoke and the compartment. Figure 7 presents temperature distributions within a plane (1800 mm deep) at different points in time. The fuel is wood cribs and the vents are fully open. The fire was ignited in the right hand corner and allowed to propagate. Initially the ceiling jet propagates across the compartment (Figure 7(a)) until a smoke layer is established (Figure 7(b)). Fire spread is very slow relative to the gas phase processes thus quasi-steady state conditions establish in a similar manner to those presented in Figure 6. As the fire continues to grow the temperature of the smoke layer starts to increase. An important aspect of this is that depending on the size of the fire and the amount of ventilation surface available, the rate at which conditions evolve in the vicinity of the fire is much different to the rate of evolution in the far field (left hand side Figure 7(c)). Furthermore, momentum-driven flows impinging on the walls start affecting the characteristics of the smoke layer (Figure 7(d)). At approximately 1500 second (Figure 7(e)) smoke layer temperatures on the right hand side of the compartment exceed 500°C within approximately a third of the compartment. At this stage rapid ignition of the fuel through almost half of the compartment occurs in a manner that resembles a localized flashover (Figure 7(f)). The fire will continue to burn to the right of the flame front (Figure 7(g)) but the burning rate is maximum at the leading edge of the flame decreasing towards the right of the compartment. For the case where the vents were fully open, the flames continue to spread towards the left of the compartment. Strong air entrainment from left to right and smoke evacuation behind the flame prevented any subsequent instantaneous ignition of the fuel.

The experimental sequence presented above is described only with the purpose of illustrating the complex dynamics of the fire within a large compartment. The different processes explained varied in their significance depending on the ventilation and it was very clear that the temperature distributions were a strong function of the geometry of the compartment. What is clear is that under these conditions the dynamics of the fire correspond to a complex mixture of the limit Regimes I and II described by Thomas et al [5] and there is no relationship between the overall opening factor \( \frac{A_0 \sqrt{H_0}}{A} \) and the temperatures or burning rates.

**SUMMARY**

Upon revisiting the original studies that define the compartment fire framework it is clear that the approach that links an averaged maximum steady state temperature, \( T_{g,\text{max}} \), and burning rate, \( R \), to an opening factor \( \frac{A_0 \sqrt{H_0}}{A} \) and an air inflow parameter \( A_0 \sqrt{H_0} \) respectively, is a simple but robust way to describe the behaviour of a Regime I fire. The conditions of a Regime I fire are defined by a series of very strong assumptions that guarantee the direct link between ventilation, temperature and burning rate. There is no theoretical link between the opening factor and the gas phase temperature for Regime II fires and any experimental evidence of a link is accompanied by great scatter of the data. This is not a new observation, from the very early studies by Thomas et al, the scatter of the data within Regime II conditions was emphasized.

There is significant experimental data that shows conditions under which the assumptions of the compartment fire framework are not valid but there are no systematic studies that truly address the boundaries of validity of this approach. Therefore, the limits of validity of the methodology are currently unknown.
A critical assumption associated to the compartment fire framework is the geometry of the compartment. Most of the data that validates the method is with quasi-cubic small (<150 m³) enclosures. Recent experimental data on well instrumented fires in larger compartments has demonstrated complex behaviour that cannot be described in terms of the compartment fire framework. Many modern building spaces deviate from the small quasi-cubic enclosure therefore there is great need to conduct research that provides physical insight on the dynamics of a fire in complex geometries. High resolution data is necessary for validation of design tools intended to describe the thermal boundary condition for a structure within a fire in a large compartment.

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REFERENCES


THE MALVEIRA FIRE TEST: FULL-SCALE DEMONSTRATION OF FIRE MODES IN OPEN-PLAN COMPARTMENTS

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Abstract

This paper aims to characterize dynamics of a fire in the Large-Scale Demonstrator Malveira Fire Test, a full-scale fire experiment carried out in a disused industrial building in Portugal. The Malveira Fire Test is the second stage in the series of full-scale experimental programmes developed for the Real Fires for the Safe Design of Tall Buildings project at the University of Edinburgh. This experiment is intended to act as a real-building demonstration of fire dynamics in large open-floor plan compartments and has as objective to provide a data set to contrast methodologies aiming at design fire inputs representative of real fire dynamics in compartments typical of tall buildings.

The Malveira Fire Test showed three distinct fire behaviour modes characterised by the ratio between the velocities of the fire front ($V_f$) and the burnout front ($V_{BO}$); a travelling fire mode with $V_f/V_{BO} \approx 1$, a growing fire mode with $V_f/V_{BO} > 1$ and a fully-developed fire mode with $V_f/V_{BO} \rightarrow \infty$. The three modes are found to have a correlation with the incident heat flux onto the surface of fuel caused by the resulting energy distribution within the compartment. The energy distribution appears to be a function of the characteristics of the compartment, the fuel distribution and the resulting aerodynamics. A description of the instrumentation and analysis of results are presented to support a theoretical justification for the transitions between fire modes.

Keywords

Enclosure fire dynamics, large-scale experiments, compartment fire framework, tall buildings
1 Introduction

The built environment has seen rapid growth in recent decades as new structures continue to evolve in height, construction materials, compartmental composition and use [1]. This growth shows no sign of slowing as the rate of complex and tall buildings being constructed continues to rise worldwide, with a 402% increase in the number of buildings exceeding 200 m in height in 2017 alone [1, 2]. The forces driving this progression are a combination of financial, political-environmental, and technological factors, which have resulted in significant advancements in construction techniques, cost optimisation, innovative materials, ease of construction, and architectural innovation [1]. One of the key trends of mainstream architecture since as far back as the 1920s is the desire for open, flexible volumes saturated by natural light through multiple large openings [3]. The result of this trend is modern tall buildings of all occupancies having large open plan compartments.

The principles and terminology commonly used to define compartment fire dynamics have been defined through the study of small compartments where the temporal evolution of the fire dominated over its spatial evolution [3]. Extrapolation of these concepts and terminology have found significant limitations when addressing the dynamics of a fire in large open plan compartments.

Current understanding is derived from pioneering research predominantly developed between the 1950s and 1990s, brought by the need for more explicit descriptions of the fire environment and engineering methods to assess the performance of fire-resistant partitions and structures. From these works, the Compartment Fire Framework was developed, which defined the fire dynamics as a function of restrictions imposed by compartmentation, with limited openings, typical of relatively small compartments [3-4].

At present, the provision of fire-safe designs within tall buildings currently hinges on three essential components [1]:

1. Ensuring effective vertical compartmentation that confines the fire to one floor,
2. Providing structural integrity that extends beyond the burnout of the fuel load, and
3. Maintaining clear egress routes for all occupants.

These three design components strongly rely on the characterisation of the fire dynamics beyond the early growth stage of the fire as the primary input parameter [1]. The Compartment Fire Framework still underpins the engineering tools used to quantify all these aspects. In cases where this framework does not apply, the thermal boundary condition imposed on load-bearing structural systems from the fire is far from being completely resolved [4]. The applicability and limitations to the use of the Compartment Fire Framework in these circumstances remains unclear. Therefore, detailed study of fires in large open plan compartments is required so that fire safety engineering principles can adapt to these new rapid developments in construction. This study attempts to provide, by means of a large well instrumented test, further clarity on the behaviour of a fire in a large open plan compartment.
1.1 The Compartment Fire Framework

The origins of fire compartment studies stem from the work of Ingberg in 1928 [5], driven by the high death rate associated with building fires and recognition that they tended to burn until structural collapse [6]. Large-scale fire experiments at the National Bureau of Standards (NBS) quantified the duration and intensity of building fires [6], whereas Ingberg’s work related these parameters to an equivalent exposure to the standard furnace time-temperature curve during a fire-resistance test. Ingberg initiated the pioneering period of fire safety engineering research, which formed the basis for the Compartment Fire Framework. The main objective of these key studies was to characterise the behaviour of fully-developed fires within compartments in order to define the thermal loads for structural assessment. Fujita and Kawagoe’s early work [7-9] realised the limitations of the standard fire resistance test and established that the compartment fire characteristics and their surroundings (i.e. geometry, fuel, ventilation etc.) are intrinsically linked, resulting in a very complex interaction in the event of a fire [10].

Due to the complexity of the coupling between compartment fire dynamics and the compartment itself, the need for simplifications was recognised in order to quantify behaviour for design purposes. This was achieved by Thomas and Heselden [11], who demonstrated that, for a specific range, the compartment and opening geometries govern the physical behaviour of the fire as the fire is controlled by the inflow of air into the compartment. Beyond this specified range, the openings are considered sufficiently large enough to no longer be a governing factor. Thus the amount of fuel surface available governs the fire. The former was labelled Regime I (ventilation-controlled) fires and the latter Regime II (fuel-controlled) fires. The traditional understanding of these fire regimes was expanded on by Harmathy [12], and further revised more recently by Majdalani [3]. Majdalani [3] discusses the importance of the compartment geometry on the aerodynamics of the air flow and on the conditions that lead to the transition between both regimes. Within the Compartment Fire Framework this is related to flashover and has been extensively studied [10], but as the geometry of the compartment strongly departs from a small cube, this transition has the potential to be more complex. The nature of Majdalani’s experiments [3] did not allow for a more detailed exploration of this transition.

A Regime I fire, a fully-developed post-flashover fire, fills the compartment with smoke due to the limited ventilation, causing rich combustion and high soot concentration. Flow within the compartment is dominated by the expansion of hot gases, allowing to neglect mass and momentum transfer. A key characteristic of Regime I fires is that the compartment exhibits high, uniform temperatures and openings must allow for the transfer of mass that is driven by the hydrostatic pressure difference between the inside and outside of the compartment [4].

A Regime II fire is also fully-developed, however, it is dictated by the fuel surface area available for combustion. Large openings allow for air exchange with the outside, allowing for high momentum buoyant flows that hinder the correlation between ventilation and fuel burning rate [3]. The significant momentum prevents the retention of smoke and results in the lack of a well-defined smoke layer. Internal temperatures are therefore generally lower.
The Compartment Fire Framework in its current form focuses on Regime I fires. Researchers, through increased simplifications, were able to articulate it theoretically and the data obtained from testing showed more clear trends in comparison to the large scatter that was associated with results from Regime II fire experiments. Furthermore, due to the higher temperatures observed in the Regime I, this was deemed the most ‘severe’ scenario for the structure. Advancements in research have typically exclusively focused on characterising the energy exchange and burning rates within a compartment as functions of the opening geometry [4]. Tools were then developed, allowing for rapid application of ‘conservative’ bounding thermal loads to structural design, which have been integrated into design standards and building practices globally [13]. Regime II fires, being more complex, have not been researched and developed theoretically. In a similar manner, the conditions leading to the transition between Regime I and Regime II have also not been studied in detail.

The Regime I design methods assume a worst-case uniform temperature, which is much higher than the apparent range of possible temperatures of Regime II fires. The lack of correlation between the actual fire behaviour in open plan compartments and current fires used for design may lead to inadequately designed structures [14].

Architectural evolution has led to tall, open-plan structures with interconnected compartments being the norm. Nevertheless, as the fire design strictly depends on compartmentation, a clear disparity between contemporary infrastructure and definitions of compartment fire dynamics has arisen. While fire characteristics of Regime II fires have historically been deemed less severe, in contemporary open-plan infrastructure, smoke and therefore heat can be transferred away from the fire yet still remain within the building. It will consequently continue its exchange of energy with the structure and unburnt combustible materials, even in areas that are remote from the fire. This introduces a possibility of spatially variant energy distributions within large compartments, which modern structural fire engineering has shown that can introduce complex thermally induced forces within a structural system, even at lower temperatures [15]. Such loading conditions are not considered by traditional approaches to establishing structural performance under thermal loading. [16].

The more widespread distribution of generated heat can lead to fires in large compartments exhibiting behaviour referred to as “travelling fires”, where fuel is burned over a limited area. This limited area will spread across the floor plate [17]. Travelling fire theory assumes two regions in the compartment – the near field and the far field. The near field refers to the region where the fire itself is located, while the far field is the areas remote from the fire. These two regions are assumed to remain constant in size but ‘travel’ through the compartment as the flame spreads and fuel is consumed [18].

Calculation methods to approach “travelling fire” behaviour have been developed in the last decade [17-21]. In the case of reference [17] a temperature distribution was extracted from a Computational Fluid Dynamics (CFD) calculation and used to calculate the spatial and temporal evolution of the heat flux to the structure. Later studies [18-21] substitute the CFD calculations by different correlations and simplified approaches towards defining spatial temperature histories. The simplified approaches are based on the assumption that the fire
characteristics will not change as the fire spreads through the compartment. Furthermore, the correlations used are based on fires that have not attained flashover. While this approach allows for a more practical application of the “Travelling Fires” concept, it is clear that it relies on many assumptions and simplifications that have still not been fully validated with adequate experimental data.

1.2 Real Fires for the Safe Design of Tall Buildings

In recent years, the University of Edinburgh undertook the Real Fires for the Safe Design of Tall Buildings (RFSDTB) project, which aimed at producing a methodology that could be used to provide design fire inputs representative of real fire dynamics in large open-plan compartments typical of tall buildings. The RFSDTB project consisted of two series of full-scale experimental programmes, the Edinburgh Tall Building Tests and the Large-Scale Demonstrator Malveira Fire Test.

In 2013, the Edinburgh Tall Building Tests (ETFT) programme was carried out at the Building Research Establishment, Watford, United Kingdom [22]. The first stage of tests (Jan-May 2013) consisted of gas burner tests in a compartment of internal dimensions 5 m (width) x 18 m (length) x 2 m (height), and where different fire and ventilation modes were replicated. The second stage (May-June 2013) consisted of two wood crib tests in the same compartment with two different static ventilation conditions. The gas burner tests provide characteristic energy distributions for different fire and ventilation modes with prescribed energy input (heat release rate). Three different fire modes were studied based on the relationship between the spread velocity of the fire front ($V_f$) and the spread velocity of the burnout front ($V_{BO}$):

1. Mode 1: a fully-developed fire where $\frac{V_f}{V_{BO}} \to \infty$ (representative of a post-flashover).
2. Mode 2: a growing fire where $\frac{V_f}{V_{BO}} > 1$.
3. Mode 3: a “travelling fire” where $\frac{V_f}{V_{BO}} \approx 1$.

Three ventilation modes where studied based on the inverse opening factor ($\phi' = \frac{AT}{A_w\sqrt{H}}$):

1. Static ventilation with $\phi' = 4.1$.
2. Static ventilation with $\phi' = 23.3$
3. Variable with the inverse opening factor transitioning from $\phi' = 23.3$ to $\phi' = 4.1$
   (indicating increasing opening area as would be the case with window breakage).

Preliminary results from energy distribution analyses applied for the gas burner stage have been presented by Maluk et al. [23]. These clearly indicate different characteristic energy distributions within the compartment for the aforementioned fire modes and ventilation conditions. The wood crib fires were described briefly by Torero et al [4]. These test highlighted that a transition between the three modes used for ETFT gas burner tests was possible and, for the specific fuel configuration used, seemed to be a strong function of the ventilation conditions.

In 2014, a single full-scale fire experiment was carried out in a disused industrial building in Póvoa da Galega, Malveira, Portugal. The purpose of this test was to reproduce an open-plan compartment fire within a real building of a similar configuration to the ETFT gas burner
stage, and try to observe some or all of these fire modes. This paper describes the experimental
compartment in the LSD Malveira Fire Test, including installed sensors array, main results and
an initial analysis of the experimental output data. Data will be made available through the
University of Edinburgh Data Share repository (https://datashare.is.ed.ac.uk/handle/10283/3109) along with data from the Edinburgh Tall
Buildings Fire Tests.

2 Description of the compartment

The compartment selected for the experiment was originally an open-plan office within a two-
storey building. At the time of the experiment, the building was used by the Fire Service of
Malveira (Bombeiros Voluntários da Malveira) to practise firefighting techniques and observe
fire growth phenomena. The office compartment was selected for this experiment due to its
similarity in dimensions and opening characteristics to previous purpose-built experiments
from this project [22]. Even though this industrial building does not correspond to a tall
building, which is the main scope for this research, the key feature of this compartment is the
open plan space geometry, representative of office spaces in tall buildings [22]. The building
was constructed as a concrete frame structure with masonry block infill. The layout and
dimensions of the compartment are described in detail in the following sections.

2.1 Overview, dimensions and coordinate system

The internal dimensions of the experimental compartment were approximately 4.7 m (depth),
21.0 m (length), and 2.85 m (height). In places there were protrusions into this space due to
beams, columns and fittings. The compartment along with details of these protrusions are
presented in Figure 1 in (a) plan and (b) section. The origin of the coordinates system used to
describe locations within and around the compartment is in the rear left corner of the
compartment as viewed from the outside looking in (refer to Figure 1). The average floor to
ceiling height prior to installation of a false floor (described later) was 2850 mm. This is not
inclusive of a 100 mm deep layer of combustible cork insulation covering approximately 60%
of the ceiling. This layer was on the right-hand side of the compartment as shown in Figure
1b.
Figure 1. (a) The central diagram shows the floor plan of the compartment with overall dimensions. Surrounding diagrams give details of columns and other protrusions and shape irregularities. (b) Front view, section A-A': Dashed lines indicate positioning and dimensions of concrete columns and beams against back wall. The layer of cork and false floor are represented as hatched areas.

It is believed that, when the building was in use, this large open space originally corresponded to two different office rooms separated by a partition where the soffit beam is located. The two spaces were likely to be built in different stages, thus explaining the presence of cork insulation only in a fraction of the open space. It should be noted that cork is sometimes used as interior insulation in South Europe.

2.2 Positioning and dimensions of the openings

The primary openings were formed by five windows of varying dimensions, located along the front wall of the compartment. The positioning and dimensions of these windows are shown in Figure 2. There was one further opening formed by a door. This door was initially closed, however, it was opened during the test to encourage a concurrent flow through the fire and over the fuel bed, and thus encourage a more rapid fire growth. The position of this door is shown in Figure 1(a) and Figure 5 (c). The door opening was 0.85 m wide and 1.72 m
high. All other original openings to the compartment were sealed and remained so throughout the test.

![Diagram of compartment](image)

Figure 2. Elevation of the front wall as viewed from outside the compartment. (a) Sketch with location and dimensions of the windows. (b) Picture of the external view of the compartment. External Thin Skin Calorimeters (TSCs) are present on the façade above windows 1 and 2.

![Images of compartment](image)

Figure 3. View of the openings W5 (a), W4 and W3 (b) and W2 (c) from inside the compartment. Internal TSCs are visible above and below the openings.

### 2.3 Floor plan and floor system

The dimensions of the floor of the compartment are shown in plan in Figure 1. A false floor system was designed to enable mass loss measurements whilst maintaining a level floor throughout the compartment. The total height of this false floor system was 280 mm. The floor layer consisted, from top to bottom, of 100 mm of ROCKWOOL CONLIT™, a 10 mm plasterboard, and a 20 mm particleboard. When supported by a mass loss scale, the floor system was attached to a wooden frame that supported the floor 50 mm above the surface of a 100 mm deep mass loss scale. The frame system enabled passage of air beneath the floor and all around the mass loss scales in order to insulate and provide cooling. Elsewhere, the floor layer was supported by evenly distributed feet consisting of 50 mm of ROCKWOOL CONLIT™ and 100 mm deep masonry bricks, again to allow air to circulate beneath. The global height coordinate \( z = 0.0 \) m is level with the top of the false floor. Mass loss scales supported floor platforms with dimensions of 1.2 m x 2.4 m. The distribution of floor
platforms is shown in Figure 4. The final compartment effective height was thus 2570 mm in
the area without cork and 2470 mm in the area with cork.

3 Description of the sensor arrays

A large number of sensors were provided within the experimental compartment and on the
external façade. These were designed with the aim of characterising the fire environment at a
spatial resolution that enables the benchmarking of tools and methodologies developed by
the RFSDTB project, while at the same time considering the physical and time constraints
implied by working within an existing, partially derelict building. The measurements
provided by this instrumentation are subject to experimental errors, which have generally
been described in detail in the preceding experimental series – the Edinburgh Tall Building
Tests [22] and references within. The present test will be subject to the same error analysis
conducted for all instrumentation and described in [22], but given that the focus here is to
describe the characteristics of the fire and not to deliver a detailed quantitative analysis, the
reader is referred to [22] to determine the errors associated to each instrument. Where new
corrections are applied or new instrumentation is used, these are presented within each
particular section below.

3.1 Gas-phase temperature

1.5 mm bead K-type thermocouples were used to establish the spatial and temporal gas-phase
temperature fields inside the compartment and in each of the openings. A total of 24
thermocouple trees, in three rows of eight trees, with each tree containing eight thermocouples
were evenly spaced throughout the interior of the compartment. Each tree had thermocouples
at 0.77, 1.07, 1.37, 1.67, 1.87, 2.07, 2.27 and 2.42 m above false floor level (z = 0.0 m). The spacing
and locations of these internal trees are shown in Figure 4a. A further nine thermocouple trees
were located in the window openings. Each of these trees contained five thermocouples at
heights 0.15, 0.35, 0.55, 0.75, and 0.9 m above the window ledge, which corresponds to heights
0.82, 1.02, 1.22, 1.42 and 1.57 above the false floor level (z = 0.0 m). The locations of these trees
are shown in Figure 4b.
Figure 4. (a) Plan diagram showing floor, ceiling, gas-phase sensor locations and platform (1A – 7B) outlines. (b) Elevation diagram showing the window and façade sensor locations. The origin is consistent with the origin shown in Figure 1.

3.2 Incident radiant heat flux

As per previous experiments in the RFSDTB project [22], thin skin calorimeters (TSCs) were used to quantify incident radiant heat flux to solid surfaces. A total of 93 TSCs were located on all internal surfaces of the compartment, with further nine mounted in three columns of three gauges on the façade above windows 1 and 2. The layout of these TSCs are shown in Figure 5. The external TSCs are shown in Figure 7b.

The TSCs comprised a 10 mm diameter, 0.5 mm thick 304b stainless steel plate, with a KX-type thermocouple welded to the centre of the unexposed face. The plate was embedded in a 80 mm diameter, 25 mm deep Superwool® HT disc. The thermocouple wires pass through the Superwool® HT and exit through the rear. The design was such that a corresponding hole could be cored from the compartment wall, ceiling or floor and the Superwool® HT with TSC imbedded inserted, leaving the TSC flush with the surface of the wall, floor or roof. The calibration of these gauges, calculation methodology and associated error analysis are given by Hidalgo et al. [24].
3.3 Mass loss

A total of 14 scales were distributed beneath the fuel bed to measure mass loss from the wood cribs used as the design fuel load. The scales were a bespoke design for this test, designed, constructed and installed by LEVANTINA DE PESAJE LABORATORIO, S.L. Each scale was 1 m x 1 m x 0.1 m high and supported a 1.2 m x 2.4 m false floor platform. The arrangement of these platforms and installation are shown in Figure 4a and in Figure 6, respectively. The maximum load capacity of each scale was 300 kg with an expected accuracy in the reading of ± 20 g. The scales were calibrated on-site before the test.
Figure 6. (a) View of the floor from the left end of the compartment, with all the scales in place ready to hold the false floor platforms. (b) View of the floor on the right end of the compartment, with some scales holding the 1.2 m x 2.4 m platforms for the false floor. (c) Sketch of the false floor system (view from the bottom)

3.4 Gas flow velocity at the openings

A total of 29 bi-directional velocity probes [25] were distributed between each of the windows to characterise gas in- and out-flow. The locations of the probes corresponded to the thermocouple trees located there and sit above the external edge of the window sill. Each thermocouple tree location had three corresponding velocity probes except for one which had five velocity probes in window 2. Where three probes were present, they corresponded in height to the upper, middle and lower thermocouples of the window trees (i.e. 0.82 m, 1.22 m,
and 1.57 m from the false floor). The single location with five probes had a probe at each of the heights of the thermocouples in the corresponding tree (i.e. 0.82 m, 1.02 m, 1.22 m, 1.42 m, and 1.57 m from the false floor). The specific positioning of each probe relative to the windows is shown in Figure 4b. A representation of the system used to install the pressure probes is shown in Figure 7.

![Figure 7. (a) Window 1 showing the arrangement of bi-directional velocity probes and the cantilever system for the external network cameras. (b) View of the windows with bi-directional velocity probes and external network cameras, and the façade with thin skin calorimeters above windows 1 and 2.](image)

The bi-directional velocity probes were connected to differential pressure transducers. The set probe-transducer has recently been calibrated in a wind tunnel facility. Detailed results from these calibrations are presented by Gupta et al. [26]. The relation between velocity and voltage output from the transducers is shown in Figure 8 below.

![Figure 8. Correction factor for the bi-directional velocity probe and differential pressure transducer setup [26].](image)

### 3.5 Video imaging

A total of eight network cameras were employed to capture video footage of the experiment. A camera was embedded in each of the end walls looking along the length of the compartment. To enable analysis of the fire and burnout front position, cameras were also placed to look in through each of the four large windows (refer to Figure 7b). These cameras
were mounted to an insulated wooden beam cantilevered approximately 2 m out from the corresponding window sill. Two final cameras were positioned on the external façade of the compartment looking along the face of the openings. These cameras were positioned at mid window height in order to provide visual confirmation of the smoke layer height and evolution of the fire spread and burnout fronts. Further to the network cameras, a digital video camera and a thermal imaging camera were setup on the roof of a building in front of the experimental compartment to provide an overview of events inside the compartment and fully capture any smoke and flames emerging from the compartment front openings.

3.6 Data logging

Data logging was performed by two Agilent 34980A Switch/Measure Units, equipped with 34925A 40/80 Channel Optically Isolated FET Multiplexer modules. Each data logger was fitted with a 4-wire RTD in order to provide an external reference temperature for the thermocouples and connected via LAN cable to a unique PC to ensure that any computer issues had minimal impact on the amount of data recorded. Two PCs were assigned to log data from eight network cameras and a laptop was provided to record data from the thermal imaging camera. A final PC was associated to a bespoke data logging system for the mass loss scales. The bespoke system was designed and installed by LEVANTINA DE PESAJE LABORATORIO, S.L.

4 Fuel, ignition and opening factor

The fuel used in this experiment was wood cribs of Pinus Pinaster, with an assumed density of 510 kg.m\(^{-3}\) and a heat of combustion of 18 MJ.kg\(^{-1}\) provided by CIBSE Guide E to estimate fire loads in terms of the equivalent weight of wood [27]. Wood cribs were used, as in many other historical fire experiments, as it enables an idealised, simplified and evenly distributed fuel source. The intended fuel load was approximately 420 Mj.m\(^{-2}\), average design fuel load for an office according to EN 1991-1-2 [13]. The fuel bed was comprised of three full layers and one-half layer of Pinus Pinaster sticks. Each stick was 1.2 m long with a 5 cm x 5 cm cross section. In full layers, sticks were spaced at 5 cm thus each full layer was comprised of 10 sticks per metre length of fuel bed. In the half layer, sticks were spaced at 15 cm giving 5 sticks per metre run. The overall fuel bed size was 16.8 m long x 2.4 m wide as shown in Figure 9. The total amount of fuel was calculated using the total floor area of the compartment.
Figure 9. The image shows the arrangement of the beams and columns protruding into the experimental volume. It shows the fuel bed with the ignition fuel tray highlighted in red.

Moisture content measurements taken on the day of the experiment suggest an average moisture content of the individual sticks of 19% ± 6%. The average moisture content for the crib measurements along the approximated crib weight on each platform is shown in Table 1.

Table 1. Estimated mass and moisture content measurements for the wood cribs on each platform. Three data points per platform were taken for moisture measurements.

<table>
<thead>
<tr>
<th></th>
<th>1A</th>
<th>2A</th>
<th>3A</th>
<th>4A</th>
<th>5A</th>
<th>6A</th>
<th>7A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>153.7 kg</td>
<td>158.1 kg</td>
<td>166.6 kg</td>
<td>167.9 kg</td>
<td>174.3 kg</td>
<td>166.5 kg</td>
<td>158.7 kg</td>
</tr>
<tr>
<td>1B</td>
<td>158.0 kg</td>
<td>170.8 kg</td>
<td>164.1 kg</td>
<td>167.2 kg</td>
<td>171.1 kg</td>
<td>159.8 kg</td>
<td>169.7 kg</td>
</tr>
<tr>
<td></td>
<td>17% ± 2%</td>
<td>20% ± 5%</td>
<td>22% ± 13%</td>
<td>13% ± 1%</td>
<td>15% ± 1%</td>
<td>16% ± 2%</td>
<td>15% ± 3%</td>
</tr>
</tbody>
</table>

In addition to the wood crib, the only other fuel source available in the compartment was the 100 mm cork layer attached to the ceiling on the right-hand side of the compartment (Figure 1b). The cork layer was an energy efficiency feature of the building. It was decided not to remove it in order to provide a different boundary condition which could induce a change in fire mode due to lower heat losses or heat release contribution.

Thermogravimetric studies on the wood and cork were applied to characterise the volatile content and yield residue of both materials. These were tested with a heating rate of 20°C.min⁻¹ in three conditions: air, nitrogen, and air after testing in nitrogen. The normalised mass and derivative of the normalised mass versus temperature are presented in Figure 10 below. In nitrogen tests, it is shown that both wood and cork provide a char yield of approximately 20%.
The char appears to oxidise above 450°C, whereas the pyrolysis reactions are approximately observed within 200-400°C for wood and 250-450°C for cork. This indicates that pyrolysis and condensed-phase oxidation reactions occur within a very similar temperature range for cork and wood nevertheless, for both materials, pyrolysis and char oxidation occur in different temperature domains. Thus, the wood and the cork are identified as very similar charring burning fuels. Additionally, these fuels show similar heat release rate per unit area (120 - 206 kW.m⁻² for cork [28] and 54 – 177 for Radiata Pine [29]). The differences between the cork and wood fuel are the exposed surface area (much larger in the wood crib) and the material density and thermal conductivity (160 kg.m⁻³ for cork and 430-640 kg.m⁻³ for pine; 0.043 W.m⁻¹.K⁻¹ for cork and 0.112-0.147 W.m⁻¹.K⁻¹ for pine according to Table A.28 in [30]). Therefore, a lower burning rate is expected from the cork, however, the lower thermal inertia of cork (insulation) implies a faster ignition and flame spread [31, 32].

![Figure 10. Thermogravimetric analyses of wood (a) and cork (b) used in the test. Plots on the top indicate the normalised mass versus temperature, whereas plots on the bottom indicate the derivative of the normalised mass versus temperature. Tests were carried out in air, nitrogen, and in air after decomposition in nitrogen at 20°C.min⁻¹.]

Ignition of the wood crib was achieved through a 2.4 m line fire. A mixture of 5 litres of kerosene and 0.5 litres of diesel fuel was placed in a 2.4 m long x 10 cm wide and 5 cm high metal tray. This tray was placed at the start of the crib in place of the lowest two sticks, shown highlighted in Figure 9. A blow torch was applied to the liquid fuel mixture until ignition was achieved.

Table 2 shows the inverse of the opening factor calculated for the compartment under different assumptions. Table 2 uses three different calculation methods. The first is the
conventional method used by Thomas and Heselden [11], while the second and third columns use alternative methods that either include the cork or exclude all fuel in the calculation of $A_T$. For all cases, it is shown that the inverse of the opening factor is below $10 \, m^{-0.5}$, where Regime II fires are generally identified. The conditions were thus set to allow the exploration of the fire dynamics of Modes 2 and 3. The right hand side of the compartment (Figure 1) has slightly lower inverse ventilation factors, leading to the expectation that the fire will remain well within Regime II as it transitions towards the area with the cork. It is important to note that the inverse opening factor was not defined for an open floor plan geometry like the one presented here, therefore these calculations are only presented for reference. The theoretical underpinnings of concepts such as fully developed fires, ventilation limited firers, the Compartment Fire Framework or flashover have been extracted from experimental studies where the compartment is sufficiently small that the fire is allowed to spread across the fuel on the floor of the compartment until it reaches a static boundary [4,11]. While flashover can occur before the fire has reached its bounds all other terms have been defined using a fire where the burning fuel has static boundaries.

Table 2. Estimated opening factor for the compartment under different assumptions such as considering the compartment as a whole or separated sections divided by the central 500 mm deep beam dividing the two areas with different ceilings. The right hand column is not a conventional way of presenting the inverse opening factor and it is just presented to show that even with this bounding value the fire will remain within Regime II.

<table>
<thead>
<tr>
<th>Compartment</th>
<th>Inverse opening factor $\phi' = \frac{A_T}{A_{w\sqrt{H}}}$ ($A_T$ excludes floor and openings) /m$^{0.5}$</th>
<th>Inverse opening factor $\phi' = \frac{A_T}{A_{w\sqrt{H}}}$ ($A_T$ excludes wood crib and cork surfaces and openings) /m$^{0.5}$</th>
<th>Inverse opening factor $\phi' = \frac{A_T}{A_{w\sqrt{H}}}$ ($A_T$ excludes only the openings) /m$^{0.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall compartment</td>
<td>4.6</td>
<td>6.4</td>
<td>9.5</td>
</tr>
<tr>
<td>Left-hand compartment</td>
<td>4.6</td>
<td>5.9</td>
<td>6.6</td>
</tr>
<tr>
<td>Right-hand compartment</td>
<td>3.4</td>
<td>5.3</td>
<td>10</td>
</tr>
</tbody>
</table>

5 Results

A set of characteristic results that provide an overview of conditions throughout the experiment are presented.

5.1 Principal events and visual analysis of the evolution of the fire

After ignition the fire grew at a slow rate, continuing to travel at an apparent constant rate throughout the left-hand side of the compartment. This was visually confirmed with the fire front and burnout front displacing at a slow rate. The flame height was not uniform along the depth of the compartment. At 148 min after ignition, the door on the left wall of the
1 compartment was opened in order to study whether lateral flow would accelerate the fire
2 front spread velocity. After the door was opened, the computer system shut down, thus
3 interrupting the data logging system. The problem was solved approximately 5 min later,
4 resuming data logging. As the travelling fire approached the beam that differentiated the
5 compartment with and without cork on the ceiling, the fire appeared to grow in size as the
6 flames were apparently larger. After reaching the beam, it was observed that the cork
7 insulation ignited and soon after the flame on the cork spread vigorously. The fire front on
8 the crib then experienced a quick acceleration; soon the whole wood crib on the right-hand
9 side of the compartment was burning. External flaming was then observed. After two minutes
10 manual extinction was applied by the Fire Service due to the potential risk of collapse of the
11 building. Several instances of spalling were observed from the wall linings and beams.
12
13 A list of the major events observed in the test is provided in Table 3 below. Based on these
14 events and the data obtained from the experiments, five distinct time domains are defined to
15 ease the interpretation of results and fire behaviour. The timeframe for each domain is selected
16 based on the trends observed in the burning rate presented in further sections.

<table>
<thead>
<tr>
<th>Event</th>
<th>Time</th>
<th>Analysis time domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition</td>
<td>0 min 0 s (13:10:47)</td>
<td>Domain I (0-19 min)</td>
</tr>
<tr>
<td>Burnout front starts to develop</td>
<td>21 min 22s (13:32:09)</td>
<td>Domain II (19-152 min)</td>
</tr>
<tr>
<td>Opening of door</td>
<td>147 min 57s (15:18:44)</td>
<td></td>
</tr>
<tr>
<td>Generator shut down – data logging stopped</td>
<td>192 min 18 s (16:23:05)</td>
<td>Domain III (152-237 min)</td>
</tr>
<tr>
<td>Generator turned on – data logging resumed</td>
<td>206 min 59 s (16:37:46)</td>
<td></td>
</tr>
<tr>
<td>Fire front reaches central frame</td>
<td>224 min 42s (16:56:09)</td>
<td></td>
</tr>
<tr>
<td>Ignition spotted on cork ceiling</td>
<td>228 min 21s (16:59:19)</td>
<td></td>
</tr>
<tr>
<td>Rapid flame spread on the ceiling</td>
<td>237 min 11s (17:07:58)</td>
<td>Domain IV (237-238 min)</td>
</tr>
<tr>
<td>Rapid flame spread of the wood crib</td>
<td>237 min 53s (17:08:40)</td>
<td></td>
</tr>
<tr>
<td>External flaming</td>
<td>238 min 0s (17:08:47)</td>
<td></td>
</tr>
<tr>
<td>Extinction by Fire Service</td>
<td>241 min 6 s (17:11:53)</td>
<td>Domain V (238-242 min)</td>
</tr>
</tbody>
</table>

Figure 11 shows the different events and stages of the fire captured from the exterior with
video and SLR cameras.

Table 3. List of principal events observed in the test and time domains for analysis.
Figure 11. Sequence of images from the front video and SLR camera. (a), (b) and (c) show the travelling fire mode. (d) shows the ignition and fire spread of the cork insulation. (e) shows transitioning to a “fully-developed” mode as shown in (f).

Using the video footage from the front cameras and a video image processing technique [33], the position of the fire and burnout fronts are estimated for the whole duration of the test (Figure 12a). The length of the fire is calculated as the difference between the positions of these two fronts. Assuming that the fire spread and burned out uniformly along the width of the crib (2.4 m), the length and size (area) of the fire can be estimated (refer to Figure 12b). From the five distinct time domains defined in Table 3, Figure 12 shows clear different growth rates:

- Domain II with 2 mm.min\(^{-1}\) (0.005 m\(^2\).min\(^{-1}\)), corresponding with the definition of Mode 3 \((V_s/V_{BO} \approx 1)\);
- Domain III with 28 mm.min\(^{-1}\) (0.067 m\(^2\).min\(^{-1}\)), corresponding with the definition of Mode 2 \((V_s/V_{BO} > 1)\); and
- Domain IV with 1686 mm.min\(^{-1}\) (4.046 m\(^2\).min\(^{-1}\)), corresponding with the definition of Mode 1 \((V_s/V_{BO} \rightarrow \infty)\).

The growth rates for domains I and V are not assessed as for domain I the burnout front was not established yet, whereas for domain V all the wood crib was burning. It should be noted that the chosen trend lines hide other trends in smaller time scales, e.g. the fluctuations in domain III. Despite the smoothing effects, this approach is preferred for easier interpretation of results.

The transition between Domaine II and Domaine III is not related to the opening of the door. As it can be seen from Figure 12(a) (dotted black lines), the deviation from the parallel line fits can be traced to an earlier time. In contrast, an analysis of the burning rate shows the transition to occur later (see Mass Loss section). The transition point is difficult to determine and quantifying it is beyond the scope of this study. For the purpose of this description, the opening of the door will therefore be used as indicative of the moment of transition.
Figure 12. (a) Position of the fire spread and burnout front obtained with image processing techniques using video footage from network cameras located at the windows. The shading area corresponds to the location of the beam that separates the region of compartment with different ceilings. (b) Estimated length and size of the fire based on the assumption that the fire grows uniformly along the width/depth of the compartment.

5.2 Mass loss

Figure 13 shows the normalised readings of each of the 14 scales, with 1A and 1B corresponding to the ones on the left-hand side of the compartment next to the wall and next to the window, respectively. Wherever possible, the data have been cleaned so that increase of mass due to debris from the cement linings falling onto the scale is minimised. Until 125 minutes, it is shown that only the fuel on 1A and 1B decreases. The mass loss follows a linear decrease, suggesting a steady burning rate. It is also observed that, up to 58 minutes, 1A and 1B experience similar mass loss, however, the burning rate of 1B is slightly higher afterwards. From 125 minutes to 160 minutes, the wood cribs on 2A and 2B appear to be burning along with 1A and 1B, which burn at a very low rate probably experiencing smouldering. After 170 minutes, the wood cribs 1A and 1B appear to be almost completely consumed; instead, 2A
and 2B show a linear decrease, suggesting again a steady burning rate. Although 2A initially shows a lower burning rate, after 160 minutes it appears to be faster than 2B. After 195 minutes, the cribs 3A and 3B start to burn with the same pattern as shown by the previous pair of cribs. It is clearly shown that the slope of 3A and 3B is larger than the slope of 2A and 2B, and the slope of these is larger than 1A and 1B. 3A is also shown to burn much faster than 3B, presumably due to higher radiant feedback as 3A was closer to the wall whereas 3B was closer to the window (refer to section 5.4). After 238 minutes the rest of the cribs start to lose mass significantly faster and at a higher rate, as shown by the drastic loss of mass. This transition is more clearly shown in Figure 13b. At 241 minutes a sudden increase of mass is shown, corresponding to the manual extinction by the Fire Service. Previous increase of mass shown by scales 2A, 3A and 3B correspond to falling debris that was not possible to correct.

Figure 13. Normalised mass for each platform for (a) the whole duration of the test and (b) for a zoom in at 230-244 minutes. Extinction is shown as a vertical dotted line.

In order to establish a clear burning rate of the overall wood crib fuel in the compartment, Figure 14 shows the total mass loss rate from the wood cribs. Figure 14a shows the five clear domains with significantly different burning rates. These domains are denoted visually with vertical dotted lines. The ‘slope’ of the burning rate is used to represents the rate of change in
the burning rate, which theoretically correlates to the increase of burning surface area as shown in Figure 12. Note that the odd choice of units, g.s\(^{-1}\)/min, is justified to provide a better interpretation of the variation in burning rate (normally expressed in g.s\(^{-1}\)) for a long duration test (easily expressed in minutes).

- **Domain I (0 – 19 min)**: an initial peak up to 4 minutes, related to the kerosene-diesel mixture, and a growth up to 19 minutes (refer to Figure 14b).

- **Domain II (19 – 152 min)**: from 19 minutes until 152 minutes, the burning rate is lightly increasing from 36 g.s\(^{-1}\) to 55 g.s\(^{-1}\), thus a rate of 0.14 g.s\(^{-1}\)/min (refer to Figure 14b).

- **Domain III (152 – 237 min)**: after 152 minutes the burning rate experiences a faster acceleration followed by a deceleration; this cycle is observed twice during this period and it is not clear exactly what causes these fluctuations. However, a global (average) linear increase rate of 0.47 g.s\(^{-1}\)/min can be observed. The region corresponds to the fuel from the pairs {2A,2B} and {3A, 3B} (refer to Figure 14b).

- **Domain IV (237 – 238 min)**: at 237 minutes the burning rate accelerates significantly with an approximated rate of 298.35 g.s\(^{-1}\)/min (refer to Figure 14c).

- **Domain V (238 – 242 min)**: a peak mass loss rate of 1.3 kg.s\(^{-1}\) is observed at 238 min, with a stabilisation of the mass loss rate around 800-900 g.s\(^{-1}\). Data beyond 242 minutes is not shown as the insertion of water inhibits estimating the actual decrease of burning rate (refer to Figure 14c).

It is shown that the variation in burning rate observed for domains II to IV are consistent with those variations in observed fire length and size presented in Figure 12b. Therefore, it can be confirmed that the differences between domains are associated to an acceleration of the fire front.

The fluctuations in fire length and size observed for domain III (Figure 12b) are also observed in the burning rate (Figure 14); even more dramatically. Since these fluctuations occur when only one scale is affected, it is believed that this may not be caused by the transition between scales. Instead, it is believed that this could be caused by areas of the crib with increased moisture content as shown in section 4.
Figure 14. Total mass loss rate from the wood crib measured with the scales. Data has been corrected taking into account debris that fell on the platforms and applying a locally weighted scatterplot smoothing (LOESS) filter [34] for different domains independently.

(a) Complete duration of the test. (b) Zoom-in for a maximum MLR of 200 g.s⁻¹. (c) Zoom-in for 230-244 minutes. Green vertical dotted lines indicate transitions between domains observed in MLR. Black vertical dotted line indicates the manual extinction by the fire service.
5.3 Gas-phase temperature

The evolution in the gas-phase temperature within the compartment is shown using contour plots based on the data from thermocouple trees. Figure 15 to Figure 18 show the representative thermal evolution for each of the domains observed in the previous section. These contour plots correspond to the centre-line thermocouple trees along the length of the compartment. Linear interpolation is used to represent the temperature in areas between thermocouple trees. White areas are regions where temperature data were not collected. The beam located in between areas of the compartment with and without cork attached to the ceiling is shown as an L-black shape. The cork is shown as a thin brown layer, whereas the thermocouples are represented as green dots. To better describe these plots, each of the domains from II to V are described independently:

- **Domain II** (Figure 15, 19 to 152 min): characteristic temperature fields in the near field and the far field are clearly identifiable. Plots at 19 and 152 min suggest that the fire appears to be travelling, i.e. spreading via Mode 3 ($V_a/V_{bo} \approx 1$), since a distinctive plume temperature field is observed. This is consistent with the slowly growing burning rate of the crib, which grows at a rate of 0.14 g.s$^{-1}$.min$^{-1}$. It is observed a slow but consistent increase in the overall gas-phase temperature, both in magnitude and volume of hot areas. Maximum gas-phase temperatures in the ceiling above the near-field are below 300°C.

![Figure 15. Gas-phase temperature contour along the centre-line of the compartment from 19 to 152 min (domain II).](image)

- **Domain III** (Figure 16, 152 to 237 min): between 160 and 234 min, the fire appears to be travelling as per Domain II, however, the temperatures are increasing. This is consistent with the increase in burning rate, which grows at a rate of 0.47 g.s$^{-1}$.min$^{-1}$, and increase in fire size, which grows at a rate of 28 mm.min$^{-1}$ (or 0.067 m$^2$.min$^{-1}$) as described in the previous sections. This confirms that the fire is not only travelling but growing in size (surface area) as the burning rate increases – transition from Mode 3...
(V_s/V_{BO} \approx 1) to Mode 2 (V_s/V_{BO} > 1). This behaviour is verified by the increasing area of the near-field temperatures which are characterised by higher temperatures. Additionally, it is observed that the beam disrupts the ceiling jet, as the temperature distribution observed on the far left-hand side of the compartment are higher than those observed beyond the beam on the right-hand side of the compartment. This behaviour changes from 234 min, when a localised area of the cork ceiling on the right of the beam is increasing in temperature, with temperatures above the maximum temperature below the ceiling on the left of the beam. This is due to local ignition of the ceiling material in that location, which was verified visually. The flame on the ceiling appears to spread as the regions with higher temperature spread towards the right-hand side of the compartment. During this process, the flame is not rapidly spreading over the crib since the temperatures on the bottom thermocouples are significantly lower. At 237 min, the fire on the crib reaches the thermocouple tree located on the right-hand side of the beam (close to y = 9 m).
Figure 16. Gas-phase temperature contour along the centreline of the compartment from 152 to 237 min (domain III).

- Domain IV (Figure 17, 237 to 238 min): following the ignition and flame spread of the cork insulation attached to the ceiling, after 237 minutes the fire transitions from Mode 2 ($V_s/V_{BO} > 1$) to Mode 1 ($V_s/V_{BO} \to \infty$), accelerating rapidly over the surface of the wood crib. This is consistent with the large increase in burning rate presented in previous section, transitioning from a rate of $0.47 \text{ g.s}^{-1}\text{min}^{-1}$ to $298.35 \text{ g.s}^{-1}\text{min}^{-1}$.
Figure 17. Gas-phase temperature contour along the centreline of the compartment from 237 to 238 min (domain IV).

- **Domain V (Figure 18, 238 min to 240 min):** once the flame of the wood crib has spread up to the right end of the compartment, temperatures on the right-hand side of the compartment are approaching 800-1,000°C, typical of fully-developed fires. The temperatures are more uniform at the centre of the crib ($y = [9 \, \text{m}, 17 \, \text{m}]$), with lower temperatures on at the edges ($y < 9 \, \text{m}$ and $y > 17 \, \text{m}$), presumably due to air entrainment and the absence of fuel on those areas. On the left-hand side of the compartment, there is a clearly defined two-zone behaviour. Nonetheless, a ceiling jet temperature pattern is observed in the hot layer, with increasing temperatures close to the area where all fuel burning ($y > 9 \, \text{m}$).

Figure 18. Gas-phase temperature contour along the centreline of the compartment from 238 to 240 min (domain V).
5.4 Incident radiant heat fluxes onto floor

The evolution of the incident radiant heat flux onto the floor are shown in Figure 19. The two rows of TSCs correspond to Row ‘Z0-A’ and ‘Z0-B’ which are the rows of sensors along the 850 mm and 3850 mm planes in the x-axis, respectively. For the heat flux calculation using TSCs, it was assumed that the gas-phase at the floor level remained at ambient temperature, since thermocouples were not at the ground level and these would include radiation errors.

The plots have been divided into the five domains.

- **Domain I (0 to 19 min).** It can be seen that the measurements by most sensors are less than 1 kW.m\(^{-2}\) with the exception of HF-Z0-A1 and HF-Z0-B1, the TSCs located at x = 2200 mm, and correspond to the sensors closest to the flames at this time. The heat flux of HF-Z0-A1 and HF-Z0-A1 increase from 0 kWm\(^{-2}\) to roughly 5 kWm\(^{-2}\) and 3 kWm\(^{-2}\), respectively. The heat flux recorded by HF-Z0-A1 is higher than HF-Z0-B1, suggesting that the fire front position is not uniform in width or extra radiative feedback is received near the wall.

- **Domain II (19 to 152 min).** HF-Z0-A1 and HF-Z0-B1 experience a decrease at approximately 20.7 minutes, which corresponds to the time at which the liquid ignition source consisting of the mixture of 5 L of kerosene and 0.5 L burning out, as confirmed visually by the video footage, whereby the production of smoke reduces as the liquid fuel is consumed. All other sensors indicate an increase in heat flux throughout the duration of this Domain. HF-Z0-A2 shows the highest increase from roughly 1 kWm\(^{-2}\) to 6 kWm\(^{-2}\). This change is not reflected by HF-Z0-B2, and this sensor reads consistently low values throughout the duration of the test indicating sensor failure. HF-Z0-A3 and HF-Z0-B3 read the third highest values throughout this Domain increasing to roughly 2 kWm\(^{-2}\). These readings correspond to the fire location, which is between y = 2200 and y = 5200 during this stage of the test.

- **Domain III (152 to 237 min).** The period between 192 and 209 minutes is represented by a straight line as this corresponds to the period where the data logger failed and was rebooting, and thus no data was collected. HF-Z0-A2 remains the highest heat flux between 152 and 192.3 minutes as during this stage the fire is still closest to this sensor, as the flame front travels from approximately y = 5200 to y = 7000 mm and the burnout front travels from y = 1650 to y = 2410 mm, and the values remain consistent for the entirety of the Domain. During the period where data was not collected, HF-Z0-A3 and HF-Z0-B3 begin to read the highest heat fluxes up until 236.9 minutes. The peak heat flux recorded during this stage by HF-Z0-A3 and HF-Z0-B3 are 15 and 10 kWm\(^{-2}\) respectively. HF-Z0-A4 and HF-Z0-B4 begin to rise rapidly in their heat flux readings at around 220 minutes as the fire reaches the soffit, as confirmed by video footage. HF-Z0-A5 and HF-Z0-B5 show a similar trend, however to a less extent being located further downstream of the fire. Between 221 and 226 minutes the data recorded by HF-Z0-A3 was removed due to artificial noise from the TSC.

- **Domain IV and Domain V (237 to 240 min).** Once the fire rapidly and almost instantaneously spread throughout the right side of the compartment at
approximately 238 minutes, all TSCs failed, as indicated by a drop-in heat flux. Therefore, to reduce artificial data, all data following a decrease in heat flux beyond 238 minutes was removed.

![Graph](image)

Figure 19. Incident radiant heat flux imposed on the floor along the length of the compartment at $x = 850$ mm (a – next to back wall) and $x = 3850$ mm (b – next to window). (a2) and (b2) show a zoom-in for 234 to 240 min, transition from domain IV to V.

Sensors 4 through 6 for both Rows A and B read the highest heat fluxes at this stage, as they are located to the right of the soffit where the fire first rapidly increases in size as it spreads throughout the right side of the enclosure. The peak heat fluxes recorded by each sensor during this Domain are provided in the table below, with the exception of TSC rows 1 and 2 as their peaks were recorded in Domains I and II.

Table 4. Peak heat fluxes recorded by the TSCs during Domains IV and V of the test.

<table>
<thead>
<tr>
<th>y-position</th>
<th>Row HF-Z0-A - $x = 850$ mm (kW.m$^{-2}$)</th>
<th>Row HF-Z0-B - $x = 3850$ mm (kW.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>49</td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>117</td>
<td>80</td>
</tr>
<tr>
<td>5</td>
<td>139</td>
<td>112</td>
</tr>
<tr>
<td>6</td>
<td>107</td>
<td>84</td>
</tr>
<tr>
<td>7</td>
<td>75</td>
<td>69</td>
</tr>
<tr>
<td>8</td>
<td>64</td>
<td>45</td>
</tr>
</tbody>
</table>

The values recorded by Row B are generally lower, indicating that the flame front position was not constant with depth, and Row B was possibly impacted on by its location being adjacent to the openings.
5.5 Opening Flow Velocities

The evolution of the gas in- and out-flow velocities are shown for each window. The associated thermocouple trees are used in conjunction with the bi-directional probes to calculate the respective density of air. Figure 20 shows the flow velocity of each bi-directional probe located within a vertical array, with a negative flow velocity reading indicating an in-flow, and positive flow velocity indicating an outflow. The transition between the in-flow to out-flow is described as the neutral pressure plane region. Like Section 5.3, each of the plots describe each domain independently.

Figure 20. Flow velocities at each of the five window openings during the time of domain II (19 min to 152 min). Each plot represents in ascending order, each opening along the length of the compartment (i.e. the plot on the left corresponds to W1 and the plot on the right corresponds to W5).

- **Domain II** (Figure 15, 19 to 152 min): at 19 min, characteristic velocities through opening 1 and opening 2 are higher than the other openings, indicating that the plume from the fire is starting to develop and hot convective flows are leaving locally through the openings close to the fire. Opening 3 onwards shows constant inflow velocities for each height, up until the neutral plane region, $H_N$, which is defined as the transition region from inflow to outflow velocities and lies in-between 1.42m and 1.57m above the false floor level. The plots at 152 min show that at $y = 4.6m$, the velocities recorded are all negative (i.e. flowing into the compartment). This could be induced by local entrainment of air from the near-field of the fuel-controlled travelling fire, which is indicative of the region for which the flame front is located. The peak velocity is recorded at 1.4m/s, which is the probe array located just downstream of the flame front ($y = 6.95m$).
Figure 21. Flow velocities at each of the five window openings during the time of domain II (152 min to 237 min). Each plot represents in ascending order, each opening along the length of the compartment.

- Domain III (Figure 21, 152 to 237 min): between 160 and 215.5 min, the fire front (as defined from the mass loss rate recorded using the scales) is located in-between the two probe arrays in opening 2. This is observed with the low flow readings at L = 4600mm at 160 min, and then at L = 6950 mm at 215.5 min, indicating a local entrainment effect dominating the flow field at the opening of this point. Within this period, the highest flows are recorded at the probes just downstream or upstream of the fire front, followed by opening 1. Between 215.5 min and 237 min, the fire front has transitioned to the region in-between opening 2 and opening 3, with the upstream velocities in opening 1 and opening 2 increasing substantially. At 234 min, the neutral plane height has descended at opening 2, such that the neutral plane region lies in-between 1.22 m and 1.42 m, corresponding with visually observed descending smoke layer triggered by the ignition of the cork ceiling. Peak outflow velocities are recorded in-between 2.5 m.s\(^{-1}\) and 2.7 m.s\(^{-1}\) at L = 6950 mm, which is the probe upstream of the rapidly expanded fire front, followed by the probes located in opening 1, which range from 1.6 m.s\(^{-1}\) to 2.3 m.s\(^{-1}\). Near-wall velocities recorded by the probe array at L = 1460 mm consistently records the second highest outflow velocities. It is important to note that inflow velocities through Domain III are shown to be constant, with probes located downstream of the fire, also recording consistent values.

The probe data for domain IV and domain V are not presented herein, as the probes located downstream of the fire were engulfed in external flaming, with the plastic hoses connecting the probes and transducers starting to heat and possibly melting.

5.6 Heat release rate quantification

The heat release rate of the fire is estimated using a mass loss rate calorimetry approach, using the burning rate of the wood crib. A range of [12.8 – 20.4] MJ.kg\(^{-1}\) for the heat of combustion of two species of pine wood [Error! Reference source not found.] is assumed to consider the uncertainty in the material and efficiency of the combustion. The HRR is shown in Figure 22, and it can be identified that the transition to fully-developed fire (or flashover/thermal runaway) is shown approximately near 2.1MW. It should be noted that this HRR estimation does not consider the burning of the cork insulation, and therefore the true value would be expected to be higher from 237 min, where the transition is identified.
6.1 Fire behaviour modes

A preliminary analysis of the results presented in the previous section indicates that the compartment fire experienced the three distinct fire modes for the floor fuel load formerly presented by Hidalgo et al. [22]. Applying a linear fit to the fire front and burnout front position for each of the domains presented in Figure 12, an average velocity can be estimated using the slope of the linear fit. Average velocities and the ratio between these are presented in Table 5 below.

Table 5. Average fire front and burnout front velocity for each time domain using linear fitting functions. Ratio between these velocities and fire behaviour mode are shown.

<table>
<thead>
<tr>
<th>Time domain</th>
<th>Fire front velocity ($V_s$) /mm.min$^{-1}$</th>
<th>Burnout front velocity ($V_{BO}$) /mm.min$^{-1}$</th>
<th>$V_s/V_{BO}$ /-</th>
<th>Fire mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>21</td>
<td>0</td>
<td>$\rightarrow \infty$</td>
<td>-</td>
</tr>
<tr>
<td>II</td>
<td>13</td>
<td>12</td>
<td>1</td>
<td>$V_s/V_{BO} \approx 1$</td>
</tr>
<tr>
<td>III</td>
<td>54</td>
<td>26</td>
<td>2</td>
<td>$V_s/V_{BO} &gt; 1$</td>
</tr>
</tbody>
</table>
Each of the fire modes identified were characterised by the following conditions. It should be noted that domain I is excluded from the three modes, since it corresponds to the early transient growth with the burnout front not developed yet.

- A **travelling mode** \( \frac{V_s}{V_{BO}} \approx 1 \) corresponding to domain II with a burning rate in the range 36 g.s\(^{-1} \) – 55 g.s\(^{-1} \) that lasted 133 min. The fire length had an average value of 1.2 m (corresponding to a fire size of 2.88 m\(^2 \)), which grew at an average rate of 2 mm.min\(^{-1} \). The incident radiant heat flux imposed on the fuel bed ahead of the fire front was below 6 kW.m\(^{-2} \).

- A **growing mode** \( \frac{V_s}{V_{BO}} > 1 \) corresponding to domain III with a burning rate in the range 55 g.s\(^{-1} \) – 100 g.s\(^{-1} \) that lasted 85 min. The fire length had an average growth rate 28 mm.min\(^{-1} \) (corresponding to a size growth of 0.067 m\(^2 \).min\(^{-1} \)). The average rate at which the burning rate grew was 0.47 g.s\(^{-1} \).min\(^{-1} \), caused by an increase in the burning area. The incident radiant heat flux onto the floor ahead of the fire front were below 10-15 kW.m\(^{-2} \).

- A **mode with an extremely rapid or instantaneous spread of the fire front such that the fire immediately covers the entire available fuel surface in the compartment** \( \frac{V_s}{V_{BO}} \rightarrow \infty \), commonly defined as flashover transitioning to a fully-developed fire. This corresponds to domain IV with an extremely rapid fire growth (1.686 m.min\(^{-1} \) for the fire length and 298.35 g.s\(^{-1} \).min\(^{-1} \) for the burning rate) that occurred within a minute and reached a peak burning rate of approximately 1.3 kg.s\(^{-1} \). Subsequently, in domain V, the fire covered the available fuel surface on the floor, for 2 min and an average burning rate in the range 800 – 900 g.s\(^{-1} \). This short duration was due to the intervention of the fire service for safety reasons. It should be noted that this stage would have been expected to continue until the consumption of the fuel load. Incident radiant heat fluxes onto the floor during domain IV were increasing above 15 kW.m\(^{-2} \) and reaching maximum values within the range 112 to 134 kW.m\(^{-2} \) during domain V until the sensors failed.

### 6.2 Transition between fire modes

Analysis of the conditions governing the transition between fire modes is of extreme importance towards establishing a comprehensive framework for compartment fires in open-floor plan spaces. This section presents a brief discussion of the conditions observed within each fire mode, and the transition between modes.

The initial mode, the travelling fire mode \( \frac{V_s}{V_{BO}} \approx 1 \), was characterised by being almost steady process with very slow increase in burning area and therefore burning rate. It can be assumed that the energy distribution in the compartment enabled a fire front spread velocity equivalent to the burnout front velocity (refer to Figure 12 and Table 5). It is theorised that the principal driver dictating the flame propagation is the local radiation from the flame itself, given that the heat fluxes from the smoke layer onto the floor were relatively low (<6 kW.m\(^{-2} \)).
2), with a relatively thin smoke layer. At these heat fluxes, preheating of the crib by the smoke will be very slow and thus not affect the flame spread or burning rates.

The transition of the fire from the travelling mode \( (V_s/V_{BO} \approx 1) \) into the growing mode \( (V_s/V_{BO} > 1) \), and subsequently to a fully-developed mode \( (V_s/V_{BO} \to \infty) \) is justified by an acceleration of the fire front over the burnout front, which is evidenced by the increasing burning area and therefore burning rate. In this stage, the heat from the smoke layer appears to affect the fire front velocity, i.e. a flame spread surface phenomenon, than the burnout front velocity, i.e. the burning rate phenomenon controlled by charring. The development of an increasing heat flux ahead the fire front was observed, up to 10-15 kW.m\(^{-2}\) (refer to Figure 19) before the transition to a fully-developed fire.

Until detailed energy distribution analyses are performed, it can be assumed that the increase of heat flux is due to a change in the energy balance in the compartment. The change in the energy balance may be induced by a reduction of heat losses through the boundaries, trapping or containment of heat in a localised area of the compartment by the physical geometry, and extra heat release contribution within the compartment – essentially all playing the same role.

The results presented in previous sections show that both the 500 mm deep soffit beam located at \( y = 9940 \) mm and the cork insulation have played a driving role in the transition of fire modes.

It is hypothesised that the transition of the fire from the travelling mode (domain II) to the growing mode (domain III) of the test might be triggered by the presence of the soffit beam. This is illustrated in the temperature contour plots shown in Figure 15 and Figure 16. While domain II displayed a thin smoke layer, as the fire approaches the beam it results in an obstruction that promotes smoke layer accumulation within the left side of the compartment which in turns provide a source of heat feedback into the fire and fuel allowing for the burning rate to increase. For domain II the fire plume temperatures in the nearfield were consistently lower than 200 °C; these near-field temperatures increase to above 300 °C as the fire approaches the soffit. The analysed data supports the belief that the opening of the door did not play a major role. This may need to be verified using models to describe the velocity fields induced by the opening of the door.

It was observed that the transition of the fire from the growing mode (domain III) to the fully-developed mode is strongly related to the presence the cork on the ceiling. Due to its low thermal inertia \( (< 10^4 \ W^2 \ s \ m^{-4} \ K^{-2}) \) \[\text{[Error! Reference source not found.]}\), ignition and fire spread over the cork on the ceiling is very fast, thus the transition is abrupt. The cork insulation, although a charring material, can sustain burning if sufficient heat is provided leading to a significant change in the thermal balance in the compartment. Even though cork has been shown by several authors to provide a relatively low HRR \( (120 - 206 \ kW.m^{-2}) \) as shown by [28]) it is clear that in this case the heat released by the cork has an impact sufficiently important to trigger the transition. Presumably, as the energy was released on the ceiling of the compartment heat losses and air entrainment are reduced, with both effects contributing towards the transition. These two mechanisms of behaviour/contribution from the insulation have previously been discussed by Hidalgo et al. [30].
The presence of soffit beam and the thermal insulation material, whereas very characteristic of the scenario studied, evidences the importance of adequately defining the thermal energy balance in the compartment so that realistic fire modes can be used as input design scenarios in open-plan floor compartments.

Further investigation is required to provide a better understanding of the sensitivity of the spread velocity of the fire front \( V_s \) and the burnout front \( V_{bo} \) to the external heat flux.

Consolidated research has demonstrated that the flame spread \( V_s \) is primarily a function of the fuel thermal inertia and the external heat flux whereas the burnout time is a function of the fuel density and mass loss rate per unit area, which depends on the external heat flux [35].

### 6.3 Identification of fire regime in domain V

The analysis of fire regime is only undertaken for the domain V of the fire, which corresponds to a fully-developed fire. The temperatures observed in the right end of the compartment following ignition of the cork ceiling and rapid flame spread across the right end of the compartment have been compared to the theoretical temperatures in Regime I fires using the Thomas plot [11]. The opening factor was then calculated by dividing the enclosure into two compartments (refer to Table 2), as the fire was effectively only taking place in the right end as all fuel on the left of the central beam had been consumed. The temperatures used to compare the experimental results to the ‘Comartment Fire Framework’ were taken as the average temperature within the right end of the compartment during the steady-state burning of domain V, which took place approximately between 239 and 241 minutes as shown in Figure 23.

![Figure 23. Average temperature within the compartment during domain V.](image)

The average temperature was found to be \( 862 \pm 131 ^\circ C \); this interval corresponds to the spatial variation in temperature. The peak temperature reading throughout the entire test was found to be \( 1056 ^\circ C \). A comparison of these values to the Thomas plot is shown in Figure 24. Note that the opening factor is computed by excluding the fuel and opening surfaces from \( A_T \). The steady-state fire briefly observed during domain V is shown to be representative of a Regime II fully-developed fire, with the average fire temperature during this stage being very closely estimated by the data collected by Thomas and with significant spatial variability. The
maximum temperature reading within the compartment is more indicative of a Regime I fire; however, this was recorded by thermocouple A5-5 at 239 minutes with similar temperature recorded in Row 5 of the thermocouple trees. It is assumed that this occurred as the flame engulfed the sensors.

Figure 24. Comparison of experimental results of domain V (fully-developed fire) to the Thomas plot [11]. The blue point represents the average temperature within the compartment during this phase and red the maximum recorded temperature. The dashed line depicts the maximum temperature according to Regime I theory

7 Conclusions

This paper presents the characterisation of the Large-Scale Demonstrator ‘Malveira Fire Test’, which took place in a well-ventilated, open-plan compartment in Povoa de Galera, Malveira, Portugal in 2014. The principal source of fuel was a continuous bed of wood cribs running the length of the compartment, parallel to the ventilation, closely replicating the setup of the Edinburgh Tall Building Tests. The high density of instrumentation enabled significant spatial resolution of the thermal conditions and thus enabled a quantitative interpretation of the visual observations.

Three fire behaviour modes are clearly identified based on the experimental data, corresponding to a travelling fire, a growing fire, and a fully-developed fire; appearing sequentially as the fire moves along the entire length of the compartment. These modes are defined by the ratio between the flame front velocity and burnout front velocity. The transition between fire modes, and thus evolution of energy production appears strongly linked to the spatial redistribution of energy produced, and specifically to the evolution in heat feedback to the unburned fuel. This energy redistribution is strongly coupled with the variation in physical characteristics of the compartment along its length, e.g. openings, thermal characteristics of the boundaries, compartment geometry, etc.

This test illustrates the importance of, and thus need for, accurate characterisation of the dominating mechanisms driving the flows within the compartment at each stage of the fire
development. The above governs the energy redistribution during the fire and therefore the ability of the fire to transition from one fire mode to another. Accurate characterisation of the expected fire dynamics during each expected mode will in turn enable the adequate design of the fundamental elements (pressurisation systems, structural fire protection, etc.) underpinning the success of fire safety strategies for tall buildings.

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Defining the Thermal Boundary Condition for Protective Structures in Fire

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Abstract

Protective structures are designed explicitly to fulfil a function which in many cases is an extreme event, therefore, the explicit design has to properly and precisely account for the nature of the solicitation imposed by the extreme event. Extreme events such as explosions or earthquakes are reduced to design criteria on the basis of either empirical or historical data. To determine the design criteria, the physical data has to be translated into physical variables (amplitudes, pressures, frequencies, etc.) that are then imposed to the protective structure. While there is debate on the precision and comprehensive nature of this translation, years of research have provided strong physical arguments in supporting these methods. Performance is then quantified on the basis of the structure’s capability to perform its required function. Classified solicitations may then be used to translate performance into prescribed requirements that provide an implicitly high confidence that the structure performs its function. When addressing fire, performance has been traditionally determined by imposing standardized requirements that only bear a weak relationship with the reality of potential events – the fire performance of a protective structure is thus defined as a fire resistance period. This paper addresses the concept of fire resistance and its relevance to the design of protective structures. The mathematical description of the thermal boundary condition for a fire is of extreme complexity, therefore simplified approaches, that include the Fire Resistance concept, are currently used. By using classical heat transfer and structural engineering arguments, it is demonstrated what is the adequate level of complexity that is appropriate for the thermal boundary condition and when a precise definition of this input parameter is fundamental to adequately understanding the response of a structure to fire event. Simple criteria are presented to qualify the relevance of current approaches and to highlight important issues to be considered.

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Fire; fire resistance; protective design; explicit performance; boundary conditions
1. Introduction

The capability of a protective structure to perform its function is defined by a design process that should contemplate the different solicitations that a structure may have. In many cases, this requires understanding the effects of single or potentially multiple solicitations. Moreover, critical infrastructure is generally design to withstand combined hazards, therefore, protective structures are also generally designed to perform their function when affected by combined hazards. While protective structures can be designed to withstand the effects of fire, it is often necessary to introduce fire as part of a multiplicity of hazards. This is the case when designing mines protective seals against explosions, where fires tend to follow explosions, or when designing structures that protect the core of nuclear reactors that could be subject to terrorist attacks or earthquakes followed by fires. When considering the potential of combined hazards, the design of structural protection to fire assumes that the capability of the structure to withstand fire remains intact. This assumption has the potential of not being realistic (or even un-conservative), nevertheless, because of the nature of the fire safety design process, the assumption is often unavoidable.

When designing for fire, performance is not explicitly calculated but is calculated on the basis of a presumption that “fire resistance” represents a worst case fire scenario condition that if imposed onto a single element of the structure, will result in a solicitation not exceeded by any realistic potential fire.

Fire is an extremely complex combination of physical phenomena that currently cannot be fully described by means of mathematical models. Thus, some level of simplification is always necessary. In particular, in the case of structural analysis the necessary simplifications are very significant because the structure also needs to be described. When focusing on structural performance, coupling between gas and solid phase is commonly avoided and the fire is treated as a thermal boundary condition. The choice of what is the appropriate complexity necessary for the thermal boundary condition and to what section of the structural system should it be applied remains a matter of current debate. This paper will review some basic concepts to clarify the implications of specific simplifications and establish simple criteria that allow to establish when more or less complexity is needed.

In current practice, the fire solicitation and its manifestation on the behavior of the structure is typically solely defined in the temperature domain and does not require any explicit quantification of heat transfer (energy conservation) or mechanical structural performance. During design, elements of the structure
might be subject to the standard “fire resistance” testing procedures – for assuring the compliance of single elements considered in isolation. Single element performance under fire as part of a whole structural system behavior is rarely addressed. Once the requirements for “fire resistance” are met, then it is assumed that all serviceability requirements for the structure will be met independent of any other solicitation or the integral nature of the structural system. This approach implies strong simplifications that assume that global structural behavior can be bounded by single element performance assessment and that heat transfer from the fire to the structure can be adequately characterized by gas phase temperatures and standardization of the thermal environment (i.e, a test furnace).

This paper examines the two stages that must be considered as part of any design process for a structure to withstand the effects of fire. Specifically considered are:

- the assessment of thermal performance i.e. the fire and how thermal energy released during fire is transferred into the structure; and
- the structure. i.e. how the structure responds as a function of the thermal boundary conditions.

The paper evaluates, in very simple terms, the conditions under which certain simplification are valid or invalid allowing to clarify the limitations of current performance assessment procedures. Given the complexity of the fire-structure interactions there will be many criteria that can be used and a comprehensive treatment is beyond the scope of this paper. Instead, as a very relevant example, the focus of this particular paper is on the role of the thermal gradients in structural behavior inferring when it is necessary to precisely establish these gradients. This approach, in principle, applies to any structure, but in particular to protective structures, given their critical function.

2. Assessing Thermal Performance

2.1 Fire Dynamics

At the core of a fire there is a flame or a reaction front that is effectively the result of a combustion process, and thus is governed by the mechanisms and variables controlling combustion [1]. The interaction between fire and its surrounding environment determines the behavior of the flame and nature of the combustion processes. An extensive introduction to the topic is provided by Drysdale [2].
As indicated by Drysdale [2], the dynamics of a fire involves a compendium of different sub-processes that start with the initiation of a fire and end with its extinction. The onset of the combustion process, i.e. ignition, in a fire is a complex process that implies not only the initiation of an exothermic reaction but also a degradation process that provides the fuel effectively feeding the fire. During a fire, it is common to have different materials involved in the combustion process, and given the nature of the fire growth many could be involved simultaneously but others sequentially. The sequence of ignitions of items in an enclosure will affect the nature of the combustion processes. Thus, ignition mechanisms set the dynamics of the fire and also are affected by the fire itself, creating a feedback loop [3].

Once a material is ignited, the flame propagates over the condensed fuels by transferring sufficient heat to the fuel until a subsequent ignition occurs. This process is commonly referred to as flame spread and is described in detail by Fernandez-Pello [4]. Flame spread defines the surface area of flammable material that is delivering gaseous fuel into the combustion process. The quantity of fuel produced per unit area is known as the mass burning rate. The mass burning rate multiplied by the surface area determines the total amount of fuel produced. If the total amount of fuel produced is multiplied by the effective heat of combustion (energy produced by combustion per unit mass of fuel burnt), it yields the heat release rate. Generally, the heat release rate is considered the single most important variable to describe fire intensity [5]. Given the nature of the surrounding environment, the oxygen supply might not be enough to consume all the fuel, thus in many cases combustion is incomplete (i.e. under-ventilated) and therefore the heat of combustion is not a material property but a function of the interactions between the environment and the fire. In these cases, it is usually deemed appropriate to calculate the heat release rate as the energy produced per unit mass of oxygen consumed multiplied by the available oxygen supply.

If the fire is within a compartment, smoke will accumulate in the upper regions of the compartment. Hot smoke will radiate and/or convect heat towards all surfaces in the compartment. If the surfaces are flammable, remote ignition of different materials might occur. If remote ignition occurs in the lower (i.e. cold) layer then the fire tends to suddenly fill the entire compartment. This transition is generally known as flashover. Before flashover, the lower layer tends to have enough oxygen to burn the pyrolyzing fuel and the heat release rate is determined by the quantity of fuel generated. This period is termed pre-flashover, fire growth or fuel limited fire. After flash over, fuel production tends to exceed the capability
of air to enter the compartment, the compartment becomes oxygen starved and the heat release rate is
determined by the supply of oxygen through the various ventilation inlets/outlets of the compartment
e.g. doors, windows, etc.). This period is termed as post-flashover, fully developed fire or oxygen
limited fire. The process of fire growth and the definition of the different variables affecting it is provided
by Drysdale [2].

For small compartments (approximately 4 m x 4m x 4m) a characteristic time to flashover is of the order
of 4-6 minutes while the post-flashover period can reach tens of minutes depending on the compartment
size and fuel available [6]. Structures tend to have high thermal inertia, thus the temperature increase, at
the surface (or in-depth) of solid elements, to levels where the loss of mechanical properties is
significant, takes also in the order of tens of minutes. Thus for purposes of structural assessment, the
effects of fires tend to be only considered at the post-flashover stage [7]. The temperature inside the
compartment as well as the burning rate can be established simply as a function of the available
ventilation, this process can follow different levels of complexity; Drysdale [2] reviews all these. It is
important to note, that while the compartment temperature can be established by means of a simple
energy balance, the heat being transferred to each structural element does not necessarily correlate with
this temperature [6]. These relationships and time scales are of particular importance for protective
structures, given that fires can cover a very wide range of characteristics when originating in
environments that are different from the conventional compartment. Any analysis involving unusual
compartments will have to revisit the evolution of the fire in a very detailed manner because many of
the assumptions embedded in current design practices will no longer be valid.

A fire can end when it is extinguished or when oxygen or fuel supplies are depleted; oxygen starvation
and burnout, respectively. In all cases, extinction of the combustion process is brought by the interactions
of fuel, oxygen supply and the energy balance that fundamentally allows for the combustion reaction to
remain self-sustained [8]. Suppression agents affect a fire by reducing fuel and oxygen supply, or by
removing heat. At each stage of fire growth, it becomes more or less feasible to have an effect over these
three fundamental variables of fire. Thus the effectiveness of a suppression system is dictated by its
capability to affect the targeted variables at the moment of deployment. Once again, time scales are of
critical importance. If the effect of suppression agents is to be incorporated to the design of protective
structures, then it will have to be demonstrated that the time scales of deployment, heat transfer and
fuel/oxygen displacement are consistent with the time scales of other solicitations and with those that deliver the desired effect.

A common way to describe the evolution of a fire in a compartment is by means of design temperature-time curves. There are numerous variants of these, from a purely standardized version [9] used to conduct standard furnace tests, to others supposedly more representative of ‘real’ fire conditions [10]. A commonly used expression is that proposed by Lie [11] and simplified here for small fuel loads:

\[
T_g = 250(10F)^{0.1} \exp(-F^2t) \left[3(1 - \exp(-0.6t)) - (1 - \exp(-3t)) + 4(1 - \exp(-12t)) \right] \quad (1)
\]

Where \( T_g \) is the temperature of the gas phase inside the compartment and \( t \) is time in hours. \( F \) is the ventilation factor, which is a commonly used combination of the opening surface area \( (A_w) \), the height of the opening \( (H) \) and the total area of the compartment \( (A_T) \) excluding floor and opening \( F=A_wH^{1/2}/A_T \) [10]. Fig. 1 describes a typical scenario where all stages have been marked.

The thermal boundary conditions at the exposed surface of a solid element (i.e. structural element) are fundamentally based on conservation of energy [12], and thus typically formulated in terms of heat fluxes. In Fig. 1, the maximum heat flux at the exposed surface of the structure has been calculated assuming that the solid surface remains at ambient during heating (based on the assumption that heating of the gases and that of the solid occur in different time scales) and at \( T_g \) during cooling. The gas phase temperature is assumed to be 20°C during cooling. The total heat transfer coefficient, \( h_T=45 \, W/m^2 \), is a value commonly used by fire engineers to account for convection and radiation [2, 8]. While clearly, the surface and gas phase temperatures will vary during heating and cooling, this value of the heat flux is indicative of the conditions that a structure will experience during a fire.
Figure 1 – Typical temperature and heat flux evolution for a small compartment fire. From ignition to flashover there is a period of approximately 5 minutes where temperatures and heat fluxes are negligible. This is followed by a longer period where temperatures and heat fluxes increase. The cooling period starts with burn-out (total fuel consumption). The plots were obtained using a 4 m x 4 m x 4 m compartment with a single opening (2 m x 3 m) a fuel load of 60 kg/m² and a total heat transfer coefficient of 45 W/m². The temperature vs. Time curve was obtained using the expression by Lie [11], Eq. (1).

In summary, structures exposed to fire will see temperatures close to ambient and negligible heat fluxes during the pre-flashover period (4-6 min for a small compartment). Temperatures and heat fluxes will increase after flashover reaching values of approximately 1200°C and 60 kW/m², respectively. These thermal exposures can last for periods in excess of an hour, depending on the fuel load, compartment
geometry and ventilation. Finally, fuel will inevitably burn-out and the compartment will cool down.

In the cooling period the heat flux will be negative denoting heat losses from the structure surface to the colder gases inside the compartment. The correlation between temperature and heat flux can be linear, but this is only under the assumption that an overall constant heat transfer coefficient can be established in space and time. It is important to emphasize, that if this procedure is followed, then the thermal boundary condition at the surface is being imposed not calculated.

The thermal boundary conditions at the surface of the solid is defined by means of Equation 2.

\[ q_{\text{tot}}^* = -k \frac{dT}{dx} \bigg|_{x=0} \]  

(2)

Where \( k \) is the thermal conductivity of the solid material. As can be seen in Fig. 1, the range of heat fluxes vary between 60 kW/m² and −60 kW/m² therefore the in-depth gradients of temperature of the structural elements will vary significantly, and in a manner that does not necessarily resemble the gas phase temperature evolution inside the compartment. The importance of the gradients and the resemblance of their evolution to that of the temperature are a function of the thermal properties of the material (e.g. thermal conductivity) and of the gas phase conditions. Therefore, when trying to understand the explicit behaviour of structures in fire it is essential to discuss its evolution not only within the context of the characteristic conditions and time scales involved in a fire but also as a function of the thermal properties of its solid phase. The material thermal properties define if the in-depth thermal gradients within the structure will be insensitive or sensitive to the characteristics of the gas phase. For certain materials where the thermal gradients are very insensitive to the gas phase conditions, major simplifications still deliver precise answers, the opposite will happen when temperature gradients are a strong function of the gas phase. In the latter case a detailed description of the gas phase might be necessary to achieve an appropriate thermal boundary condition.

While the analysis presented above is simplistic in nature, and the values presented are only rough estimates, it does provide a clear image of the thermal conditions that a structural element will experience in the event of a fire. Furthermore, it illustrates the importance of making an apriori analysis of the thermal properties of a material before simplifications to the gas phase treatment are proposed. It is current practise to accept certain simplifications without first establishing their validity (ex. Constant heat transfer coefficients, constant emissivities, fire representation by means of a temperature, etc.).
2.2 Heat Transfer

As abovementioned, when analysing the heat transfer from the fire to a structural element the problem needs to be formulated in terms of heat fluxes. While temperature of the solid phase results from solving the energy conservation equations, all quantities to be balanced are energies [13]. In this section some basic heat transfer concepts are reviewed simply to extract the relevant parameters that will be used in later sections for discussion. These concepts are not novel and can be found in any heat transfer book, for details the reader is referred to reference [13], nevertheless, its novelty relies on the application as a screening tools for the assessment of the thermal boundary condition that is required for different structural configurations.

Heat is transferred from gases to solid surfaces via radiation and convection resulting in a total heat flux, \( \dot{q}_{\text{tot}} \), where:

\[
\dot{q}_{\text{tot}} = \dot{q}_{\text{rad}} + \dot{q}_{\text{con}}
\]  

(3)

Where, \( \dot{q}_{\text{rad}} \) is the heat transfer via radiation and \( \dot{q}_{\text{con}} \) is the heat transferred via convection. For simplicity, within the scope of the work presented herein, the problem will only be examined in the direction of the principal heat flux, hence considered to be a one dimensional problem and with the thermal boundary condition of the solid element (i.e. structural element) defined as:

\[
\dot{q}_{\text{tot}} = -k \left. \frac{\partial T}{\partial x} \right|_{x=0}
\]  

(4)

Which is a generic version of Eq. 2 and where the thermal conductivity \( k \) is a property of the solid and the gradient of temperature is taken at the surface. In other words all the heat arriving at the surface of the solid is conducted into the solid. If there are multiple layers then at each interface the following boundary condition should apply:

\[
-k \frac{\partial T}{\partial x} = -k_s \frac{\partial T}{\partial x}
\]  

(5)

Where the gradients correspond to each side of the interface and the sub-index “s” is a generic way to represent the next layer of solid. Once the thermal boundary conditions are defined, the energy equation
can be solved for each material involved. In the case where two layers of solid are involved ("i" and 
"s"), then the energy equations take the following form:

\[ \rho_i C_p^i \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k_i \frac{\partial T}{\partial x} \right) \] (6)

and

\[ \rho_s C_p^s \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k_s \frac{\partial T}{\partial x} \right) \] (7)

The solution of the energy conservation equations yields the temperature evolution of the material in 
space and time. Eq. 6 and 7 could be repeated for as many layers as necessary. If the geometry or the 
fire exposure is complex, then the problem needs to be resolved in two or even three dimensions. If the 
properties vary with temperature then, as the temperature increases, these properties need to evolve with 
the local temperature. Variable properties thus require a numerical solution. If a simple analytical 
solution is to be obtained, then adequate global properties need to be defined. It is important to note 
that whatever the solution methodology adopted, the temperature of the structure is the result of the 
resolution of Eq. 6 and 7 using thermal boundary conditions such as those presented in Eq. 4 and 5. To 
obtain the numerical solution it is necessary to input material properties for the different layers ("i" and 
"s"). The material properties required are all a function of temperature and are as follows:

\[ \rho_i, C_p^i, k_i \]

\[ \rho_s, C_p^s, k_s \]

Where, \((\rho_i, \rho_s), (C_p^i, C_p^s), \) and \((k_i, k_s)\) are the densities, specific heat capacity, and thermal 
conductivity for each layer, respectively. For some materials such as steel the thermal properties are 
very well characterized and thus very little difference can be found between the literature [14]. For other 
materials such as concrete, wood or building construction thermal insulation materials, the scatter is 
much greater [7]. The uncertainty is associated to the presence and migration of water, degradation, 
and crack formation, etc.

Furnace data (i.e. in-depth temperature measurements of the solid material taken during standard furnace 
testing) is generally used as a substitute for the uncertainties associated with defining thermal properties. 
In many cases global thermal properties are extracted by fitting calculated temperatures to the furnace
data. These properties are then extrapolated and widely used in equations such as Eq. 4 to 7 for assessing the thermal performance. Nevertheless, this practice has also its unique complexities. First of all, the model needs to include all the physical variables necessary, so if physical processes such as the degradation or water migration within the material are not explicitly included in the model, the thermal properties extrapolated from furnace data become hybrids that implicitly include these physical parameters. Implicitly introducing physical phenomena into constants inevitably narrows the range of application, thus most of these ‘calibrated’ thermal properties can only be used to re-evaluate furnace data. Based on these grounds, extrapolation to drastically different scenarios, such as a ‘real’ fire, becomes doubtful. Harmathy discusses in great detail how to formulate the heat transfer problem within a furnace emphasizing its complexity [15].

An important aspect, many times overlooked, is the need to make sure that the thermal boundary conditions are properly represented. The heat exchange between a furnace and a sample is extremely complex and many times simplifications relevant to furnaces are not valid for ‘real’ fires. It is essential to understand all those simplifications. The differences between furnace behaviour and fire behaviour are all manifested in the boundary condition associated with Eq. 2.

A common misunderstanding is to attempt representing the evolution of the temperature of a material by a single temperature as represented in Fig. 2. Fig. 2 shows the evolution of temperature for unprotected steel subjected to different fires; defined by gas phase temperature inside a compartment. While plots of this nature serve to compare the evolution of the steel temperature they hide numerous assumptions that while relevant to steel, they are not relevant to other materials, for example, concrete.

Establishing the nature of temperature gradients within a solid allows to establish the range of validity of the assumption that a single temperature can represent the heat transfer process. This is an essential component of the thermal assessment of a material in a fire. The nature of the temperature gradients is defined by the Biot number:

\[ Bi = \frac{h \delta d}{k} \]  

(8)

The Biot number provide a very simple representation of the relationship between the temperature
gradients in the gas phase and the temperature gradients in the solid phase. For a very large or very small
Biot number the solid phase gradients are very insensitive to gas phase gradients and therefore the gas
phase can be treated with very simple approximations. Depending on what extreme of the Biot number
range the material is, the simplifications will be different. Intermediate range values of the Biot number
will require precise treatment and most simplifying assumptions will lead to major errors.

Figure 2 – Temperature evolution of the gas phase of a compartment fire and a small cross section unprotected steel beam.

Standard temperature time curve per ISO-834 [9], DFT stands for Dalmarnock Fire Test [17].

Fig. 3 provides a simple schematic showing the influence of the Biot number in a one dimensional
heat transfer – evidencing the scope for potential simplifications of the heat transfer problem. If the Biot
number is close to one (case (b) in Fig. 3) temperature gradients in the gas and solid phases are large
and therefore Equations 6 and 7 will need to be fully resolved, hence no simplifications are possible. If
the Biot number is much greater than one (case (c) in Fig. 3) the temperature differences in the gas phase
are much smaller than those in the solid phase and it can be assumed that surface and gas temperatures
are almost the same. This simplification is very important when modelling furnace tests because it
enables to ignore the complex boundary condition imposed by the furnace and simply imposed the
monitored gas temperature at the surface of the solid. Finally, if the Biot number is much smaller than
one (case (a) in Fig. 3) then the temperature differences in the solid phase are much smaller than those
in the gas phase, therefore temperature gradients in the solid phase can be ignored and a single
temperature can be assumed for the solid. Heat conduction within the solid can be approximated by the
boundary conditions and Eq. 6 and 7 lead to a single temperature solution like the ones shown in Fig. 2.

The representation of a structural element by means of a single temperature is therefore only valid if $Bi << 1$. This simplification is called a “lumped capacitance formulation” and while it does not resolve spatial temperatures distributions it still requires an adequate definition of the heat transfer between the source of heat (e.g. furnace or ‘real’ fire) and the solid. An important observation is that for materials with Biot numbers much smaller than one, the thermal energy is rapidly diffused through the integrity of the material, so if the density was to be high (see Eq. 6 and 7), then the lumped solid will lag significantly the gas phase temperature (Fig. 2). Heat transfer is therefore dominated by the temperature difference between the solid and the gas phase, and errors in the definition of the heat transfer coefficient become less relevant. It is common for studies attempting to understand the behaviour of structures in fire to make use of constant heat transfer coefficients [7], this will be appropriate for materials with a $Bi << 1$. Nevertheless, there is also significant inconsistencies in the numbers quoted and furnace heat transfer coefficients are many times extrapolated to natural fire coefficients. These values are not necessarily the same, in particular if radiation and convection are to be amalgamated into a single heat transfer coefficient [3].

![Fig. 3. Schematic of the typical temperature distributions for different extreme values of the Biot number.](image)

Given the importance of the Biot number in the characteristics of the temperature gradients, it is
important to estimate the thickness of a material that leads to a $Bi=1$. Samples that are much thicker will allow approximating the surface temperature to that of the gas phase. Samples that are much thinner will allow to “lump” the solid phase into a single temperature.

Table 1 shows typical thermal properties for different construction materials and the characteristic thickness ($L$) that will result in a Biot number of unity. As can be seen for high thermal conductivity materials like aluminium or steel, sections a few millimetres thick can be lumped without any major error. In a similar manner very low thermal conductivity materials like plasterboard or expanded polystyrene (EPS) will allow to assume that the surface temperature of the solid is that of the gas phase. In contrast, concrete has a Biot of unity for a thickness of 50 mm that is in between typical concrete cover thicknesses and the overall thickness of the sample. Therefore, whether the concrete is used as cover for the reinforcement or analysed as the load bearing material, the full resolution of an equation similar to Eq. 6 is necessary. Furthermore, the boundary condition cannot be simplified because the thermal gradients are fully defined by $q''_{tot}$ as per Equation 4.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density ($\rho$, kg/m$^3$)</th>
<th>Thermal Conductivity ($k$, W/mK)</th>
<th>Specific Heat ($C_p$, J/kgK)</th>
<th>Thermal Diffusivity ($\alpha$, m$^2$/s)</th>
<th>“$L$” for $Bi=1$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>2,400</td>
<td>237</td>
<td>900</td>
<td>1.10E-04</td>
<td>5,300</td>
</tr>
<tr>
<td>Steel</td>
<td>7,800</td>
<td>40</td>
<td>466</td>
<td>1.10E-05</td>
<td>900</td>
</tr>
<tr>
<td>Concrete</td>
<td>2,000</td>
<td>2.5</td>
<td>880</td>
<td>1.42E-06</td>
<td>50</td>
</tr>
<tr>
<td>Plasterboard</td>
<td>800</td>
<td>0.17</td>
<td>1,100</td>
<td>1.93E-07</td>
<td>4</td>
</tr>
<tr>
<td>Expanded polystyrene (EPS)</td>
<td>20</td>
<td>0.003</td>
<td>1,300</td>
<td>1.15E-07</td>
<td>0.1</td>
</tr>
</tbody>
</table>

3. **Structural Fire Performance**

3.1. **Steady State Thermal Gradients**

Given that the thermal properties of concrete do not allow for a simplified analysis, the temperature gradients within the structural element needs to be estimated. The resulting gradients can then be incorporated into a structural analysis to define the significance of thermal bowing.

If a slab of thickness $L$ separates a fire of temperature $T_f$ and ambient conditions, $T_{amb}$, then, at thermal
steady state the energy conservation equation leads to the equalities presented in Equation (9). Note that heat exchange at the surfaces has been split in convective and radiative terms.

\[ \sigma \varepsilon (T_f^4 - T_{\text{max}}^4) + h_i(T_f - T_{\text{max}}) = \frac{k}{L}(T_{\text{max}} - T_{\text{min}}) = \sigma \varepsilon (T_{\text{min}}^4 - T_{\text{amb}}^4) + h_0(T_{\text{min}} - T_{\text{amb}}) \quad (9) \]

Where sub-indexes “max” and “min” is a generic way to represent the exposed and unexposed surface of the solid. The explicit solution of Equation 9 yields the following expressions for the minimum and maximum temperature (\(T_{\text{min}}, T_{\text{max}}\)) within the solid:

\[ T_{\text{min}} = \frac{\varepsilon L}{k} \left( \sigma \varepsilon T_{\text{max}}^4 + h_f + \frac{k}{L}T_{\text{min}} \right) - T_f \left( \sigma \varepsilon T_f^4 + h_f \right) \quad (10) \]

\[ T_{\text{max}} = \frac{\varepsilon L}{k} \left( \sigma \varepsilon T_{\text{min}}^4 + h_b + \frac{k}{L}T_{\text{max}} \right) - T_0(T_{\text{min}} - T_{\text{amb}}) \quad (11) \]

Then, the heat flux between the exposed and unexposed surface of the solid can be formulated as:

\[ \sigma \varepsilon (T_f^4 - T_{\text{max}}^4) + h_i(T_f - T_{\text{max}}) = \sigma \varepsilon (T_{\text{min}}^4 - T_{\text{amb}}^4) + h_0(T_{\text{min}} - T_{\text{amb}}) \quad (12) \]

This can be rearranged as follows:

\[ \sigma \varepsilon (T_f^4 - T_{\text{max}}^4) + h_i(T_f - T_{\text{max}}) - h_i(T_{\text{min}} - T_{\text{amb}}) = 0 \quad (13) \]

When the relevant substitutions are made, this results in a 7th order polynomial which can be solved numerically. Where the assumption of total heat transfer coefficient is adopted, this can be simplified to allow \(T_{\text{min}}\) and \(T_{\text{max}}\) to be expressed as a function of Biot. This can be achieved as follows:

\[ h_i(T_f - T_{\text{max}}) = \frac{k}{L}(T_{\text{max}} - T_{\text{min}}) = h_0(T_{\text{min}} - T_{\text{amb}}) \quad (14) \]

Then:

\[ Bi_i(T_f - T_{\text{max}}) = (T_{\text{max}} - T_{\text{min}}) = Bi_0(T_{\text{min}} - T_{\text{amb}}) \quad (15) \]

The sub-indexes “i” and “o” represent the exposed and unexposed face, respectively. Therefore, at the exposed surface:
\[ T_{\text{max}} = \frac{B_i(B_i+1)T_f + T_{\text{amb}}B_i}{(B_i+1/B_i+1)} \]  

(16)

By assuming that the Biot number is the same for the exposed and unexposed surfaces (i.e. \( Bi_i \approx Bi_o \)), this expression can be simplified to:

\[ T_{\text{max}} = \frac{(Bi+1)T_f + T_{\text{amb}}Bi_i}{(Bi+2)} \]  

(17)

and

\[ T_{\text{min}} = (T_f - T_{\text{max}}) + T_{\text{amb}} \]  

(18)

This approach or the numerical solution of Eq. 9 may be used for calculating a reference thermal gradient within a structural element. Selection of the method used will depend on the resolution (or accuracy) at which the solution is required. While this approach is not precise it allows to establish the impact of changing the Biot number on structural behavior.

### 3.2 Steady State Thermal Gradients

The fire response (or behavior) of the structure is defined by thermally-induced changes of the mechanical properties, and the developments of thermal expansion \[ [18] \]. However, the interaction of these two parameters has a significant impact on the response of a structure. This interaction is a function of the bulk temperature increase within the material and thermal gradients. The temperatures and thermal gradients are a function of the thermal boundary conditions, thermal properties, and material thickness as examined above.

Where the temperature distribution of an unrestrained structural element is simplified to a one dimensional (through- or in-depth) heat transfer analysis, a linear thermal gradient will result in a member curvature. Where a thermal gradient is non-linear, this will result in the development of internal mechanical strains within the depth of the structural element; these strains (or rather, the force and moment induced by them) must be resolved in order to maintain static equilibrium of the structural element. Assuming that the material remains in the elastic range, the curvature (\( \phi \)) and total axial strain (\( \varepsilon_a \)) of the structural element can be solved using the following equations:

\[ 0 = \sum_{i=1}^{n} \{(\phi y_i + \varepsilon_a + \alpha T_i)E_i(T_i)y_iA_i\} \]  

(19)
0 = \sum_{i=1}^{i=n} \left\{ \left( \phi y_i + \varepsilon a + \alpha T_i \right) E_i(T_i) A_i \right\} \tag{20}

Where “n” is the number of fibres into which an element is discretized, “y_i” is the distance from the centroid of the section to the centroid of each fibre, “a” is the coefficient of thermal expansion, T_i is the temperature of each fibre, E_i(T_i) is the temperature dependent elastic modulus of each fibre, and A_i is the area of each fibre.

For a simply supported beam, the axial elongation then becomes:

\[ dL = L - \varepsilon a L - \frac{\sin \left( \frac{L \phi}{2} \right)}{L \phi / 2} \tag{21} \]

and the total deflection due to thermal curvature becomes [18]:

\[ d = \frac{1}{\phi} \left( 1 - \cos \left( \frac{L \phi}{2} \right) \right) \tag{22} \]

3. Canonical Example

On the basis of the equations shown in this paper, the full set of heat transfer and structural calculations can be solved. This allows the comprehensive study for the effects of the thermal boundary condition, as a function of the Biot number on the mechanical behavior of the structural element. This section executes this analysis.

Equations (17), (18), (21), and (22) represent the terminal state of temperature distributions and mechanical deformations. This allows establishing the general influence of the Biot number on the ultimate state of the structure. Nevertheless, this might not represent the critical state of the structure because the coupled effects of bulk expansion and temperature gradient induced curvature might result in worst case conditions before thermal steady state is attained. The thermal properties (and consequently the Biot number) will influence also the transient state. Therefore, a numerical analysis of the transient evolution was performed to establish the role of the Biot number on transient deformation.

The equations were solved for a unit length, unit width structural concrete element subject on one side to a constant gas temperature of 1,000°C. It was assumed, for the numerical simulations, that h_i =
$35 \, W/m^2, h_o = 8 \, W/m^2$, and $\varepsilon = 0.7$; where these represented the internal and external convective heat transfer coefficients and $\varepsilon$ the emissivity for the radiative component (equations 9 and 10). The values used as inputs are common values used in the literature. The thermal properties of concrete were as described above, and it was assumed that the degradation of elastic modulus was as illustrated in Fig. 4. Three material thicknesses were analyzed: 28, 50, and 100 mm. This is a convenient way of changing the Biot number without changing thermal properties. These values correspond to a Biot number of 0.5, 1, and 2 (assuming and approximate linearized heat transfer coefficient of $h_T = 45 \, W/m^2$). The analysis was continued until an approximate steady state was achieved after 2 hrs, and the results for a simply supported section in terms of total deflection and total elongation are illustrated in Fig. 5.

*Figure 4. Degradation of elastic modulus (corresponds to the tangent stiffness of concrete at zero strain as per BS EN 1992-1-2)*
These results demonstrate that, at the steady state, different Biot numbers induce different structural behavior. As the Biot number increases, the bulk change in length diminishes as well as the deflections showing an overall less significant effect of heat on the structural element. For lower Biot numbers the overall expansion of the structural element results in a greater final deflection. However, the results of the numerical model also demonstrate that highest deflections occur during the transient stages of a fire. Indicating that the Biot number also has a significant importance on the nature of the transient deformation and potentially early adverse effects. The maximum deflections in the steady state and in the transient analysis were calculated for a wide range of Biot numbers and the results presented in Figure 6. The results show that, for the canonical structure studied here, above a Biot number of approximately three transient and steady state solutions are almost identical, with a negligible error if only a steady state solution was to be applied (Figure 6). For smaller Biot numbers the two solutions diverge and given the worst-case deflections of the transient period, a transient analysis is necessary. This is a very important observation in that it allows not only to establish the precision required in the
definition of the thermal boundary conditions but also to determine if a transient analysis is necessary.

Figure 6. Resulting transient deflections and elongations. Absolute values of deflection obtained from the two analyses (top), and the relative errors associated with the different between the steady state value and the transient analysis (bottom).

4. Conclusions

An assessment of the role of detailed boundary conditions has been made. A simple analysis based on classic principles shows that the temperature gradients within a material are primarily a function of the Biot number. A demonstration of the role of the Biot number on deflections and elongation was used to illustrate how the Biot number can be used to establish if it is necessary to conduct a transient thermo-mechanical analysis as well as to determine the level of precision necessary when treating the thermal boundary conditions. The following conclusions were drawn:

• structural performance is an unavoidable result of the real evolution of the in-depth temperature of a structural element in space and time;
• to define the performance of a structural system in fire it is necessary to establish the correct thermal boundary condition. The evolution of this boundary condition will determine internal temperature distributions and thus structural behavior;

• the Biot number is a simple non-dimensional parameter that combines material characteristics and the thermal boundary condition allowing to establish the sensitivity of structural behavior to the precision of the boundary conditions as well as to transient behavior;

• the Biot number is an effective method to classify different forms of thermally induced structural behavior. The higher the Biot number the lesser transient effects and the more effective steady state modelling of a structure is to define the worst-case conditions. The lower the Biot number the more important is to model transient behavior;

• for the particular case studied, the greater the Biot number the less significant the effect of a fire on structural deformations;

• defining the thermal boundary conditions in terms of a single temperature (e.g. during the analysis of data from a standard “fire resistance” furnace test) can only be done for structural elements with $Bi<<1$. In this case the sensitivity to the thermal boundary condition is low therefore a global heat transfer coefficient will suffice. Nevertheless, appropriate quantification of the overall heat transfer coefficient is necessary. Extrapolation of furnace coefficients to “real” fire conditions may provide an unrealistic representation of the thermal conditions;

• and the gas phase temperature can be used as a boundary condition only if $Bi>>1$, in this case, furnace or “real” fire are only differentiated by the gas phase temperature differences; and

• constitutive properties of various building construction materials (e.g. concrete) are intimately linked to the formation of in-depth thermal gradients and therefore, current values are at best approximate.

Protective structures for fire safety are complex systems that require a precise and detailed representation of their transient behavior – as different solicitations are considered. In some areas such as explosions, this is done in a very careful way, and while questions remain about the adequacy of the calculations
and testing procedures, all these are perfectly geared towards the explicit determination of performance. When it comes to the representation of fire performance, this paper has shown that current methods do not represent the underlying physics behind the definition of the thermal solicitation induced by the fire. This inadequate representation of the boundary conditions has been shown to have significant consequences on the predicted mechanical behavior of structural systems that are not consistent with the common belief that current methods are representing a “worst-case” performance scenario. This is particularly true for concrete structures.

The performance of protective structures has to be addressed in an explicit manner; this will enable not only to establish their reaction to a single hazard but their resilience when it comes to multiple hazards – fire being one of them. In the absence of an explicit performance assessment strategy for fire it is not possible to determine the adequacy of the protection provided by a structure.

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References


GRENFELL TOWER: PHASE 1 REPORT

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23rd May 2018

Revised: 21st October 2018
EXECUTIVE SUMMARY

A fire originated in the kitchen of Flat 16 of Grenfell Tower on June 14th, 2017. While there are numerous ways in which this fire could have originated, at the date of submission of this report, there is no conclusive evidence that constrains the cause, origin and initial stages of the fire to a single timeline or set of events. Nevertheless, analysis of the evolution of the events and of the observable damage enables a detailed analysis of many of the factors influencing the nature of the event and its consequences.

Fires evolve in space and time leading, in many instances, to a complex sequence of events and multiple processes and activities occurring simultaneously. It is therefore useful to structure these events, processes and activities. So, for the purpose of this report, the timeline of the Grenfell Tower fire will be divided into four stages, each of which reflects a key phase in terms of this particular fire event:

- **First Stage:** From the initiation of the event to the breaching of the compartment of origin
- **Second Stage:** From the breaching of the compartment of origin to the point when the fire reaches the top of the building
- **Third Stage:** The internal migration of the fire until the full compromise of the interior of the building, including the stairs
- **Fourth Stage:** The untenable stage

The geometrical configuration of the kitchen and the available ventilation did not allow the kitchen fire to attain flashover. The temperature of the smoke accumulated below the ceiling of the kitchen will remain within the approximate range of 100-220°C. As will be described below, these temperatures are capable of damaging components of the window, but the accumulated smoke cannot ignite any of the combustible materials in the vicinity of the window or within the façade system.

The temperature of the smoke accumulated below the ceiling of the kitchen is sufficient to heat the uPVC components of the window to temperatures that result in complete loss of mechanical properties (90°C). These temperatures would have been attained within an approximate period

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1 The stages are qualitative in nature therefore no exact times are proposed here, details on times can be found in the body of the report and in references [2], [4] and [5]. The times are roughly First Stage (00:54 - 01:05), Second Stage (01:05 - 01:30), Third Stage (01:30 - 02:30) and Fourth Stage (02:30 - extinction).

2 The term tenability is intended to describe in a qualitative manner, the conditions within different parts of the building as it pertains to the interactions of the fire and smoke with people. Tenability and safety are difficult terms to define and therefore have to be interpreted in a relative manner. That is because the concept of tenable conditions inside a building will vary between different persons e.g. between adults and children and it is possible to adopt very technical definitions of tenability depending on what is being assessed. For the purpose of this report, I use the phrase untenable conditions to mean conditions that are life-threatening (e.g. high temperatures, high concentration of carbon monoxide, etc.) or perceived by occupants as life-threatening (e.g. poor visibility). In contrast, a tenable or safe environment will be one where conditions remain or are perceived by occupants not to be life threatening. Typical approaches and quantitative data that serve to define tenability are provided in the literature [6] but for the purpose of this report only the qualitative approach described above will be used.
between 5-12 min which is consistent with the time available between the discovery of the fire (initial call to the fire brigade) and the first observation of smoke and burning debris external to the building. The geometry of the uPVC elements and approach used for their fixation would have resulted in the eventual fall-off of these elements. The failure of the uPVC leaves all other combustible components of the façade system exposed.

Flames have higher temperatures than the smoke accumulating below the ceiling of a room. Therefore, an unobstructed fire of 300 kW placed at a maximum distance of 3.1 m from the window would have been sufficient to ignite any of the combustible components of the façade system. A fire of 300 kW is no greater than a fire originating from a pan fire of 40-50 cm radius. A pan fire will cover its entire surface immediately after ignition so it will remain of constant size. In contrast, a fire originating from appliances will ignite and then spread through the different combustible materials within the appliance, thus the fire will grow in time. Appliances with significant mass of combustible materials (e.g. refrigerators) can release heat beyond 1000 kW, while those with less mass of combustible materials (e.g. electrical stoves) might never reach 300 kW.

If the fire was obstructed (i.e. there was an obstacle between the fire and the window) then a 300 kW fire would have had to be placed less than 1 m from the combustible materials of the window if those materials were to ignite. A fire placed further away, capable of igniting combustible materials in the window, would have most likely brought the room to flashover.

Almost any appliance within a common kitchen could have sustained a fire of the size (300 kW) required to ignite combustible components of the façade system if placed close enough to the window. Therefore, the cause an origin of this fire is of minor importance to the outcome. To complete an investigation, it is important to understand how and where the fire started. Nevertheless, the precise cause and origin of this fire is, on one respect, irrelevant to the event which subsequently occurred. From a design perspective, a fire of 300 kW occurring in a residential kitchen, and in the proximity of the window, should be considered to have a probability of one. In other words, a fire of this nature will happen in a residential unit and therefore the building is required to respond appropriately.

Once any of the combustible components of the façade ignited, their proximity and complex arrangement would have inevitably resulted in the ignition of other components leading to external flame spread. This point marks the end of the first stage of the fire.

Through this first stage of the fire the building was operating as intended and in accordance with the assumptions which underpin the existing regulatory framework. Firefighting operations remained within the bounds of conventional practice and the structure could be considered to pose no risk of failure. A “stay put” strategy (i.e. occupants of flats adjacent to the flat on fire or on levels above or below can remain safely within their own flat) would have implied minimum risk to the occupants during the first stage of the fire.

Vertical fire spread characterizes the second stage of the fire. Vertical flame spread is significantly faster and more robust than lateral flame spread, so the fire rapidly propagates upwards but propagates laterally with greater difficulty.

Only in the final 5 – 10 minutes of the second stage (from 01:20 onwards) and before the fire reaches the top of the East façade, was there a significant number of emergency calls indicating smoke or flames within the building. These calls were not related to the original kitchen fire. Video camera
recordings show that during this period, occupants were, for the most part, able to egress with little or no evidence of smoke. With the exception of some short time periods, it can be concluded that the stairs remain safe during this stage of the fire. The moment when the fire reaches the top of the building is defined here as the end of the second stage of the fire.

Through this second stage of the fire the building is operating outside the conditions contemplated by the existing regulatory framework. Firefighting operations are outside the bounds of conventional practice and therefore have to be driven by a dynamic risk assessment. A “stay put” strategy is not consistent with the characteristics of the second stage. To a large extent the building remains tenable and the stairs still retain the characteristics required for them to be a safe egress path. Egress is outside the bounds of conventional protocols, therefore is not free of risk, but nevertheless it can be considered a better strategy than “stay put.” The heating period from the fire, even if an extreme heating rate is considered, is too short to result in structural temperatures that would have posed any challenge to the integrity of the structure. The structure can be deemed safe in this period.

Cavity barriers, no matter how well or badly they were designed and / or implemented, would not have prevented vertical or lateral flame spread in the Grenfell Tower fire. Flames can propagate through the interior cavities of the façade system but can also project over the façade system. Flames in the interior cavities will face and be slowed by the cavity barriers. Flames projected over the façade system will spread unobstructed via the exterior (this includes joints, damaged areas, etc.). Typical flame temperatures are higher than the melting temperature of aluminium (650°C) therefore the aluminium plates of the composite panels would have offered no protection to the combustible materials.

Details of the cladding will have an impact on flame spread rates, although in the case of Grenfell Tower, upward flame spread rates are not uniquely fast. A comparison with other international events shows that upward flame spread for the Grenfell Tower is among the slowest. It is therefore possible to ascertain that detailing of the façade system (as opposed to its material composition) has only a minor impact on the evolution of this fire.

Lateral spread in the initial stages of the fire is much slower than vertical flame spread. Once the fire reaches the top of the building, the fastest rate of spread occurs in the area of the architectural crown. Lateral flame spread results in significant amounts of debris falling downwards igniting the façade system in lower floors of the building. All these fires then proceeded to propagate upward. Therefore, the main mechanism of lateral fire spread is falling debris, and thus the rate of lateral spread is defined by the rate of lateral spread of the fire at the architectural crown.

Different details in the façade system (materials, geometry, cavity barriers, etc.) seem to show different levels of impact on the rate of flame spread. Tests conducted after the Grenfell Tower fire do provide some further information. But the complexity of this façade system is such that observations and tests, such as BS 8414, do not provide sufficient information to be able to reach incontestable conclusions. The specificity of the scenario used for these tests and the quantity and quality of the data recorded does not allow for a reliable extrapolation of the test results. Adequate performance assessment of systems of the complexity of these façade systems require better and more detailed data for a range scenarios and test configurations.
Compliance of the façade design relies on establishing if it “adequately resists the spread of fire.” The only path to compliance is performance assessment “from test evidence” used by a competent engineer using “relevant design guides.” The complexity and importance of the façade system requires more than guides and therefore the reliance is fully on professional competency. There is no clear definition of professional competency, therefore this is a matter that needs to be studied with great attention.

There are no provisions in the Building Regulations that require the designer to control inward penetration of an external fire occurring on the building. Emphasis is given to the risk posed by heat fluxes of a magnitude typical of those received from adjacent buildings (12.6 kW/m²). Furthermore, given that glazing is an unavoidable part of the function of a residential building it is certain that in the presence of an impinging external flame the glazing will fail. Glazing is generally considered to fail with heat fluxes of 5 - 10 kW/m² while external fires occurring on the building have been measured to deliver heat fluxes within a range of 20-120 kW/m². It is therefore not reasonable to expect that an external fire occurring on the building will not start internal fires within the building.

In the third stage of the Grenfell Tower fire, internal fires were started at multiple levels as the fire propagated upwards. In a similar manner, but at a much slower rate, internal fires would have been initiated after the fire propagated laterally. Grenfell Tower had multiple pathways for internal propagation, many of them much less robust than glazing (i.e. the extraction fan, window detailing, etc.) and they all contributed to fast ingress of flames into the units.

Analysis of the emergency calls and a damage analysis shows that internal penetration happens in many ways, with a wide range of consequences and in many different locations. Internal penetration occurs first in floors 5, 12 and 22. Rapid internal penetration above floor 20 can be attributed to the presence of the architectural crown and the debris falling from it. Due to immediate proximity to the architectural crown, the upper floors were more readily exposed to the build-up of falling debris on external ledges. Furthermore, a buoyant plume will carry heat upwards further explaining the rapid ingress of flames into the units above floor 20.

Analysis of other international fire events shows that the buoyant plume generated by the fire cannot significantly accelerate lateral fire spread in the absence of other contributing factors. Several international fire events show that once the fire reaches the top of the building it starts to decay, showing only minor lateral fire spread. In some cases, extensive lateral fire spread similar to Grenfell Tower occurred. Most international events are poorly documented therefore it has not been possible to identify any design features that are consistent to all fires where significant lateral fire spread occurred. Nevertheless, the fire occurring at the Monte Carlo Hotel & Casino in Las Vegas showed rapid lateral propagation at the top of the building. This fire serves as an example that illustrates how debris from a high-level fire can initiate multiple lower fires creating lateral fire spread over a more extensive area of the building.

Once the external fires have breached the exterior of further units, they may or may not act as an ignition source for a compartment fire, depending on the layout of the fuel within the breached compartment and the location of the ignition point. At Grenfell Tower, and increasingly with height,

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3 Functional requirement B4 (ADB) and performance criteria specified in Section 12.5 (ADB).
4 Section 12 of ADB and Appendix A of ADB bullet point (b).
5 Section 12 of ADB and Appendix A of ADB bullet point (b).
the internal fires developed into post-flashover fires, rapidly filling the units with smoke and involving combustible materials within the units.

At this point the boundary of the units (i.e. perimeter walls and doors) should act as barriers to the progression of smoke. Several international events have shown that means of egress can be protected effectively by means of compartmentalization. Very large fires, with comparable internal fire spread, have not resulted in penetration of smoke and flames into the stair lobby or stairs.

Compartmentalization is a required part of the Building Regulations and it is a critical feature of the design of high-rise buildings. Furthermore, ventilation may be necessary to provide a redundancy that protects the stair lobby. The stairs are further protected by a second redundancy consisting of the stair enclosure (including the doors). Therefore, there is an expectation that smoke can still be prevented from entering the remaining safe area of the building (i.e. the stairs).

It has been reported that samples of the Grenfell Tower doors failed a standard test approximately 15 minutes into the test. The standard test does not replicate a fire event (in terms of the progression of the fire) but creates conditions whereby there is a steady growth of the temperature in time. In 15 minutes the temperature of the standard test would have reached approximately 740°C. In a real fire, 740°C is a temperature characteristic of a post-flashover fire. Therefore, it is possible to infer that failure of the doors leading to the lobby would have occurred only after the units would have been fully involved in the fire (post-flashover fire).

A feature of these doors is that they are of combustible construction resulting in ignition at failure. If the doors ignite they would have inevitably compromised the lobby. Given such a fire, the cross-ventilation strategy (even if it was operational and well maintained) would not have served as an effective redundancy. Because of the small dimensions of the lobby and the fact that it was surrounded by multiple units burning, it is very likely that the stair doors would have been challenged by impinging flames. Impinging flames would have provided enough heat to possibly challenge the performance of any doors similar to those tested after the Grenfell Tower fire.

Inspection of all the doors shows that areas where there was major fire impact (i.e. evidence of high temperatures and significant soot deposition) correlate well with areas where doors are either missing or significantly damaged. Other potential paths for smoke and flames have been identified (e.g. inadequate fire stopping material surrounding service penetrations, absent door seals, etc.) nevertheless no significant compartmentalization deficiencies could be established in the post-event inspections. While any deficiency could have contributed to the migration of smoke into the lobby, it would have been highly unlikely that flames could have migrated into the lobby via these routes to create conditions that could compromise the doors separating the lobby from the stairs.

A feature of the Grenfell Tower fire was the observation of smoke escaping from windows opposite to the initial location of the fire (i.e. escaping via the west and south faces of the building). These observations occur as early as 40 min from the reporting of the initial fire in Flat 16. Migration of smoke across the building would have required at least two breaches of barriers that were separated from each other (i.e. two flat entrance doors). No clear explanation can be proposed, nevertheless,

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6 Compartmentalization is a process by which physical barriers (ex. walls, floor slabs, doors, etc.) that can withstand the effects of a fire (for a sufficient period of time) are used to maintain the fire within a unit, therefore not allowing heat and smoke from entering adjacent areas of the building.

7 Section 2 – Means of Escape from Flats (ADB).
given the information available, it is most likely that this occurred because doors were open. This
highlights the importance of self-closing mechanisms for doors.

Once the fire has re-entered the building, compartmentalization is the main line of defence. Compliant
systems would have helped to protect egress paths and deliver safe paths for the occupants to
evacuate. While the external fire contributes to ignition of the unit furnishings, the energy
contribution to the unit from this external fire is limited and localized to the areas around the window.
Thus, there is no reason for compartmentalization requirements designed to withstand a post-
flashover fire not to be suitable for a fire of the nature of that of Grenfell Tower.

Occupant movement (combined with potential absence of functioning self-closers and therefore
leaving doors open) or firefighting operations most likely had an impact on the capability of smoke
and flames to migrate from the units towards the lobby and stairs. Nevertheless, this possibility cannot
exonerate the need for compliant compartmentalization features (walls, fire doors, fire stop, etc.).

The migration of building occupants was analysed showing that the patterns of descent varied in time.
First, people reported a dynamic evolution of the smoke within the building. Within some time periods
people migrated downwards showing that the stairs still remain tenable. At other points in time
people migrated upwards, reporting that the stairs were filled with smoke. Through the third stage of
the fire, tenability evolves in a dynamic manner as the fire spreads laterally and different failures
occur. In this period, most of the calls reporting smoke and flames come from floors 10-15 and above
floor 20.

Between approximately 60 and 70 min from the initiation of the fire, reports of smoke in the lobby
and fire and smoke in units become more generalized. This marks the end of the third stage and can
be considered as a point when there is generalized loss of tenability in the building.

Through this third stage of the fire, the building is operating outside the conditions contemplated by
the existing regulatory framework. Firefighting operations are outside the bounds of conventional
practice. The magnitude of the event has significantly reduced the capacity of the fire service to
manage the situation. A thermal analysis of the structure shows that the structure was still safe.
Temperatures of the structure would have not reached magnitudes where significant damage would
have been expected. A “stay put” strategy is not consistent with the characteristics of the third stage.
Tenability of the egress paths is highly questionable therefore egress and rescue both represent a high
risk during this stage.

Stage four is characterized by multiple calls indicating critical conditions. Many sectors of the building,
including lobbies and stairs are untenable. This stage will also be characterized by multiple forms of
failure that could potentially include breaches of the gas lines, penetration of fire stopping, structural
deterioration, etc. Given the potential temperatures of the structure, a detailed structural assessment
would have been essential to establish the stability of the building. This type of assessment requires
inspection and analysis not possible during fire rescue and response activities. During this stage, egress
or rescue operations are probably still possible within some sectors of the building, nevertheless these
activities would be implemented well outside the scope of any regulated practices and will imply
significant risk for occupants and fire fighters. The fourth stage does not guarantee safe firefighting
operations inside the building.

The tragic consequences of the Grenfell Tower fire highlight the significant shift in complexity that
occurs when intricate façade systems are incorporated into high rise buildings. Functional
requirements, guidelines and simple standardized tests become insufficient tools to establish adequate performance\(^8\) of systems where performance is a function of the interactions of the building and building envelope.

The inadequacy of these methods of performance assessment / regulation is such that systems that introduce obvious dangers can be incorporated by designers in a routine manner. These systems can be used without necessitating sufficient consideration of the effect that that inadequate performance can have on the overall validity of the fire safety strategy\(^9\). This is despite the explicit understanding that one of the fundamental assumptions backing almost all aspects of a tall building fire safety strategy is that external fire spread shall be prevented.

The regulatory framework relies very heavily on competent professionals to provide the necessary interpretation that will bridge the gaps and resolve the ambiguities left by functional requirements, guidelines and standardized tests. Nevertheless, a competent engineer should be capable of interpreting the requirement to “adequately resist the spread of fire over the walls ... having regard to the height, use and position of the building\(^{10}\)” within the context of the needs of the fire safety strategy in the case of a specific tall building. In the case of the fire safety strategy of Grenfell Tower, “adequately resist” should have been interpreted as being “no” external fire spread.

There is currently no definition of what is the competency required from these professionals, or skill verification approaches that should be used, so as to guarantee that those involved in the design, implementation, acceptance and maintenance of these systems can deliver societally acceptable levels of safety. There is a need to shift from a culture that inappropriately trivializes “compliance” to a culture that recognizes complexity in “compliance” and therefore values “competency,” “performance” and “quality.” Otherwise, the increasing complexity of building systems will drive society in unidentified paths towards irresponsible deregulation by incompetency.

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\(^8\) Performance is defined as adequately fulfilling all functions that support and enable the fire safety strategy to deliver an acceptable level of safety.

\(^9\) Fire Safety Strategy, as referred here, is not a specific document but a conceptual representation of the ensemble of measures introduced to guarantee adequate fire safety (Section 1.6)

\(^{10}\) Section B4. (1) External Fire Spread (ADB).
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1 INTRODUCTION

1.1. THE INQUIRY’S TERMS OF REFERENCE

The Inquiry’s Terms of Reference have been approved by the Prime Minister and have been published on the Inquiry’s website. The Inquiry has also published on its website a detailed provisional List of Issues which identify the matters with which its investigation will be concerned. This provisional List may be revised in due course.

1.2. STRUCTURE OF THE INQUIRY

The Chairman has indicated that Inquiry will be conducted in two phases. Phase 1 of the Inquiry is intended to investigate the development of the fire itself, where and how it started, how it spread from its original seat to other parts of the building and the chain of events that unfolded during the course of the hours until it was finally extinguished. Phase 1 is also examining the response of the emergency services and the evacuation of residents. The Chairman has noted that it is necessary to address these questions first for two reasons:

1. there is an urgent need to identify what aspects of the building’s design and construction played a significant role in enabling the disaster to occur; and
2. until the chain of events is understood, it will not be possible to pinpoint the critical decisions that had a bearing on the fire.

The Chairman asked me to provide a report for Phase 1 on:

(a) The ignition of the Grenfell Tower façade materials.
(b) Fire spread to and on the exterior of Grenfell Tower.
(c) Fire and smoke spread within Grenfell Tower.

The current document is my Phase 1 Report.

1.3. STRUCTURE OF REPORT

The report will be structured around a series of general topics that attempt to describe how a high-rise residential building should have responded to a single fire event (Fire Safety Strategy). A fire is a chemical reaction governed by Newtonian physics, therefore its behaviour can be described in terms that are consistent with this framework. In a similar manner, the response of a building to the fire can be described using basic and well accepted scientific principles. The report will first present the fire safety strategy in these terms. It is clear that the complexity of the interactions is very significant, therefore the description of the different processes will remain general and simplified. It is accepted that the general presentation will not cover some of the important details. These will be left for later sections.
Building Regulations provide structured approaches that address the progression of a fire and its interactions with a building. Building Regulations accept that a single fire event will occur in a building. Then, the objective of Building Regulations is to manage this fire event in a manner such that the consequences are acceptable to society. For that purpose, Building Regulations invoke engineering tools and engineered systems as well as reference to the fire brigades. The interaction between the building, the engineered systems and the fire brigades with the fire are governed by the laws of physics and in principle could be describable by means of engineered tools. Nevertheless, the complexity of some of these interactions is such that sometimes the implemented solutions have to be sufficiently over-dimensioned (or robust) to provide confidence of adequate performance without the explicit representation of the physics. Building Regulations are, in principle, meant to provide these robust solutions that meet the objectives of the fire safety strategy. Some Building Regulations approach these solutions as functional requirements others as detailed sets of rules.

An analysis of Building Regulations and their manifestation in building design is beyond the scope of this report, nevertheless, this report will include references to particular Building Regulations that aim to address each aspect of the fire safety strategy applied to Grenfell Tower. Examples of these Building Regulations will be extracted from Mr Todd’s report [1] to serve as illustration of how those Building Regulations provide solutions to the requirements of the fire safety strategy.

The events of June 14th, 2017 will be discussed following the structure described below:

1. Assessment of the evolution of the fire within the room of origin. The room of origin is assumed to be the kitchen of Flat 16 based on references [2] and [3]. An analysis of the potential dynamics of the fire event will be used to provide some insight into the mechanisms by which the fire exited the compartment of origin. These mechanisms will be contrasted against the fire safety strategy and compliance failures as per reference [4].

2. Assessment of the external fire growth and its impact on tenability\(^{11}\). Details of the evolution of the external fire will be extracted from reference [5] together with video, photographs and other documentation provided by the Public Inquiry. These will be used to describe the time evolution of tenability through the building.

3. Comparison with prior events. The evolution of the Grenfell Tower fire will be contrasted with past fire events with similar characteristics and where there were similar compliance failures as per reference [4]. This information will be used to provide some insight into aspects of the fire safety strategy that were critical to the outcome.

The description of human behaviour in the event of a fire requires more than a Newtonian physics framework. A fire safety strategy is intended to provide sufficiently robust solutions that do not depend upon a detailed analysis of human behaviour. The interactions between people and the fire, human behaviour and decision making will therefore not be discussed in this report. In contrast, the evolution of the fire as it pertains to tenability of the different areas of the building will be discussed in detail. Placement and communications from individuals within the building will be contrasted with

\(^{11}\) See footnote (1) for approximate times for each stage.
the evolution of the fire to draw conclusions on the impact that each element of the fire safety strategy had on the evolution of tenability.

The intervention timeline and firefighting procedures are beyond the scope of this report, but nevertheless, the evolution of firefighting activities relative to the fire growth and the attainment of untenable conditions will be discussed. The evolution of the fire will be contrasted with fire brigade related information to draw conclusions on the role of each element of the fire safety strategy.

1.4. FIELD OF EXPERTISE

1.4.1. My name is José L. Torero. I am the John L. Bryan Chair at the Department of Fire Protection Engineering and the Director of the Center for Disaster Resilience at the Department of Civil Engineering at the University of Maryland, USA. I also serve as Director of TAECC. Previously, I was Prof. of Civil Engineering and Head of the School of Civil Engineering at the University of Queensland, Australia (2012-2017). Before moving to Australia, I held the Landolt & Cia Chair for Innovation for a Sustainable Future at the Ecole Polytechnique Fédéral de Lausanne, Switzerland (2012) and the BRE Trust/RAEng Chair in Fire Safety Engineering at the University of Edinburgh (2004-2011). Between 2004 and 2011 I was also the Director of the BRE Centre for Fire Safety Engineering and in the 2008 to 2011 period I was Head of the Institute for Infrastructure and Environment, both at the University of Edinburgh. I have held other positions at CNRS (France), University of Maryland (USA), NIST (USA) and NASA (USA).

1.4.2. My field of expertise is fire safety; a field in which I have worked for more than 25 years. I was trained as a Mechanical Engineer obtaining a Bachelor of Science from the Pontificia Universidad Católica del Perú in 1989. In 1991 I obtained a Master of Science and in 1992 a PhD from the University of California, Berkeley, both in Mechanical Engineering with specialty in Fire Safety. I am a Chartered Engineer by the Engineering Council Division of the Institution of Fire Engineers (UK), a Registered Professional Engineer in Queensland and a full member of the Society of Fire Protection Engineers (USA).

1.4.3. I am a Fellow of the Royal Academy of Engineering, the Royal Society of Edinburgh, the Australian Academy of Technological Sciences and Engineering, The Institution of Civil Engineers, The Institution of Fire Engineers, the Society of Fire Protection Engineers and the Combustion Institute. In 2008 I was awarded the Arthur B. Guise Medal by the Society of Fire Protection Engineers (USA) and in 2011 the David Rasbash Medal by the Institution of Fire Engineers (UK) in recognition for eminent achievement in the education, engineering and science of fire safety. In 2016 I was awarded a Doctor of Science Honoris Causa from Ghent University, Belgium. I am the author of more than 500 technical documents in all aspects of fire safety of which more than 200 are peer review scientific journal publications. I have been invited to deliver more than 100 keynote lectures in conferences and professional fora worldwide of which more than 20 have been in the area of Fire Investigation.

1.4.4. I was the Editor-in-Chief of Fire Safety Journal (2010-2016), the most respected scientific publication in the field, Associate Editor of Combustion Science and Technology (1997-2008) and a member of the Editorial Board of Fire Technology, ICE Journal of Forensic Engineering, Fire Science and Technology, Case Studies in Fire Safety, Progress in Energy and Combustion Science and the
Journal of the International Council for Tall Buildings. I am one of the Editors of the 4th Edition of the Fire Protection Engineering Handbook of the Society of Fire Protection Engineers (USA) and an author of several chapters. I am regularly in the Scientific Advisory Boards of most conferences in the field and a member of the Committee of many professional organizations. I chaired the Fire Safety Working Group for the International Council for Tall Buildings and Urban Habitat and was the vice-Chair of the International Association for Fire Safety Science.

1.4.5. I have been involved in numerous fire investigations many of which have been landmark studies. Between 2001-2010 I was involved in an independent investigation of the World Trade Center buildings 1 and 2 collapses. I was involved in the fire and structural modelling of the World Trade Center building 7 collapse in support of litigation and conducted an independent investigation of the fire growth and structural failure of the Madrid Windsor Tower Fire commissioned by the British Concrete Institute. I conducted a cause and origin investigation of the Texas City explosion and subsequent fires as well as a damage correlation analysis. I conducted dispersion fire modelling supporting the litigation of the Buncefield Explosion and of the Sego mine explosion (USA). I supported the fire service investigation of the Ycu Bolanos supermarket fire in Paraguay to establish the cause of the fire and to analyse the reasons for the fatalities. I conducted the fire investigation of La Rocha prison fire in Uruguay where 12 inmates died where we developed analytical and numerical model of fire growth in support of the investigation. I conducted the fire investigation of the San Miguel prison fire in Chile where 26 inmates died where we developed analytical and numerical models of fire growth in support of the investigation. I worked with the Scottish Fire Service on the Balmoral Bar fire investigation. I conducted the post-fire structural assessment of the Abu-Dhabi Plaza fire in Kazakhstan, probably the biggest ever fire of a building under construction. Recently, I led the fire investigation of the Ayotzinapa 43 murder case driven by the Organization of American States that encouraged the Mexican government to reopen the investigation. (Science, 11 March 2016, vol. 351 Issue 6278, pp.1141-1143 and Science, 29 April 2016, vol. 352, issue 6285, p.499) and by the National Academy of Science (USA) (http://www7.nationalacademies.org/humanrights/).
I served as advisor to the Attorney General of Mexico in the subsequent investigation. I have given expert testimony in several forensic fire investigations worldwide.


1.4.7. For more than 20 years I have been involved in the education and training of fire engineers, fire investigators and the fire service. I have developed training programmes on fire investigation for the Bureau of Alcohol Tobacco and Fire Arms (USA), fire investigators and fire brigades in the UK (University of Edinburgh short course in Fire Science and Fire Investigation, 2001-20012), the RAIB (UK) and the Police Scientifique of Lyon (France) among others. I have taught courses at Fire Service College Gullane, for the Queensland Fire and Emergency Services and for the fire services in numerous other countries (Costa Rica, Chile, Peru, Argentina, Singapore, Malaysia, etc.). I have developed curriculum and taught the Fire Protection Engineering programme at the University of Maryland, the Structural and Fire Safety Engineering course at the University of Edinburgh, the Civil and Fire Safety Engineering course at the University of Queensland and the International Masters in Fire Safety Engineering (Ghent, Lund and Edinburgh Universities). I was external examiner to the Fire Safety programme of Glasgow Caledonian University (UK) and I am on the Advisory Board of Worcester Polytechnic Institute (USA) Fire Protection Engineering programme. I am a Distinguished Visiting Chair Prof. in Fire Safety Engineering at the Hong Kong Polytechnic University.

1.4.8. In the period 2007 to 2010 I lead the development of the FireGrid project funded by the Department of Trade and Industry and in partnership with the London, Manchester, Strathclyde and Lothian and Borders Fire Brigades where a detailed study of the role of information on fire brigade emergency response was analysed. This project was featured in the 2007 BBC Horizon Documentary “Skyscrapers Fire Fighters” that has been shown in more than 30 countries. In 2010 I was awarded a GBP 2M grant by the Engineering and Physical Sciences Research Council UK to study the Real Fires for the Safe Design of Tall Buildings.

1.4.9. I have been involved in numerous advisory roles for industry and government many of them including the fire service. I was involved in the Nuclear Regulatory Commission (USA), PRiT Committee on Fire Modelling, a member of the Expert panel of the Fire and Resilience Directorate (Communities and Local Government, UK) and of the Forum of Chief Fire Officers of Scotland (SDAF). I was advisor to the Department of Transportation and Main Roads (Queensland, Australia), special advisor to the vice-President of Peru on the Utopia Club and Mesa Redonda fire investigations and a member of the CFOA Training Needs Analysis Gateway Review Group. I am currently special advisor to the Minister of Housing (Queensland) on issues of façade fires. I am a regular participant in standards development committees worldwide.

1.4.10 A full and up to date CV (current at the time of Torero’s initial instruction as Expert Witness) has previously been provided to the Inquiry’s Core Participants.

1.5. STATEMENTS

I confirm that I have made clear which facts and matters referred to in this report are within my own knowledge and which are not. Those that are within my own knowledge I confirm to be true. The opinions I have expressed represent my true and complete professional opinions on the matters to which they refer.

I was assisted in the production of this report by the following individuals:
Dr Adam Cowlard - Director and senior engineer at Torero, Abecassis Empis and Cowlard Ltd. Dr Cowlard holds a PhD in Fire Safety Engineering and an MEng in Civil Engineering from the University of Edinburgh. He has undertaken a wide range of consultancy and research work encompassing development of fire safety strategies for a wide range of complex infrastructure, development of design fires and heat transfer modelling, and fire and evacuation modelling. Dr Cowlard supported my work primarily on modelling, data analysis, reporting and reviewing.

Dr Richard Krupar III – While conducting this work he was a post-doctoral research associate at the Center for Disaster Resilience at the University of Maryland. Dr Krupar holds a PhD in Wind Science and Engineering and is an expert in damage assessment. He has conducted damage assessment for many major events such as Hurricane Harvey. Dr Krupar supported my work primarily on the damage analysis, video footage assessment, reporting and reviewing.

Mr Alex Duffy – Faculty Assistant at the Department of Civil Engineering (University of Maryland. Mr Duffy holds a Master in Design Studies from Harvard Graduate School of Design, and a Master in Civil Engineering from the University of Edinburgh. He has more than five years’ experience in fire safety engineering design. Mr Duffy supported my work primarily through data collection, analysis, organization of information, reporting and reviewing.

I confirm that I understand my duty to assist the Inquiry on matters within my expertise, and that I have complied with that duty. I also confirm that I am aware of the requirements of Part 35 and the supporting Practice Direction and the Guidance for the Instruction of Experts in Civil Claims 2014.

I confirm that I have no conflict of interest of any kind, other than any which I have already set out in this report. I do not consider that any interest which I have disclosed affects my suitability to give expert evidence to the Inquiry on any issue on which I have given evidence and I will advise the Inquiry if, between the date of this report and the Inquiry hearings, there is any change in circumstances which affects this statement.

Signed: Dated: 23 May, 2018
2 BACKGROUND

2.1. THE FIRE SAFETY STRATEGY FOR HIGH-RISE BUILDINGS

To guarantee the safety of people occupying a high-rise building during a fire event, it is necessary to implement a complex and precise fire safety strategy [7, 8]. The components of such a fire safety strategy can be explicitly stated or introduced in an implicit manner through prescriptive requirements. In both cases, the design of such a strategy requires careful consideration because the safe use of a high-rise building is a complex problem [7, 8].

Fire safety strategy, as referred to in this document, is the concept by which different measures are taken to guarantee a societally accepted adequate level of safety of people against fire. It is also implied that by guaranteeing the adequate safety of people, material losses will also be mitigated. In many countries, the concept of a fire safety strategy is required to be translated to documents that are part of the approvals process and might be referred by the same name or others (e.g. Fire safety brief, fire protection strategy, fire engineering brief, etc.). For the purpose of this report the term fire safety strategy is not related to any of these documents but remains purely as the concept explained above.

The fire safety strategy is linked to how the building is defined or classified. The definition of a building that is to be classified as a high-rise building is also complex. Regulations many times propose simple definitions of a high-rise building only on the basis of height, (Sections 4.1.5 and 4.1.6 [1]) nevertheless numerous assumptions hide behind the classification. These assumptions, together with the many protective measures implemented, allow these buildings to be used in a safe manner. The assumptions and protective measures will vary depending on the specific characteristics and use of a building (Section 4.1.6 [1]).

Conceptually, the fire safety strategy for a high-rise building recognises that the main characteristic that defines a high-rise building is a convergence of time scales. In a high-rise building, people will take significant time to evacuate (several minutes), therefore the time to egress is of the same order of magnitude as the time for failure or the time required for fire and rescue service intervention [8]. Time for failure could be defined in many ways, such as attainment of conditions that are untenable, structural failure, etc. In buildings that are not classified as high-rise, egress times are generally very short compared to all other characteristic times, therefore occupants are not expected to interact with firefighting operations or with the different potential modes of failure. It is clear that this will only be the case if the fire safety strategy works appropriately during the fire event.

Given this convergence of time scales, there is insufficient time to evacuate everyone and therefore a high-rise building requires the existence of safe areas within the building. These safe areas are intended to assure the wellbeing of occupants while the fire grows and while countermeasures and fire fighter operations are in progress. Furthermore, in the case of vulnerable people, these safe areas will serve to provide protection until rescue is achieved (Section 2.105 [1]).

The most common safe areas are the stairwells. Stairwells are intended to remain isolated from the event during the duration of the fire, guaranteeing the egress process. There is no limit to the time where stairwells are to remain safe. To maintain the stairs as safe areas during the fire, these have to
be constructed such that the fire is prevented from damaging the enclosure (i.e. walls and doors).

Furthermore, redundancies are necessary for all safety systems; therefore, supplemental protection
can be introduced to prevent smoke from entering the stairs. Typical approaches are: ventilated
lobbies that create a buffer between areas with combustible materials and the stairs, or increasing
the pressure within the stair thus ensuring a flow of air from the stair to the lobby (as opposed to
smoke from the lobby to the stair), etc. Some of these are discussed in Section 3.2.20 of Dr. Lane’s
Phase One report [4].

Also, it is important for safety systems to have redundancies, therefore having more than one means
of egress is highly desirable. Nevertheless, it is recognised that emergency stairs can occupy a
significant fraction of the surface area of a high-rise building, challenging its functionality. Limiting the
number of stairs therefore might be necessary. In this case, other forms of redundancy might be
introduced. A common form of redundancy is to prevent the fire or smoke from escaping the sector
of the building where the fire originated. This is achieved by means of barriers that block the
progression of a fire out of a sector. Egress, in this case, can be contained to the high-risk sectors of
the building and the rest of the occupants will remain in place. All other sectors of the building are
deemed safe. Firefighting operations will proceed with occupants in the building, therefore, provisions
have to be made to account for firefighter-occupant interactions. These provisions are in part
designed into the building but also relate to firefighting operations. This strategy is generally named
“stay put” or “defend-in-place. 12

Buildings will bound these sectors by means of barriers that are qualified as “fire resistant.” Typically,
for residential units, each unit represents a sector, therefore the perimeter of the unit needs to meet
“fire resistance” requirements. Certain boundaries of the sector can be deemed more important than

12 The term “stay put” is common in the UK and it is directed towards the occupants and the instructions that
need to be provided to them so that their actions during a fire are consistent with the fire safety strategy [1].
The term “defend in place” is more common in North America and emphasizes firefighting operations. The term
“defend in place” indicates that firefighters will be aware that occupants will remain in place while firefighting
operations proceed. While both terms might represent slightly different procedures, the primary intention is the
same for “stay put” and “defend in place” strategies. In both cases, rescue (i.e. firefighter managed egress) and
firefighting operations supersede occupant driven egress. These definitions are not identical but consistent with
those presented in Dr. Lane’s Phase 1 Expert Report (Sections 2.8.7 and 2.8.20 [4]).

13 Fire resistance is a standard term used to describe the performance of structural components in a standard
test. This test is recognized internationally (BS 476, ISO 834, ASTM E 119, etc.) and it provides a standard and
severe thermal exposure to the structural element by means of a furnace. The structural element is introduced
in the furnace and the furnace temperature is then increased in a predefined and standard manner. The term
“fire resistance” is then defined as the time (in intervals of 30 minutes) that the structural element can withstand
the thermal exposure before it reaches a predefined failure criterion (normally specified as a critical
temperature). It is important to clarify that the standard thermal exposure does not correspond to a typical
thermal exposure during a fire and structural elements do not behave in exactly the same manner in a furnace
as in a building, therefore the “fire resistance” does not represent a real time to failure. “Fire resistance” is
nevertheless considered as a “worst case scenario” that provides a relative ranking between structural elements.
Structural elements that are to act as barriers (floors, walls, doors, etc.) will therefore have to meet requirements
of “fire resistance” before they can be used in a building. Products such as doors, fire-stop systems, etc. will be
tested and listed with a “fire resistance” before they can be sold as barriers. Commonly used structural elements
such as partition walls will be designed and built in a manner consistent with systems that have been tested and
certified. Some variations can be permitted but, in general, given the complexity of these systems, any variation
will have to be analyzed and approved by a competent professional.
others, therefore a higher “fire resistance” might be required. It is typical to recognize that global structural integrity and containment of a fire to the floor of origin are of critical importance for high-rise buildings, therefore floor slabs and main structural elements generally will have higher fire resistance requirements than doors or non-load bearing partition walls.

It is recognized that certain components of these sectors cannot behave as barriers to the same extent as walls or floor slabs. Windows are some of these necessary components. Windows will incorporate glazing and could be potentially open, nevertheless, provisions are still necessary to prevent a fire from entering the adjacent sectors. Figure 1 shows an external photograph of the recent Trump Tower fire in New York (April 8th, 2018). Figure 1(a) shows the magnitude of the fire and Figure 1(b) the external glazing after the event. The figure shows that the fires did not progress to the sectors above or adjacent to the sector of fire origin. In this case the compartmentalization provisions performed adequately. Unfortunately, a detailed investigation is currently unavailable and therefore the design features that enabled the adequate behaviour of this building cannot be established.

![Figure 1: Trump Tower fire, April 8th, 2018 (A) The fire during burning showing a fully developed post-flashover fire (B) The aftermath showing the extent of damage of the glazing.](image)

It is important to note that robustness and redundancies are paramount for high-rise buildings because for these buildings the evolution of a fire, as it scales-up, can be extremely complex [9] and the behaviour of occupants over such long time-scales is highly uncertain. Furthermore, the performance of many of the fire safety systems and that of the fire brigades is stretched [8]. Given the characteristics of high-rise buildings, Building Regulations will therefore stipulate robust solutions and many redundancies [1].

### 2.2. THE GRENFELL TOWER FIRE SAFETY STRATEGY

The Grenfell Tower was classified as a high-rise residential building due to its height and occupancy. As such a fire safety strategy that is consistent with this classification would have been implemented. This section explores the different fire safety measures observed in Grenfell Tower and structures them in the context of a conceptual fire safety strategy. This section does not analyse any document on the matter of the fire safety strategy that could have been written for approvals or other purposes.

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14 Compartmentalization is the term used to describe the concept of delivering a sector that is expected to fully contain a fire. The sector is therefore generally termed a compartment. A compartment is protected by fire resistant barriers and is designed to prevent a fire from spreading to any adjacent compartment.
The building had limited means of egress (one stair) and therefore required a “stay put” strategy. In conceptual terms the safety of occupants in such a high-rise situation would be guaranteed in the following general ways:

- The objective of a fire safety strategy is to mitigate the consequences of a fire. Therefore, a fire is assumed to occur. Arson and premeditated fires are not contemplated in Building Regulations and therefore the assumption is that there will be a single event. Lobbies and stairs are required to be free of combustible materials so, in a building of this nature, fires are assumed to start and remain within a residential unit. The residential unit represents the sector to be enclosed by “fire resistant” barriers.

- Maximum allowable travel distances within the unit are restricted and smoke/heat detection and alarm is required (Section 1.5 [1]). Adequate detection and alarm will rapidly start the onset of egress, and the short travel distances will guarantee that occupants of the residential unit where the fire originates will reach a safe area before conditions within the residential unit are untenable.

- Sprinklers can be used as a means to control the rate of growth of a fire, giving the tenant more time to exit the unit. Whilst sprinklers can potentially extinguish the fire of origin, thus eliminating the problem, responsible design cannot assume that, due to the presence of sprinklers, a fire event that challenges the lives of tenants will not occur. Sprinklers will only reduce the probability of a life-threatening fire and therefore can be included as supplemental protection, but do not supersede other elements of the strategy (Section 2.30 [1]). In the case of Grenfell Tower it was not required to have sprinklers [1] as supplemental protection given the time that it was built and sprinkler protection was therefore not incorporated.

- Detection and alarm systems within a residential unit are not interconnected to the rest of the building. Interconnected detection systems are not generally desirable because otherwise a minor event can lead to the unnecessary evacuation of a building. Instead, the residential unit is the sector that is enclosed (walls, floor and ceiling) such that the fire/smoke cannot escape the unit until the full burn-out of all combustible materials (fire resistant compartmentalization). A detection/alarm system that is interconnected to the rest of the building could then be placed in the lobby outside the residential unit. If the smoke has breached the barrier and compromised the lobby an alarm will occur. This signals the onset of egress for all floors at risk. It is possible to adopt an alternative approach. For example, it is possible to have a detection system in the lobby which will activate and provide a means by which egress paths can be kept clear of smoke, allowing for safe evacuation of the occupants if necessary (Section 1.5 [1]). In the Grenfell Tower the smoke detector in the lobby was not required to be interconnected (Section 1.5 [1]) but was introduced as part of the smoke control system whose objective was to maintain egress paths clear from smoke.

- To deliver the enclosure of the residential unit, walls, ceilings and floors are designed in a manner that they prevent fire and smoke from penetrating throughout the duration of burning. This applies to all penetrations (electrical, water, sewage, mechanical, gas, etc.) as well as doors. Doors designed to withstand a fire as well as self-closing systems are generally

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15 Design for burn-out is a concept implicit in the definition of required fire resistance. Structural components should be capable of withstanding the heat generated by a fire until all the fuel has been consumed. Therefore, the energy delivered by a fire until burnout should be less that the energy delivered by the fire resistance furnace until the time associated to the required fire resistance. Other factors can enhance the required fire resistance such as safety factors that serve as multipliers used to manage situations with different levels of risk.
required to prevent smoke from escaping the residential unit (Section 2.4 [1]). The requirements of all these barriers are expressed in terms of “fire resistance.”

- An unavoidable penetration of the residential unit are the widows and other outward facing openings (e.g. extraction systems). These penetrations need to be designed in a manner that prevents a fire from entering any of the areas adjacent to the residential unit. It is recognized that glazing will either be open or fail in the event of a fire, therefore spreading to adjacent spaces is controlled by carefully defined strategies. Simple systems will rely on geometrical constraints that do not allow flame projections to enter adjacent spaces; more complex systems require more intricate solutions. The original design of Grenfell Tower achieved these objectives by means of simple geometrical constraints imposed on the external geometry and non-combustible fabric of the building. The refurbished building included an attached cladding system that required a more complex approach to the problem that included cavity barriers as well as detailed flammability assessment requirements for the systems used. It is important to note that the objective is to prevent a fire or smoke generated in a residential unit from penetrating any of the adjacent spaces (Section 2.24 [1]).

- In a similar manner, all vertical pathways need to be protected to prevent smoke and fire from progressing internally through the building beyond the residential unit of origin. Vertical pathways will include services, lifts, etc.

- In the event of a fire, occupants within the residential units at risk will proceed to evacuate immediately. The lobby is expected not to contain any combustible materials and to be separated from all combustibles by a barrier (Section 2.95 [1]). These barriers can be properly designed walls, enclosures or doors (Section 1.4 [1]). The units at risk could be interpreted as those in the floor of the fire or even just the unit were the fire originated (Section 2.10 [1]).

- The pathway between the residential units and the safe area (i.e. the stairwell) has no redundancy, therefore a smoke management system is used in Grenfell Tower to provide a redundant system that could clear smoke in the event that any of the barriers does not fulfill its function (“smoke dispersal,” Sections 2.7 and 2.8 [1]).

- The occupants might interact with the fire brigades, although such interactions are expected to be in sufficiently small numbers that they will be well structured. Fire brigade predefined procedures will enable adequate interactions (Sections 2.11 to 2.14 [1]).

- Occupants in units that are not deemed at risk will remain in their flats (“stay put”) until instructions are received from the fire brigade. Fire brigade predefined procedures will enable proper management of information to all building occupants (Sections 2.11 to 2.14 [1]).

- Fire brigade operations have the potential to affect the displacement of smoke and flames, therefore, firefighting operations take priority and occupant/fire fighter interactions are expected to be minimized. Fire brigade protocols govern these interactions (Sections 2.11 to 2.14 [1]).

- The building design will consider measures for firefighters to perform their duties adequately (section 2.9 and 2.27 [1]). This includes water supplies, means of access but also all provisions necessary for fire fighters to conduct their duties in a manner that is effective and safe.

- Through the entirety of any firefighting intervention the structure should keep sufficient mechanical strength so that it can fulfil its functions. All structural elements are therefore required to withstand a fire until burn-out. This is normally expressed in terms of “fire resistance” (Section 4.1.16 [1]) and is generally specified not as withstanding burn-out but as “stability will be maintained for a reasonable period” (Section 5.1.14 [1]).
2.3. ASSUMPTIONS EMBEDDED IN THE GRENFELL TOWER FIRE SAFETY STRATEGY

A fire safety strategy relies on many assumptions. Some of these assumptions are associated with the design and implementation process, others with maintenance and many with adequate performance. Having explained the rationale behind the measures implemented or not implemented within the conceptual fire safety strategy for Grenfell Tower it is important to establish some of the key assumptions that enable the performance of these measures:

- That the means to establish performance of all fire safety systems can deliver a performance assessment that is sufficiently accurate and robust. Thus, performance is assumed to be as intended.
- That all components of the fire safety strategy are designed with the intention that they can be built such that the prescribed performance of the design is achieved. The most common means to validate this assumption is through pre-completion inspections and commissioning of the different systems. It is assumed that these occur where necessary.
- That all components of the fire safety strategy are built such that they can be appropriately maintained. Provisions for inspection and maintenance with adequate means to manage repairs and improvements are assumed. It is also assumed that these provisions and means are consistent with the complexity of the systems implemented (Section 2.32 [1]).
- That all professionals involved in the design, building, commissioning, inspection and maintenance have the competency necessary to perform their duties for the specific systems being addressed [10]. Thus, it is possible for the user to rely on the outcome of all professional assessments which have been made (Section 2.32 [1]).

A fundamental performance assumption key to all high-rise buildings is the containment of the fire within the unit of origin. Particularly important is the prevention of vertical flame spread. Horizontal spread to adjacent units is also important albeit I will focus first on vertical flame spread. It has to be noted that the LGA Guide does not envisage “no” external flame spread but states that the external facades of blocks of flats “should not provide potential for extensive fire spread” (Section 2.96 [1]). This will be addressed in detail in the next section.

It is clear that when assessing performance, it is not possible to make absolute statements. Nevertheless, in this particular case, it is important to analyse the implications of vertical flame spread by contrasting that with the scenario of “no” vertical flame spread. If it is assumed that there will be no vertical flame spread then the following performance statements are valid:

1. “Stay put” strategy: If the fire is to be contained to one floor then, in the event of a fire, only the floor of the fire (critical) and the floor above and below need to be evacuated (robustness). The rest of the occupants can remain in the building and wait until the fire service delivers evacuation instructions. Many countries assume the need for a robust approach that requires the evacuation of multiple floors. In the Building Regulations and guidelines applicable to Grenfell Tower there is no requirement for provisions that allow for occupants of more than the flat of fire origin to evacuate (Section 5.1.57 [1]). It is expected that the fire service will control the fire (which might require the use of the stairs) and then establish if there is a need to proceed to evacuate the rest of the occupants. The standard fire service instructions for all occupants away from the immediate floors of the fire will be to remain in place. These
instructions will only change as a function of a dynamic risk assessment performed by the fire fighter in command (Section 12.25 [1]). But this is only possible if no vertical flame spread occurs. As indicated in Section 5.2.94 [1], this has been acknowledged in 2011 and 2015 versions of BS 9991 where “both versions of the Standard noted that this is (vertical flame spread) particularly important where a “stay put” strategy is in place.”

2. Required Safe Egress Time (RSET): The RSET will be the time for the occupants to reach the stairs if it is possible to consider the stairs as a safe area. The total time for egress of the occupants of the building is no longer a factor of consideration. This is only valid if no vertical flame spread occurs.

3. Stairs as a Safe Area: Dimensioning of the stairs is calculated to accommodate occupants from a reduced number of residential units and potential firefighting operations (critical). If many floors are evacuated congestion is possible and this has the potential to disable the orderly evacuation process necessary for an emergency. As stated by Colin Todd in his Phase 1 Report (section 5.1.58 [1]) “...if all residents in a high-rise block chose to evacuate simultaneously, this might well place residents at risk and would create a major impediment for fire-fighting activity by the fire and rescue service.” Adequate fire resistance of walls and doors (critical) and a smoke management strategy for the lobby (robustness) will guarantee the safety of the stairs. The air intake and exhaust systems will be designed on the basis of a single floor fire. But this strategy that makes the stairs a safe space is only applicable if no vertical flame spread occurs.

4. Detection and Alarm: Detection systems will provide sufficient warning by means of an alarm. Detection systems are only implemented in units and are intended to warn only the occupants of the unit where the fire originates. The fire will not be detected in any other unit. In the absence of adequate conditions for a “stay put” strategy, the detection and alarm system will not deliver adequate warning to the rest of the occupants.

5. Notification: Instructions that a “stay put” strategy is enabled are not considered necessary and notification is restricted to the unit where the fire originates. Building Regulations and guidelines require no provisions of information to the occupants (Section 9.1.24 (Fire Safety Order Article 13), Section 9.1.26, Section 12.18 [1]). It is not deemed necessary or appropriate to provide detection, alarm or notification in common parts of blocks of flats other than what is required for smoke management. In the absence of mechanisms to provide instructions, and in the event that conditions that nullify the viability of a “stay put” strategy exist (i.e. vertical flame spread), occupants will be left to their own means (and those available to the fire service), to determine that adequate conditions for a “stay put” strategy no longer exist and that an alternative approach is necessary. This is a particularly vulnerable aspect of the approach currently used and supported by Building Regulations and guidelines applicable to Grenfell Tower. If the fire remains within the unit where it originated, this approach remains viable because only those within the unit of origin are in real risk. This is, therefore, only an acceptable approach to public safety or a reasonable requirement for the fire service in the absence of vertical flame spread.

6. Sprinkler Systems: The design of a sprinkler system enables the control of fires of a magnitude and characteristics consistent with very strict operational requirements. In a residential setting, the design of a sprinkler system serves to control fires that involve furniture and other common materials such as paper, clothing, carpets, etc. The design of the water supply for sprinklers provides sufficient water to control a fire for a limited number of sprinkler heads (normally those that will activate in a one sector/floor fire). If the sprinklers operate in an adequate manner, they will control the fire and eliminate the problem. If the sprinkler is not capable of controlling the fire then the rest of the fire safety strategy has to guarantee the desirable outcome. Therefore, for high-rise buildings, sprinklers are only a supplement to the...
fire safety strategy. Their primary purpose is to reduce the probability of a significant compartment fire. The performance of external sprinklers has never been studied with sufficient detail to establish what conditions will result in adequate fire control of external fires. Furthermore, multiple floor fires will exceed the water supply capacity of the sprinkler system. Therefore, a sprinkler system will not provide any protection and is not designed to operate in the event of external flame spread.

7. Structural Performance: The structural system of a high-rise building needs to provide adequate performance during the period where the building still holds occupants or fire fighters. In a “stay put” strategy, an estimation of the time required to fully evacuate the building is difficult. Statistics on the performance of fire fighters in high-rise buildings are not very extensive or quantitative. It is therefore preferable to design a high-rise building to withstand burn-out of the fuel load. The implementation of this methodology is normally done by means of fire resistance testing; single-element testing that assumes adequate load redistribution from the areas affected by the fire to areas that remain cold (and thus have their full design strength and stiffness). Horizontal and vertical compartmentalization becomes essential for the fire resistance framework to be valid. Fire resistance can only be a reasonable methodology for structural assessment if no vertical flame spread occurs. It is possible to establish the performance of a structure for different fire sizes in a quantitative manner by using complex analytical methods of structural analysis. Nevertheless, the application of these methods to conditions that involve multiple floor fires is not required or common and was therefore not applied to Grenfell Tower.

8. Firefighting operations: Firefighting protocols for response to high-rise building fires are intimately linked to a single floor fire. Furthermore, for residential buildings, the firefighters should find, upon arrival, a single unit fire. Firefighting provisions, such as water supply, are also dimensioned under the expectation of a certain magnitude event. If vertical flame spread occurs this will require the drastic modification of firefighting protocols and advance planning. These modifications rest within the remit of the command structure of the responding units. As indicated in Section 12.20 [1] of Colin Todd’s Phase 1 Report, “It is the role of the fire and rescue service to make the decision as to whether... evacuation is necessary.” Furthermore, the means by which the fire service can alter the strategy are very basic (by knocking on flat entrance doors, by operating sounders within residents’ flats, etc. (Section 12.20 [1]) and these are all approaches that are inconsistent with a fire that has spread vertically or horizontally.

As is demonstrated from the analysis above, the occurrence of any form of vertical flame spread disables every element of the fire safety assumptions underpinning the Grenfell Tower design.

Horizontal flame spread compromises the adjacent units and has the potential to enhance vertical flame spread. The combined effects of horizontal and vertical flame spread in systems of this scale and complexity has never been studied in any detail. Acceptable rates of flame spread are defined by means of performance scenario testing. The assessment of the validity of these tests is outside the scope of this Phase One report nevertheless should be explored in Phase Two.

In the case of fires progressing inwards, there are no provisions to prevent the inward spread of fires, therefore in the event of vertical or horizontal flame spread there is no structured barrier that will prevent the involvement of further units through fires spreading inwards.

It will however be necessary to examine the active and passive fire safety systems which were in operation at Grenfell Tower at the time of the fire. The Grenfell Tower design incorporated other
layers of fire protection that, in principle, could have enhanced its robustness, even in the event of significant external flame spread. A detailed analysis of the fire performance of this specific building is necessary to establish how the fire penetrated the boundaries of the residential units, resulted in vertical and horizontal flame spread and ultimately disabled all components of the fire safety strategy.

It is important to note that current Building Regulations and firefighting practices will not touch upon a scenario where vertical and horizontal flame spread occurs [1]. Thus, from a regulatory perspective, the assumption of “no” vertical and horizontal flame spread is made. As referred to in Section 9.2.35 (v.) of Colin Todd’s Phase 1 Report [1], the LGA Guide indicates that “The “stay put” principle is undoubtedly successful in an overwhelming number of fires in blocks of flats. In 2009-2010, of over 8,000 fires in blocks of flats, only 22 fires necessitated evacuation of more than five people by the fire and rescue service.” While the statistics support the “stay put” approach, there is no indication of the relationship between its success and the success of compartmentalization. Furthermore, there is no indication of the conditions of the fires in the 22 cases that necessitated the evacuation of more than five people. This lack of detail further emphasizes the assumption that “no” vertical and horizontal flame spread will occur and that there is no need for further analysis of the relationship between the success of compartmentalization and success of the “stay put” strategy.

An implicit difficulty with the Building Regulations is the acceptance of some level of fire spread, by referring to the concept of “adequate” fire spread. This will be discussed in more detail in the following section.

2.4. DIFFERENTIATING “ADEQUATE” FROM “NO” FIRE SPREAD

It is clear from Section 2.3 that all Building Regulations and firefighting practices relevant to Grenfell Tower do not touch upon a scenario where vertical and horizontal flame spread occurs [1]. Thus, from a regulatory perspective, the assumption of “no” vertical and horizontal flame spread is implicitly made.

Section 12.5 of Approved Document B (ADB) [11] recognizes the hazard associated with external fire spread. It states: “External Wall Construction. The external envelope of a building should not provide a medium for fire spread if it is likely to be a risk to health and safety. The use of combustible materials in the cladding system and extensive cavities may represent such a risk in tall buildings.” Given the importance of this matter to the fire safety strategy, this issue is one that requires detailed consideration and section 12.5 addresses it in absolute terms.

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16 For the purposes of this report the relationship between the building and the fire will be defined as follows. An internal fire is one that originates and grows within the confines of a compartment in the building. These fires might project flames externally but the fuel is internal to the building compartment. The flame projections deliver heat to the building locally (heat fluxes as high as 120 kW/m² [12]) but unless they ignite materials placed on the exterior of the building or break into adjacent units, they will not spread because the fuel is all located within the building compartment. Beyond the compartment there will be no fuel to burn. Fires external to the building can be separated in two, external fires fueled by materials on the building envelope and external fires occurring in adjacent buildings. Fires fueled by materials within the building envelope can spread vertically and horizontally and provide heat fluxes similar to those of flame projections from internal fires (up to 120 kW/m²). Fires from adjacent buildings are fueled by materials in a different building and only deliver heat. The magnitude of the heat is assumed not to exceed 12.6 kW/m² (ADB).
When the matter is addressed in the functional requirements, the functional requirement B4 indicates: “External fire spread: (1) The external walls of the building shall adequately resist the spread of fire over the walls and from one building to another, having regard to height, use and position of the building.”

The language used in B4 introduces the ambiguity of “adequately” and it also refers to performance in terms such as “resistance.” Furthermore, it requires that external walls shall “resist the spread of fire over the walls and from one building to another.” This leads to many potential interpretations (some of them inadequate) particularly by using the terminology “resist” which suggests that it is related to the concept of “fire resistance.”

While codes commonly introduce ambiguity to allow for flexibility (which is often necessary for design purposes), in this case it hides a misunderstanding of the significance of vertical and horizontal flame spread to the fire safety strategy. Furthermore, it mixes two fundamentally different issues: fire spreading from another building, with fire initiated within the building and spreading to the external walls. While the latter is introduced in some of the relevant sections, it is clear that fire spreading from adjacent buildings is the main driver of the text.

The difference is very significant because in the case of fire spreading from one building to another, the generally accepted approach is to establish that the heat reaching the perimeter wall of an secondary building comes from a single compartment fire within the first building at a defined distance from that wall.

When the issue of fire spreading from an adjacent building is quantified, the main assumption in ADB is (Section 13.2): “a. that the size of the fire will depend on the compartment of the building, so that a fire may involve a complete compartment, but will not spread to other compartments.” Therefore, an explicit requirement for vertical and horizontal compartmentalization is once again introduced. Given a one compartment fire, Section 13.16 of ADB indicates that: “The aim is to ensure that the building is separated from the boundary by at least half the distance at which the total thermal radiation intensity received from all unprotected areas in the wall would be 12.6 kW/m² (in still air).” The value of 12.6 kW/m² therefore defines the thermal load expected on external walls (and glazing) for the scenario of fire spreading from an adjacent building. This is of fundamental importance because it defines the requirement that all external components need to meet to prevent fires igniting or entering a compartment from the outside.

In the case of a fire initiated within a building (i.e. issued from a compartment fire spill plume) and spreading on an external wall (including arson scenarios such as waste bin fires, etc.), the expected heat fluxes on the external wall can reach values in excess of 120 kW/m² [12]. This is not only an order of magnitude greater in intensity, but it is also a fire whose temporal evolution will be very different.

In my opinion, the two scenarios are very different and need to be addressed in an independent way. Nevertheless, ADB does not separate these scenarios. In terms of Guidance and the B4 functional requirement the following is stated:

“Performance:

In the Secretary of State’s view the Requirements of B4 will be met:
a. If the external walls are constructed so that the risk of ignition from an external source and
the spread of fire over their surfaces, is restricted, by making provision for them to have low
rates of heat release;

b. If the amount of unprotected area in the side of the building is restricted so as to limit the
amount of thermal radiation that can pass through the wall, taking the distance between the
wall and the boundary into account; and

c. If the roof is constructed so that the risk of spread of flame and/or fire penetration from an
external fire source is restricted.

In each case so as to limit the risk of a fire spreading from the building to a building beyond the
boundary, or vice versa.

The extent to which this is necessary is dependent on the use of the building, its distance from the
boundary and, in some cases, its height.”

Section (a) states “the risk of ignition from an external source and the spread of fire over their surfaces,
is restricted, by making provision for them to have low rates of heat release”. This introduces a further
ambiguity through the use of the word “restricted.” In the case of a 12.6 kW/m$^2$ “external source”
many materials will not ignite or sustain spread. These include materials listed in Tables A6 (non-
combustible) and A7 (limited combustibility) of ADB. Thus, in that context, the provision is logical.

But, in the case of a 120 kW/m$^2$ “external source” only completely inert materials such as metals or
ceramics will not ignite or sustain spread (materials classified as non-combustible – Table A6-ADB).

Section (a) also indicates that the “restriction” is achieved “by making provision for them to have low
rates of heat release.” When addressing a thermal load of 120 kW/m$^2$ on an external wall to achieve
the objective of “no” spread, the correct focus should be on the mechanisms controlling the capacity
of a flame to spread. For very high heat fluxes and external walls, the rate of heat release is not the
controlling variable$^{17}$ so a provision for a “low rate of heat release” is inappropriate.

Section 12.7 deals with “Insulation Material Products” and states “In a building with a storey 18 m or
more above ground level any insulation product, filler material (not including gaskets, sealants and
similar) etc. used in external wall construction should be of limited combustibility (see Appendix A).”

Many materials that are classified as limited combustibility (e.g. National Class B (Table A7-ADB),
National Class C (table A7-ADB), materials listed in item (5) of Class 0 (Table A8, ADB)) will ignite and
spread a flame when subject to 120 kW/m$^2$. So, it is unclear how they will “adequately resist the spread
of fire.”

Furthermore, ADB indicates “External walls should either meet the guidance given in paragraphs 12.6
to 12.9 or meet the performance criteria given in BRE Report Fire performance of external thermal
insulation for walls of multi storey buildings (BR135) for cladding systems using full scale test data from
BS 8414-1:2002 or BS 8414-2:2005.” But none of that testing contemplates heating from an “external

$^{17}$ The mechanisms controlling vertical and horizontal flame spread will be discussed in detail in Section 5.
source” of a magnitude of 120 kW/m² [12]. It is necessary to conduct a detailed analysis of BS 8414
aimed at establishing its true relevance and the value of information that can be extracted from the
test results. This analysis is beyond the scope of this Phase One report.

Finally, Section 12.1 provides: “for the external walls to have sufficient fire resistance to prevent fire
spread across the relevant boundary.” This is followed by Section 12.2: “Provisions are also made to
restrict the combustibility of external walls of buildings that are less than 1000 mm from the relevant
boundary and, irrespective of boundary distance, the external walls of high buildings and those of
Assembly and Recreational Purpose Groups. This is in order to reduce the surface’s susceptibility to
ignition from an external source and to reduce the danger from fire spread up the external face of the
building.” All these sections address solely the issue of fires spreading from an adjacent building.

While ambiguity is expected and accepted in functional requirements and guidance, any such
ambiguity must nevertheless be compatible with the ability of competent professionals to understand
and address any such ambiguity, in a way which means that safe and robust fire strategies can be
created.

As I have illustrated above, in the case of external fire spread, the current functional requirements
and guidance do not distinguish between external flame spread originating from a fire in an adjacent
building from that originating in a room within the building. Given the drastically different
characteristics of the thermal input for each scenario, this creates a complex ambiguity that affects
classification and performance assessment procedures. The guidance adds to the confusion by not
indicating which clauses apply to each scenario and by suggesting performance assessment
procedures that might only be applicable to one scenario.

Given the extraordinary importance of external spread to the integrity of the fire safety strategy, I
would expect that the ambiguity introduced by these functional requirements and guidance could be
easily resolved by competent professional practise. But this is not the case for many materials and in
particular for complex assemblies. In my opinion, functional requirements and guidance are not
compatible in their current form. The ambiguity associated with performance objectives such as
“restricted” and “adequate” is acceptable when addressing external fire spread but the associated
performance criteria (e.g. “limited combustibility”) and performance terminology (e.g. “resistance”) relate to a scenario that is very different (fires providing heat from an adjacent building). In my
professional opinion, it is not reasonable to expect professionals, no matter how competent they are,
to correct the inconsistencies of functional requirements and guidance.

In the case of Grenfell Tower the combination of materials within the façade system was well known
to catastrophically challenge the requirement for “no” external fire spread. A detailed report
commissioned by the USA National Fire Protection Association and published in 2014 [13] showed
statistics of significant fires with similar assemblies dating prior to 2010. Furthermore, this report
explicitly presents several specific cases where similar material combinations had resulted in fires that
rapidly compromised many floors and in some cases resulted in fatalities. Thus, façade systems of
these nature were an accepted concern worldwide. Thus, whilst I consider the functional
requirements and guidance to have been unacceptably unclear, this should not have prevented
professionals with a minimum level of competence from establishing that such a system would
completely undermine the integrity of the fire safety strategy and therefore provide a medium for fire
spread that would definitely pose a risk to health and safety. Given the importance of “no” vertical
and horizontal spread, it would have been clear that the occupants of a high-rise building cladded by
such a façade system would have been at risk and thus a detailed analysis of the impact of vertical and horizontal flame spread should have been a critical consideration in the design and implementation of the fire safety strategy.

2.5. KEY STAGES OF THE TIMELINE

The prior sections provide the general background and considerations that should govern the design of any high-rise building and the manner in which these background and considerations pertain to Grenfell Tower. If the fire safety strategy had delivered the intended outcome, an accidental fire within a residential unit of Grenfell Tower would have remained contained within the unit of fire origin. Occupants of the unit (and maybe adjacent units) would have evacuated and the fire brigade would have controlled the event within a matter of minutes. The occupants of all other units would have stayed put and the building normal operation could have resumed in a matter of hours. The event, nevertheless, followed a completely different and tragic timeline characterized by the overwhelming failure of many of the fire safety provisions. It is therefore essential, before drawing any conclusions, to first study the evolution of this timeline.

The following sections provide an assessment of the events of June 14th, 2017. The sequence of events has been broken down into key stages of the fire. The defined stages of the fire correspond to periods where distinctive interactions between the fire, the building, its occupants and the fire brigade were observed. While different ways of structuring the timeline are possible, in this case, I considered that for clarity, the stages of the fire timeline were to be separated as follows:

- **Stage One**: From the initiation of the fire event to the breaching of the compartment of origin.
- **Stage Two**: From the breaching of the compartment of origin to the point when the fire reaches the top of the building.
- **Stage Three**: The internal migration of the fire until the full compromise of the interior of the building, including the stairs.
- **Stage Four**: Conditions in the building are deemed untenable.

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18 See footnote (1) for approximate times for each stage.
3 STAGE ONE: BREACHING OF THE COMPARTMENT

3.1. INTRODUCTION

All buildings are designed on the understanding that accidental fires will occur. As indicated above, the fire safety strategy is required to provide adequate management of these events in a manner that guarantees a performance acceptable to society. In the particular case of a unit in a high-rise building, the required performance is that the building will prevent propagation of a fire beyond the unit of origin. Thus, the first aspect to be analysed is how the fire escaped the unit of origin and thus was able to spread externally both vertically and horizontally. The period between the first report of a fire (00:54:29) and the first observation of smoke or debris originating from outside the compartment (01:08:06) is defined as the First Stage of the fire.

A number of potential routes for fire spread from the compartment of fire origin to the external cladding system at Grenfell Tower have been identified in the Phase One expert reports by Dr Lane [4] and Prof. Bisby [5]. The authors do not identify the exact mechanism by which the compartmentalization was breached, principally due to the scarcity of reliable data, in terms of both the exact point of origin of the fire and the contents of the kitchen.

With the objective of better identifying the exact mechanism by which the fire breached the compartment, a simple first principles elimination analysis is conducted here to try to bound the actual fire scenario within the kitchen more precisely. The nature of the analysis (i.e. simple and adopting some basic first principles) is necessitated by the constraints imposed by both the complexity of the problem and lack of reliable data with which to bound the scenario. More complex models can be used, however these models require greater inputs and a precision that is currently not consistent with the available information. Major assumptions have had to be made reducing their value to simple validation of the general physical principles.

It is especially important to note that this analysis is conducted from the basis that the origin of the fire is not established as concluded by Prof. Nic Daeid [2]. If in future more data becomes available, more complex and exact analytical and computational modelling techniques can be performed to provide a greater degree of certainty as to the likely mechanism of spread.

Prof. Bisby [5] identifies in detail three principle potential routes, corroborated by Dr Lane [4], for the fire inside the kitchen to ignite the cladding system components:

Mechanism 1. Fire products (flames and smoke) escaping through the open window and impinging on the cladding directly ignite the Aluminium Composite Panels (ACPs) above the window.

Mechanism 2. Secondary ignition of the kitchen fan leading to direct flame impingement on, and ignition of, the ACPs above the window.

Mechanism 3. Loss of structural integrity and / or combustion of the uPVC window surround, exposing passages by which flames and / or fire products can impinge directly on the various flammable component materials of the cladding system.
This section of the report describes a methodical analysis that aims to bound the fire scenario and in doing so, address each of these mechanisms within the constraints of the available evidence.

Figure 2: Diagram taken from Prof. Bisby [5] showing the layout of the kitchen of Flat 16 and its various appliances (not to scale).

3.2. THE FIRE COMPARTMENT

The Bureau Veritas report [3], corroborated by Prof. Nic Daeid [2], identifies that two separate fire events occurred in Flat 16 of Grenfell Tower. The initial event was the fire in the kitchen, which both aforementioned authors agree did not reach flashover. This is corroborated by post-fire photographic evidence of the kitchen [MET00007448] and firefighter statements [MET00005251, MET00005214, MET00005674, MET00005701]. The second event was likely a more significant fire in the bedroom adjacent to the living room, likely a result of re-entry of the fire that had propagated externally via the cladding system.

The compartment comprising the kitchen of Flat 16 is approximately 4.8m long, 1.9m wide, and 2.35m high. The diagram shown in Figure 2 taken from Prof. Bisby [5] shows the layout of the kitchen and the various appliances currently believed to have been present there. The window cavity, located on the east side of the compartment, has a sill height of approx. 1.05m and a total opening height of approx. 1.2m. These dimensions have been extracted from various drawings provided to the inquiry [SEA00000230].
3.1.1 Ventilation Sources

In total, there are three principal ventilation sources in the kitchen; the principal entry door, the window, and a sliding door connecting to the living room. Thermal imaging camera footage [MET00005816] suggests that the kitchen door is closed during the kitchen fire phase of the fire, aside from the time when the flat occupant entered the kitchen to confirm the presence of the fire prior to evacuating the flat, and during firefighter intervention itself.

The sliding doors to the living room are believed to be closed during the kitchen fire phase, at least up to the point of firefighter intervention. The flat occupant, who had been sleeping in the adjoining room, states that he entered the kitchen via the corridor [MET00006339] and Thermal Imaging Camera (TIC) footage [MET00005816] shows the doors closed at the time of the initial firefighter intervention.

The flat occupant states [MET00006339] that the window in the kitchen was open by about 10 inches. Drawings supplied to the inquiry indicate that the windows are tilt and turn windows and that in the tilt position, the upper side of the windows open approximately 100mm inwards [SEA0000230]. In the turn position, the windows open fully.

3.1.2 Fuel Sources

A number of items known to be present in the kitchen contain flammable materials. These are labelled in the diagram in Figure 2. Most items are well identified however the exact nature of any objects between the Hotpoint fridge freezer and the window have not been fully confirmed at the time this report was written. Sufficient detail is not provided in the witness statement by the flat occupant [MET00006339] or included on the annotated sketch of the kitchen [MET00005190]. It is visible however in the thermal imaging camera footage [MET00005816] as identified by Prof. Bisby [5]. A report by Exponent [14] designate this as some kind of cabinet. Prof. Nic Daeid [2] also identifies that as yet unknown items were likely located there. This is deemed relevant as the occupant that discovered the fire describes smoke coming from the area between the fridge and the window [MET00006339] and identifies this area on their sketch, shown in Figure 4. The sketch does not show anything between the fridge-freezer and the window, however, to the extent of the evidence available, all other items are apparently shown.

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19 New witness testimony was made available a few days before the submission of this report. This information has not been considered in this report because 1) it does not alter the analysis or conclusions presented here 2) because this information needs to be verified and analyzed by means of appropriate testing. The outcome of this verification analysis and testing might alter some of the details of this report.
Figure 3: The image from [MET00005816] shows an unknown object between the fridge-freezer and the window in front of the corner column.

Figure 4: Sketch [MET00005190] produced alongside statement [MET00006339] of flat occupant that initially discovered the fire. Location marked E is that identified by occupant as area where they saw smoke.
3.3. TIMELINE OF THE KITCHEN FIRE

For the purpose of providing a time-scale for the analysis, the following two pieces of evidence bound the timeline of the kitchen fire:

00:54:29 - The 999-call reporting the presence of fire is received [MET000080589].

01:05:57 (+2mins) - The first evidence of fire having reached the cladding system is shown on a video recovered from a mobile phone [MET000083355]. A still image from this video (shown in Figure 18 in Section 4) shows molten material / debris falling from the cladding system to the left of the Flat 16 kitchen window as viewed from the outside. Prof. Bisby [5] identifies that the video appears to be two videos spliced together and thus the timestamp may not be exact. The timestamps on the filenames of these videos are likely to depend on the accuracy of the clock on the mobile phone device that was being used. A subsequent video from the same phone [MET000083356] timed at 01:08:06 filmed from approximately the same location shows the fire at a more advanced stage therefore the clip can be inferred to have been taken before this, thus between 01:05:57 and approx. 01:08:00.

An image taken by a member of the public at 01:14:53 [MET00006589] shows the fire to be well established on the outside of the cladding system, again to the left side of the Flat 16 kitchen window as viewed from the outside. This image is shown in Figure 5.
The time of the firefighters’ initial interaction with the fire and subsequent entering of the kitchen to extinguish the fire is unclear due to the discrepancy between the time-stamps on thermal imaging cameras used by the first responders. However thermal imaging camera footage of a significant quantity of burning debris / droplets falling past the window moments after the firefighters had initially entered indicates that the fire had already spread to the façade before they entered the kitchen [MET00005816].

The events stated here are also identified in the report by Prof. Nic Daeid [2]. This timeline provides an approximate bounding for any proposed mechanism for fire spread from the kitchen interior to the external façade of approximately 11.5 -13.5 minutes. It is only approximate as it does not include the time taken for activation of the alarm (assumed to be minimal given the size of the kitchen\(^{20}\)) and any delay between the occupant discovering the fire and calling 999 (again assumed to be minimal given the occupants’ statement [MET00006339]). The reports by Prof. Bisby [5] and Prof. Nic Daeid [4] compile the available information.

3.4. BOUNDING THE COMPARTMENT FIRE

Ignition of the flammable components of the cladding system requires the fire within the kitchen to be able to provide a sufficient flux of heat to any component made of combustible materials so as to bring the component to its ignition temperature. This could either be through direct flame impingement, or as a result of sustained contact with smoke and/or heat accumulated in the kitchen at a remote location from the immediate fire plume.

It is also the case with certain polymers that loss of rigidity / stiffness and melting can occur pre- or post-ignition. It is therefore possible that polymer components of the construction can fall or flow away from their original positions when exposed to elevated temperatures, potentially exposing / uncovering other flammable materials.

The following section estimates (1) the fire sizes that might have existed in the kitchen of Flat 16, (2) determines the thermal conditions that could have resulted from them (be that in the direct path of the fire plume or in the hot gas layer that forms), and (3) compares them with the ignition temperatures of the various polymer materials in the cladding system and surrounding the window frame.

3.4.1 MATERIAL PROPERTIES

Table 1 details the relevant material properties of selected polymers applicable to this analysis. These have been taken from the report by Prof. Bisby [5] as well as work from Hidalgo [15] and Ogilvie [16]. It is also of note that uPVC begins to rapidly lose its structural integrity above 60°C, losing 80% of its stiffness by 80°C and 100% of its stiffness by 90°C [17].

\(^{20}\) Smoke detectors will generally activate at the very incipient stages of a fire and therefore the time to detection is normally considered to be very small compared to typical times for fire growth. Given the type of materials present in the kitchen of Flat 16, activation would have been expected to occur when the fire was a few centimetres in diameter. This can be verified through a reconstruction of the event.
<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene (PE)</td>
<td>Ignition Temperature (piloted)</td>
<td>377°C [5], 363-415 [16]</td>
</tr>
<tr>
<td>Polyisocyanurate (PIR)</td>
<td>Ignition Temperature (piloted)</td>
<td>306-377°C [5], 377 [15]</td>
</tr>
<tr>
<td>Unplasticised Polyvinyl Chloride (uPVC)</td>
<td>Ignition Temperature (piloted)</td>
<td>318-374°C [5]</td>
</tr>
<tr>
<td>Unplasticised Polyvinyl Chloride (uPVC)</td>
<td>Melting Temperature</td>
<td>75-105°C [5]</td>
</tr>
</tbody>
</table>

**Table 1: Material properties of various polymers relevant to this section of the analysis.**

### 3.4.2 Fire Size and Compartment Temperature

When a combustible material ignites, it starts burning and producing smoke. Smoke migrates towards the ceiling accumulating at the top of the compartment. The accumulated smoke is generally referred to as a smoke layer (see Figure 6). The height of the smoke layer ("H") will increase in time because the fire will continue to produce smoke. The faster the fire grows the faster the smoke layer height and its temperature increase. There are several possible scenarios. If there are open vents (e.g. doors, windows, etc.) a portion of the smoke will exit the compartment. The loss of smoke decelerates the descent of the smoke layer but if smoke cannot flow out faster than it is produced, the smoke layer will continue to descend until it fills the compartment. It is likely that the fire will die in this case due to lack of oxygen. If the smoke leaving the compartment is the same as the smoke produced by the fire then the smoke layer will stabilize. If all the vents are closed the smoke will fill the compartment and potentially extinguish the fire due to lack of oxygen. As the smoke layer descends the smoke temperature generally increases. The increase in temperature results in heat being transferred from the smoke to the unburnt combustibles by radiation. If sufficient heat is transferred, all combustibles within the room will ignite. This phenomenon is called "flashover." The relationship between the smoke layer height and its temperature is complex and there is no guarantee that the smoke layer will reach a temperature that will result in flashover. As indicated above, in the case of Grenfell Tower, the fire in the kitchen of Flat 16 did not reach "flashover." The fact that the smoke layer did not reach temperatures that resulted in flashover provides evidence that allows for the bounding of the temperature of the smoke layer and thus the extraction of important information.

The first step of the analysis estimates the maximum size of fire, known as the Heat Release Rate (HRR) (kW), that could exist within the kitchen and that would not bring the compartment to flashover. Next, the likely smoke layer temperature range that would result from fires within the kitchen compartment is estimated. For this purpose, a simple zone model has been developed which is valid for the time it takes to fill the compartment with smoke.

For this model, all openings (doors and windows) are taken as closed. If doors and windows are open (it is known, in this case, that the windows were partially open) larger fires could have been attained.

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21 Prof. Bisby [5] indicates (lines 452-457) that smoke was emerging from the window at 1:05:36 but that multiple components of the window were damaged or ignited by then. Figure 58 of the same report shows evidence of smoke at this stage. The amount of smoke is noticeable but not very significant. Given that these first images are approximately 10 minutes into the fire (towards the end of the period being studied), it is very likely that very little smoke would have escaped through the window in the first few minutes of the fire.
before the room filled with smoke. Thus, the present values of the heat release rate should be taken as a lower bound of the heat release rate that will fill the compartment with smoke. The modelling strategy conforms with well accepted practises and provides the information necessary. While very simple in nature, the model precision is consistent with the information available. Details of the model are presented in Appendix A.

A simple way of characterizing the growth of the fire is by defining the growth rate of the heat release rate. Simple approaches classify fires as being of slow, medium, fast or ultra-fast growth. The slow and ultra-fast fires will be the extremes. These two extremes have been introduced in the model described in Appendix A and the evolution of the temperature of the smoke layer has been ascertained. The results presented in Figure 7 illustrate the bounding cases, i.e. the slow and ultrafast fires. The curves end when the smoke layer has reached the floor and further temperature increase (or fire growth) is not possible. The smoke layer temperature within the kitchen of Flat 16 would have been somewhere between these two values.

The results show that the compartment fills with smoke very rapidly in both cases, which is to be expected given the small volume of the kitchen.

The model reached a peak HRR before smoke filled the volume of the kitchen during the ultrafast fire growth of the order of 300kW. This corresponds to a hot layer temperature of approximately 220°C. At the lower bound, the slow fire growth results in a peak HRR of approximately 60kW and a hot-layer temperature of approximately 110°C. Limiting the HRR to a peak of 25kW resulted in a temperature slightly above 100°C thus this value is taken as the lower bound. These results are summarised in Table 2.

Given the relatively small fire sizes (i.e. 60-300kW), it is assumed that the available leakage via the open tilted window, and around the kitchen door and partition to the lounge will provide sufficient air supply to maintain the internal fire at these levels but probably no bigger.
Figure 7: The plot shows the estimated bounds of compartment temperature evolution during the growth phase of the kitchen fire. The fire in the kitchen of Flat 16 would have been somewhere between these two bounding growth rates.

<table>
<thead>
<tr>
<th>Property</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Heat Release Rate [Q]</td>
<td>60 kW &lt; Q &lt; 300 kW</td>
</tr>
<tr>
<td>Hot-Layer Temperature [T_g]</td>
<td>100°C &lt; T_g &lt; 220°C</td>
</tr>
<tr>
<td>Fire Growth Rate [α]</td>
<td>0.0029 &lt; α &lt; 0.1876</td>
</tr>
<tr>
<td>Fire Growth Time [t_{growth}]</td>
<td>40 s &lt; t_{growth} &lt; 138 s</td>
</tr>
</tbody>
</table>

Table 2: Bounding characteristics of the kitchen fire growth phase. The parameter “α” characterizes the fire growth rate (see Appendix A).

These values have been subsequently verified with a computation zone modelling tool CFAST\(^{22}\), the output of which correlates well with the values described here. CFAST solves the same equations as those described in Appendix A, but the added functionality of this tool enabled modelling of the scenario with an open kitchen door. The model results show that flashover could be reached if the door was open. If the door is open, then smoke will exit the kitchen allowing for the fire to continue to grow without the smoke layer reaching the floor. This results in higher temperatures and the potential for flashover. The contents of the kitchen were sufficient to deliver a heat release rate greater than 1000 kW which, the model established was the heat release rate necessary to attain flashover. This appears to confirm that the kitchen door was likely closed during this phase of the fire. A description of this modelling and details of the output are described in Appendix B. A simple assessment was made of the impact of having the window partially open. This assessment shows that the area through which the smoke could vent was too small to have an impact on smoke filling. The window was not observed to break during this stage so that scenario was not evaluated.

3.4.3 Estimation of Fire Base Area

An analysis is performed to approximate the area of the base of the fire when the fire sizes identified above (60 – 300kW) are reached. This analysis is based on the assumed fire growth rates and assumed characteristic materials. Details of the calculations are presented in Appendix C.

For the slow growth rate fire, the fire area corresponding to the maximum possible heat release rates equates to a 17 – 20cm radius circular base, or a 29 – 37cm sided square base. By means of comparison, [12] reports that a 30cm x 30cm pan fire will produce a HRR in the range of approx. 47-65 kW. This matches well with the 60kW calculated HRR and thus gives confidence in the result despite the crudity of the technique. For the ultrafast fire growth rate, the fire equates to a 40 – 50cm radius circular base, or a 68 - 87cm sided square base.

If there was sufficient ventilation to allow for a fire to grow beyond the values reported here (i.e. if there was extra supply of oxygen that would be available to the fire), the fire would have progressed to flashover. The photographic evidence shows that the fire did not progress to flashover so it can be concluded that the kitchen fire would not have been bigger than a 300 kW (40-50 cm radius) fire. The maximum distance between the fire and any combustible materials that could potentially ignite will be calculated with this value. This will establish the potential location of the initial fire.

3.4.4 Thermal Performance of the uPVC Window Surround

The uPVC window surround system is described in detail by Prof. Bisby [5]. This system covers the existing window frame and extends out to the new windows housed within the cladding system (Figure 8). As this system extends beyond the original façade to the new windows that are mounted on a system of Aluminium rails, they also span across the cavity between the window and the original façade. The uPVC components are adhered to the original window frame with adhesive [5].

Clearly, damage, removal, or poor workmanship could expose the cladding components covered by this system to a lesser or greater extent, providing a direct path for flames to impinge on the external flammable materials as highlighted by Prof. Bisby [5] and Dr Lane [4]. Thus, it is important to understand the effect that elevated temperatures resulting from the fire in the kitchen could have had on uPVC.

Section 3.3 above lists some relevant properties of uPVC. Of particular interest in this case are the melting temperature and the elastic modulus shown in Figure 9. The former, with a range of 75 – 105°C, represents the range at which the material will transition from a solid to a liquid. The latter is closely correlated to the elastic modulus and therefore is a measure of stiffness or the rigidity of the material and is thus a measure of its ability to support its own weight. The plot in Figure 9 shows that the material begins to rapidly lose stiffness around 60°C, losing 80% by 80°C and 100% by 90°C. Logically, this overlaps with the temperature range for melting. It is clear that these temperatures are well within the range expected in the compartment as per the calculations of Section 3.4.2.
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1223 (A)  (B)

1224 **FIGURE 8:** The image shows a cross-section through the window as designed [SEA00000230] with the original components shown in black and the new system in red.

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1228 **FIGURE 9:** Mechanical properties of uPVC as a function of temperature [°C]. The modulus (in blue) is related to the elastic modulus of the material. The plot indicates that the material begins to drastically lose stiffness at approx. 60°C, losing 80°C by 80°C and 100% by 90°C. Tests were conducted at the University of Edinburgh and the data was provided by Prof. Bisby.

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1231
Once the material has lost the ability to support itself, it will only be held in place at the locations where the bonding adhesive is located (Figure 10). That bonding adhesive is a material which itself will be vulnerable to heating and thus is not expected to be functional in this temperature range. Given the sparse application of the adhesive, its ability to secure the uPVC at elevated temperatures is considered negligible. While demonstrating this sequence of failure is difficult, several examples of the uPVC falling due to heating can be observed in post-event inspections (some examples are presented in Figure 11) strengthening these arguments.

Photographic evidence obtained following the fire at the Grenfell Tower has identified many instances of this type of failure as shown in Figure 11. It should be noted that these elements do not all show signs of charring implying that they did not all combust but simply lost stiffness. Typically, it is the head and jamb boards that exhibit de-bonding as this mechanism is gravity assisted for these elements.
A simple energy storage analysis is conducted to approximate the change in temperature of the uPVC as a result of exposure to the hot-layer gases (details of the analysis are presented in Appendix D), and thus establish if any thermal degradation of the material is possible within the timeframe provided by the evidence in Section 0. The results of the model are presented in Figure 12. They illustrate the range of effects that a fire, within the ranges defined by the limited evidence, could have on the uPVC.

The lower bound, defined by a slow growing fire reaching a peak HRR of 60kW and a hot-layer temperature of 100°C, brings the uPVC to a temperature of approx. 65°C within the 11.5 minute timeframe. This, as stated earlier, is slightly above the onset temperature of rapid loss of stiffness (60°C).

The upper bound, defined by an ultrafast growing fire peaking at a HRR of 300kW and a hot-layer temperature of 220°C, brings the uPVC to 150°C within the 11.5 minute timeframe, reaching the point of loss of 100% stiffness (90°C) in less than 5.5 minutes.
The minimum conditions required to bring the 9.5mm thick uPVC to a temperature of 90°C within the 11.5 minute timeframe are a fire growth rate, $\alpha$, of 0.0091kW/m$^2$ which falls between the slow (0.0029) and medium (0.0117) fire growth rates, reaching a peak HRR of 90kW and peaking at a temperature of 140°C.

From these results, it can be concluded that most fires originating from fuels typical of a domestic kitchen will have the capacity to significantly damage the uPVC. It is very likely that the loss of stiffness will result in deformations and the generation of gaps. The adhesive, as it was applied, will have no capacity to prevent this.

3.5. MECHANISMS OF IGNITION OF AN EXTERNAL FLAME

The maximum temperature of the smoke layer cannot exceed 220°C even if an ultra-fast fire is considered (Figure 12). Ignition of the combustible materials of the façade surrounding the window requires at least 306°C (Table 1). Therefore, ignition of any of the combustible facade materials by means of the smoke layer is not possible. Ignition must occur by means of direct impingement of the flame.

Different hypotheses regarding the cause and origin of the fire have been postulated and described in detail in the Phase 1 Expert Report submitted by Prof. Nic Daeid [2]. Prof. Bisby’s Phase 1 Expert Report also provides information on the different means by which the fire started [5]. This report will not expand on matters of cause and origin.
From the analysis presented so far in Sections 3.3 and 3.4 it is clear that the most significant events leading to the involvement of the façade elements in the fire would have occurred within the first 5 minutes from ignition. The reports by Prof. Nic Daeid [2] and Prof. Bisby [5] establish that with the exception of the occupant witness statement [MET00006639] there is no other information on that period. A detailed analysis of the fire scene after the event would have also been able to provide some additional information, nevertheless, this information is not presented in the available forensic reports [3]. Despite the limited information, Prof. Bisby postulates three hypotheses in his Phase 1 Expert Report [5]. These are transcribed here for clarity:

Line 575. “Hypothesis B1: The route of fire spread from inside the kitchen of Flat 16 to the external cladding was via the infill sandwich panel within which the extract fan was mounted, or via the extract fan itself, and igniting the external cladding adjacent to the kitchen window of Flat 16. This subsequently led to sustained burning of the external cladding.”

Line 579. “Hypothesis B2: The route of fire spread from inside the kitchen of Flat 16 to the external cladding was due to flame impingement from the internal fire venting from the window opening. This subsequently led to sustained burning of the external cladding.”

Line 582. “Hypothesis B3: The route of fire spread from inside the kitchen of Flat 16 to the external cladding was due to parts of the internal window surround and external cladding system being penetrated by the fire, thus allowing fire spread directly into the back of the cladding cavity from within the room of origin. This subsequently led to sustained burning of the cladding either within the cavity or on its external surface, or both.”

Hypothesis B1, as indicated by Prof. Bisby [5], is highly unlikely and very easily disproven by means of testing. Section 6.10.2.4 in Prof. Nic Daeid’s Expert Report [2] indicates that “the extractor fan associated with the kitchen window of Flat 16 can be eliminated as being within the area of origin of the fire as no physical evidence of electrical damage has been observed.” The materials present in the fan and casing (type and quantity) are too small to provide a sufficient heat flux to ignite the cladding by means of external flames [16]. A simple analysis that demonstrates this will be provided in Section 3.5.3. This analysis uses a simplified geometry and cannot be conclusive because geometrical intricacies of the assembly might affect the flame geometry and subsequently the heat flux distribution. While very unlikely, the hypothesis cannot be completely discarded with the current information, nevertheless, a test can serve to exclude this hypothesis. This should be a matter for Phase 2.

Hypothesis B2 can be split into two different cases, the first case corresponds to the gases from the smoke layer venting from the window and subsequently igniting the cladding, the second is flames close enough to the window so that they can directly vent from the window opening. The first case can be discarded on the basis that the smoke layer would have never been hot enough for the smoke venting from the window to ignite the cladding. The second scenario is a subset of Hypothesis B3 given that the window surround will be much closer to the fire than the cladding, thus would have most likely ignited first by direct impingement of flames. The following analysis will address the scenario of direct impingement. This is consistent with the conclusion of Prof. Bisby [5] who states:

Line 597. “There is insufficient evidence to fully accept Hypothesis B3 at present. However, on the balance of probabilities and the evidence presented in this section, I consider Hypothesis B3 to be the most likely, by a considerable margin, of hypotheses B1, B2, and B3.”
As stated by Prof. Bisby [5], the following sequence of events is necessary before the fire could spread into the cladding cavity.

Line 585. “(1) The uPVC window boards forming the sill, jamb, or head of the internal window framing enclosure would have to be penetrated or removed;”

Line 586. “(2) The thermal insulation applied to the back face of the uPVC window boards would have to be penetrated or removed; and”

Line 587. “(3) The EPDM rubber membrane would have to be penetrated (or not be present in that location).”

Details of all these components are presented in Sections 4.5 to 4.9 of Prof. Bisby’s Phase 1 Expert Report. Section 3.4.4 of this present report has shown that it is very likely that in the presence of the smoke layer the uPVC would have deformed establishing paths for the fire to reach any of the other components (EPDM Synthetic Rubber Membrane, PIR insulation and ACP panel). None of these components would have ignited with the temperatures attained by the smoke layer, therefore the conditions that will lead to direct impingement of flames on these materials need to be analyzed.

A series of potential scenarios for the origin of the fire were established by the Phase 1 Expert reports of Prof. Nic Daeid (Section 6.10.2) [2] and Prof. Bisby (Section 5.7.2) [5]. These scenarios require the analysis of two conditions, an open fire that could directly impinge on the materials part of the window assembly or a fire occurring behind an appliance/obstacle, where the flame will have to migrate to the ceiling before travelling towards the window assembly. Figure 13 shows a schematic of the two conditions.

**Figure 13:** Schematic of the two conditions to be analyzed, direct impingement over a distance “z” or fire behind an appliance/obstacle where the flames have to first reach the ceiling and then progress towards the target following a path “H + r.”

The following sections will use very simple analysis methods. These methods are not necessarily very precise or strictly valid for the conditions of the Grenfell Tower fire, nevertheless the results serve to provide a clear idea of scenarios that can be discarded. If more precise methodologies become necessary, these will be used as part of subsequent reports.
3.5.1 Ignition by Direct Impingement

This part of the analysis aims to determine what are the necessary conditions where direct flame impingement could result in ignition. This is depicted by the diagram in Figure 14. A plot created by McCaffrey [18], reproduced in Figure 15, is used to establish the characteristics of the fire in the kitchen that could lead to ignition of various flammable components. The ignition temperatures of each component material are used to define the value of $\Delta T = T_g - T_a$ ($T_g$ is the ignition temperature and $T_a$ the ambient temperature). “$z$” is defined as the height above the base of the fire (m) at which the flame or plume comes into direct contact with the flammable material. Using these two values and the plot in Figure 15, $\dot{Q}_c$, the convective portion of the heat release rate, can be established. The total HRR, $\dot{Q}$, is then established from the following relationship [20]

$$\dot{Q}_c = \frac{\dot{Q}}{1.5}$$

**Equation 1**

**Figure 14**: The diagram illustrates the window and cladding system as constructed at the time of the fire. It illustrates the concept of flame and plume impingement on the flammable materials around the window cavity.
Using the example of Hypothesis B3 depicted in Figure 14, the ignition temperature of the Polyethylene in the ACP panel is given in Table 1 as 377°C, thus $\Delta T = T_{ig} - T_a = 362°C$. Using the plot in Figure 15, this equates to a value of $\left( \frac{x}{Q_c^{2/5}} \right) = 0.18$ where $\eta = 1$ and is located in the intermittent plume. The distance “$z$” is approx. 2.3m (point a to point b in Figure 14), thus solving for $Q_c$, and subsequently for $Q$, gives a required HRR of 875kW to ignite the ACP panel above the window (point b) from direct flame / plume impingement from a fire within the kitchen at floor level, immediately beneath the window (point a). This method is reproduced for the three relevant ignitable materials, for the range of relevant heights i.e. top to bottom of the window cavity. Table 3 summarises the results from this analysis.

There are two columns of results presented in Table 3. The ‘Smallest Fire’ column represents the smallest fire located, at floor level, necessary to cause an ignition of the given material at the given location. For example, the uPVC window surround can theoretically be ignited at the sill level by a 20kW fire, however would need a 120 kW fire to ignite it level with the top of the window. Heights in between would require a fire size, at this location, between these two bounding values. The PIR insulation shows similar requirements in terms of fire size. For means of illustration, Figure 16 shows two buoyant flames, the smaller $\approx 25$ kW and the large $\approx 75$ kW.
The second group of results labelled ‘max distance’, represents the maximum horizontal distance that the largest possible fire (300 kW) could be from the base of the wall beneath the window, in order to result in an ignition via direct impingement. This assumes a tilted plume forming a straight line between the base of the fire and the ignition location.

<table>
<thead>
<tr>
<th>Material</th>
<th>Window Location</th>
<th>Smallest Fire [kW]</th>
<th>Max Distance [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>uPVC</td>
<td>Top</td>
<td>120</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>20</td>
<td>3.1</td>
</tr>
<tr>
<td>Polyethylene (ACP)</td>
<td>Top</td>
<td>830</td>
<td>No Ignition</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>125</td>
<td>1.2</td>
</tr>
<tr>
<td>Insulation (PIR)</td>
<td>Top</td>
<td>110</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>20</td>
<td>3.2</td>
</tr>
</tbody>
</table>

**Table 3: Results from the McCaffrey Plot. Shows both the smallest fire that could ignite the material at a specified location and the furthest a fire could be to ignite a material without reaching flashover.**

**Figure 16:** Two buoyant flames, the left approx. 25 kW and the right approx. 75 kW, from [HTTPS://WWW.YOUTUBE.COM/WATCH?v=7B9-bZCCUXU](https://www.youtube.com/watch?v=7B9-bZCCUXU).

Table 3 indicates that a fire located at ground level of 300 kW of less, could not provide the required ΔT to cause ignition of the ACP directly above the window. The base of a 300kW fire would have to be within 1.5 m (direct line) of the ACP outside the window to be capable of causing direct ignition via flame / plume impingement. A fire at floor level, even directly beneath the window, would need to be...
of the order of 830kW to ignite the ACP through the window. A fire of this size, with the compartment ventilation as it was, would have brought the compartment to flashover, thus is not consistent with the evidence.

3.5.2 FIRES BEHIND AN OBSTACLE

If the plume originating from a fire at floor level is obstructed by appliances and unable to directly impinge on the flammable materials around the window (Figure 13), impingement must occur indirectly. The flames must migrate first towards the ceiling and then travel horizontally as a ceiling jet until reaching a combustible component. This scenario corresponds to the fire suggested as having its origin in the Hotpoint FF1758P.

A correlation by Alpert [22] that describes the decay in temperature of the smoke products as they travel horizontally across the ceiling is used to determine the Heat Release Rate (HRR) required from an obscured fire to ignite PIR and uPVC materials at ceiling height, as a function of distance from the window of a ground level fire. The temperature of the ceiling jet, $T_{\text{max}}$ [°C], in the area where the plume impinges on the ceiling is given by Alpert as:

$$T_{\text{max}} = T_{\infty} + \frac{16.9Q_c^{2/3}}{H^{5/3}}$$

EQUATION 2

Where $T_{\infty}$ [°C] is the ambient temperature, $Q_c$ [kW] is the convective portion of the heat release rate, and $H$ [m] is the height of the room. The radius of impingement $r$ [m] is defined as 0.18H. Outside of this radius, the temperature of the ceiling jet is defined as:

$$T_{\text{max}} = T_{\infty} + \frac{5.38 (Q_c/r)^{2/3}}{H}$$

EQUATION 3

The lower bound of the range of ignition temperatures of PIR (insulation) and uPVC (window surround) is approx. 305°C. The blue line in Figure 17 shows the HRR required to produce a ceiling jet temperature above 305°C at the top of the window if the fire is at floor level. The horizontal axis shows the distance between the fire and the external wall. In all cases, the required HRR is of sufficient magnitude that the fire would be expected to result in flashover. This implies that only direct, unimpeded flame / plume impingement would result in ignition of these materials at the upper window level.

A fire that starts at the floor level and finds combustible materials to spread vertically can eventually produce temperatures that could ignite ceiling covers (i.e. PURBoard (Section 4.2.3 [5]: Line 312: “a band approximately 350 mm wide on the ceiling around the entire exterior perimeter of all intact and partially intact flats”)) or potentially find its way to the window. Proof of the viability of any scenario of this nature will require the testing of the fire source with the potential source of ignition. These tests should be carefully instrumented to quantify all relevant variables and should be undertaken as part of a Phase 2 analysis.
The orange line in Figure 17 indicates the HRR required to attain a temperature of 90°C impinging on the window. This corresponds to the temperature at which the uPVC will lose its structural integrity. The plot indicates that the initial ceiling jet of a fire less than 300kW in size, at floor level up to 1m away from the window, could result in smoke impingement on the uPVC at 90°C.

**Figure 17:** The plot shows: Blue line - the HRR [kW] required to produce a ceiling jet with sufficient temperature to ignite PIR and uPVC components at the top of the window, as a function of the distance [m] of the originating fire from the window at floor level. Orange line - the HRR [kW] required to produce a ceiling jet with sufficient temperature to cause the uPVC to lose 100% of its structural integrity [90°C].

### 3.5.3 The Fan and Fan Mounting Unit as an Ignition Source of the ACP

In the same video that indicates the first instance of spread to the cladding [MET000083355], flames are visible in or around the location of the fan and its mounting panel. This is shown in detail by Prof. Bisby [5] and leads to Hypothesis B1. It is not clear from the video footage if it is the fan and/or the fan mounting panel that are alight, or if it is a flame emerging from the window beneath the mounting panel. Prof. Bisby indicates that the source of the flame is initially located at the base of the mounting panel, thus for this to be the ignition source of the ACP panels, the flame either had to originate in the compartment or, by some means of exposure due to failure of the window system, originate from the base of the fan mounting panel. The former has been addressed in Section 3.5 The latter is addressed here. The report by Dr Lane [4] gives dimensions of the fan mounting panel as approx. 0.5 x 0.5 m, with a 1.5 mm aluminium skin either side of a 25mm thick PIR core.

Assuming the underside of the fan mounting is burning, the methodology described in Appendix C is used to establish an upper bound heat release rate of approximately 5 kW. Using the plot by McCaffrey ...
in Figure 15, the flame and plume resulting from this fire would have a temperature above the ignition temperature of any of the combustible materials for less than 30cm from its base. This means that the temperature in the plume issued from a fire at the base of the mounting panel could have not ignited the ACP panel or any of the combustible materials present in the façade system.

3.6. RELEVANT ACTIVE AND PASSIVE FIRE SAFETY SYSTEMS

As indicated in Table A [4], the following items would have been relevant to preventing a typical residential kitchen fire from impacting the building beyond Flat 16:

- The loadbearing elements of structure of the building are capable of withstanding the effects of fire for an appropriate period without loss of stability; Structural Stability - Temperatures between 100 - 220°C will pose no challenge to any of the structural systems. Therefore, the structure can be deemed to be sound.
- The building is sub-divided by elements of fire resisting construction into compartments; Compartmentalization – Only the south facing wall of the kitchen serves as boundary to a different unit, thus is required to provide compartmentalization. Temperatures between 100 - 220°C will pose no challenge to this wall. The walls facing outwards are not required to maintain compartmentalization (Line 3.4.2 [4]), thus window system and glazing are not included in this requirement. Therefore, compartmentalization is maintained.
- Any openings in fire separating elements are suitably protected in order to maintain the integrity of the element (i.e. continuity of fire separation); Fire stopping – This requirement only pertains to the south facing wall of the kitchen and there is no evidence that there was any fire stopping on this wall.
- Any hidden voids in the construction are sealed and sub-divided to inhibit the unseen spread of fire and products of combustion, in order to reduce the risk of structural failure and the spread of fire, insofar as they pose a threat to the safety of people in and around the building; Cavity barriers – Given that the uPVC window surround acted as a barrier between the façade system cavities and the compartment, these should have inhibited the spread of fire and products of combustion. Given the low temperatures that will breach this barrier (less than 90°C), any fire common to a residential kitchen would have resulted in failure of the intended barrier in a few minutes (less than 12 min for Grenfell Tower).

3.7. SUMMARY

- The photographic evidence indicates that this fire never reached flashover [2,3].
- Analysis based on the geometry of the compartment and the known ventilation conditions (door and window closed) establishes that a fire would have reached a steady temperature between 100°C-220°C. These temperatures are below those capable of inducing flashover. These temperatures are not capable of igniting any of the combustible components adjacent to the window.
- If the door and main window were to provide a means for smoke to exit the kitchen, a fire in excess of 300 kW would have brought the room to flashover. This indicates that it is most likely
that the door to the kitchen (as well as the partition) must have been closed for most of the initial stages of the fire.

- The fire that occurred in the kitchen of Flat 16 of the Grenfell Tower would have not exceeded 300 kW and a lower bound approximation for the temperatures of the smoke would have been between 100°C-220°C.

- Heating of the uPVC by smoke between 140°C - 220°C would have resulted in the uPVC reaching temperatures that led to total loss of its mechanical strength in a period between approx. 5 - 11.5 min.

- A fire of characteristics common to any residential kitchen fire would have therefore resulted in the loss of strength of the uPVC surrounding the window. This would have happened within a period consistent with the time gap between the first observation of the fire and the first evidence of involving external to the building (11.5 - 13.5 min) [2].

- The dimensions of the kitchen are sufficiently small that the location of the fire is irrelevant when it comes to breaching the uPVC by loss of mechanical strength. This failure can be deemed as a failure of the barrier to protect the cavity.

- The uPVC served as the single barrier between the interior of the building and the components of the cladding system. Thus, after breaching the uPVC barrier, any of those components would have been exposed.

- Given the low temperatures of the smoke, ignition of the combustible components adjacent to the window requires direct flame impingement.

- Given that flashover was not observed, the maximum fire size that will not result in flashover was used to determine how far from the window this fire could be. A fire of 300 kW will have to be at the most 3m way from the window to ignite any of the combustible materials adjacent to the window.

- Therefore, as an upper bound, a fire of characteristics common to a kitchen fire and that will not lead to flashover (less than 300 kW), if placed within 3 m of the window, is capable of triggering external flame spread.

- As a lower bound, a fire at floor level directly beneath the window, greater than 20kW, is capable of igniting exposed flammable materials (PIR, uPVC) at window sill level via flame/plume impingement, thus potentially leading to ignition of external cladding and external fire propagation.

- Flames from fires behind an obstacle will have much longer paths, therefore will require larger fires in order to cause direct ignition of combustible materials within the cladding system. Given the narrow window, it is probable that any obstructed fire capable of igniting any of the window materials will have to be of such a magnitude that it would have led to flashover.

- An obstructed fire that finds combustible materials to spread upwards cannot be discarded as a potential source of ignition of the combustible materials that make up the cladding system.

- The extent of burning as a result of secondary ignition of the fan / fan mounting unit is not sufficient to induce ignition of the ACP panels as a result of plume impingement.

- Evidence of initial dripping and external flame development point to ignition of the cladding to the left side of the kitchen window as viewed from the outside.

- Temperatures between 100°C - 220°C will pose no challenge to any components of the structure. Therefore, the structure can be deemed to be sound. Furthermore, a fire of this nature would have not been perceived by occupants or firefighters as a challenge to structural stability.
Structural stability is essential to enable egress and firefighting operations. The perception that the structure might be compromised could also affect decision making.

- The size of the fire that breaches the uPVC and the size of the fire that will ignite the exposed combustible materials of the façade system are within a range that can be considered as a feasible event within a residential kitchen. Many activities and appliances could serve as sources of ignition and can experience a fire consistent with the values reported here (less than 300 kW). The probability of such an event can therefore be considered one.

- Given that the initial fire event cannot be considered unusual in any way, determination of the cause and origin of the fire is therefore of secondary relevance to the definition of the development of the fire after ignition of the façade system.
4 STAGE TWO: VERTICAL FIRE SPREAD

4.1. VERTICAL FIRE SPREAD AT GRENFELL TOWER

Once the fire enters the façade system it initiates its spread outwards and then upwards. The first image where flaming debris and smoke is observed emerging outside the compartment is presented in [2] and timed stamped at 01:05:57 (see Figure 18 from [2]). By 01:14 the fire is visibly established on the outside the building (Figure 19) and has compromised many components of the façade system and by 01:26 it has propagated upwards past floor 18 (see Figure 20 from [4]). The fire appears to reach the architectural crown of the building before 01:30. During the process of vertical flame spread the fire does not propagate in the south direction (contained by the column) but it does spread laterally towards the North/East corner. It is evident that vertical flame spread is much faster than horizontal flame spread. Much more detailed recounts of the process are provided by Dr Lane and Prof. Bisby’s Phase One expert reports [4, 5].
4.2. VERTICAL FIRE SPREAD OVER ACP PANELS

Flame spread is controlled by the transfer of heat from the flame to the combustible material. This is a complex process, in particular for products such as Aluminium Composite Panels where spread requires breaching non-combustible layers such as aluminium. The literature on the physics of flame spread provides extensive data characterizing vertical and lateral flame spread which shows that vertical flame spread rates are generally at least ten times faster than lateral flame spread rates [23]. Furthermore, the bigger the burning zone, the faster the rate of spread of a vertical flame i.e. upward flame spread self-accelerates. In contrast, lateral spread does not accelerate unless external heat is provided. Most data on flame spread is associated to combustible materials with not much data available on composite systems such as Aluminium Composite Panels (ACP). There are few studies on this matter, with the most specific being that of Ogilvie [16]. Ogilvie confirms that vertical flame spread rates are more than three times the rates of lateral flame spread.
The most comprehensive review of external fires was produced by the NFPA [13]. This document describes briefly a significant number of fires occurring prior to 2014 but unfortunately provides very few details of each event. An independent review of international events involving external fires was conducted for the purpose of this report. This review shows that the most common scenario is that of a flame rapidly spreading upwards with very limited lateral flame spread. Figure 21 shows three examples, the Torch Building in Dubai, the Lacrosse Building in Melbourne and the Address Building in Dubai. With the exception of the Lacrosse fire, where a report was made public, there is not much reliable data on the characteristics of these events. Nevertheless, the available footage clearly shows that once the fire has spread to the top, it proceeds to decay and eventually extinguish. There are many reasons why this could happen. The main one is that the amount of fuel per unit area is small so the local duration of the fire is limited to a few minutes.

In most of these cases lateral flame spread was limited. This is to be expected because the amount of energy necessary to spread a flame (critical heat flux for ignition) over an ACP panel is significant. Common materials will not exceed a critical heat flux for ignition of 15 kW/m² [24], while ACP panels can commonly reach values as high as 18 kW/m² [16]. Lateral spread is controlled by radiative heat transfer from the flame to the unburnt material, with convection cooling the same area of material, thus the net heat flux provided by the flame is the difference between the two. Heating areas are very small because convective flows carry heat from the material towards the flame, limiting the preheating area (Figure 22 (a)). In contrast, in vertical flame spread, convection and conduction both heat the material, so not only is the heat flux to the unburned surface greater (the sum of the two), but it also heats a larger area. The larger the flame the larger the heated area and therefore the faster the spread (Figure 22 (b)). Therefore, as time progresses, vertical flame spread accelerates while lateral flame spread tends to have a constant velocity.

Literature review on past fire events in high-rise buildings involving vertical flame spread via external cladding shows a very similar behaviour in most cases. This literature includes official reports, media, video footage, and industry and academic papers. Quantified rates of vertical flame spread based on available evidence were developed and are presented in Figure 23. As can be seen from Figure 23, vertical flame spread for Grenfell Tower is among the lowest reported. Fire spread rates range from less than 1 m/min to approximately 20 m/min.
Figure 21: Examples of vertical fire propagation where there was minor horizontal fire spread.
Figure 22: Schematics of lateral and vertical flame spread. (a) Shows a flame spreading only upwards and covering the entire width of a material. The area in green (burning region) produces fuel and it degrade in-depth (black area). The fuel feeds the flame that is longer than the burning area. Therefore, there is an area that is to be heated (Heated Region). Given that the flow and the flame spread are going in the same direction, the amount of heat landing in the heated region is large and the size of the heated region is large. The result is robust and fast flame spread vertically. (b) Shows the case where the flame does not cover the entire with of the material (green), in this case it can continue to spread vertically as per figure (a) nevertheless it can also spread horizontally. Horizontal flame spread will not be in the same direction of the flow, so most of the heat will be carried upwards, therefore the amount of heat reaching the heated region is very small. The horizontal projection of the flame is almost of the same size as the burning region therefore the heated region itself is very small. The result is that horizontal flame spread will be weak and slow.

The Grenfell Tower cladding system was composed of multiple components, these are described in detail in [4] and [5] so they will not be described here. This system included multiple combustible materials (ex. Polyisocyanurate insulation (PIR), polyethylene infill for the ACP panels, EPDM Synthetic Rubber Membrane, etc.). All these materials would have sustained combustion. The polyethylene infill was placed between two aluminium plates that will melt in the range 580 - 650°C. Thus, in the presence of a significant flame the aluminium would have represented no protection to the polyethylene. Flames are typically between 600°C-800°C, thus are hotter than the melting
temperature of aluminium. Furthermore, polyethylene is a thermoplastic, thus will melt and drip. This can happen before or after ignition. In the case of polyisocyanurate, this material is low density closed pore insulation that will not melt. Instead it will char and stay in place. Polyisocyanurate has been studied in detail by Hidalgo et al [25]. Polyisocyanurate foams when heated and releases very little heat per unit area (less than 60 kW/m²). In the absence of any external heating it will generally extinguish leaving approximately 60% of its mass as residue. When heated by more than 40 kW/m² it will generally be consumed fully [25].

Figure 23: External flame spread rates for past fire events, compared to Grenfell Tower. Not included in this plot is a residential building fire in Baku, Azerbaijan in 2015, which had an unexplained rate of flame spread of ~110 m / min. This figure present average values for comparison purposes, nevertheless it is recognized (as indicated above) that the fire spread rate will accelerate. Values for Grenfell Tower and Address Downtown Dubai Hotel show consistency with those reported in (Figure 97 [5]).

Figure 24 shows the different levels of damage of the cladding system. In the bottom and bottom right corner, sectors of the cladding appear undamaged, with the aluminium plates intact. Other sectors towards the middle of the photograph show the melted aluminium with the fully consumed insulation (centre of the image). Other sectors show the charred insulation which indicates that heat fluxes were not sufficiently high to consume the char. Finally, other sectors show the distinctive yellow colour of
the unburnt PIR. The infill is extracted from Hidalgo et al [25] for illustration. This shows a sample exposed to 25 kW/m² for a period of 22.5 minutes. The range of conditions observed from a single image (In Figure 24) demonstrates that the heat exposure was not homogeneous, with areas of intense local heating and areas of mild heating. These same observations can be seen in multiple locations on the building after the fire.


It is less common for fires to spread laterally. In most cases, once the fire has reached the upper parts of the building, the lower areas are progressing towards extinction because most of the fuel has been either consumed or melted and dropped downwards. It is common to see burning debris descend but the debris is generally localized within the area of the fire.

FIGURE 25: SULAVA TOWER (DUBAI) DURING THE FIRE. LATERAL PROPAGATION EXTENDED TO ALMOST HALF OF THE BUILDING.

There are a few exceptions where the fire has propagated laterally fully or partially involving the building (Figure 25). There is very limited information about the construction details of any of these buildings, therefore it is not possible to establish what enabled the horizontal flame spread.
4.3. CONTROLLING MECHANISMS OF FLAME SPREAD

Vertical flame spread over combustible materials has been studied for decades [26] and the mechanisms controlling the different modes of flame spread have been described in great detail. The effect of flow velocity, external heat fluxes, material properties, etc. have been analysed extensively. Adequate models for simple scenarios such as vertical spread or lateral spread over a flat plate have also been studied. Less attention has been given to the spread of flames within cavities [12]. Nevertheless, it has been found that the width of the cavity (“W” in Figure 26) plays a fundamental role in the rate of flame spread. At the extremes, if “W” is large, radiative feedback and buoyantly driven chimney effects disappear with flames spreading at similar rates, as in the case of an exposed surface. Conversely, if “W” is very small, thermal expansion of the gases block the flow and the flames cease to spread internally remaining outside the gap. This information provides valuable insight and can potentially be used to explain some of the visual observations of the fire spread process during the Grenfell Tower fire [4, 5]. Accelerated spread can be explained by the presence of open vertical channels, inducing chimney effects associated to their width (“W”) and also by preferential burning of polyethylene over PIR insulation, based on their material properties. Nevertheless, the adequacy of these interpretations is limited to very simple scenarios and requires caution.

**Figure 26: Processes Controlling Flame Spread.**

It is often the case that when construction systems are developed, little attention is given to the extreme complexity introduced. Figure 26 shows a very simplified schematic of the different processes
occurring during the spread of a flame within a simplified version of the system used in Grenfell Tower.

In a system of such complexity, many other processes are introduced beyond simple effects such as the role of “W” (i.e. the cavity width). The low melting temperature and high thermal conductivity of aluminium results in complex heat transfer from external flames into the infill. Furthermore, melting of the aluminium is possible, so the loss of protection needs to be accounted for. The polyethylene infill will also melt at low temperatures, while the temperature gradients between the inside and the outside will result in differential deformations of the plates. This can lead to splitting of the plates and exposure of the polyethylene [16]. Inside the cavity, the PIR will pyrolyze, char, burn but also potentially burn-out. The PIR has a very low thermal inertia [5] which favours a fast flame spread rate, nevertheless its charring potential results in small fuel production and therefore short flame lengths.

Charring, therefore, has a detrimental effect on flame spread. The outcome of these two competing effects is determined by the radiative feedback from the ACP, thus the way the ACP burns defines the way the PIR will spread a flame. Furthermore, the way the PIR burns will then affect the rate at which the ACP will degrade, melt and burn. Faster degradation induces further melting and thus might reduce spread rates but increase the rate at which molten debris falls. The interactions between the two materials are therefore difficult to uncouple.

These are only a few of the complexities introduced in these systems. When the systems are applied in construction, a multiplicity of other complexities are introduced (cavity barriers, complex geometries, other materials, intumescent sealants, etc.). The level of complexity is such that a very careful analysis is necessary to establish the fire performance of such a system. A comprehensive treatment of all complexities is beyond the objectives of this section, nevertheless, some of these complexities are introduced to highlight the need for a different form of thinking.

Tests such as BS 8414 [27] provide a single scenario deemed consistent with an external fire, a very limited number of measurements and a very simple failure criterion. The combination of these three characteristics does not provide a sufficiently comprehensive assessment of performance. Many details can be hidden within the results of the test and therefore great caution needs to be exercised when interpreting such tests. In particular, it is essential to recognize the limitations of the failure criteria and the complexities associated to its extrapolation to real systems.

Observation of the images associated with the Grenfell Tower fire can establish patterns of behaviour specific to this incident. These patterns of behaviour are a combination of multiple processes interacting with each other (Figure 26 and many more) and leading to specific observations. These observations are by no means universal, they are intimately associated with the conditions of the building and this specific event, and should only be extrapolated with great care.

A critical aspect that is missed by BS 8414 [27] and observations is the burn-out of the insulation material. As explained in previous sections, the residual PIR has different levels of degradation, thus it burns-out at different stages as a function of the heat flux that is fed back to the material. All other components of the cladding either melt or have a small mass per unit area, thus their burning time is very short. The insulation has the potential to burn for a much longer time period. The duration of localized burning will be critical when defining the capacity of these fire to break back into the building. Observations focus on visible flames, but these can over emphasize the burning of the rain-screen. The fire source, the focus on flame spread and duration of the test in BS 8414 [27] all mask the role of the insulation and over emphasize the role of the rain-screen. None address the burn-out times and their role on sustaining localized burning.
It is important to emphasize that a significant reason for the numerous external fires that have occurred in the last few years is the incapacity of these traditional approaches to establish the performance of these complex systems (assessments and/or tests). The information that can be extracted from current tests and observations of events is very limited. This information is of a quantity and quality which is inconsistent with the complexity of the systems. If these performance assessment methodologies are to be used, then the façade systems need to be drastically simplified. If systems of this complexity are to remain, so as to fulfil other functions, then a more comprehensive methodology of testing and a very different approach to performance assessment needs to be implemented.

As indicated in Dr Lane’s Phase One Expert Report [4] in section 2.29.2 and 2.29.3, the introduction of these complex façade systems results in “complex and confusing” National and European reaction to fire tests. This results from the inadequate use and adaptation of tests that were never intended to define what “adequate” flame spread should be. While all these tests provide valuable information, this information requires interpretation beyond what can be issued by means of guidance. Appendix F (Section 1.1) of Dr Lane’s report [4] illustrates the resulting complexity of the different accepted testing regimes. It is important to note that the testing options are so extensive that materials well known to challenge the concept of “adequate” flame spread can find a path to be routinely used in high rise buildings.

There is fear that a comprehensive testing methodology will be impractical and expensive and that simple failure criteria with standardized tests is the most practical approach to performance assessment. In my view, this is an incorrect way of thinking. A comprehensive methodology establishes the specific processes that matter, provides the information that is necessary and allows for establishing the robustness of the system. Gathering this information might only require simple and fast experimentation. What will be unavoidable is a comprehensive analysis that can only be conducted by a highly proficient professional.

No detailed differentiation of the mechanisms controlling flame spread will be proposed here. A detailed analysis of BS 8414 [27] to establish is value and limitations is proposed for Phase Two. The development of a testing protocol that will allow for comprehensively determining the influence that each material, components and geometry had on the spread of fire on the Grenfell Tower will also be a fundamental aspect of Phase Two. It is my firm view that only on the basis of this new approach can recommendations for future designs be made.

4.4. EFFECT ON TENABILITY AND STRUCTURAL STABILITY

At the time of writing, available evidence and expert reports point to at least three internal fires igniting as a result of the initial vertical propagation, within the timeframe of Stage 2. These fires occurred on the 5th, 12th and 22nd floor, in flats directly above the flat of fire origin, and were ignited at approx. 01:18, 01:24, and 01:28 respectively. This fire re-entry is discussed in detail in the following section (Section 5).

Towards the end of Stage 2, calls to emergency services rapidly began to increase reporting inability of residents to evacuate their flats due to smoke build-up in communal lobbies, both on and around
the floors with known fires. This indicates a rapid failure of horizontal and potentially also vertical compartmentalization within the tower.

While tenability was beginning to be compromised locally, this time period (01:15 – 01:30) falls within the period of peak egress rate of occupants from the tower according to Table D in Dr Lane’s Phase 1 Expert Report [4], indicating that the egress stair was still passable and smoke propagation was confined to communal lobbies.

4.5. COMPLIANCE ISSUES AFFECTING THE CHARACTERISTICS OF STAGE TWO

The main issue of compliance stems from Section 12 of ADB and Appendix A of ADB (covered in Section F1.1.5 [4]) where it is stated at paragraph 1:

“In such cases the material, product or structure should:

a. Be in accordance with a specification or design which has been shown by test to be capable of meeting that performance; or

   Note: For this purpose, laboratories accredited by the United Kingdom Accreditation Service (UKAS) for conducting the relevant tests would be expected to have the necessary expertise.

b. have been assessed from test evidence against appropriate standards, or by using relevant designs guides, as meeting that performance; or

   Note: For this purpose, laboratories accredited by UKAS for conducting the relevant tests and suitably qualified fire safety engineers might be expected to have the necessary expertise.

For materials/products where European standards or approvals are not yet available and for a transition period after they become available, British standards may continue to be used. Any body notified to the UK Government by the Government of another member state of the European Union as capable of assessing such materials/products against the relevant British standards may also be expected to have the necessary expertise. Where European material/products standards or approvals are available, any body notified to the European Commission as competent to assess such materials or products against the relevant European standards or technical approval can be considered to have the appropriate expertise.

c. where tables of notional performance are included in this document, conform with an appropriate specification given in these tables; or ...

As the above extract from Appendix A of ADB indicates, there are three clear paths towards acceptance of a material or product; in section (a) performance is established “by test,” in section (b) performance is established by “test evidence” against “appropriate standards” or “design guides” and in section (c) by means of tables of notional performance.

The performance criteria specified in Section 12.5 (ADB) [11] states: “The external walls of the building shall adequately resist the spread of fire over the walls and from one building to another.” As explained in Sections 2.3 and 2.4 of this report, for a building like Grenfell Tower the criteria of “adequately resist” is intimately linked to the fire safety strategy, thus a material or product to be used needs to be analysed in conjunction with the fire safety strategy and the building itself. Analysis of the material separate to the building will not guarantee the performance of the fire safety strategy. This invalidates paths (a) and (c) because both paths focus on the material/product and do not include
statements about the design. Path (b) requires performance assessment “from test evidence against appropriate standards, or by using relevant designs guides” and as such remains as the single performance assessment route. Test evidence is to be provided by “laboratories accredited by UKAS for conducting the relevant tests” and used as evidence by “suitably qualified fire safety engineers” who “might be expected to have the necessary expertise.”

Path (b) is not explicit on what are the “relevant design guides,” furthermore when it comes to competence the vague terms “suitably” and “might” are used. Given that this is the only path to compliance, this performance assessment is of critical importance to the integrity of the fire safety strategy, and given that the consequences of inadequate performance are enormous; it is not acceptable to treat the problem in this manner. As indicated in Section 4.3 this matter is of a level of complexity that is not suitable for design guidelines, and instead requires a competent designer. A competent designer has to be properly qualified and assessed and it is not acceptable to treat competence in such a vague manner on a matter of such importance to safety. To my knowledge, a clear definition of necessary competence is currently not available and therefore this is a matter of critical importance that needs to be explored in Phase Two.

4.6. UNDERSTANDING THE RELATIONSHIP BETWEEN COMPLIANCE, PERFORMANCE AND QUALITY

The concepts of compliance, performance and quality should be related. One potential path to guarantee adequate performance and adequate quality should be compliance with existing building regulations and guidance. Other mechanisms, such as explicit performance assessment, are not excluded in Building Regulations (Section: Use of Guidance – The Approved Documents, paragraph 3 (ADB)).

In a system where compliance is the means of establishing adequate performance and adequate quality, it is necessary to introduce a process of approval. An approvals process seeks to evaluate compliance by establishing that the performance and quality criteria defined by Building Regulations and guidance are “complied” with. Approval will therefore, indirectly, establish adequate performance and adequate quality.

It is important to note that quality is only mentioned in ADB in matters pertaining to detection systems (Section 1.23, Section 1.37 and Appendix E (ADB)). In matters pertaining to functional requirement B4, only performance is discussed and it is defined as a function of criteria specified by means of standard tests (e.g. BS 476 Parts 4, 6, 7, 11, etc.), other guidance documents (BR 135), Council Directives (e.g. Council Directive 89/106/EEC, etc.), European Standards, etc. These criteria shall be used within the context of the three possible paths defined in Section 12 of ADB which are presented in the previous section.

In the case of the Grenfell Tower façade systems, it was established that path (b), which requires performance assessment “from test evidence against appropriate standards, or by using relevant designs guides” is the single path to compliance (Section 12 of ADB). Dr Lane in her Phase One expert report [4] states that: “2.29.21 I have concluded in Appendix D that the legal requirement is to demonstrate compliance with the functional requirement of the Building regulations 2010.” In the
case of the façade system this is functional requirement B4. (1) “adequately resist the spread of fire” (ADB).

Section 4.3 of this report describes the complexity of these façade systems and concludes that these systems are of such complexity that the direct results from any of the relevant tests are not sufficient. This is consistent with path (b) as specified by ADB and therefore this is the only path to compliance.

The relevant standard testing methodologies are discussed in detail in Appendix F of Dr. Lane’s Phase One expert report [4]. Those of direct relevance are BS 476 (parts 4, 6, 7 and 11). These methods address combustibility (part 4), fire propagation (part 6), surface flame of spread (part 7) and heat emission (part 11). All variables are of great relevance to the spread of a fire over a façade system of this nature even if they are not required by ADB (Table A7).

When following “path (b)” (ADB), “evidence” from these or other tests is to be used by “suitably qualified fire safety engineers” to establish if the performance of the system meets the functionality requirement B4. (1). The physical relationships that govern the spread of flame over façade systems of this nature are of extreme complexity (Section 4.3 of this report). In contrast, the tests are very simple, perform very basic measurements and none of them, by itself, incorporates all relevant features. Thus, the competency of the qualified fire safety engineer is of paramount importance. Any approval process attempting to establish “compliance” should therefore have focused on the performance analysis presented by a qualified fire safety engineer and on the qualifications of such a professional.

Instead, in Dr. Lane’s Phase One expert report (Section 2) [4] it is stated:

“2.19.2 I have found no evidence yet that any member of the design team or the construction team ascertained the fire performance of the rainscreen cladding system materials, nor understood how the assembly performed in fire. I have found no evidence that Building control were either informed or understood how the assembly would perform in a fire. Further, I have found no evidence that the TMO risk assessment recorded the performance of the rainscreen cladding system, nor have I found evidence that the LFB risk assessment recorded the fire performance of the rainscreen cladding system. I await further evidence on these matters, which I will explore in my Phase 2 report.”

Furthermore, and as an example, Appendix E of Dr. Lane’s report [4] discusses the available testing evidence on relevant Celotex products. Here, she provides assessments of non-compliance (e.g. Table E.2) and concludes:

“E2.3.4 I therefore conclude from my comparison that there are multiple significant differences between the rainscreen system tested in BS 8414-2:205 Test on Celotex RS500 insulated system with a ventilated Eternit Rainscreen produced by BRE Global on 01/08/2014, when compared with as built Grenfell Tower construction.

E2.3.5 The most significant discrepancies are: ...

... E2.3.6 This test report therefore does not certify the as built Grenfell façade construction as compliant with ADB 2013, nor do I consider it to demonstrate compliance with the functional requirement B4 of the Building Regulations.”
Dr. Lane presents further examples where other discrepancies between reported tests and the as built Grenfell façade system were observed leading to the same conclusions. These are described in detail in Appendix E [4].

In my opinion, Dr. Lane’s conclusions [4] are correct. In the complete absence of an analysis of the test evidence, any differences between the as built and the tested systems will result in direct failure to comply. Furthermore, any tests that are not exactly those required by ADB, cannot be used for compliance purposes.

Nevertheless, of even greater importance is the fact that, even if the tested system was identical to the as built system, the tests conducted were exactly those required by the guidance, and that all failure criteria for the tests were met, the Grenfell Tower façade system could have not been deemed compliant without a detailed performance analysis and an appropriate assessment of the qualifications of the fire safety engineer involved. These are requirements for “path (b)” (ADB).

What is evidenced in this section is a misunderstanding of the process of compliance. The evidence provided by Dr. Lane in her Phase One expert report (in particular Sections 2, Appendix E and Appendix F) [4] demonstrates a culture by which “compliance” is trivialized by assuming that being “compliant” only requires meeting the individual requirements stated in the Building Regulations and guidance. In an approvals environment dominated by this culture, compliance simply becomes the process by which approval is being sought/granted as a function of establishing that each individual criterion set by standard tests, guidance documents, Council Directives, European Standards, etc. has been met. Concepts such as adequate performance or adequate quality, which are the real objectives of Building Regulations, are not proven to be attained by “compliance.” The simple fact that ADB does not introduce the term quality in section B4 is further demonstration of this culture. Finally, competency of the engineer is completely disregarded.

This section represents a brief presentation of the current culture of “compliance” and its non-existent relationship with competency, performance or quality. It is of paramount importance to give further attention to this matter in Phase Two.

4.7. SUMMARY

- Due to the comparative physical manifestations of buoyancy and air entrainment on heat feed back to the unburned fuel, flames on a vertical surface will spread far more rapidly in the upward direction than they will laterally.
- This was observed at Grenfell Tower where, in approximately the first 15 minutes following the establishment of flames on the exterior of the building, the flame spread rapidly from Level 4 to the top of the building, while in the same period only spreading laterally a matter of meters to the North.
- The rate of upward flame spread observed was not unusual when placed in the context of other historical events of this nature. In fact, at approximately 4m/minute it was one of the slowest upward propagating examples.
- The flames can be seen to take hold on the outside of the ACP panels from the very early stages of vertical flame spread. Any non-conformity of cavity barriers or other detailing would...
therefore have not significantly affected the rate of vertical spread once the fire was established on the exterior of the building.

- As detailed in the following section, the initial vertical spread ignited a kitchen fire directly above Flat 16 on Level 5.
- Towards the end of this stage, a fire is ignited in Flat 196, Level 22. This fire apparently resulted in reports of smoke blocking the communal corridor on this level however this is believed to have happened later, probably in Stage Three.
- Given the continued evacuation of occupants, the stairwell is still presumed to be tenable, at least in parts, for the duration of this second stage of the fire. It is not known however which floors in the building the evacuating occupants originated from. It can therefore not be discounted that parts of the stairwell may have experienced smoke infiltration.
- The vast majority of the heat produced by the combustion of the cladding will be lost in the smoke plume or absorbed by the unburned cladding ahead of the flame front and therefore will not have reached the load bearing structure of the tower. The structure is not considered to be at any risk during this stage of the fire.
- Different details in the façade system (materials, geometry, cavity barriers, etc.) seem to impact in different ways on the rate of flame spread [4,5]. Test conducted after the Grenfell Tower fire [4,5] seem to provide further information. The complexity of this façade system is such that observations and tests such as BS8414 [27] do not provide sufficient information to be able to understand these differences. The quantity and quality of the data is inconsistent with the complexity of the problem. At Phase Two I will be suggesting a testing protocol that will provide information that is more pertinent to the complexity of these systems. At this stage, this Phase One Report will not reach any conclusions on what are the controlling mechanisms for flame spread in this stage of the fire.
- Compliance of the façade design relies on establishing if it can “adequately resist the spread of fire.” The only path to compliance is performance assessment “from test evidence” used by a competent engineer using “relevant designs guides.” The complexity and importance of the façade system requires more than guides and therefore the reliance is fully on competency. There is no clear definition of competency, therefore this is a matter that needs to be studied with great attention in Phase Two.
- The relationship between compliance, performance and quality is currently poorly established. The means by which performance, quality and compliance for the Grenfell Tower façade system were assessed are deeply flawed. The current culture of “compliance” needs to be revisited in great detail in Phase Two.
5 STAGE THREE: LATERAL FIRE SPREAD AND INTERNAL MIGRATION

5.1. LATERAL MIGRATION OF THE EXTERNAL FIRE

The Grenfell Tower fire is unusual in that horizontal flame spread enveloped the entirety of the building. The fires spread laterally around the building in less than three hours. It is clear that there are multiple pathways for the fire to spread through the façade system [4, 5], nevertheless, in my opinion, none of these explain the lateral propagation of the fire. As can be seen from the earlier footage of the fire, there is very limited lateral spread across the face of the building. Dr Lane [4] and Prof. Bisby [5] present in their Phase One expert reports, ample evidence of many pathways to lateral spread and specific photographic evidence is presented for each of these pathways, but, nevertheless, no dominant pathway is conclusively established. Furthermore, video and photographic images do not seem to determine clear and consistent propagation characteristics.

5.1.1 MECHANISMS DRIVING LATERAL FLAME SPREAD

This section serves as a complement to Dr Lane [4] and Prof. Bisby’s [5] Phase One expert reports with the objective of adding further clarity to a mechanism of fire spread that is particular to Grenfell Tower. This is not intended to diminish the importance of other hypotheses (Section 6.3.4 [5]) nor to diminish the complexities associated with external spread over these type of façade systems (as indicated in Section 4.3 of this report).

Figure 27 shows a different mechanism. The fire reaches the architectural crown of the building and this crown behaves as a preferred path for lateral propagation. Hot smoke plumes from fires lower down on the building façade will also contribute to lateral spread. The rising plume will widen with height and transfer heat over a greater width in the upper levels of the building. This hot smoke preheats upper sections of the cladding which facilitates later ignitions in these areas. Thus, the expanding smoke plumes would serve to accelerate lateral flame spread at the upper areas of the building.

While this is clearly a factor that needs to be considered [5], it seems that a different process drives horizontal spread. In particular, it can be observed that lateral fire spread is more rapid over the architectural crown structure of the building than elsewhere.

Figure 28 shows a view of the East façade where it can be clearly seen that the fire is propagating faster over the architectural crown structure. The following figure shows how debris from this fire starts to ignite the areas below. In the meantime, the fire continues to propagate through the architectural crown structure towards the South-East corner.

By 02:16:41 (Figure 29) falling debris continues to spread the fire downwards while the flames now involve several floors underneath the architectural crown structure almost to the South-East corner.
The final photograph of the sequence (Figure 30, 02:30:10) shows the fire turning the South-East corner and starting its propagation over the architectural crown structure in the south face of the building.

**Figure 27:** East Façade - Burning debris gathering on ledges below fire at ~Level 18 (Flat 151, 2:09:20)

**Figure 28:** East Façade – Significant downward fire spreads in 6 minutes (2:16:14)
Figure 29: Flaming falling debris have ignited 3 further floors downwards (02:16:41)

Figure 30: Fire spreading to south façade from east façade architectural crown (2:30:10)
It is important to note that the lateral spread of the flames through the architectural crown structure is faster than the lateral propagation through the façade system in the building. The characteristics of the architectural crown structure have been described in detail by Prof. Bisby in his Phase One expert report [5]. As indicated by Prof. Bisby [5], the characteristics of the façade system in this region of the building will clearly allow for faster propagation (Hypothesis E5, lines 858-864).

Finally, simple calculations show that the average lateral fire spread in the architectural crown structure remains less than 0.5 m/min which is about one eighth of typical vertical fire spread rates.

As debris falls from burning areas, they will accumulate on window ledges or indeed on any available horizontal surface, igniting new localised fires. Figure 31 shows an example of such a spread mechanism. Debris will ignite a fire which will then propagate upwards to meet with other fires thereby covering completely that sector of the building. This appears to be the governing mechanism for lateral spread observed at Grenfell Tower.

![Image](image.png)

**Figure 31:** Fire visible on façade below fire on East elevation

This mechanism (lateral flame spread over the architectural crown of a building) has been observed in previous fires, in particular in the Monte Carlo Casino & Hotel Fire in Las Vegas on January 25th, 2008 (Figure 32). At the Monte Carlo Casino & Hotel, the polystyrene and polyurethane portions of the exterior insulation and finishing panels (EIFS panels) and trim burned along the building’s parapet. Molten material ran down the exterior edge of the hotel, starting fires in other EIFS panels. As the fire spread from the centre of the west and south wings of the hotel, it also began to burn downward, impinging the windows of the suites on the 32nd floor. The heat caused several windows on the 32nd floor to fail and flames spread into the building.

This mechanism was also recently observed in a fire at the Taksim Ilk Yardim Hospital in Istanbul, Turkey on April 5th, 2018 (Figure 33). Local news coverage reported the fire started on the roof of the hospital and spread downwards and laterally to incorporate the external façade of the building. The fire did not spread into the interior of the building, however there was smoke spread internally. Patients were evacuated and no casualties have been reported to date from the event.
**Figure 32: Monte Carlo Casino & Hotel Fire, Las Vegas, January 25th, 2008.** (A) Shows the external fire spread from the initial ignition at the roof level of the building. (B) The fire spreads laterally across the parapet. (C) Molten burning material drips down the façade and builds up on lower level parapets. (D) Build-up of molten material ignites fresh fires which break in through windows and results in further compartment fires.
5.1.2 Detailed Analysis of the External Spread of the Fire

To understand the timeline of external fire spread it was necessary to analyse multiple images. This enabled identification of the mechanisms by which fire spread around the building and confirmed a timeline of spread.

The building was divided in sectors as indicated in Figure 34 extracted from [MET00008024].

![Figure 33: Still images from Cogan News Agency coverage of the Taksim Ilk Yardim Hospital fire in Istanbul, Turkey on April 5th, 2018, showing the progressive downward and lateral spread of flames.](image)

![Figure 34: This figure was extracted from reference [MET00008024] and indicates the coordinates of each residential unit. The nomenclature stipulated in the figure will be used for the fire spread analysis.](image)
In an effort to examine, floor by floor, external flame spread (both lateral and vertical), floor versus time plots were created using time stamped facade elevation tower plan views that highlighted fire coverage, including the public footage sourced from MET00008024. A series of steps were executed to estimate and visualize the external flame spread across each facade.

The first step involved plotting approximate fire coverage (i.e. highlighted markings) from 01:14 am local time onward based on time stamped facade elevation tower plan views in MET00008024. For examples of this step, see Appendix E Figure 98 - Figure 102, Figure 105, Figure 107 - Figure 109, and Figure 111 - Figure 128.

The second step was to identify any space and time gaps (i.e. greater than 30 min) in the analysis. The north elevation was the only facade where there were any such gaps. Public footage between 1:42 am and 3:07 am on the north elevation was sourced from MET00008024 to help fill in these spatial and temporal data gaps (Appendix E Figure 103).

To be able to discern some of the details of the images, it is necessary to process the images. In this case the brightness of the flames hides details behind the fire and therefore it is necessary to illuminate the fire to see what is behind. Well accepted professional tools exist in specialized commercial packages such as MATLAB. For the purposes of this analysis MATLAB’s image processing toolbox and a modified Spectral colorbar native to ColorBrewer\(^2\) was used to illuminate fire coverage. This toolbox was only deployed on three public images of the north elevation (Appendix E Figure 104; Figure 106; and Figure 110).

The resultant characterisation of the external fire spread is condensed into the plots in Figure 35. The plots show spread to the north and south respectively from the initial external fire on the east façade. The key indicates which of the sectors each data point refers to as established in Figure 34. A step by step guide through the external evolution of the fire is presented in Appendix E.

The initial vertical line of markers, common to each plot, represents the initial vertical fire spread from the initial point of ignition on the external façade. By following the subsequent markers for each sector, it is clear that the initial ignition in each sector, beyond those immediately adjacent to the initial vertical spread, is at the top of the building where lateral spread happens most rapidly. Subsequent ignition of each of these sectors further down the building happens noticeably later in time.

The plot also captures how spread down the façade happens in clusters of floors. This is due to the spread mechanism identified above. The lowest marker identified represents the level at which flaming debris or molten material has collected and resulted in a remote ignition. The data points representing floors above this appear to be a result of upward flame spread from this remote ignition.

5.2. INTERNAL PENETRATION

The external flames established on the façade system encounter multiple paths of entry into the building. The building envelope is designed to serve as a barrier for fires occurring in adjacent buildings (heat fluxes as high as 12.6 kW/m²), but not to withstand an external fire generated within the building (see Section 2.4). External fires will result in very significant heat fluxes (as high as 120 kW/m²) that will damage numerous components.
of the building, in particular the window systems. Mechanisms for re-entry via the window systems principally follow three paths:

1. Failure of the window glazing
2. Failure of kitchen extraction fans
3. Failure of the uPVC window surrounds

While mechanism 3 is discussed in detail in Section 3.4.4, mechanisms 1 and 2 are discussed here. This discussion is presented here only with the objective of providing examples of paths through which the fire re-entered the building and in order to explain how none of the components of the window system were designed to serve as a barrier to prevent the fire from re-entering the building. It is not the intention of this section to describe a preferred path of re-entry.

Dr Lane’s Phase One expert report (Section 9 [4]) also provides a detailed account of all the weakness of the window as designed and built. Any of these weaknesses would have accelerated the ingress of the flames back into the building (as shown by the multiple evidence and testimonies presented). While all these weaknesses are important, and in many cases, will appear to dominate the ingress process, they will not be further discussed here. Given that the windows could not have been designed to withstand the level of heating provided by an external fire, there cannot be any expectation that the performance of the window system would have prevented ingress of the fire to other units. The presentation here should be seen as complimentary to Dr Lane’s descriptions [4].

Following any one of these failures, if the flames are then in contact with other combustible materials in the interior of the unit, then an internal fire will occur that could progress in a manner consistent with any compartment fire.

5.2.1 GLAZING FAILURE

Ogilvie [16] summarizes the range of heat fluxes delivered by external flames as reported by different authors (Table 4). FM Global considers in their testing requirements that the range should be extended up to approximately 120 kW/m² [12]. While the range is very large, it is clear that the magnitude of potential heat fluxes is above the critical heat flux for ignition of almost all combustible materials [28]. In particular, it is above the critical heat flux for ignition of all combustible materials present in the façade of Grenfell Tower [5]. Building design guidelines suggest that the external envelope of a building shall withstand 12.6 kW/m² (see Section 2.4).

Glazing has been extensively studied and experimental data shows that all forms of glazing will fail between 5-10 kW/m² in a period of exposure between 60-300 seconds [29]. The higher the heat flux, the shorter the failure time. Given the typical heat fluxes for external fires, it will be expected that once the windows become engulfed by flames the fire will find a path inwards.
### Table 4: Typical Values Reported for Heat Fluxes Emerging from External Flames, Taken from [16] Citing [30,31,32,33]

<table>
<thead>
<tr>
<th>Author</th>
<th>Heat Flux Value (kW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saito et al.</td>
<td>25</td>
</tr>
<tr>
<td>Mowrer and Williamson</td>
<td>30</td>
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<tr>
<td>Delichatsios et al.</td>
<td>30</td>
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<tr>
<td>Delichatsios and Delichatsios</td>
<td>25</td>
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<tr>
<td>Delichatsios and Chen</td>
<td>25</td>
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<tr>
<td>Grant and Drysdale</td>
<td>20</td>
</tr>
<tr>
<td>Anderson et al.</td>
<td>35</td>
</tr>
<tr>
<td>Kokkala et al.</td>
<td>25</td>
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<tr>
<td>Qian and Saito</td>
<td>25</td>
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<tr>
<td>Quintiere and Lee</td>
<td>25</td>
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<tr>
<td>Lee et al.</td>
<td>60</td>
</tr>
<tr>
<td>Markstein and de Ris</td>
<td>50</td>
</tr>
</tbody>
</table>

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2155

#### 5.2.2 Kitchen Extraction Fan Failure

2156

2157 Based on actual photos taken after the fire, it is possible to identify different scenarios where the failure of the kitchen extraction fan occurred. An analysis of the damage patterns to different components in this part of the windows shows clearly the multiple routes for the passage of flames from the exterior of the building to the interior of the building.

2158

2159 Figure 36 shows a scenario where the heat fluxes available have not been able to breach any of the components of the window i.e. flames have not penetrated through any component of the window. But the detailing of the window, as described by [4,5], does not provide an adequate barrier between the interior and the exterior of the building and thus smoke is observed to have entered through any of the existing gaps.

2160

2161 Figure 37 shows a slightly higher level of heat insult. This time the fan, which appears to be the weakest component (to heat), has deformed and is beginning to fall from its casing. A greater amount of smoke is present in the interior of the unit but this has not resulted in the ignition of any of the combustible materials of the compartment. It is important to note that in this case, the window is open allowing for smoke to penetrate freely.

2162

2163 In Figure 38 it can be observed that the fan has now failed leaving a circular opening on the panel at the location of the original placement of the fan. Smoke has not only penetrated through this opening but has also entered the compartment through gaps between the window frame and the window. Flames did not propagate to the interior of the unit.

2164

2165 In the next sequence of images (Figure 39, Figure 40 and Figure 41) the fan has failed, the windows are open, the glazing has, in some cases, failed (in others not) and the fire has penetrated and damaged the unit. In all of these cases, the panel originally holding the fan is still in place.
A similar scenario can be seen in Figure 43 where the kitchen and adjacent room are significantly damaged, but the extractor fan panel still remains in place. The window in the room adjacent to the kitchen is severely damaged including the frame.

Figure 36: Kitchen window Level 9, Flat 62

Figure 37: Kitchen window Level 10, Flat 71
Figure 38: Kitchen Window level 5, Flat 25

Figure 39: Kitchen window, level 7, Flat 44
Figure 40: Kitchen window, Level 6, flat 31

Figure 41: Kitchen window, Level 7, flat 43
Figure 42: Kitchen window, level 8, flat 54

Figure 43, Figure 44 and Figure 45 show examples where the extractor fan panel has failed and the adjacent rooms have suffered different levels of damage. In Figure 42 and Figure 43 the external flames have ignited some elements of the unit while in Figure 44 and Figure 45 the elements of the unit are intact while the linings of the unit have been damaged but with very minor signs of a fire. Different levels of damage can also be observed on the window. Different levels of charring can be observed on the uPVC covering the window side (Figure 44 and Figure 45) while in other cases the window side is undamaged.

Figure 43: Kitchen window, Level 6, Flat 36
Figure 44: Kitchen window, Level 8, flat 53

Figure 45: Kitchen window, Level 12, flat 93
An important observation from Figure 42 and Figure 43 is the tall refrigerators located close to the windows. These refrigerators have similar characteristics to that which was present in the kitchen of Flat 16. The damage patterns seem to be quite similar, therefore it is important to explore the possibility that the external cladding fire outside the kitchen of Flat 16 might have been the cause of the damage to the tall refrigerator that was witnessed after the event. Given the information available, this is currently not possible to verify.

5.2.3 INTERNAL PENETRATION SUMMARY

In summary, the analysis of these images (and others around the building (Figures 10.48, 10.49 and 10.50 [4])) shows that penetration of the fire could have happened in multiple ways. While some components, like the fan, seem to be more vulnerable than others, there is no evidence that they would have represented a preferred path for an external fire to ignite the interior of a unit.

Given the high levels of heat flux that would be incident on the external façade due to the external fire, a path for the fire to re-enter the building will inevitably be created. The controlling factor therefore for the subsequent damage in the interior of the building is the characteristics of the external fire not the characteristics of the window, or its components.

5.3. FIRE AND SMOKE MIGRATION TO THE INTERIOR

Once the external envelope of the building is breached by the external fire, the possibility of ignition of combustible materials within the units is introduced. These combustible materials will then lead to conditions which are controlled by the fire dynamics of a pre-flashover compartment fire [2,34] that could potentially lead to a post-flashover fire [35]. It is important to note that, despite major damage in many of the units, a significant number of flats only resulted in fires that did not attain flashover. This would have impacted on the temperature of the smoke and its capacity to ignite other combustible materials, although it is important to approach this issue with some caution. The presence of an external flame can result in a very hot and potentially thin ceiling layer. This ceiling layer might have a very high temperature, severely damaging the ceiling, but be too thin to be able to provide sufficient radiation to ignite materials close to the floor (these flames are commonly referred to as optically thin). It is therefore possible, in these very unique circumstances, to have very hot gases that can ignite materials when touching them but that will not lead to generalized burning or flashover. Figure 46 and Figure 47 show two examples of such cases. The damage in each case is different, more structural damage is evident in Figure 47, while more fire damage is evident in Figure 46, but neither case experienced flashover.
In other cases, the fires would have managed to ignite all the combustible materials within the compartment. These will be discussed later in more detail because they are relevant to the breach of compartmentalization of the units. Fires that did not attain flashover would have been less likely to thermally compromise the main door of the unit given the distance between the windows and the main door.
5.3.1 Early Passage of Smoke Through the Building

Once fires have entered the building, the next level of protection are the boundaries of the units. These boundaries are fire resistant walls and doors. These fire-resistant walls and doors are intended to stop the propagation of flames and smoke into the lobbies and stairs. The requirements for these doors are described in Dr Lane’s Phase One Expert report (Section 2.21 and Appendix I) [4]. These requirements pertain to fire resistance, smoke seals and self-closing mechanisms. It is clear from the earlier stages of the fire at Grenfell Tower that internal compartmentalization was breached, and smoke had migrated into the stair lobby. Smoke was observed from very early on emerging from windows in areas very far from where the external fire was progressing (Figure 48 to Figure 52). This clearly indicates that the boundaries of at least two units had been breached. These observations need to be further explored in Phase Two.

Figure 48: Night Vision Camera (Time: 01:57:03), Smoke Coming from Flat 94 on Level 12

Figure 49: Night Vision Camera (Time: 01:58:32), West façade, smoke coming from multiple windows of Flat 174 on Level 20

Figure 50: Night Vision Camera (Time: 02:40:47), West façade, smoke coming from Flat 205 on Level 23
A review of past fire events in high-rise buildings involving internal smoke spread shows that in most cases where casualties occurred, smoke had spread into vital parts of the building. Events with high casualties include:

- Andraus Fire, Sao Paulo, Brazil, 1972 – 16 fatalities, 375 injuries
  - smoke entered stairwell
- Joelma Fire, Sao Paolo, Brazil, 1974 – 179 fatalities, 300 injuries
  - smoke entered stairwell
- MGM Grand Hotel, Las Vegas, NV, 1980 – 85 fatalities, 600 injuries
  - smoke travelled through the entire building because of unprotected openings in compartmentalization walls
  - Fans drew smoke from the mechanical room, spreading into occupied spaces
  - Smoke spread in the elevator shaft due to doors remaining open on the first floor
- Dupont Plaza, San Juan Puerto Rico, 1986 – 98 fatalities
  - Smoke was coming through air conditioning system vents and was an initial warning to the fire (alarms were not functioning). Smoke entered the foyer due to a missing panel. Extensive compartmentalization breaching.

In contrast, events where compartmentalization was not breached and the stairwells remained clean of smoke resulted in none or limited casualties:

- 7 buildings that experienced large external fires had no injuries or fatalities
- 2 of the buildings had effective external compartmentalization that prevented the fire or smoke from spreading into the building until the occupants had all escaped
- 2 of the buildings did have smoke spread/fire spread in the building. One of those buildings (Wooshin Golden Suites) had fire brigade access to the roof where many occupants were saved. Another building (Al Tayer tower) had an isolated staircase that held out smoke and fire until all of the occupants had left.

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At the moment of writing this report there is no reliable information on how this was achieved, therefore, this matter needs to be further explored.
The vital role of compartmentalization is expressed clearly in all Building Regulations and it is summarized in Dr Lane’s Phase One expert report (Section 3, Section 4, Appendices I and J) [4]. At the point where the perimeter of the building is breached by the external fire, this becomes the next line of defence. It is therefore important to assess the performance of the compartmentalization to understand the role it played in allowing smoke migration through Grenfell Tower.

5.3.2 COMPARTMENTALIZATION PERFORMANCE FOLLOWING FIRE RE-ENTRY

Once the external fire has breached the boundary of a flat unit, the potential for ignition of items within the unit and a subsequent compartment fire is realised. At this stage, it is reasonable to assume that the compartmentalization separating this unit from the surrounding units and communal areas should be adequate to prevent the fire and smoke progressing in a way that compromises these areas.

The performance of these boundaries is quantified by providing a regulatory specified, required level of fire resistance. Fire resistance refers to the ability of a building element to not exceed specified failure criteria (related to its function) for a duration of exposure to a specific thermal loading in a test furnace. The length of time that an element is required to perform in the testing environment is designated according to the expected fire load of the eventual occupancy in which the building element will be deployed. The fire load is a surrogate for the expected severity of the fire that could exist in that space, i.e. a larger fire load is expected to result in a more severe fire, a more severe fire requires a more robust building element, and therefore the building element is required to endure a greater time in the furnace test to be considered robust enough to perform adequately in the real fire.

Figure 53 shows the temperature curve that a fire resistance test is required to follow. The insert shows two photographs of typical furnaces used to test elements that require fire resistance. Also indicated in the figure is a typical compartment fire temperature. As can be seen from the figure, a compartment fire temperature is very different to the temperature history followed by the regulatory test. Therefore, while fire resistance is presented in terms of time, it needs to be understood that fire resistance does not correlate to time to failure in a real event. All structural elements requiring fire resistance (i.e. doors, fire stop materials and other component parts of fire rated compartments), are required to be tested according to this specified testing regime.

For the compartmentalization to be expected to perform in the case of a re-entrant fire, the severity of the compartment fire must be assumed to be primarily a result of the consumption of the fire load within the flat unit and the external fire’s contribution assumed negligible. The external fire can then be simply categorised as the source of ignition of a pre-flashover fire. This is a reasonable assumption given that the amount of fuel provided by the cladding per unit area is less significant than the fuel within the flat and also because most of the energy from the external flames will be dissipated outwards.
5.3.2.1 THE CONTRIBUTION OF THE RE-ENTRANT FIRE

In the case of Grenfell Tower, a forensic quantitative assessment of the external fire contribution is not viable given the availability of evidence, however the external fire contribution can be assessed qualitatively by observation of the damage in flats where the external fire breached the compartmentalization.

It is important to note that, despite major damage in many of the units, a significant number of flats never attained flashover. This impacts on the potential temperatures of the smoke and its capacity to ignite other combustible materials, although it has to be interpreted with caution. As indicated earlier in this section, the presence of an external flame can result in a very hot and potentially thin ceiling layer creating the very unique circumstances of having a layer of very hot gases that could ignite materials when touching them but that will not lead to generalized flashover. Examples of this scenario can be seen in Figure 54 and Figure 55.
An assessment of the damage in flats other than that of the fire origin (Flat 16) is described later in detail in Section 6.2. Of the 113 flats where fire or smoke breached the compartmentalization, 13 experienced minor damage, 9 experienced moderate damage, and 91 experienced major damage.

Minor damage is defined as smoke ingress, low levels of heat damage, or small localised fires around the point of entry. This may be in the form of soot deposition, localised deformation of polymer-based furniture and fittings, or evidence of localised burning. Figure 56 and Figure 57 shows typical examples of this level of damage. This is not expected to challenge the compartmentalization of the flat unit.
Moderate damage corresponds to localised damage around the point of re-entry of the fire where this has occurred in more than one location within a single flat unit. This could range from localised charred surfaces to localised fires that failed to involve other objects in the room and thus did not progress to flashover. Figure 58 and Figure 59 show typical examples of this level of damage. In certain cases, the localised fires resulted in some level of damage to components such as windows or furniture but no structural damage could be observed.

Severe damage is characterized by the presence of spalling on ceilings and compartment walls, as well as evidence of structural damage to ceilings and compartment walls. In some cases, one room may have significant structural damage (e.g. living room), while the remainder of rooms had no visible structural damage with spalling on ceilings and walls present and sometimes not present. Examples of this degree of damage are displayed in Figure 60 and Figure 61. The impact of these fires on compartmentalization is difficult to assess, nevertheless it is expected that damage to the walls and doors separating the unit from the lobby would have been minor. This is mostly because of the distance between the perimeter of the building and the boundary to the lobby.

Major damage is typified by an ignition resulting from external flaming that subsequently develops into a fully-developed compartment fire (flashover). The majority of the sources of fuel within the room or even flat would be involved in the fire and without intervention, consumed by it. This level of fire is expected to challenge the compartmentalization. Examples of this type of damage are shown in Figure 62 and Figure 63.

The presence of this entire range of behaviours indicates that the influence of the external fire alone is not sufficient to consistently result in a fully-developed fire in a flat unit. This implies that the heat introduced by the external fire is typically only significant locally to the entry point, and it is the characteristics of the fuel distribution in a flat and specifically of the first internally ignited item(s) that determines if a fire will subsequently grow to be fully-developed. The aleatory (i.e. unpredictable) distribution of combustible materials in residential units correlates well with the variability of damage in different units. It is very likely that in a residential unit there will be sufficient fuel to attain flashover and develop a fire that could lead to major damage, thus is not surprising that 91 of the 113 affected flats experienced major damage.

It should therefore be considered that, with regard to the compartmentalization of the internal boundary of a flat unit, the thermal loading imposed by the external fire is secondary in comparison with the thermal loading imposed by combustion of the furniture and fittings. Given the type of construction of Grenfell Tower and the minor compartmentalization non-compliances between flats (Section 4 [4]) it is also appropriate to assume that the compartmentalization separating each flat from neighbouring flats should be capable of restricting any significant passage of smoke, heat and fire from one unit to another.

Finally, it is expected that for the 91 units with major damage, compartmentalization of the boundary between the unit and the lobby (in particular the doors) would have been challenged.
FIGURE 56: EXAMPLE OF MINOR DAMAGE FROM FLAT 62, FLOOR 9.

FIGURE 57: EXAMPLES OF MINOR DAMAGE FROM FLAT 62, FLOOR 9.
Figure 58: Examples of moderate damage from Flat 93, Floor 12.

Figure 59: Examples of moderate damage from Flat 93, Floor 12.
Figure 60: Examples of severe damage from Flat 45, Floor 7.

Figure 61: Examples of severe damage from Flat 45, Floor 7.
Following the fire at Grenfell Tower, investigations have noted a number of flat doors that were damaged to various extents. Such damage to compartmentalization therefore represents a viable path for fire and smoke migration to the communal lobbies, egress stair, and surrounding flats. It is important therefore to establish under what conditions these doors might have failed and to ascertain how this relates to the timeline of the fire and smoke progression through Grenfell Tower, thus contextualising the impact of any door failure.
Tests conducted at BRE on flat doors [36] removed from the building demonstrated a fire resistance rating of the order of 15 minutes. As described previously in this section, this means that the doors failed defined performance criteria after 15 minutes of thermal exposure to the ISO 834 temperature-time curve (Figure 53) within a furnace. This corresponds to a failure temperature of the order of 740°C (739°C in Figure 53). Figure 53 also shows the evolution of the temperature in a typical residential compartment. In a fire that starts within the compartment, flashover will most likely occur in the first 5 minutes when temperatures reach values between 500°C and 600°C, the post-flashover fire can then reach temperatures as high as 1200°C. Eventually, all combustibles will be consumed and burn-out will occur. This will generally take no more than 40 minutes. If the fire is ignited externally, flashover can be attained very rapidly but the characteristic compartment temperatures will remain the same because a post-flashover fire is not limited by the fuel but by the available ventilation.

To establish the typical range of post-flashover compartment fire temperatures, a brief analysis is performed for a typical one-bedroom flat in Grenfell Tower. Upper and lower bound temperatures and corresponding fire durations are established for both of the principle rooms in this flat configuration.

Temperatures are assessed using the experimental data provided by Thomas [37] (Figure 64) which uses an inverse opening factor, $\delta'$, to establish a representative compartment temperature. The inverse opening factor represents the relationship between the size of the compartment and the size of the ventilation, assuming that the amount of combustion in a post-flashover fire is limited by the air available to it. Inverse opening factors for these spaces range from approx. 10 – 25 m$^{-1/2}$. This corresponds to characteristic compartment temperatures in the range of 850 – 1000°C.

To estimate the duration of burning for such a compartment, the experimental data provided by Kawagoe [38] (Figure 65) is used to determine characteristic burning rates, as a function of the typical fuel type and compartment temperature. Assuming a mixture of wood and PU foam as the principle fuel sources in a bedroom or living room, this gives burning rates in the range 0.012 – 0.018 kg/m$^2$.s.
Figure 65: The plot by Kawagoe [38] defines burning rate \([g/\text{m}^2\cdot\text{s}]\) as a function of compartment temperature \([\circ\text{C}]\).

Eurocode 1 [39] gives an average fire load density for a dwelling of 780 MJ/m\(^2\). For the assumed fuel sources, the typical energy content is taken as \(~30\text{ MJ/kg}\) [40], which equates to a fuel load of approximately 26 kg/m\(^2\).

Given the estimated range of burning rates from Figure 65, this gives a fire duration of the order of 25 – 35 minutes for a single compartment.

It has been reported [35] that standard testing of the doors showed failure at approximately 15 min. Furthermore, it is reported that, given the composition of the doors (i.e. Section 14.5.12, Appendix I [4]), failure was characterized by flaming of the doors. If the failure times of these tests are used to indicate the conditions necessary for failure, then Figure 53 shows that the gas temperature during the test when failure occurred was of the order of 740\(^\circ\text{C}\). This temperature is above characteristic flashover temperatures and therefore would most likely occur in cases were the units had major damage. Furthermore, failure of the doors would have only occurred after conditions in the unit were untenable. Section 4.4 indicates that the vertically propagating fire was observed to start internal fires on the 5\(^{th}\), 12\(^{th}\) and 22\(^{nd}\) floor as early as approximately 01:18, 01:24, and 01:28 respectively. Therefore, the lobbies in these floors could have been compromised prior to 02:00.

In cases where moderate or severe damage was observed, smoke and flame entering the unit from external fires would not provide sufficient thermal insult for sufficient duration to affect such failures. This is evidenced by the fact that the flat doors in flats where damage was of this nature (See Section 5.3.2.2) i.e. no post-flashover fire, did not experience damage that cannot be explained by either firefighter intervention or thermal insult from the communal lobby side due to failure of all other flat doors on that floor. In the majority
of cases where flat doors were damaged (and still identifiable), this coincided with a major, post-flashover fire in the flat.

5.3.2.3 MECHANISMS FOR INTERNAL SMOKE SPREAD

As explained above, for a fire to bring smoke and heat to the stairs it is necessary to breach several barriers. For the purposes of this section, a barrier is defined simply as a physical obstruction to the smoke and heat. Some of these barriers have regulatory requirements for levels of fire resistance, however for the purpose of this section, barriers are differentiated by an expectation of their level of robustness. These are illustrated in Figure 66.

Green lines indicate barriers that are not expected to afford significant robustness in respect to the resistance to the passage of heat and smoke, while pink lines represent barriers that are expected to provide a significant level of robustness. Red arrows indicate a barrier of either type that must be breached for smoke and / or heat to reach the protected stairwell. Barrier (1) is the building façade. As explained in previous sections, there are no expectations for windows on the external wall to protect the building in a manner that they will serve as a barrier to an external fire. Nevertheless, this will be deemed the first level of containment. Barrier (2) is defined as the boundary of the internal hallway within the unit (walls and doors). This hallway is defined as a protected hallway therefore, these elements are expected to represent a robust barrier. Barrier (3) is the entrance door to the unit. Again, this is expected to provide a robust barrier. Barrier (4) is defined as the lobby ventilation system which, while not a physical barrier, is expected to provide a preferential pathway for smoke in the lobby. Finally, barrier (5) is the stair door which is expected to provide a robust barrier to smoke and heat ingress into the stair.

If the breach of barrier (1) was not sufficient to ignite the combustible materials in the compartment adjacent to the external wall, then smoke from the external fire would have had to migrate through the internal doors (2), the unit entrance door (3) overwhelmed the lobby ventilation system (4) and then finally the stair door (5). The fire itself would have been too remote to thermally damage any of these layers as distance L (the distance between the point of entry of the flames and subsequent barriers) is too large. Smoke migration could have been either through poor design of walls and doors or poor installation or maintenance leading to leakages.

Another alternative is if all the doors were left open. The state of the lobby ventilation system, the doors and the walls are described in detail in Dr Lane’s Phase One expert report [4]. It was established that no significant issues could be found with the walls (Section 19.7.8 [4]) but that there was no sufficient evidence to establish the state of the lobby ventilation system (Section 19.7.21 [4]). So, smoke migration had to occur through the doors.

Barrier (4*) represents doors to other units that open to the lobby. Section 5.3 of this report shows that path (4*) occurred in several places slightly after 02:00 further emphasizing that smoke migration had to occur through the doors. The issue of self-closing mechanisms for the flat and stair doors thus needs to be considered.
Figure 66: Mechanisms of smoke spread to the lobby, assuming fire has spread inside via the external wall assembly
If the breach of containment was sufficient to ignite combustible materials in the compartments adjacent to the external wall, then flames and smoke, hot enough to cause damage to the flat doors, would have been present. The fire would have been brought towards the entry of the unit, thus, distance L will be small enough that the unit doors (2) and entrance door (3) would have been damaged and, given their characteristics, would have ignited. There is sufficient evidence to establish that the doors ignited in many of the units with major damage. Ignition of the doors would have posed a severe challenge to the lobby. Because of its small size, the lobby would have rapidly filled with smoke but also potentially with flames. Post fire inspections by Dr Lane indicate that there is sufficient evidence of high temperatures between floors 13 and 16 (Section 19.6.7 [4]). The lobby ventilation system (4) would have been inevitably overwhelmed and stair doors (5) and other unit doors (4*) would have also been compromised. For this scenario, there is no need for the doors to be open for smoke to migrate into the stairs.

The following sections discuss in more detailed how all these levels of containment could have potentially been breached.

5.3.2.3.1 OCCUPANT EGRESS

Occupant egress necessitates the opening of fire doors; thus smoke would have been able to escape into communal lobbies during occupant movement/evacuation and, to a lesser extent, into the egress stair. CCTV video evidence from the Level 7 lift lobby corroborates this breach of compartmentalization [MetUSB:NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/7th floor.mp4]. This action is a very brief event and the impact of this action is likely to be negligible providing doors are closed promptly behind the evacuating occupants.

5.3.2.3.2 FIRE DOOR DEFICIENCY / LACK OF DOOR CLOSERS

It has not been possible to establish if apartment doors were not fitted with functioning door closers and or installed deficiently [Section 2.15.15 [4]] nor is there conclusive evidence that door closers on the stair fire doors were not working (Section 2.21.34 [4]). Nevertheless, if any of these mechanisms did not function during internal circulation and evacuation, smoke would have been able to spread from fire affected compartments into communal lobbies. This is a viable mechanism for the early passage of large quantities of smoke through the building (Section 5.3) and for the early compromise of lift lobbies in and around floors where compartment fires were ignited within Stage 2 (Section 4.4).

5.3.2.3.3 FIREFIGHTER INTERVENTION

Emergency response by firefighters frequently has an impact on compartmentalization. Typically, this is not an issue as occupants that are able to will have already evacuated. In the case of a “stay put” strategy most occupants will remain safe in their units. This leaves firefighters free to fight the fire and perform any required search and rescue activities. Firefighters have specific protocols with regards to high rise buildings, however as outlined in Mr. Todd’s Phase One expert report [1] and as is likely to be outlined in their operational procedures (information remains incomplete at the moment of writing this report), these protocols will be driven by the unique characteristics of these buildings and, by extension, the implications for firefighter safety that these characteristics bring about.
One characteristic is that fire appliances and hoses cannot always directly reach the compartment of fire origin therefore requiring responders to enter the building and connect hoses to risers. Typically, this action is performed at a bridgehead set up two floors below the floor of the fire compartment to allow responders to enter the floor on which the fire is located and be primed to immediately fight the fire, should it be necessary. This tactic of establishing a bridgehead beneath the fire floor necessitates running hoses via an emergency stair, and in doing so propping open the door to the stairwell and flat simultaneously. This will potentially result in the passage of smoke into the egress stair which will reduce the capacity of the stair itself due to the presence of the hose.

In the context of a single unit fire and a functioning “stay put” strategy, this practice is acceptable as occupant use of the stair is minimal and restrictions caused by the presence of the hose and smoke in the stair are therefore negligible. This is borne out by reports from the period of time following the initial firefighting activity in Flat 16. The fire was at a pre-flashover stage when the hoses were potentially compromising the egress stair, thus smoke production and migration into the egress stair was minimal. There is a continued, steady flow of occupants down the stair subsequent to these actions ([Section 14 (4)]) and Section 5.3.4). Once the scenario escalated however, firefighting activities became required on multiple floors and smoke from increasingly developed fires was able, by some means, to reach the stairwell which also later became increasingly unnavigable due to the quantity of hoses present. These issues are discussed in great detail in Dr Lane’s Phase One expert report (Sections 14, 17 and 19) [4] and will therefore not be further discussed here.

Beyond the logistics of supplying water, gaining access to flats as part of firefighting and search and rescue activities may require forced entry. This has the potential to compromise the integrity of the door and, by extension, its ability to fulfil its role as a fire barrier. Again, in the context of a single flat fire which is controlled and extinguished by the responders, this is not a significant issue. Once multiple fires exist however, the effect of the loss of fire barriers on the single egress stair is compounded. Firefighter testimony establishes numerous occurrences of damage to flat entry fire doors by responders during both firefighting and search and rescue activities [MET00005251, MET00005700, MET000080558, MET00005429, MET00005467, MET00005413].

Statements of the initial responders [MET00005251] establishes that firefighters forced the door of Flat 16 as they initially responded to the kitchen fire. Even though the initial kitchen fire was extinguished, a later more severe fire occurred within the flat, following re-entry of the fire into a bedroom. [MET00005700, MET000080558] reports response to a fire that developed in Flat 26 on Level 5, immediately above Flat 16, following re-entry of the fire from the cladding. In this case the firefighters “kicked the door in”. Unable to extinguish the fire due to the hose being snagged elsewhere, the firefighters retreated to the lobby where they noted that conditions in the lobby were “almost as bad as in the flat”. In this case, a flashover event occurred later in time potentially without the benefit of a fully functioning fire door at the flat entrance to protect the lobby.

Seemingly later in the fire, at an undetermined time, [MET00005429] describes firefighting activities on the 12th floor where numerous fire doors were forced open. “…we think entered the twelfth floor [sic]. The door was opened by WM McKay and I pulsed some water into the floor. We then moved into the floor and started fire-fighting. First, I fired water into the flat down the left-hand end which knocked the remainder of the door off its hinges and created a lot of helpful light and cooler air. We then tried to get into the flat next to it. Fired the jet into the flat after forcing our way in as there was bedding behind the door. After more water was fired into the flat we then searched it and found nothing. Moved onto the next flat, number 82. Same scenario with bedding behind the door. ” This evidence may correspond to the early passage of smoke (Section 5.3.1) seen.
emerging from the west face of Flat 94 on Level 12 at the end of Stage 3, and significantly earlier than the arrival of fire on that side of the building.

[MET00005467] reports using an enforcer to smash through a door panel, “cow kicking”, and “smashing” doors open in order to search 4th and 5th floor flats. Re-entering the building later to resume search and rescue activities on the 11th floor, the same statement describes taking sledgehammers and axes, presumably to gain access to individual flats. [MET00005413] describes braking a hole in the door (9th floor) beneath the door handle in order to reach through to open it.

These tactics, though likely inconsequential under a controlled “stay put” strategy, have a strong impact on the protection of egress paths and thus may disable any strategy change, later in time, when occupant evacuation becomes more critical.

Further investigation is required to understand if continued following of the “stay put” protocol and corresponding firefighting, search and rescue activities, contributed to the rapid decline of general tenability in the egress passages. It is important to understand what the implications were for the egress routes given how early on in the incident the framework for a “stay put” strategy was undermined. This need is highlighted further when considering other fires of a similar nature, described in Section 4.2, where maintained tenability of the egress stair was key to ensuring the safe evacuation of building occupants once extensive external fire spread had occurred. This matter will require significant attention in Phase Two.

5.3.2.3.4 LARGE SCALE EFFECTS

For completeness, other mechanisms of smoke migration have been evaluated. Large-scale buoyancy (stack effect) and lift shafts provide mechanisms for vertical smoke movement. Two mechanisms, described briefly here, are associated with such vertical smoke movement.

**Stack Effect:**

The stack effect is the process through which air flows through a building due to temperature differential between the inside and outside of the building. When the outside air is below room temperature, this cold air enters the building and heats up to room temperature and flows upwards. At Grenfell Tower on the day / night of the fire, outdoor temperatures ranged from around 18.3°C (12:00 PM)-15.5°C (5:00 AM), or slightly below room temperature. Some qualitative conclusions can be drawn from this:

- The stack effect will be fairly negligible in driving smoke up the building.
- The stack effect may draw smoke into the elevator shaft, which could potentially rise up under its own buoyancy.

It is also possible that, later in the fire, this effect may begin to happen in reverse due to the outside air being heated by an exterior fire as well as many windows being breached. This effect could have led to significant motion of smoke around the building. Currently research into this scenario is limited and therefore the stack effects on Grenfell Tower are difficult to assess.

While the influence of the stack effect might be relevant, its effects would have been very unique to the Grenfell Tower fire scenario. It is not clear if any lessons might be learnt from a detailed analysis of the stack effect, thus I consider studying this phenomenon of lesser priority.
**Piston effect in lift lobby:**

The piston effect is the process where a vertically-moving lift creates suction pressure in its wake, which pulls air from in front of it to the area behind it. This mass flow can then pull air through the openings and leakage areas between the elevator shaft and the wall, creating a vertical flow between floors above an elevator and below an elevator.

The number of necessary assumptions regarding the air flow and exact conditions of the building preclude the undertaking of a detailed analysis of the impact of this effect. However, the NFPA reference “Smoke Movement and Control in High Rise Buildings” chapter 4.5 [42] provides a comprehensive background to this issue. In a multiple-car elevator shaft, the adverse effects of a single elevator moving are typically negligible. From video evidence [MetUSB:NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Southlift.mp4] of the south lift it can be inferred that this lift remained at the 2nd floor between approximately 01:03 and 01:37, thus it can be assumed that these early stages of a fire can be treated as a single car in a double car shaft. The chart Figure 67 shows the upper limit pressure difference between the elevator shaft and the lobby and it has been calculated that the elevator car in Grenfell Tower moved at between approximately 1.5 m/s. Thus, the max pressure difference is around 3 Pa, which is negligible. This effect can therefore be discounted and should be given no further attention.

**Figure 67: Pressure differences as a function of car velocity for lift shafts.**

5.3.2.3.5 **MISSING OR DAMAGED FIRE STOPPING**

The state of the fire barriers leading to the lobby (Section 19.7.8 [4]) and in particular the stair enclosure shows only minor weaknesses in regard to its capacity to deliver adequate compartmentalization (Section 19.6.2 [4]). These often provide small leakage paths for smoke to pass, nevertheless do not seem to have had a major impact on what should be smoke proof compartmentalization.
5.3.2.3.6 VIA THE SMOKE CONTROL SYSTEM

It is unclear if the smoke management system, designed to vent smoke from communal lobbies, performed as specified or was indeed even compliant (Section 19.7.21 [4]). A correctly designed and specified system would be sized to perform within the framework of a contained single compartment fire, with the intention of maintaining a single lobby as passable. Given the scale of the event and the number of lobbies that were simultaneously compromised by smoke ingress, a fully functioning, compliant system would have provided negligible benefits to egressing occupants, thus any discussion of its compliance or functionality is secondary in the context of the Grenfell Tower fire.

5.3.3 INTERNAL SMOKE SPREAD

The following section provides an approximate overview of the spread of fire and smoke, from the exterior façade, via individual flats, to the interior common elements of the tower. An approximate timeline is constructed from 999 calls, firefighter statements and videos and images to reconstruct as accurately as possible the time period until general conditions within the building could be deemed as untenable.

The previous sections have analysed the potential for smoke migration on the basis of physical variables and fire dynamics. This section takes information from the event with the purpose of contrasting this information with the physical arguments made in previous sections. This analysis is not intended to be comprehensive, but is presented to demonstrate the importance of contrasting different forms of information. Dr Lane’s Phase One expert report [4] provides a complementary, and in many cases more detailed analysis of this information. Correlation of all this information, and any new information made available, should be conducted as part of Phase Two.

Despite the many photos and videos available for review, limited time-stamped photographs and videos exist from which to build an internal smoke spread timeline. Exterior photographs taken during the fire event were analysed to help infer smoke/fire spread within compartments, however, the quality of available images limited the effectiveness of this approach.

The most reliable videos from of the interior of the building during the event were CCTV footage provided by the Metropolitan Police. These CCTV cameras were located at:

- Inside the South Lift
- Ground floor Lift Lobby
- Level 7 Lift Lobby

Furthermore, the following sources were used to provide temporal information:

- Transcripts of 999 calls handled by the LFB and other fire authorities.
- CCTV exit times (MET000080493)
- Facebook Live video from Rania Ibrahim

The data recorded in Table 5 is used to establish a smoke movement timeline for the first hour of the fire (00:54 to 02:00). When residents from the same apartment make multiple calls, additional calls are listed under the time of the first call. While this list is not complete, it is indicative of rates of internal smoke spread.
<table>
<thead>
<tr>
<th>Time</th>
<th>Action</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:54</td>
<td>LFB 999 call: Resident of Flat 16 (Level 4) indicates fire in the flat kitchen: Caller reports a fire in Flat 16 on the 4th floor. Refers to the “fridge”. Caller is outside and says “...quick, quick... It’s burning”.</td>
<td>LFB00000301</td>
</tr>
<tr>
<td>00:56</td>
<td>Four people enter the south lift. Lift rises to Level 4, doors open and smoke spills into lift from lift lobby.</td>
<td>NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Southlift.mp4</td>
</tr>
<tr>
<td></td>
<td>One of the lift occupants, Miguel Alves: “I just arrived when the fire started...I was in the lift, I pressed 13, and somebody pressed four.” When the doors opened at the fourth floor, where the fire had started, smoke billowed into the lift, Miguel said. “I just came out of the lift because I didn’t know what was going on, and I went up by the staircase to wake up my son and daughter.”</td>
<td>IWS00000537</td>
</tr>
<tr>
<td>01:02</td>
<td>Fire Brigade enter south lift at ground level, rise to Level 2. Lift door held open by fire hoses.</td>
<td>NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Southlift.mp4</td>
</tr>
<tr>
<td>01:04</td>
<td>Tiago Alves: “Me and my sisters ran down the stairs. My dad stayed upstairs and he was knocking on the neighbours’ doors.”</td>
<td>IWS00000123</td>
</tr>
<tr>
<td></td>
<td>CCTV shows Ines and Tiago Alves exiting the building</td>
<td>MET000080463</td>
</tr>
<tr>
<td>01:08</td>
<td>CCTV shows Miguel Alves exiting building with others – possibly Level 13 occupants</td>
<td>MET000080463</td>
</tr>
<tr>
<td>01:14</td>
<td>Fire spreads from Flat 16 window to external cladding</td>
<td>MET00006589</td>
</tr>
<tr>
<td>01:21</td>
<td>LFB 999 call: Flat 195 (Level 22): Caller is Naomi Li. She describes smelling smoke “from the lift side”. Advised to “stay inside and keep your door and windows shut.”</td>
<td>LFB00000303; IWS00000515; LFB4828_0038</td>
</tr>
<tr>
<td>01:22</td>
<td>Occupants seen moving (presumably evacuating) from 7th floor. No smoke visible in lift lobby.</td>
<td>NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/7th floor.mp4</td>
</tr>
<tr>
<td>01:24</td>
<td>LFB 999 call: Occupant in Flat 96 (Level 12) indicates that fire has spread internally through the kitchen window: Says “I can’t breathe’</td>
<td>LFB00000304; LFB00000309; IWS00000771</td>
</tr>
<tr>
<td>01:25</td>
<td>LFB 999 call: Occupant in Flat 111 (Level 14) unable to egress due to smoke in lift lobby: Caller says “it’s [the fire] coming right past my window from next door.” There is fire “all on my side” but it is not inside the flat. The caller can smell smoke. There is smoke coming into the flat from the landing. Caller says that he has “tried to open the door and there’s a lot of smoke”.</td>
<td>LFB00000308</td>
</tr>
<tr>
<td>01:26</td>
<td>LFB 999 call: Neighbour from Flat 95 (Level 12) confirms fire in Flat 96, with smoke outside. The caller states her neighbour has had a fire in the kitchen already and says</td>
<td>LFB00000309</td>
</tr>
<tr>
<td>Time</td>
<td>Action</td>
<td>Evidence</td>
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<tr>
<td>01:27</td>
<td>CCTV footage shows two occupants arriving at Ground Level using the north lift (the south lift at this time is being held at Level 2). Smoke spills into the lobby as occupants exit. As the occupants open the door to the lift lobby, rush of make-up air causes smoke to be drawn back in to the lift shaft. This occurs again when a firefighter opens the same door to enter the lift lobby.</td>
<td>NORTLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Lift lobby.mp4</td>
</tr>
<tr>
<td>01:28</td>
<td>Caller in Flat 73 (Level 10) Grenfell Tower. Reports smoke ‘coming onto my floor’ and ‘seeping into my house’. Also reports ‘smoke outside the flat’.</td>
<td>INQ00000282</td>
</tr>
<tr>
<td>01:28</td>
<td>LFB 999 call: 3 Occupants from Flat 82 (Level 11) unable to egress due to smoke in lift lobby: Caller states she is stuck on the 11th floor and does not know how to get out. Asked if there is any smoke coming into the property, the caller responds, “Not at the moment but if I open the door there’s smoke on the landing.” There are further 999 calls from Flat 82 at 01:33 (states no smoke in flat but it is getting worse outside, asks for assistance in evacuating), 02:02, 02:18, 02:32 (no smoke coming in), 02:37 (flames on landing), 02:44 (smoke coming through windows and fire coming through kitchen window), 03:00, 03:03, 03:04, 03:13 &amp; 03:32 (fire in flat, egress not possible due to smoke).</td>
<td>LFB00000307 LFB00000313 LFB00000338 LFB00000347 LFB00000360 LFB00000367 LFB00000377 LFB00000393 LFB00000394 LFB00000401 LFB00000410 LFB00000425</td>
</tr>
<tr>
<td>01:29</td>
<td>Caller in Flat 142 (Level 17), reports that there is smoke ‘on our floor’ and ‘in our house’. Caller also explains the fire is ‘right next door’. They can see flames from the window.</td>
<td>INQ00000264</td>
</tr>
<tr>
<td>01:29</td>
<td>LFB Call: Caller in Flat 201 (Level 23). Confirmed as Jessica Urbano Ramirez. The call lasts 55 minutes. Jessica states that she came out of her house because of the fire. She is now in a group of 10 in a bedroom in a flat on the top floor. The fire is in the living room. Jessica describes smoke coming from “everywhere” including the floor. People have tried to go outside but there was a lot of smoke. The operator refers to a smoke alarm making it difficult to hear. Jessica says more than once that she and others “can’t breathe”. She confirms seeing “flames coming up through the window”. Later she says that fire is “coming through the window” and that the window is on fire.</td>
<td>LFB00000507</td>
</tr>
<tr>
<td>01:30</td>
<td>LFB 999 Call: Caller is Mariem Elghwary (from Flat 196 on Level 22) who is calling from Level 23 (she is in a neighbour’s flat – Flat 205 on level 23): states “we are all stuck on the top floor and the doors [presumably to the roof] won’t open”. Caller continues that there is smoke everywhere and the fire is in our house on the 22nd floor. Everyone is now on the 23rd floor. Caller states the fire had “broken into the kitchen of our flat” and she had run into the neighbour’s flat.</td>
<td>LFB00000310</td>
</tr>
<tr>
<td>Time</td>
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<tr>
<td>01:30</td>
<td>LFB 999 Call: Caller on Level 22. States it is “terrible up here” and “you can’t see your hand in front of you.” Caller advised to put towels down to stop smoke coming in.</td>
<td>LFB000000459</td>
</tr>
<tr>
<td></td>
<td>LFB 999 Call: Caller is Naomi Li on Level 22. She states she is in a neighbour’s house and there is smoke now everywhere.</td>
<td>LFB00000311; IWS00000515</td>
</tr>
<tr>
<td>01:30</td>
<td>LFB 999 Call. Caller is in Flat 175 (Level 20) with her husband and 3 children. The caller indicates that the fire is “in my neighbour’s.” She reports that smoke is coming into her flat. Her husband has blocked the doors and the family is now in the living room. Caller states she is “really scared” and “panicking.” She has seen the flames and can smell smoke.</td>
<td>LFB00000314</td>
</tr>
<tr>
<td>01:32</td>
<td>Caller lives in Flat 155 but has moved to Flat 201 on Level 23. Smoke is coming into the flat and the ‘windows already burning up’. Another person in the flat reports that fire and smoke is coming through the window.</td>
<td>LFB000000667</td>
</tr>
<tr>
<td>01:33</td>
<td>LFB 999 Call: Caller from Level 11 says “Please, please, the fire is inside of my flat.” He continues that “it’s inside of the room.”</td>
<td>LFB00000312</td>
</tr>
<tr>
<td>01:33</td>
<td>Caller in Flat 152 on Level 18. No smoke ‘in my house yet’ and ‘tried to go out through the fire escape and there’s just thick black smoke’.</td>
<td>LFB00000662</td>
</tr>
<tr>
<td>01:34</td>
<td>LFB 999 Call: Occupant in Flat 192 (Level 22) states “we are trapped in 192 ...” and continues “We couldn’t get down the stairs, because the stairs is full of smoke.” Operator advises the caller to close doors and windows to keep the smoke out of the flat.</td>
<td>LFB00000315</td>
</tr>
<tr>
<td>01:36</td>
<td>NWFC 999 Call; Occupant in Flat 9 (Level 3). The caller is identified as Mariko Toyoshima-Lewis. She explains that as a wheelchair user she is unable to self-evacuate. Mrs Toyoshima-Lewis reports that she can see smoke coming into the flat. Operator confirms that information has been passed to the fire crews. The call ends with the arrival of fire fighters to assist evacuation (exit building at 2:10 am).</td>
<td>LFB00000506</td>
</tr>
<tr>
<td>01:37</td>
<td>Caller from Flat 133 on Level 16. Reports that the fire is underneath, they tried to get out to the stairs, but it was dark and there was so much smoke they ‘ran back inside our flat’. Smoke coming underneath flat door.</td>
<td>INQ00000280</td>
</tr>
<tr>
<td>01:37</td>
<td>Caller in Flat 113 on Level 14. Smoke is coming in to the flat from the corridor. Tried to escape but had to come back.</td>
<td>LFB00000678</td>
</tr>
<tr>
<td>01:38</td>
<td>MPS calling LFB to say they have had a call from Flat 142 on Level 17. Caller apparently said, ‘they say there’s smoke coming into the...’. No further audio.</td>
<td>LFB00000668</td>
</tr>
<tr>
<td>01:38</td>
<td>LFB 999 Call: Caller is in Flat 205 (Level 23). 7 persons in the flat altogether. The caller confirms that no smoke is coming into the property but adds “but our flat was underneath, and that -- there was no smoke in there. It was absolutely</td>
<td>LFB00000317</td>
</tr>
<tr>
<td>Time</td>
<td>Action</td>
<td>Evidence</td>
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</table>
| 01:38  | LFB 999 Call: Occupant in Flat 95 (Level 12), reiterates fire is in neighbour’s flat (Flat 96), implies that smoke is in lift lobby. Additional calls are made from the same flat at 01:44 (embers have come through window and started fire in kitchen of Flat 96), 01:54 (caller reports that surrounded by fire - next door, on the “landing” and near the lift, below and on the flat windows. Describes the smoke in the flat as “terrible”. At the end of the call the flat occupants are advised to leave and appear to encounter fire fighters on doing so). | LFB00000318  
LFB00000324  
LFB00000332 |
| 01:37- 01:38 | Fire brigade re-enter south lift, rise to smoke effected floor at Level 11 or Level 12, discharge onto smoke-filled lobby. | NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Southlift.mp4 |
| 01:38  | Caller in Flat 182 on Level 21. Caller reports ‘not from outside but the smoke is coming from… the front of the flat.’ And ‘It’s very smoky in the landing.’. Occupants had tried to leave but was too smoky. Caller states that, ‘Something is right next door to us, it’s burning, it’s really burning.’. Further transcript seems to imply that the fire has reached the adjacent flat (presumably Flat 181) and begins to threaten their kitchen window. | LFB00000677 |
| 01:38  | Rania Ibrahim (Flat 203, Level 23) starts Facebook Live videos which shows the corridor filled with black smoke with very limited visibility. | Facebook Live:  
https://www.facebook.com/ribraham/videos/1499323993925/  
(NB. Accuracy of timing is not confirmed) |
| 01:40  | An increase of smoke is observed on CCTV footage on the 7th floor lobby. CCTV footage jumps from 01:25 to 01:40 between which there has been a significant build-up of smoke. | Op Northleigh Spread of Fire/Interactive/CCTV/7th floor.mp4 |
| 01:38  | LFB 999 Call. Caller is in Flat 115 (Level 14). She is alone with her baby. Reports smoke is coming in under the front door and through the windows. Advised to block the door and close windows. Caller cries, “there is fire coming from the door”. The call appears to end abruptly.  
Occupant calls back at 01:48. Asked if there is a room without smoke, caller replies, “All of them have smoke…” The smoke is coming in through the door the windows. She confirms she has already blocked the door and closed the windows. | LFB00000321  
LFB00000331 |
<table>
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<th>Time</th>
<th>Action</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>01:39</td>
<td>Caller from Flat 204 on Level 23. His flat is not yet compromised but for a little smoke, but he cannot escape through the lobby as, ‘I can’t see at all’. ‘I can’t see to get out, that is the problem.’</td>
<td>LFB00000329</td>
</tr>
<tr>
<td>01:40</td>
<td>Reduced visibility in Level 7 lift lobby. Occupants evacuated with assistance from firefighters.</td>
<td>NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Lift lobby.mp4</td>
</tr>
<tr>
<td>01:40</td>
<td>LFB Call. Occupant in Flat 111 (Level 14). Caller states he is on his own and his “whole flat is full of smoke.” The smoke is coming in through the windows and the door. Caller has locked himself in the bathroom. The operator advises him to put towels around the door to stop smoke coming in.</td>
<td>LFB00000322</td>
</tr>
<tr>
<td>01:41</td>
<td>Call from Flat 201, Level 23. Smoke in flat is getting thicker and occupants are getting sick. Fire subsequently breaches into flat.</td>
<td>LFB00000486</td>
</tr>
<tr>
<td>01:41</td>
<td>LFB 999 Call. Occupant in Flat 73 (Level 10): asked if there is smoke in the flat, the caller says “...there’s smoke coming up and the door [to lift lobby] is completely hot. Advised to stay in flat and block the door to stop any smoke coming in.</td>
<td>LFB00000319</td>
</tr>
<tr>
<td>01:43</td>
<td>Caller from Flat 175 on Level 20. Smoke is entering flat but not certain where from, however caller states that ‘It’s really smoky in the hallway now’ suggesting it is from the lobby. Unable to leave due to black smoke in the hallway.</td>
<td>LFB00000444</td>
</tr>
<tr>
<td>01:43</td>
<td>Caller from Flat 82 on Level 11. Caller asked if they can leave, states ‘The stairs will be completely full of smoke now’. Firefighter arrives at the flat.</td>
<td>LFB00000323</td>
</tr>
<tr>
<td>01:43</td>
<td>Caller in Flat 41 on Level 7. States smoke is coming into flat but no indication of where from. Firefighter arrives at the flat.</td>
<td>INQ00000373</td>
</tr>
<tr>
<td>01:44</td>
<td>LFB 999 Call. Occupant of Flat 95 (Level 12) states that, “fire embers have started a fire in the flat next door ... it’s come up through the windows, it’s gone into number 96”. The kitchen of 96 is on fire. The caller states that smoke is coming in to his flat and that it is “really smoky in here” and “someone’s trapped on 11th floor”.</td>
<td>LFB00000324</td>
</tr>
<tr>
<td>01:46</td>
<td>MPS conference call with LFB CRO and Occupant of Flat 133 on Level 16. Smoke is coming in through the front door.</td>
<td>LFB00000326</td>
</tr>
<tr>
<td>01:47</td>
<td>LFB 999 Call. Two callers from Flat 74 (Level 10): Caller 1 says they are still “inside”, asks how they are going to get outs and then says that they are going outside. Caller 2 then comes on the line. She confirms to the operator that they “can’t leave because there is smoke in the corridor, but people are leaving.” Call again at 02:00 (asking for further advice - smoke still coming in - and told to put sheets and towels down). Follow up calls from relative outside the building at 3:53</td>
<td>LFB00000330 LFB00000336 LFB00000592 LFB00000600</td>
</tr>
<tr>
<td>Time</td>
<td>Action</td>
<td>Evidence</td>
</tr>
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<td>-------</td>
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<tr>
<td>01:48</td>
<td>Caller in Flat 193 on Level 22. Caller says, ‘it’s getting smoky in the house’, and ‘a lot on the 22nd floor’.</td>
<td>LFB00000325</td>
</tr>
<tr>
<td>01:48</td>
<td>Caller from Flat 115 on Level 14. Smoke is coming from the front door and the window.</td>
<td>LFB00000331</td>
</tr>
<tr>
<td>01:50</td>
<td>LFB 999 Call. Caller from Flat 194 (Level 22). Occupant says smoke is coming into the flat and he can’t see anything. The operator advises that he close any windows, block doors and and stay low.</td>
<td>LFB00000328, LFB00000337, LFB00000695, LFB00000352, LFB00000395, LFB00000407</td>
</tr>
<tr>
<td></td>
<td><strong>02:00</strong>: a further call from Flat 194. Caller says he has been waiting for 15 minutes. He says the flat is “worse. It’s black in here. I can’t see a thing”. He is a pensioner and “can’t get about.” He mentions that his letterbox won’t close and is advised to block it with a towel.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>2:24</strong>: Call from Flat 194. Caller says “I’m so fucking frightened up here! ... 45 minutes I’ve been in my flat ... I’m jumping out the window...”</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>3:01</strong>: Call from Flat 194. Male says, &quot;Please come and get me&quot;. Says he is not able to get out of the property. “It’s too dark, it’s too hot.” He confirms that the fire is “next door” and says, “it’s on the other side as well.” Advised by operator to wrap himself in sheets and towels and get out. The caller asks for someone to come up and get him but then the call is cut off.</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>3:10</strong>: Surrey Fire &amp; Rescue call LFB. Surrey have just spoken to the family of the occupant of Flat 194. Surrey reports that there is so much smoke and flame that he cannot get out of the flat - “He is literally going to be running through flame – “. LFB advises Surrey to tell people to just get out.</td>
<td></td>
</tr>
<tr>
<td>01:54</td>
<td>Caller in Flat 95 on Level 12. Caller reports that fire is in the kitchen of Flat 96. Smoke is coming into the flat through the windows and front door. Reports that fire is outside his front door and has reached his landing. Looking out of the door he can see ‘dark and yellow’. Fire is burning the windows and later ‘coming in the window now’. Firefighters eventually arrive at the flat.</td>
<td>LFB00000332</td>
</tr>
<tr>
<td>01:56</td>
<td>Caller from Flat 165 on Level 19. Cannot leave as there is too much smoke outside.</td>
<td>LFB00000334</td>
</tr>
<tr>
<td>01:57</td>
<td>Caller in Flat 92 on Level 12. They could not get out because there was too much smoke and ‘we couldn’t breathe’. Smoke coming in from the door.</td>
<td>LFB00000335</td>
</tr>
<tr>
<td>02:00</td>
<td>Caller in Flat 74 on Level 10. Smoke is coming into the property, unclear exactly where from.</td>
<td>LFB00000336</td>
</tr>
</tbody>
</table>

**TABLE 5: BASIS FOR THE FIRST HOUR OF THE INTERNAL SMOKE SPREAD TIMELINE**
The compilation of 999 calls, including those presented in Table 5, is summarised in Figure 68 and Figure 69. There is still a large amount of data in the form of firefighter statements and testimony to the inquiry, surviving residents’ statements, and (albeit coarse) camera footage that could, when combined, allow for a more complete picture of internal fire spread and smoke migration.

Figure 68 shows that smoke was reported for the first time in the lobby area in 10th to 14th and 22nd and 23rd floors approximately 30-35 minutes after the first 999 call. Figure 70 shows that at approximately the same time, internal fires were reported on the 12th and 22nd floors. The fire on the 12th floor is in Flat 96, directly above the flat of fire origin. This flat was first reported on fire at 01:24.

At same time as the report of fire on 12th floor (01:24), a 14th floor occupant reports lobby as impassable due to smoke. Within two minutes of call from occupant of 12th floor fire flat (01:26), 12th floor neighbour reports smoke coming from outside the main door of Flat 96. This implies that the 12th floor lobby has smoke but not flames. Four minutes after report of fire on 12th floor (01:28), smoke is reported on the 11th floor landing that is preventing occupants from leaving.

The location of the flat on the 22nd floor is not identified in the 999-call transcript however calls suggest that occupants evacuated up to the 23rd floor. They then quickly became trapped in that flat due to smoke in the lobby on that level. Other calls at 01:30 from the occupants on Level 22 state that the visibility is “terrible” on the 22nd Floor.

Given the timelines and fire characteristics required for door damage, it is clear that early smoke migration (01:24 to 01:28) between floors 11th and 14th would have to be through open doors. Figure 70 shows the consequent damage of the area associated to Flat 96. Ultimately, Flat 96 suffered severe damage and the door was found half broken in the doorway. However, smoke is clearly spreading very rapidly in this area and at a rate that is not compatible with the fire induced failure of the entrance door of Flat 96. Therefore, other mechanisms must be responsible for the rapid ingress and spread of smoke. These mechanisms are not immediately clear but appear to have led to a single flat fire compromising the stairwell and lobbies of floors 10 – 14. It is important for Phase Two that, once all evidence is collected, the correlation between physical variables and evidence is considered in more detail.
Figure 68: Locations of 999 callers describing smoke in lift lobbies & smoke in stairs. Note that the locations shown here are not necessarily on the same floor as the fire or smoke being described by the caller, but instead the location of the caller at the time. No calls recorded from level 13 can be attributed to the early evacuation of level 13 occupants in the first 30 minutes of the fire event. Additional call received at T=251 from caller on 10th floor, describing smoke in lobby.
**Figure 69:** Locations from which 999 calls were made describing smoke and fire in flats. Note that the locations shown here are not necessarily on the same floor as the fire or smoke being described by the caller. Plot does not capture call durations; for example, call from level 23 at T=35 lasts for 55 minutes, not known at what time during caller describes fire in flat. No calls recorded from level 13 can be attributed to the early evacuation of level 13 occupants within the first 30 minutes of the fire event. Additional call received at T=251 from caller on 10th floor, describing smoke in flat.

**Figure 70:** Flat 96 as viewed from the Level 12 lobby, with broken front door visible in doorway.
5.3.4 Onset of General Untenable Conditions

At some point during this third stage of the fire, as more and more compartment fires were ignited, and smoke migrated into the egress paths and unaffected flats, general conditions within the building can be deemed to have become untenable. Figure 68 and Figure 69 show the increase in calls reporting smoke and fires in units as well as smoke in the lift lobbies and stairs.

Figure 71: Number of occupants in Grenfell Tower during the fire event from [4].

Dr Lane’s Phase One expert report [4] shows an overview of the number of people remaining in the building over time from the onset of the fire (Figure 71). The rate of evacuation slowed significantly at 01:50. At this point the fire has reached the East elevation windows of approximately 25 separate flats, and the North elevation windows of approximately 9 of those same flats (Figure 72). In this first hour of the fire most of the calls reporting smoke are localized in areas where the fires have been observed to breach the external envelope of the building (Floors 11th to 16th and 22nd and above). Given the significance of the external spread on all subsequent events potentially leading to the involvement of the compartment and then the breaching of the unit, the consistency of all this information is as expected.

See footnote (1) for approximate times for each stage.
5.3.4.1 INTERPRETATION

During this stage of the fire, the smoke was passable by firefighters with Breathing Apparatus (BA), and as shown in Figure 71 (adapted from Figure 14.17[4]), during this period at approx. 01:50, occupants stop evacuating the building. At this point, there was a period of approximately 20 minutes where no egress took place. At 02:06 the fire was declared a major incident and from this point, egress appears to have resumed however at a much lesser rate than before. The reasons for this are unclear.

Up to 02:45, 1/3rd of the 80+ calls had come from Levels 22 and 23 and another 1/3rd had come from Floors 10 – 12 suggesting these areas in particular were unpassable. Firefighters issued an official end to the “stay put” guidance and initiation of evacuation of remaining residents at 02:47, however they had been in a search and rescue mode prior to that.

The rapid decrease in egress of occupants at approximately 01:50 corresponded with the fire spreading laterally to the central panel of the east elevation and to the North elevation. Egress paths from the floors around Level 12 and above Level 20 had become unpassable, evolving from sporadic, localised unpassable areas at the start of Stage 3 to blocks of unpassable levels by this time. Therefore, the time range 01:50 – 02:00 is considered to mark the onset of generalised untenable conditions and the beginning of Stage 4.
5.4. ASSESSMENT OF CHARACTERISTIC STRUCTURAL HEATING DURING STAGE THREE

Heating of the structure is briefly assessed here to provide an indication of the likely impact of a typical compartment fire on the Grenfell Tower structure. The intent is not to provide an assessment of structural stability, but to give a baseline assessment purely based on a thermal analysis. This assessment utilises the temperature of the reinforcing steel (rebar) in the slab to make a crude assessment of any impact compartment fires might have had on load bearing capacity. Details of the analysis are provided in Appendix F. Two scenarios are evaluated, the presence of a post flashover compartment fire and heating via the external fire.

Information available at present is limited to the depth of the slab, indicated as 200mm in [SEA00000271] and [43] with a 50mm screed on the top side. The rebar depth is not known exactly at the present time. Coring results reported in [43] imply that the rebar could be located between 25 – 35mm from the slab underside, and a minimum concrete cover of 25mm is typically required in order for rebar to act effectively [44]. A 1D heat transfer model of a typical roof slab is developed. From this model, the temperature of the rebar in the slab can be evaluated and the time to reach onset of loss of strength is established.

The model assumes that the rebar temperature can be conservatively approximated as the temperature of the concrete between 25mm and 35mm depth in to the concrete slab [44]. The gas phase temperature was taken as having a lower bounding value of 850°C and an upper value of 1000°C as estimated in Section 5.4. A conservative estimate for the onset of the rebar degradation is 300°C so this will be taken as a lower bound failure criterion, while 550°C is more commonly taken as a failure condition for the rebar, this will be used as the upper bound failure criterion. The plot in Figure 73 presents the results of the two heating regimes implemented. The results are summarised in Table 6.

<table>
<thead>
<tr>
<th>Bound</th>
<th>25mm - 300°C</th>
<th>25mm – 550°C</th>
<th>35mm - 300°C</th>
<th>35mm – 550°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>28 mins</td>
<td>120 mins</td>
<td>40 mins</td>
<td>161 mins</td>
</tr>
<tr>
<td>Lower</td>
<td>40 mins</td>
<td>220 mins</td>
<td>54 mins</td>
<td>286 mins</td>
</tr>
</tbody>
</table>

Table 6: The table gives characteristic times to heat the rebar at 25mm and 35mm depth, to temperatures of 300°C and 500°C, under upper bound (1000°C) and lower bound (850°C) gas phase exposures. Times to reach the onset of loss of strength are in the range of 30 – 60 minutes. Times to reach the typical conservative design failure criteria of 550°C are in the range of 2 – 5 hours.

The first flat unit fires ignited due to re-entry of the fire from external flame spread are reported as beginning at approx. 01:20-01:30. This stage of the fire lasts until approx. 02:00, a maximum of 40 minutes after these fires ignited. Given the structural heating timescales calculated above, it is estimated that the structure is not at risk during this stage of the fire as the rebar in the concrete slabs of the first flats to catch fire will at most only be beginning to approach temperatures at which its strength is affected. This also does not account for the time associated with the fire growing to this fully-developed phase.

This conclusion is further endorsed by Buchanan [44] who states that, “Catastrophic failures of reinforced concrete structures are rare, but some occasionally occur. Observations have shown that when concrete
buildings fail in real fires, it is seldom because of the loss of strength of materials.” Thus, the approach used here can be considered as being very conservative.

![Figure 73: Heating curves for slab rebar located at 25mm and 35mm above the base of the concrete slab for upper bound (1000°C) and lower bound (850°C) gas phase temperature exposures.](image)

Given that the characteristic times of impingement of external flames on the interior slabs will be less than 25 minutes at this stage, it is clear that this mechanism of heating would also not impact the global stability of the structure. This is due to the short exposure time, the expectation that the temperature of the impinging flames will be no greater than the values assessed above, and the fact that the heat application is typically only localised around the window (see Section 5.3.2.1).

### 5.5. Compliance Issues Affecting the Characteristics of Stage Three

At this stage, the building is experiencing a fire for which it was not designed. The building envelope was not designed to withstand an external fire emerging from the building itself, thus the failure of the different components of the window system that allow for penetration of the fire into the building cannot be explained solely by compliance issues. There are clearly stronger and weaker elements and many of the weaknesses are associated with poor quality design and/or construction; issues which are important when considering recommendations for improvements in construction practice. Nevertheless, in the case of the Grenfell Tower fire, the failure of the window system will have happened by one path or another. It is not possible to establish a detailed sequence of failure (it will vary from unit to unit) but what is clear is that, given the high heat fluxes, all failure paths would have manifested within a very narrow period of time.
Once the fire has re-entered the building, compartmentalization is the main line of defence. Compliant systems would have helped to protect egress paths and deliver safe paths for the occupants to evacuate. While the external fire contributes to ignition of the unit furnishings, the energy contribution to the unit is limited and localized to the areas around the window. Thus, there is no reason for compartmentalization requirements designed to withstand a post-flashover fire, not to be capable of withstanding a fire of the nature of that in Grenfell Tower.

Occupant behaviour (leaving doors open) or firefighting operations most likely had an impact on the capability of smoke and flames to migrate from the units towards the lobby and stairs. Nevertheless, this possibility cannot exonerate the need for compliant compartmentalization features (walls, fire doors, fire stop, etc.).

The design of the lobby and single stair egress called for greater redundancy by means of a smoke management system. The system was not designed to manage the smoke generated by fires in multiple units, therefore the performance of this system could have not been guaranteed given the nature of the Grenfell Tower fire. Independent of the conditions of the smoke management system for Grenfell Tower, it is important to revisit the compliance requirements for ventilated lobbies if the scenario of external fires is to be considered.

5.6. SUMMARY

- The third stage of the fire begins at approximately 01:30 when the external fire propagation reaches the top of the building and begins to spread laterally.
- The principle mechanism for lateral spread of fire around the external cladding of Grenfell Tower was via the architectural crown.
- Burning molten materials and debris fell from the top down, collecting on horizontal shelves and initiating new fires which then spread back up the building. These fires will progress upwards towards the fire that originated them, further up the building.
- This was more prominent higher up the building as lateral expansion of the smoke plume from fires lower down the adjacent façade resulted in more generalised pre-heating of the upper parts of the façade, aiding their subsequent ignition and downward spread.
- A fire that is capable of spreading over the surface of the façade system will impose sufficient fluxes of heat, that breaching of the façade at window locations is inevitable, regardless of the detailing of the window and its surroundings.
- Once fire has re-entered it may act as an ignition source resulting in a fire that may or may not result in flashover.
- Adequate compartmentalization would be expected to restrict any resulting fire to that unit. This is valid for a single unit fire and there is no reason why it should not be valid for a fire that spreads externally.
- Early internal spread of smoke on and around floors, where early ingress of the external fire led to compartment fires, implies compromised performance of internal compartmentalization.
- Fire induced compromise of the integrity of the flat doors would have required a post-flashover fire based on the subsequent testing of doors by the BRE. The brief period of time until loss of compartmentalization in Stage 2 and Stage 3 (as evidenced by smoke appearing in west and south facades) is not consistent with the longer timescales associated with the fire induced failure of the
doors. It is therefore very likely that doors were left open allowing free migration of some through undamaged doors.

- Analysis of emergency calls and firefighter statements indicate that communal lobbies and stairwells in the middle of the building (Levels 10-14) and at the top of the building (Level 20 and above) rapidly became either actually, if not seemingly, impassable to occupants on and around those levels by approximately 01:50.
- This rapid spread of smoke points to human factors (actions on the day, or in the design and maintenance) hindering the performance of the compartmentalization. The exact form of this involvement is unclear based on the available evidence however possibilities include:
  - Doors to flats with compartment fires being left open / door closers removed.
  - Firefighter intervention damaging flat doors through forced entry / holding flat and stair doors open to enable passage of hoses for direct intervention.
  - Poor design of compartmentalization, primarily doors, since no evidence has been found of inadequate walls.
  - Poor implementation of fire stopping during construction and subsequent renovations / works. Nevertheless, no significant evidence of poor practise has been found
  - Any use of the lift.
  - Smoke ventilation shaft.
- In general, the timeline of egress of occupants, reports of smoke and fire locations, and the actions and locations of firefighters are not well understood at this stage, based on the available evidence. This information is crucial to identifying the mechanisms by which smoke was able to migrate to, and through, the core of the structure so rapidly. Work on correlating physical evidence with testimony should continue in Phase Two.
- An analysis of the effect of compartment fires on the structural stability of the floor slabs indicates that the floors would have maintained structural integrity during this Stage.
- The third stage ends at approximately 01:50 – 02:00 when general conditions throughout the building can be considered untenable.
6 STAGE FOUR: UNTENABLE CONDITIONS IN THE BUILDING

There is not much that can be said about this stage of the fire beyond what has been described in detail in Dr Lane’s Phase One expert report [4]. This section will therefore focus simply on establishing any indication of tenability and a post event final damage assessment. At this stage, the fire has involved a very large number of units, compartmentalization has been breached at multiple levels and firefighting capabilities have been significantly exceeded by the event. Conditions in the building are difficult to establish but it is clear that a significant part of the building is untenable. Egress potential has diminished dramatically, as clearly indicated by the slow rate of evacuation of building occupants. The following provides an indication of overall tenability based on the location and movement therein of casualties from the fire. Post fire damage assessment provides further information on the conditions within the building at this later stage of the fire.

6.1. LOCATION OF CASUALTIES

Based on the DVI Reconciliation Unit final floor plan of recoveries from Grenfell Tower [MET00008018], the location and movement of casualties based on their apartment of origin and their end location was tabulated. Figure 74 shows a visualisation of casualties found on the same level on which they were known to have lived.

![Casualties found on their Level of Origin](image-url)

**Figure 74: Visual representation of casualties found on the same level as their apartment of origin. In some instances, casualties moved laterally from their own apartment to apartments in the southwest corner of**
THE BUILDING (APARTMENTS ‘3’). THE SOUTHWEST CORNER OF THE BUILDING WAS THE LAST CORNER TO BE DIRECTLY EXPOSED TO EXTERNAL FLAME SPREAD ON THE BUILDING FAÇADE.

While most casualties were found within their apartment of origin, twenty-nine (29) casualties were found in other locations. Their movement is visually represented in Figure 75.

**Figure 75:** VISUAL REPRESENTATION OF CASUALTIES FOUND ON A FLOOR OTHER THAN THE ONE OF THEIR OWN FLAT. DATA SOURCED FROM MET00008018. 19 CASUALTIES WERE ABLE TO REACH THE EXIT STAIR BUT PROCEEDED UPWARDS RATHER THAN DOWN THE STAIR. 3 CASUALTIES WERE FOUND EITHER IN THE STAIR OR IN ADJACENT LOBBIES, SUGGESTING THEY ATTEMPTED TO TRAVEL DOWN THE EGRESS STAIR.

There is a clear cut off above Levels 12 – 13 where the vast majority of occupants living on or below these floors survived. Above these levels fatalities are grouped into two distinct bands.

The number of casualties immediately above Levels 12-13 corresponds to these levels being unpassable relatively early on in the event. Below these levels, all people escaped or were rescued. Immediately above these levels (14 – 17), occupants/casualties don’t appear to have been able to move up or down. This is evidenced in the statements of firefighters which describe a sustained effort from the onset of Stage Four onwards, to extinguish and climb beyond Levels 12 and 13. There are limited reports of firefighters accessing the upper floors prior to this [MET00005348, MET00005590, MET00005350, MET00005384] however these appear to be isolated incidents during earlier stages of the fire.

By 02:05 [MET000080602] it is already documented that getting beyond these floors is presenting a significant difficulty. Numerous accounts of the building being clear up to the 12th floor and firefighting teams being sent to the 12th floor to extinguish fires are available [MET00007520, MET00005357, LFB00000007] spanning times estimated to be as late as 08:30. Typically, firefighters report a lack of water pressure when trying to extinguish fires on this floor. Numerous other statements [MET00005437, MET00005299, MET00005478] with unclear
timings report attempts to firefight and search and rescue on these floors that were impeded by consistent high levels of dense smoke and heat.

At some stage (unclear) Levels 18 – 19 also appear to have been untenable to the point that occupants from these levels attempted to move up or down the building. This would also explain why occupants/casualties were found in Levels 14 – 17, located between regions of untenability.

Above Level 20, occupants/casualties were prevented from moving downwards early on and either remained in their flats, moved to the SW corner flats, and / or moved to the 23rd floor (potentially to try and access the roof of the building) where they remained trapped.

While rescue operations continued throughout the first hours of this stage, it is unclear from exactly where these rescues took place. The dynamic location of the bridgehead does however provide some indication as to the levels which firefighters were able to reach. The following diagram (Figure 76) adapted from [4] can be used to illustrate this movement.

![Diagram](image)

**Figure 76:** Location of the bridgehead throughout firefighting activities at Grenfell Tower [4].

The diagram shows that, following the onset of generalised untenable conditions, firefighters were attempting to move up the building however were soon forced back down due to smoke concentrations as far down the building as Level 3. The implications of the extent of usable duration of breathing apparatus would mean that the firefighters were generally operating at lower levels over this period of time, therefore rescue operations would likely have been concentrated beneath Levels 10-12.

### 6.2. POST-FIRE STRUCTURAL ASSESSMENT

An assessment of images taken of all flats within the tower post fire have been assessed and categorised according to the level of damage. A summary table of this assessment is provided in Appendix G. Damage is grouped in to five categories:

- No damage
- Minor: Smoke damage only i.e. soot ingress through windows / doors
• Moderate: Smoke and partial fire damage
• Severe: Significant structural damage and spalling
• Major: Post-flashover fire conditions

All 10 instances of no damage occur from the 8th floor down with 6 of those on the lowest 2 levels. There are 15 instances of minor damage from the 10th floor down. Other than 1 flat on each of the 11th and 12th floors which have moderate damage, and 2 flats on the 11th and 1 on the 12 that have severe damage, all other flats from Level 11 upwards experienced major damage. All flats above the flat of fire origin experience severe (2) or major (16) damage. Ignition of these flats is likely to have been in the time window represented by Stages 2 and 3, and the early stages of Stage 4.

From Level 10 upwards, the vast majority of lift lobbies experienced either severe (5) or major (9) damage. There is a strong correlation with the number of flats experiencing severe damage and similar damage occurring in the lift lobbies. This implies systematic failure of fire doors following post-flashover fires. In most cases, fire doors are not visible in the images provided, indicating that they have subsequently been removed or were consumed in the fire.

From the 8th floor down, stair doors showed no signs of damage. From the 9th floor upwards, the degree of damage to the stair doors ranges from soot on the door (e.g. Level 11) to moderate fire damage on the lobby side of the door (e.g. Level 19). The variability in the degree of damage is believed to be a function of smoke ingress in the lobby, firefighter interaction with the doors, and internal penetration of flames into the lobby area. Unfortunately, not all of the stair doors could be evaluated from evidence provided because they were removed from hinges on floors where it is critical to evaluate their performance. It is not clear if the cause of this is due to the fire itself, firefighting and search and rescue activities, or subsequent removal of doors for forensic testing.

A post-fire structural assessment has been conducted by DeconstructUK [43] followed by shoring up of the structure to enable safe inspection of the site. In general, aside from sporadic inconstancies, the authors note that the worst effects of the fire, in terms of structural damage, are found between the 10th to 14th floor. Above this, fire damage is extensive but not as serious in structural terms. Below this, damage to the structure is typically negligible.

The authors state that, in all but a few locations, the effect of the fire is on the cover (the outer layer). Internally, the concrete appears unaffected. This is indicated by assessment of sample cores taken from the building. Spalling of concrete columns at 14th, 16th, 20th, and 21st floor levels has left rebar exposed, with spalling depths ranging from 35 to 100 mm. In two locations, this reinforcement has yielded. However, the authors do not believe this to be a concern in terms of the stability of the structure.
Figure 77: This figure taken from [43] indicates degrees of structural damage throughout the Grenfell Tower. Green represents flats with little or no damage and imperceptible deflection. Amber represents flats where spalling has occurred, reinforcement is partially visible, and/or visible deflections are less than 100mm. Red represents spalling has occurred, reinforcement is visible and detached from the slab or the slab is in a degraded state, and/or deflections are larger than 100mm. No explanation of the numbering system shown in the graphic is provided.

Figure 77 provides an overview of the structural damage by floor and by flat extracted from the DeconstructUK report [43]. Where slabs are coloured green, this represents flats with little or no damage and imperceptible deflection. Amber represents flats where spalling has occurred, reinforcement is partially visible, and/or visible deflections are less than 100mm. Red represents spalling has occurred, reinforcement is visible and detached from the slab or the slab is in a degraded state, and/or deflections are larger than 100mm. No explanation of the numbering system shown in the graphic is provided.

This correlation is assessed in conjunction with observed durations of fires to ascertain if the observed damage corresponds to the duration of fire exposure. Select photographs of Grenfell Tower during the fire event were sequenced and analysed to identify bounding fire durations internally i.e. the shortest and longest times for burning within flats. Figure 78 presents a sequence of photographs of the north elevation from 02:34 am to 04:43 am. Flats in the northwest corner (numbered “5”, right of centre in photos below) were the subject of focus as all northeast corner flats (numbered “6”, on the left of centre) were classified as either “severe” or “major” in the post-fire damage assessment, and thus would not have provided a clear delineation between short and long duration fires.

Flats 105 and 115, on Levels 13 and 14 respectively, are highlighted in red. These were identified in the DeconstructUK post-damage assessment as flats where spalling occurred, reinforcement was visible and detached from the slab and the slab was found in a degraded state and/or deflections were larger than 100mm. These flats are shown to be initially exposed to external flames at 02:34. Flames are visible inside these flats through to 04:43. In photos beyond 04:43, these flats were obscured by smoke, making it difficult
to determine the end of burning within these flats. In any case, the available evidence shows that fires burned internally within Flats 95 and 105 for at least 139 minutes i.e. over 2 hours and 19 minutes. This corresponds to the analysis in Section 5.4 as falling within the period of time associated with steel reaching a design failure criteria temperature.

Flats 9, 15, 25 & 35 are highlighted in green. These flats were determined by DeconstructUK to have suffered little to no damage and imperceptible deflection. As seen in Figure 78, all four flats are shown to be exposed to external flames at 03:07. Flames are no longer visible in Flats 15 and 25 at 03:44. However, at this time, flames remain visible in Flats 9 and 35, and are not seen to be extinguished until 04:20. Thus, the available evidence shows that fires burned internally within Flats 15 & 25 for less than 37 minutes, and within Flats 9 and 35 for less than 73 minutes. This again is in agreement with the results of the heat transfer analysis shown in Section 5.4, where rebar steel is expected to have reached the range in which its strength is beginning to degrade, however the slab as a whole still retains sufficient load carrying capacity hence little to no visible damage and imperceptible deflections.

The appended post-damage assessment, based on the 360 degree photographs, is visually summarized in Figure 79 below. The flats analysed above are highlighted in red and green below. As can be seen, Flats 95 and 105 suffered severe damage i.e. post-flashover conditions. Flats 15 and 25 suffered minor damage i.e. from smoke only. Flats 9 and 35 suffered moderate damage i.e. smoke and partial fire damage. Thus, the available evidence suggests that the duration of fire exposure corresponds with the severity of structural damage experienced within the impacted compartment.
Figure 78: A sequence of photographs of Grenfell Tower North elevation during fire event. Flats showing indicative long and short duration fires are highlighted in red and green, respectively.
### CONDITIONS

<table>
<thead>
<tr>
<th>Flat/Lobby Condition</th>
<th>None</th>
<th>Undamaged</th>
<th>Minor</th>
<th>Smoke damage only i.e. soot, ingress through window/doors, etc.</th>
<th>Moderate</th>
<th>Smoke and partial fire damage</th>
<th>Severe</th>
<th>Significant structural damage and spalling</th>
<th>Major</th>
<th>Post-flashover conditions</th>
</tr>
</thead>
</table>

#### Door Condition

- **No damage**
- **Damage to door/door frame**
- **Broken door with smoke/fire damage**
- **Broken door, no smoke/fire damage**
- **Door completely gone; unclear if burned or removed**

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**Figure 79: Graphical summary of post-fire damage assessment included in appendix. Flats highlighted in red and green. Note that two flats 9 and 35 correspond with moderate damage conditions, whereas flats 15 & 25 correspond with minor damage conditions.**

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**6.3. SUMMARY**

- This stage represents the period of the fire, after 02:00, where conditions within the wider building of Grenfell Tower could be considered as untenable.
- Egress / rescue of occupants from the tower during this stage was considerably slower than in previous stages providing an indication of increasingly challenging conditions within the building.
- Firefighter operations within this stage would likely have been confined to the lower levels due to the deteriorating conditions within the building, especially above floor 12.
- With multiple compartment fires already occurring and more igniting as the external fire continued to spread around the building, any firefighter operations or egress actions are far outside the intended strategy for the building and implied by regulatory compliance.
- Locations of fatalities are consistent with records from emergency calls and firefighter statements regarding locations where egress was compromised.
- Most fatalities occurred on the 14th to 17th and 20th to 23rd floors which corresponds to early reports of lobbies made impassable by smoke and heat.
- Flats on Level 12 and upwards almost exclusively experienced post-flashover fires. This corresponds well to observed visible structural damage.
• There is a direct correlation between number of severe fires and severely damaged lift lobbies indicating that fire doors separating individual flats from the lobbies were not sufficient for the thermal load experienced.

• In general, the structure remains stable, however most instances of spalling and structural damage are reported in the middle floors. The reasons for this distribution are not immediately clear. While a post-fire analysis enables this conclusion, there are no realistic means by which anyone could establish during the event that the structure remained sound at this stage of the fire.
7 CONCLUSIONS

Analysis indicates that a relatively minor, localised fire, compromised the uPVC window fittings and ignited one of the flammable components of the cladding by direct flame/plume impingement. This likely occurred before 01:05, and before first responders entered Flat 16. This marked the end of the first stage of the fire. From this point forward, the “stay put” strategy was compromised and evacuation of occupants was an option to consider. Firefighters would have been operating outside of their prescribed operating procedures. The building performance implied by the design approach followed was also breached.

Fire spread up the façade was inevitable once the fire was established on the outside of the façade system. Based on similar international events, the rate of spread was not unusual. Breaching of the window assemblies of flats higher up the building was also inevitable given the comparative levels of heat flux delivered by external fires to those required to break the window assemblies or induce glazing failure. Performance of external detailing such as fire-stopping or window units had no bearing on this outcome due to fire spreading over the exterior of the façade system. Fire reached the top of the building at approximately 01:30 which marks the end of the second stage of the fire. Throughout this stage, notwithstanding the fact that tenability levels in some lift lobbies is questionable, egress or rescue is the preferred option. The structural integrity of the building is not in question.

An important conclusion that cannot be overlooked is the complexity associated with predicting the rate of spread of a fire over a system as complex as these façade systems. Current performance criteria do not give justice to the complexity of the systems and observation of past fires does not provide sufficient information. While significant non-compliances have been established, the compliance approach used to determine “adequate” fire spread needs to be revisited and should be studied in much greater detail in Phase Two. This analysis should address not only technical issues pertaining to the fire dynamics associated with these complex systems, but should also focus on the implied competence introduced by Building Regulations. It is clear that currently there is an inconsistency between the necessary competency to address such complex systems, the levels of competency interpreted as required by Building Regulations and the mechanisms that serve to enforce competency. This applies to all aspects of the design, build, approvals and maintenance processes.

One key distinction between the fire at Grenfell Tower and other fires that have seen extensive vertical fire spread was the performance of the architectural crown, in particular its propensity to support lateral flame propagation, drip molten material and drop burning debris. This architectural crown was a key component that enabled the extensive lateral spread of fire around the entirety of Grenfell Tower.

Despite having several levels of containment, smoke and heat reached the stairwell early on in the fire. A variety of potential mechanisms, most likely linked to human action, error occurring either during the fire event or during design, construction and ongoing maintenance of the building, are most likely associated with the rapid internal spread of heat and smoke within the building. This rapidly impeded egress of occupants in the region around Floor 12 and above Floor 20. While human factors are relevant, the failure of compartmentalization needs to be treated as a compliance issue. The severity of interior fires generated by external fires is most likely very similar to that of a conventional compartment fire. Thus, fire resistance requirements, if valid for a conventional compartment fire should be valid for internal fires initiated by external fires. This aspect needs to be explored in Phase Two because compliance in matters of compartmentalization should be much less complex, and thus robust improvements should be easy to implement.
A combination of these mechanisms and also potentially fire door failure as a result of multiple severe compartment fires led to generalised untenable conditions throughout the Tower by approximately 01:50 – 02:30. This marks the end of the third stage of the fire.

Beyond this point, in the fourth stage, firefighting activities are governed by conditions in the building and are performed in an ad-hoc manner. There is considerable risk to those rescuing and being rescued, however egress remains the preferred option. Prior to widespread untenable conditions throughout the building, the structural integrity is not considered to have been compromised to an extent that put occupants and rescuers lives at risk. Only beyond the point at which general conditions in the building were untenable would the structure could be deemed at risk. Post-fire analysis indicates that this risk is generally localised and in the middle region of the building but this could have not been assessed during the event. The reasons for this are as yet undetermined. Structural assessment methods that could enable firefighters to establish the risk of structural failure appear as a potential improvement to operations and should be explored in Phase Two.
8 REFERENCES


4. Lane, B., “Grenfell Tower – fire safety investigation: The fire protection measures in place on the night of the fire, and conclusions as to the extent to which they failed to control the spread of fire and smoke; the extent to which they contributed to the speed at which the fire spread, Report, 12th of April, 2018.


17. Dynamic Mechanical Analysis Data provided by Prof. Bisby, University of Edinburgh


41. CFRA Fire and Rescue Authorities Operational Guidance, GRA 3.2 Fighting fires – In high rise buildings, Dept. CLG, Feb 2014.
APPENDIX A. SMOKE FILLING MODEL

The description of the fire growth in the early stages of the fire depends on the surface area of combustible materials burning, as well as on the type of fuels burning. In most cases it is very difficult to establish precisely what is burning, the relevant properties of the materials and also the area burning. A simple and common way of characterizing a wide range of growing fires is the “αt²” fire [20]. The value of “α” represents all the properties of the burning materials while the “t²” the growth of the area in time (t is time in seconds). Many tests have been done in the past for various materials and data sets are available that serve to characterize the corresponding value of “α” for numerous combustible materials. These classify fires in four categories: slow, medium, fast and ultra-fast fire growth. The value of “α [kW/s²]” covers the range of α=0.0029 for a slow fire to α=0.1876 for an ultra-fast fire. To represent a broad spectrum of fire growth behaviour the whole range of fire growth rates will be used here. This is necessary given the lack of clarity regarding the exact point of origin and thus type, orientation and position of the fuel exposed. The range covers all possible fires according to the available literature data. The range is not established to attempt to define the actual rate of growth of the fire, but to cover all possible conditions.

The model, described below, solves a simple set of equations over sequential, small time, increments to describe the amount of smoke produced by a fire and the subsequent contribution that it makes to the hot-layer of smoke that builds beneath the compartment ceiling, and gradually descends towards the floor. Where terms in these expressions span across time-steps, superscripts t and t+1 have been used to differentiate between terms that refer to the previous and new time-step respectively. Where no guidance is given, all terms refer to the same time-step.

The size of the fire, \( \dot{Q} \) (kW) at any point in time, t (s), post-ignition, is characterised as:

\[
\dot{Q} = \alpha t^2
\]

**EQUATION 4**

It is only the convective portion of this total energy release that contributes to the fire plume, and this portion, \( \dot{Q}_c \) (kW), is defined as:

\[
\dot{Q}_c = \frac{\dot{Q}}{1.5}
\]

**EQUATION 5**

As the plume rises due to buoyancy created by this heat, \( \dot{Q}_c \), air is entrained into the plume causing it to increase in mass the higher it rises. The mass flow rate of smoke in the plume, \( \dot{M}_a \) (kg/s), as a function of the height above the base of the fire, z (m), is given as:

\[
\dot{M}_a = E \left( \frac{g \cdot p_a^2}{c_p \cdot T_a} \right)^{1/2} \cdot \dot{Q}_c^{4/3} \cdot z^{5/3}
\]

**EQUATION 6**

Where E is a dimensionless constant (0.21), g is the acceleration due to gravity (9.81 m/s²), \( p_a \) is the density of air (1.2 kg/m³), \( c_p \) is the specific heat capacity of air (1.0 J/kg·K), and \( T_a \) is the temperature of the ambient air (288 K).
This entrained air is orders of magnitude larger than the other components of the smoke, therefore the mass flow of air is assumed to be equivalent to the mass flow of smoke in the plume, $\dot{M}_a$ (kg/s), therefore:

$$\dot{M}_a \approx \dot{M}_s$$  

**Equation 7**

It is this mass flow that creates and subsequently continually feeds the smoke layer. Thus, it is necessary to determine the temperature of the smoke plume, $T_s$ (K), to subsequently establish the temperature of the hot upper layer, $T_u$ (K). The smoke plume is given as:

$$T_s = T_a + \frac{\dot{Q}_c}{\dot{M}_s \cdot c_p}$$  

**Equation 8**

Having established the characteristics (mass and temperature) of the smoke entering the upper layer, the mass of the upper layer, $m_u$ (kg), can be established at each time-step as:

$$m_{u}^{t+1} = m_{u}^{t} + \dot{M}_{s}^{t+1} \Delta t$$  

**Equation 9**

Where $\Delta t$ is the length of the timestep (s). This mass can be equated to a height of the smoke layer, $H$ (m), using the temperature, $T_u$ (K), and subsequently density, $\rho_u$ (kg/m$^3$), of the upper layer. The temperature of the upper layer, $T_u$ (K), is established as:

$$T_u^{t+1} = \frac{m_{u}^{t} T_u^{t} + \dot{M}_{s}^{t+1} T_s^{t+1} \Delta t}{m_{u}^{t} + \dot{M}_{s}^{t+1} \Delta t}$$  

**Equation 10**

The density of the upper layer, $\rho_u$ (kg/m$^3$), is established as:

$$\rho_u = \rho_{\infty} \left(\frac{T_a}{T_u}\right)$$  

**Equation 11**

These parameters are then equated to the height of the smoke layer, $H$ (m), as:

$$H = \frac{m_u}{A \cdot \rho_u}$$  

**Equation 12**

Where $A$ (m) is the area of the footprint of the compartment. Combined, these expressions can be used to depict the evolution of the smoke layer height and temperature.
APPENDIX B. Verification of Bounding Fire Sizes

An analysis conducted with the aim of providing coarse bounds to the fire scenarios that could potentially have occurred in the kitchen of Flat 16 was presented in the body of the report. The simplest possible approach was followed to keep the precision of the analysis consistent with the range of accuracy and detail provided by evidence. Given the limited information available on the earlier stages of the fire, it is important that the calculations do not provide an unrealistic expectation of precision that then cannot be validated by evidence. Better analysis tools exist that could provide more accurate characterization of the fire, nevertheless, these tools will only be used to establish if the bounds provided by the simple model are appropriate and to explore the influence of variables omitted by the simplicity of the model. Therefore, the modelling results produced here do not attempt to match the exact timeline of the fire. Rather they intend to provide an indication of the impact of a variety of fire sizes and orientations on compartment temperatures and thus inform the reliability of the analysis presented in the body of the report.

Zone modelling of the kitchen fire in Flat 16 has been performed using the Consolidated Model of Smoke and Heat Transport (CFAST) tool developed at the National Institute of Standards and Technology (NIST), USA. This tool is used to assess temperatures and HRRs at the point in time when the smoke layer interface reaches its lowest point. Computational Fluid Dynamics (CFD) modelling using The Fire dynamics Simulator also developed by NIST was undertaken to confirm the accuracy of the range of HRRs and compartment temperatures. While use of these models is not intended to serve as a full sensitivity analysis, they do serve the purpose of testing model assumptions and several different scenarios, providing confidence in the results presented in the main body of the report.

ZONE MODELLING

CFAST MODEL SCENARIOS

Two model variations of the Flat 16 fire scenario have been constructed. Scenario 1 represents the assumed ventilation conditions during the kitchen fire event based on the available evidence. The kitchen door is closed and the main kitchen window is only partially open (tilted position). An example of this scenario is shown in Figure 80. The purpose of this model is to provide verification of the range of compartment temperatures and HRRs estimated by the analytical approach described in the main body of this report.

Scenario 2 takes advantage of the extra functionality of the model to explore the potential conditions that could result from different ventilation configurations, namely if the kitchen door was open or closed for the duration of the fire, to try to provide confirmation of this potential variable. Thermal imaging camera footage [MET00005810-17] also show the door and window to Bedroom 1 open as the firefighters enter and search the flat for the first time. The Scenario 2 model replicated this as shown in Figure 81.

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CHARACTERISTIC FIRE SCENARIOS

Four characteristic fire growth rates are simulated to establish bounding values for the compartment temperature and HRR at the point when the kitchen compartment has filled with smoke. Growth rates represent the range explored in the main body of the report i.e. slow, medium, fast and ultra-fast. The HRR is allowed to grow and the value at the time corresponding to the smoke layer interface reaching the compartment floor is recorded. The model also provides some measure of physical cap on the magnitude of the HRR and the model is allowed to run in order to see what this value is. The other results recorded are the time at which the smoke layer interface reaches the floor and the temperature of the smoke layer at this time. Results are presented in Table 7 and discussed below.

FIGURE 80: SCENARIO 1: KITCHEN FIRE SCENARIO WITH VENTILATION CONDITIONS BASED ON OBSERVED EVIDENCE. THE KITCHEN DOOR IS CLOSED, AND KITCHEN WINDOW IS PARTIALLY OPEN.

FIGURE 81: SCENARIO 2: KITCHEN FIRE SCENARIO WITH WINDOW PARTIALLY OPEN AND KITCHEN DOOR FULLY OPEN. THE DOOR FROM THE CORRIDOR TO BEDROOM 1 AND WINDOW IN BEDROOM 1 ARE ALSO OPEN AS OBSERVED IN THERMAL IMAGING CAMERA FOOTAGE [MET00005810-17].
RESULTS

Results from Scenario 1 modelling correlate well with the results from the analytical model described in the main body of the report. The results show the range of time for the smoke layer to descend as 50 – 200s (40 – 140s in empirical model), the upper layer temperature range at this point as 125 – 250°C (100 – 220°C in empirical model), the range of HRR at this time as 110 – 360kW (60 – 300kW in empirical model) and the limiting peak HRR imposed by the model as ~360kW.

Results from Scenario 2 demonstrate that the extra ventilation provided by the open door would likely lead to a flashover scenario. The smoke layer takes longer to reach its lowest point due to the extra leakage to the rest of Flat 16 (115 – 850s). The upper layer temperature at the point at which the smoke layer interface reaches its lowest point is in the range of 750 – 900°C, with temperatures beyond the 500 – 600°C range associated to flashover conditions\(^\text{28}\). The corresponding peak HRR which is the limiting value imposed by the model is of the order of 1.5MW.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Growth Rate</th>
<th>Spread Rate [mm/s]</th>
<th>Ventilation</th>
<th>Time for Smoke Layer to Reach Floor [s]</th>
<th>Corresponding Temperature of Hot Layer [°C]</th>
<th>Corresponding HRR [kW]</th>
<th>Peak HRR [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Slow</td>
<td>1.2</td>
<td>Kitchen Window 10%</td>
<td>200</td>
<td>125</td>
<td>110</td>
<td>350</td>
</tr>
<tr>
<td>1</td>
<td>Medium</td>
<td>4</td>
<td>Kitchen Window 10%</td>
<td>125</td>
<td>160</td>
<td>160</td>
<td>355</td>
</tr>
<tr>
<td>1</td>
<td>Fast</td>
<td>6.7</td>
<td>Kitchen Window 10%</td>
<td>75</td>
<td>175</td>
<td>250</td>
<td>360</td>
</tr>
<tr>
<td>1</td>
<td>Ultra-Fast</td>
<td>9.5</td>
<td>Kitchen Window 10%</td>
<td>50</td>
<td>250</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>2</td>
<td>Slow</td>
<td>1.2</td>
<td>Kitchen Window 10%, Kitchen Door 95%</td>
<td>850</td>
<td>900</td>
<td>1550</td>
<td>1550</td>
</tr>
<tr>
<td>2</td>
<td>Medium</td>
<td>4</td>
<td>Kitchen Window 10%, Kitchen Door 95%</td>
<td>500</td>
<td>875</td>
<td>1550</td>
<td>1550</td>
</tr>
<tr>
<td>2</td>
<td>Fast</td>
<td>6.7</td>
<td>Kitchen Window 10%, Kitchen Door 95%</td>
<td>220</td>
<td>850</td>
<td>1550</td>
<td>1550</td>
</tr>
<tr>
<td>2</td>
<td>Ultra-Fast</td>
<td>9.5</td>
<td>Kitchen Window 10%, Kitchen Door 95%</td>
<td>115</td>
<td>750</td>
<td>1550</td>
<td>1550</td>
</tr>
</tbody>
</table>

Table 7: Results from the 8 CFAST model configurations run.
CFD MODELLING

An overview of the CFD model is shown in Figure 82. The modelled grid resolution is 5cm x 5cm x 5cm as recommended by the FDS user manual\(^2\). A grid independence study was not conducted given that the intention was not to attain a high-fidelity model. The recommended grid resolution was therefore deemed sufficient.

It is assumed that doors to the living room and 2\(^{nd}\) bedroom are closed thus they will not participate in the simulation. These areas have therefore been excluded from the model to save on computational load. A comparison simulation with the entire flat modelled has been run and the exclusion of these areas does not change the modelling results for the kitchen compartment.

The fire is defined as a mass loss rate from a surface with properties of polystyrene. The soot yield is set at 0.2, and CO yield at 0.02. The fire locations are defined as either:

- Floor -> fire is located at floor level as per Figure 82.
- Fridge -> the fire is located on the back of the fridge as per the image in Figure 83.

When the fridge is the fire location, the entire fridge back is defined as the burning area. When the fire is at floor level, the fire area is sized to maintain a heat release rate per unit area (HRRPUA) as 0.55MW/m\(^2\). These two fires represent two extreme conditions. Fires burning on horizontal surfaces but elevated from the floor will lead to results somewhere in between these conditions. Given that the purpose of this analysis is only to bound the potential temperatures within the compartment it was not deemed essential to run these scenarios.
Several ventilation conditions were studied to assess the role of ventilation on the evolution of the compartment. Ventilation variations for the kitchen are as follows:

- **Case I**: Large window tilted inwards only, all other openings closed, as per the original assumption in the Phase One report (see Figure 84)
- **Case II**: Large window tilted inwards, small window open, all other openings closed (see Figure 83)
- **Case III**: Large window tilted inwards, door open, all other openings closed (see Figure 84).

Within these ranges for fire location and ventilation, modelling of the fire was executed for a range of fire sizes. The matrix of models run as part of this analysis is presented in Table 8. While all model results have been produced, not all are discussed in this report.
**BENCHMARKING OF THE CFD MODEL**

Results from a standalone test carried out at BRE on a fridge under a hood are used to estimate a potential the range of Heat Release Rates (HRR). The standalone fridge test conducted in the BRE Burnhall is described by Nic Daeid\(^29\). HRR data from this test is shown in Figure 85. This data displays two distinct periods of burning, the first from approximately 7 – 30 minutes, and the second from approximately 30 – 54 minutes.

The initial peak of approx. 400 kW, 7 minutes from the start of the experiment, followed by a significantly reduced rate of approx. 75 - 100kW, corresponds to burning on the rear of the fridge which then gradually spreads to the material on the inside. This range of values is relatively consistent with 60 – 300kW range estimated in the main body of this report.

The later peak in Figure 85, in the range of 1.0 – 1.6MW, at approximately 32 minutes corresponds to the fire breaking out of the fridge. The analysis provided here and in the body of this report suggests that combustion during the period of the fire following the involvement of the interior of the upper portion of the fridge will be limited by available ventilation. It is therefore likely that the values of HRR recorded in the standalone fridge test will be greater than those in the compartment.

---

Figure 85: HRR VS. TIME CURVE FOR THE STANDALONE FRIDGE BURN CARRIED OUT BY BRE.

Results from CFD models of the fire located on the back of the fridge with Case II ventilation are presented for the range of HRRs estimated in the Section 3.4.2. Figure 86 compares CFD output vertical temperature profiles for 60 and 300kW fires. The results show that temperature magnitudes, both by the window and by the door, fall within the bounds of the 60 and 300kW predictions of the simple model. Furthermore, it shows that the smoke layer interface temperatures are very similar through the compartment but that, as expected, ceiling jet temperatures near to the door are lower than above the seat of the fire near the window.

HRR output from these models, shown in Figure 87, indicates that the models have no issue maintaining the requested energy output and therefore there is sufficient ventilation capacity to support these fire sizes in the window and door configuration of Case II.
FIGURE 86: TEMPERATURE PROFILES FOR 60kW AND 300kW FRIDGE FIRE MODELS WITH CASE II OPENINGS.

FIGURE 87: HRR VS TIME PLOTS FOR THE 60kW AND 300kW FRIDGE FIRE CFD SIMULATIONS.
The HRR in the model is increased to determine the limitation imposed by the ventilation and establish the resulting temperatures. This should serve to confirm the temperatures under ventilation limited conditions. The heat release rate for a fire on the back of the fridge is set at 400kW and 500kW. The plot in Figure 88 shows the actual HRRs that the model achieved. The model manages to maintain the 400kW level, although resulting in a more scattered set of data than that shown for lower HRR (Figure 87). This suggests that this is the limit of the available ventilation. The model does not manage to maintain the 500kW HRR converging on a maximum value around 400kW. This suggests that this value is the limit imposed by the ventilation configuration in Case II. This is consistent with the simple model and with the assessment that under these ventilation conditions flashover will not be attained.

Figure 89 presents vertical temperature profiles for both models. The results seem to confirm that the fire was limited to this range of temperatures and HRR by the ventilation and did not achieve the 1.5MW (approximately) that the standalone fridge test achieved (Figure 85). In terms of temperature profiles, the CFD model profiles show a layer interface at a height of 0.8 - 1.0m in the 400kW model across the compartment. The 500kW model seems to show smoke almost reaching the floor which is consistent with a single layer dynamic which matches the predictions of the simple model.

These results give sufficient confidence however that the model is capable of representing the compartment dynamics of the kitchen while the fire is not limited by ventilation. The results are sufficiently comparable for the purposes of this part of the study therefore further refinement is not undertaken at this time. Case II provides a higher level of ventilation than the original analysis therefore delivers an upper bound to the conditions modelled in the body of the report.

**Figure 88: Actual HRRs for 400kW and 500kW fridge fire models.**
CFD – EMPIRICAL MODEL COMPARISON

CFD modelling is compared to the initial empirical modelling that was presented in the body of the report to provide an indication of its degree of accuracy. In this model, the ventilation available is restricted to the tilted window as this minimal ventilation is what was estimated at the time (Case I). The fire is also located at floor level of the kitchen towards the window end.

The model shows that under these ventilation conditions the fire becomes under-ventilated and cannot sustain 300 kW (Figure 90). These results are consistent with the simple model. The results indicate that the assumed ventilation conditions can only support heat release rates of the magnitude of 300kW for a short period of time until the room fills (see Figure 90). The model indicates that HRR’s fall away after approximately 2.5 minutes. This is believed to result from descent of the smoke layer limiting the ventilation available to sustain the fire. More in-depth analysis to investigate the limitations imposed by available ventilation on fire size (HRR) is presented later.

The CFD model shows that the time taken for the hot upper layer to fill the compartment is consistent with that estimated by the simple model. These results, along with those from the CFAST model, are shown in Table 9.
The temperature distributions also indicate that the empirical model gave representative results for the boundary conditions that were assumed. The results for the lower bound (60kW) in particular showed a very good match to the temperature calculated by the empirical model as shown in Figure 91. The upper bound (300kW) empirical model gave a good estimate of the average compartment temperature but only the CFD model can establish the spatial distribution. Therefore, Figure 91 shows that the CFD model delivers a more accentuated temperature gradient over the height of the compartment.

**Figure 90**: HRR vs. time data from the 60kW and 300kW floor fire CFD models with ventilation supplied by the tilted window.
**Figure 91: Comparison of results between CFD and empirical modelling for 60kW and 300kW floor level fire source with minimal ventilation.**

**Table 9: Rates for smoke layer to descend to kitchen floor for all model types.**

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Fire Size</th>
<th>60kW</th>
<th>300kW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CFD</td>
<td></td>
<td>110s</td>
<td>50s</td>
</tr>
<tr>
<td>Zone</td>
<td></td>
<td>200s</td>
<td>50s</td>
</tr>
<tr>
<td>Empirical</td>
<td></td>
<td>138s</td>
<td>40s</td>
</tr>
</tbody>
</table>

**Variability introduced by fire location**

The location and orientation of the fire results in different temperature profiles. Figure 92 shows temperature profiles for a 300kW fire, located both at floor level and on the back of the large fridge-freezer. Ventilation corresponds to Case II.

Magnitudes of peak temperatures do not differ significantly, only the distribution in height. The floor level model results in a more even temperature distribution over the entire room whereas the fridge back fire results in the two-layer profile observed previously.

Figure 93 shows the HRR calculated by the model indicating that both fires release similar HRR but that the fire placed at the floor will produce more scatter of the data. This is a well-known phenomenon associated to...
the fluctuating flow created by a pool fire, as opposed to the strong boundary layer flow created by a vertical fire.

**Figure 92:** Temperature profiles from the entire length of the kitchen for a 300kW floor level fire and ventilation via tilted large window and open small window. x = 10.5m is closest to the window.

The plots show temperature profiles for both cases along the length of the kitchen with x = 10.5 m being closest to the window and x = 6.5m being close to the kitchen door. The clustering of these profiles suggests that there is little variance in depth along the compartment. These relationships are replicated for the smaller 60kW fire as shown in Figure 94.
Figure 93: Model calculated HRRs for a 300kW fire located on the back of the fridge (green dots) and at floor level (red dots).

Figure 94: Temperature profiles from the entire length of the kitchen for a 60kW floor level fire and ventilation via tilted large window and open small window. x = 10.5m is closest to the window.
VARIABILITY INTRODUCED BY VENTILATION

A range of models have been run to demonstrate the variability introduced by the assumed ventilation boundary condition. The principal objective of these models is to confirm that the door to the kitchen was closed and that ventilation to the kitchen fire came from the window only.

Results above in Figure 90 indicate that for the initial ventilation assumption for the kitchen of just the large window opened in the tilted position and all other sources closed (Case I), the HRR is limited to approximately 100kW. Larger rates can only be sustained for a small period of time before the compartment fills with smoke products and the combustion becomes limited by available oxygen. This is to be expected for a small compartment like the kitchen for a scenario with limited ventilation so there is reasonable confidence in the validity of the results.

Results presented in Figure 88 indicate that for the large window in the tilted position and small window fully open (Case II), a peak HRR of approximately 400kW can be sustained. This means that a larger fire will result in higher overall compartment temperatures as shown in Figure 89 as there is more air available to support combustion.

Models were run to analyse the difference in thermal profiles created by the opening of the small kitchen window in addition to the tilted kitchen window (Case II) for a small (60kW) fire. The results, shown in Figure 95, indicate that there is little difference between the two, with the lower ventilation resulting in only slightly higher temperatures, attributable the lower heat losses from the compartment.

In order to verify the position of the kitchen door, models were run with a HRR of 1MW. The large window is open in the tilted position and the model is run with the door open and closed (Case III and Case I). Temperature profile results are presented in Figure 96. They show that for an open door, the temperature is of the order of 400-500°C hotter nearer the compartment ceiling than for the door in the closed position. Temperatures in the upper 1m of the compartment are in the range of 500-800°C which would be expected to bring all other fuel sources in the compartment to ignition i.e. cause a flashover event. This is once again consistent with the results of the simple model.

Actual HRR values for the two models are shown in Figure 97. They confirm that the increased ventilation supports more burning and thus higher temperatures for the Case III ventilation model maintaining a 1MW output. The door closed (Case I) model quickly consumes the available oxygen and the HRR rapidly falls away to the limits observed previously for a minimal ventilation scenario. These results, combined with the observation at Grenfell Tower Flat 16 that the kitchen did not experience a flashover event, support the belief that the kitchen door remained closed for the fire event prior to firefighter intervention.
FIGURE 95: VERTICAL TEMPERATURE PROFILES FOR 60kW FIRES. DASHED LINES REPRESENT CASE I VENTILATION. FULL LINES REPRESENT CASE II VENTILATION. LOCATION X = 6.5m IS CLOSEST TO THE KITCHEN DOOR, WHILE LOCATION X = 10.5m IS CLOSEST TO THE KITCHEN WINDOW.

FIGURE 96: TEMPERATURE PROFILES FOR 1MW EQUIVALENT MASS LOSS RATE FOR KITCHEN DOOR OPEN (BLUE) AND CLOSED (RED).
Figure 97: Actual HRR for 1MW equivalent mass loss rate for two ventilation configurations. Blue markers represent kitchen door in open position, red markers represent the kitchen door in the closed position. In both cases, the large window is in the tilted position.

EXTERNAL SPILL PLUME TEMPERATURES

Temperatures immediately outside the kitchen window, in a location corresponding to directly beneath the ACP cladding above the window are presented in Table 10. The table presents a range of ventilation setups, fire locations, and fire size inputs i.e. not necessarily the achieved HRR in the calculation. The table implies that the smoke temperature only reaches temperatures capable of igniting the ACP cladding for large fire sizes with ventilation available to support them and thus under conditions where post-flashover fires would exist. In contrast, for fires as low as 60 kW, smoke temperatures reach values that can compromise the mechanical integrity of the uPVC. As established by the simple model in the body of the report, for smaller fires, ignition can only be achieved with impinging flames but the smoke can compromise the mechanical integrity of the uPVC.
TABLE 10: SPILL PLUME TEMPERATURES IMMEDIATELY OUTSIDE AND ABOVE THE WINDOW FOR A RANGE OF VENTILATION CONDITIONS, FIRE LOCATIONS AND INPUT HEAT RELEASE RATES.

<table>
<thead>
<tr>
<th>Ventilation</th>
<th>Fire Location</th>
<th>Input Fire Size (Achieved Fire Size) [kW]</th>
<th>Characteristic Outflow Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big Window Tilted</td>
<td>Floor</td>
<td>60 (60)</td>
<td>95</td>
</tr>
<tr>
<td>Big Window Tilted, Little Window Open</td>
<td>Floor</td>
<td>60 (60)</td>
<td>120</td>
</tr>
<tr>
<td>Big Window Tilted, Little Window Open</td>
<td>Fridge</td>
<td>60 (60)</td>
<td>140</td>
</tr>
<tr>
<td>Big Window Tilted, Door Open</td>
<td>Floor</td>
<td>60 (60)</td>
<td>95</td>
</tr>
<tr>
<td>Big Window Tilted</td>
<td>Floor</td>
<td>300 (70)</td>
<td>120</td>
</tr>
<tr>
<td>Big Window Tilted, Little Window Open</td>
<td>Floor</td>
<td>300 (300)</td>
<td>310</td>
</tr>
<tr>
<td>Big Window Tilted, Little Window Open</td>
<td>Fridge</td>
<td>300 (300)</td>
<td>300</td>
</tr>
<tr>
<td>Big Window Tilted, Door Open</td>
<td>Floor</td>
<td>300 (300)</td>
<td>220</td>
</tr>
<tr>
<td>Big Window Tilted, Little Window Open</td>
<td>Floor</td>
<td>500 (400)</td>
<td>450</td>
</tr>
<tr>
<td>Big Window Tilted, Door Open</td>
<td>Floor</td>
<td>1000 (1000)</td>
<td>450</td>
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</tbody>
</table>

SUMMARY

Extensive modelling using simple tools, CFAST and FDS show consistent results that confirm the information and conclusions provided in the body of this report. The detail and precision of the available evidence is only consistent with the simple model, thus only these results are presented in the body of the report. The more complex models (CFAST, FDS) presented in this appendix only serve to provide confidence to these results.
APPENDIX C. ESTIMATION OF FIRE BASE AREA

From the perspective of design, fires growth rates (α values) are grouped into categories according to how quickly a fire is expected to grow in a particular occupancy, based on the typical materials found in that occupancy. For example, a fire in an occupancy with strict controls on flammable materials would be expected to experience a slow fire growth rate.

These values are essentially representative of material properties, as will be demonstrated subsequently. The slow fire represents materials that would typically propagate fire slowly, and vice-versa for ultrafast.

Given the unknowns associated to the exact fire origin in the case of Grenfell Tower, it is difficult to isolate a representative alpha, hence the inability to bound the value of alpha used in the previous section of this analysis more precisely than the two extremes used.

As stated above, α (kW/s²), is representative of the typical materials expected to be present in the occupancy under consideration, and thus can be broken down into a number of parameters that are time independent, material properties. α is related to the HRR, $\dot{Q}$ (kW), according to the following relationship:

$$\dot{Q} = \alpha t^2 = \dot{m}_f \Delta H_c$$

EQUATION 13

Where t (s) is the time from the ignition of the fire, $\dot{m}_f$ (kg/s), is the mass loss rate of the burning fuel i.e. it’s rate of decomposition from solid to gaseous fuel, and $\Delta H_c$ (J/kg), is the heat of combustion of the fuel i.e. the energy produced by burning each kg of fuel that is gasified.

The mass loss rate can be made time independent by a simple augmentation of the equation where multiplying by the area of the fire, A (m²) at any time t, it can be replaced as a characteristic mass loss rate per unit area, $\dot{m}_f^*$ (kg/s.m²), as follows:

$$\dot{m}_f^* \Delta H_c = A \dot{m}_f^* \Delta H_c$$

EQUATION 14

The $\alpha t^2$ correlation represents a radially growing fire, therefore the area, A, at any point is a circle, and thus can be expressed as:

$$A = \pi r^2$$

EQUATION 15

Where r (m) is the radius of the circle and in real terms, the distance travelled by the fire in any direction from the point of origin at any time t (s). This enables the expression of the characteristic lateral spread rate of the fire, $V_s$ (m/s) as:

$$V_s = \frac{r}{t}$$

EQUATION 16

Rearranging as:
\[ r^2 = V_s^2 t^2 \]

**EQUATION 17**

And substituting **EQUATION 17** into **EQUATION 15**, and the result into **EQUATION 14**, the result is as follows:

\[ \alpha t^2 = \left( \pi V_s^2 \dot{m}_f^* \Delta H_c \right) t^2 \]

**EQUATION 18**

Thus \( \alpha \) is expressed as a function of a mathematical constant and time independent, characteristic material properties.

According to the report by Prof. Bisby [5], most of the combustible elements in the area of the kitchen identified are polymers, therefore characteristic polymer values are assumed and taken from Drysdale [45] as:

- \( \dot{m}_f^* = 0.01 - 0.014 \text{ kg/s.m}^2 \)
- \( \Delta H_c = 40 - 46 \text{ MJ/kg} \)

Other bounding values are:
- \( \alpha = 0.0029 - 0.1876 \text{ kW/s}^2 \)
- \( t_{growth} = 40 \text{ s (ultrafast) and 138 s (slow)} \)
- \( \pi = 3.14 \)

Using these parameters, it is possible to establish a range of values for the spread rate of the fire, \( V_s \text{ (m/s)} \) as:

\[ V_s = \left( \frac{\alpha}{\pi \dot{m}_f^* \Delta H_c} \right)^{\frac{1}{2}} \]

**EQUATION 19**

And thus the area of the fire as:

\[ A = \pi (V_s t_{growth})^2 \]

**EQUATION 20**

The heat release rate, \( \dot{Q} \text{ (kW)} \), can then be verified against the earlier results using **EQUATION 14**. The results of this stage of the analysis are presented in Table 11 below.

<table>
<thead>
<tr>
<th>( \alpha ) \text{ [kW/m}^2\text{]}</th>
<th>( \dot{m}_f^* \text{ [kg/s.m}^2\text{]} )</th>
<th>( \Delta H_c \text{ [MJ/kg]} )</th>
<th>( V_s \text{ [mm/s]} )</th>
<th>( A \text{ [m}^2\text{]} )</th>
<th>( r \text{ [m]} )</th>
<th>( \dot{Q} \text{ [kW]} )</th>
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</thead>
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<tr>
<td>0.0029 (S)</td>
<td>0.01</td>
<td>40</td>
<td>1.5</td>
<td>0.14</td>
<td>0.2</td>
<td>55</td>
</tr>
<tr>
<td>0.0029 (S)</td>
<td>0.014</td>
<td>46</td>
<td>1.2</td>
<td>0.085</td>
<td>0.17</td>
<td>55</td>
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<tr>
<td>0.1876 (UF)</td>
<td>0.01</td>
<td>40</td>
<td>12.2</td>
<td>0.75</td>
<td>0.5</td>
<td>300</td>
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<tr>
<td>0.1876 (UF)</td>
<td>0.014</td>
<td>46</td>
<td>9.5</td>
<td>0.46</td>
<td>0.4</td>
<td>300</td>
</tr>
</tbody>
</table>

**TABLE 11: RESULTS OF THE ASSESSMENT TO BOUND THE FIRE AREA BY MEANS OF CHARACTERISTIC MATERIAL PROPERTIES.**
APPENDIX D. ESTIMATION OF THE uPVC TEMPERATURE

A simple heat storage analysis is conducted to approximate the change in temperature of the uPVC as a result of exposure to the hot-layer gases, and thus establish if any thermal degradation of the material is possible within the timeframe provided by the evidence in section 0. The analysis equates the energy stored in the uPVC \( E_{STO} \) to the energy provided by the fire environment \( E_{IN} \) as:

\[
E_{IN} = E_{STO}
\]

EQUATION 21

The calculation is deliberately kept to a crude approximation, thus no losses have been assumed, as the intention is simply to provide a bounding heating time. Each term can be expanded as:

\[
h_T (T_g - T_s) A = \rho \cdot c_p \cdot V \cdot \frac{\Delta T_s}{\Delta t}
\]

EQUATION 22

Where \( h_T \) is the total heat transfer coefficient (25 W/m\(^2\).K), \( T_g \) is the gas phase (hot layer) temperature (K), \( T_s \) is the solid (uPVC) temperature (K), \( A \) is the exposed surface area (m\(^2\)), \( \rho \) is the density of the solid (1390 kg/m\(^2\)), \( c_p \) is the specific heat capacity of the solid (1170 J/kg.K), \( V \) is the volume of the solid (m\(^3\)), and \( \Delta T_s \) is the change in temperature of the solid, and \( \Delta t \) is the time-step (s). This expression can be rearranged in terms of \( \Delta T_s \) as:

\[
\Delta T_s = \frac{h_T (T_g - T_s) \Delta t}{\rho \cdot c_p \cdot \delta}
\]

EQUATION 23

Where \( \delta \) is the thickness of the uPVC (9.5mm) derived from the ratio of volume (V) and surface area (A).
APPENDIX E.  STEP BY STEP LATERAL FLAME SPREAD

Figure 98: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 01:14 am on the east elevation tower plan view.
Figure 99: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 01:22 am on the east elevation tower plan view.
FIGURE 100: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 01:26 AM on the east elevation tower plan view.
**FIGURE 101:** Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 01:29 AM on the east elevation tower plan view.
**FIGURE 102**: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrows indicate the estimated position of external flames at 01:42 AM on the north elevation tower plan view.
FIGURE 103: Original public footage of lateral and vertical (downward) flame spread on the north facade of Grenfell Tower at (a) 01:42 AM; (b) 01:53 AM; (c) 02:23 AM; (d) 02:32 AM; (e) 02:49 AM; (f) 02:55 AM; (g) 03:04 AM; and (h) 03:07 AM respectively. Photos were sourced from MET00008024, page 36.
Figure 104: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 01:53 AM on the north elevation processed image (Figure 5a).
FIGURE 105: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrows indicate the estimated position of external flames at 02:10 AM on the north elevation tower plan view.
**Figure 106:** Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 02:23 AM on the north elevation processed image (Figure 5c).
Figure 107: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 02:32 am on the north elevation tower plan view.
Figure 108: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 02:51 AM on the west elevation tower plan view.
Figure 109: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 02:51 am on the west elevation tower plan view.
Figure 110: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 03:07 am on the North elevation processed image (Figure 5h).
Figure 111: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 03:20 AM on the west elevation tower plan view.
Figure 112: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 03:23 AM on the north elevation tower plan view.
Figure 113: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrows indicate the estimated position of external flames at 03:45 am on the west elevation tower plan view.
FIGURE 114: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrows indicate the estimated position of external flames at 03:55 AM on the west elevation tower plan view.
Figure 115: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrows indicate the estimated position of external flames at 04:14 AM on the west elevation tower plan view.
Figure 116: Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrows indicate the estimated position of external flames at 04:31 AM on the west elevation tower plan view.
**Figure 117:** Time history of external flame spread on the eastern (E), northern (N) and western (W) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrows indicate the estimated position of external flames at 04:44 AM on the west elevation tower plan view.
FIGURE 118: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:42 AM ON THE EAST ELEVATION TOWER PLAN VIEW.
Figure 119: Time history of external flame spread on the eastern (E) and southern (S) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 02:01 AM on the east elevation tower plan view.
FIGURE 120: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:30 AM ON THE EAST ELEVATION TOWER PLAN VIEW.
Figure 121: Time history of external flame spread on the eastern (E) and southern (S) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 02:35 am on the south elevation tower plan view.
Figure 122: Time history of external flame spread on the eastern (E) and southern (S) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 02:42 am on the south elevation tower plan view.
Figure 123: Time history of external flame spread on the eastern (E) and southern (S) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 02:45 AM on the east elevation tower plan view.
**Figure 124:** Time history of external flame spread on the eastern (E) and southern (S) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrows indicate the estimated position of external flames at 03:05 am on the east elevation tower plan view.
FIGURE 125: Time history of external flame spread on the eastern (E) and southern (S) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrows indicate the estimated position of external flames at 03:06 am on the south elevation tower plan view.
Figure 126: Time history of external flame spread on the eastern (E) and southern (S) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the legend. The red arrow indicates the estimated position of external flames at 03:25 AM on the south elevation tower plan view.
Figure 127: Time history of external flame spread on the eastern (E) and southern (S) facades. The stack of flats impacted by the external flame spread are indicated using numbers 1-6 appended to the facade descriptor in the
LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:40 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.

FIGURE 128: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:50 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.
Additional photos showing lateral and vertical flame spread

East Facade

(a)  
(b)  
(c)  
(d)
FIGURE 129: ORIGINAL PUBLIC FOOTAGE OF LATERAL AND VERTICAL (UPWARD AND DOWNWARD) FLAME SPREAD ON THE EAST FACADE OF GRENFELL TOWER AT (A) 01:22 AM; (B) 01:36 AM; (C) 01:52 AM; (D) 02:08 AM; (E) 02:22 AM; AND (F) 02:53 AM RESPECTIVELY. PHOTOS WERE SOURCED FROM MET00008024, PAGES 28-29.

West Facade
Figure 130: Original public footage of lateral and vertical (downward) flame spread on the west facade of Grenfell Tower at (a) 02:50 AM; (b) 03:15 AM; (c) 03:20 AM; and (d) 03:48 AM respectively. Photos were sourced from MET00008024, page 59.
Figure 131: Images from the West façade corresponding to (a) 03:20 AM; and (b) 03:48 AM respectively.
APPENDIX F. STRUCTURAL ANALYSIS

The properties defining loss of strength in rebar are given in Euro Code 2 [46] and shown in the plot in Figure 132. The plot indicates that typical rebar begins to lose strength at 300°C, losing 50% of its strength by 550°C, this latter threshold typically taken as a conservative failure criterion. Eurocode 2 also gives the reduction in concrete strength as a function of temperature, shown in Figure 133.

The range of thermal loading applied in the model is taken from Section 5.4 of this report, which represents estimated characteristic, upper and lower bound, compartment temperatures in a typical one-bedroom flat in the Grenfell Tower. The growth phase of the fires is ignored and gas phase temperature boundary conditions between 850°C and 1000°C are applied.

**Figure 132:** Strength reduction factor of typical rebar steels as a function of temperature according to [46].
The finite difference heat transfer model by Emmons [47] and Dusinberre [48] is described by Maluk [49]. It breaks the concrete into finite thicknesses for which the energy entering and leaving each thickness over a fixed period of time is resolved to define the resultant temperature of that thickness.

Notation is such that the subscript represents the element number (1 for the surface, 2 for the next layer and so on) and the superscript represents the timestep. The temperature of each node at the next timestep, (i+1), is defined as a function of the conditions at the current timestep, i. At the exposed surface, Node J=1, the Temperature at the following timestep i+1 is defined as:

\[
T_{1}^{i+1} = T_{1}^{i} + \frac{2.\Delta t}{(\rho. c)\Delta x} \left[ q_{abs}^{i} - \left( \frac{\lambda_{1} + \lambda_{2}}{2} \right) \left( \frac{T_{1}^{i} - T_{2}^{i}}{\Delta x} \right) \right]
\]

(Equation 24)

Where \(\lambda_{j}\) is the thermal conductivity of the material of element \(j\) at time step \(i\). \(T_{j}^{i}\) is the temperature of element \(j\) at timestep \(i\). \(\rho\) is the density of the material that forms the element, \(c\) is the specific heat capacity of the material that forms the element, \(\Delta x\) is the thickness of the element, and \(\Delta t\) is the timestep. \(q_{abs}^{i}\) is the flux of heat from the fire environment to the exposed concrete surface and is defined as:
\[
\dot{q}_{abs}^i = h_T(T_g^i - T_1^i)
\]

**EQUATION 25**

Where \(h_T\) is the total heat transfer coefficient (45 W/m\(^2\).K), \(T_g\) is the exposure temperature (K), and \(T_1\) is the temperature of the surface element (K). The temperature of any interior node \(j\), at the next timestep \(i+1\), is defined as:

\[
T_j^{i+1} = T_j^i + \frac{\Delta t}{(\rho_c)_j \Delta x^2} \left[ \left(\frac{\lambda_{j-1}^i + \lambda_j^i}{2}\right)(T_{j-1}^i - T_j^i) - \left(\frac{\lambda_j^i + \lambda_{j+1}^i}{2}\right)(T_j^i - T_{j+1}^i) \right]
\]

**EQUATION 26**

And the temperature at the unexposed face is defined as:

\[
T_N^{i+1} = T_N^i + \frac{2 \Delta t}{(\rho_c)_N} \left[ \left(\frac{\lambda_{N-1}^i + \lambda_N^i}{2}\right)(T_{N-1}^i - T_N^i) - \sigma \varepsilon (T_N^i)^4 - T_{amb}^4 - h_c (T_N^i - T_{amb}) \right]
\]

**EQUATION 27**

Where \(\sigma\) is the Steffen-Boltzmann constant \((5.67 \times 10^{-8} W/m^2.K^4)\), \(\varepsilon\) is the emissivity of concrete, \(T_{amb}\) is the ambient temperature on the unexposed side (K), and \(h_c\) is the convective heat transfer coefficient (15 W/m\(^2\).K).
APPENDIX G. DAMAGE ASSESSMENT FROM PHOTOGRAPHS

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<th>Minor</th>
<th>Moderate</th>
<th>Severe</th>
<th>Major</th>
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<td>Good example of high end Moderate damage, which contains some structural damage.</td>
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<td>Bedroom has partial fire-induced window damage but not enough to classify entire flat at moderate damage.</td>
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<td>Lobby door completely gone and hard to say for sure whether it burned completely or not; I would consider this low end Major damage.</td>
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<td>Firefighter damage to lobby door; Living room has partial fire-induced window, wall and floor damage but not enough to classify as moderate for entire flat.</td>
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<td>Partial fire-induced window damage in the living room, but not enough to classify as moderate for entire flat.</td>
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<td>Firefighter damage to lobby door.</td>
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<td>I would consider this low end Major damage based on the spalling on most ceilings and walls coupled with major interior compartment wall damage; lobby door completely gone; it is unclear if it burned or was simply removed.</td>
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<td>Living room and a bedroom both have fire-induced window damage but not enough to classify as moderate for entire flat.</td>
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<td>Lobby door frame burned.</td>
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<td>Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.</td>
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<td>Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions with major compartment wall damage.</td>
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<td>Spalling on ceiling and walls.</td>
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<td>I would consider this moderate to high end Major damage based on the spalling on most ceilings and walls with a clean bedroom; lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.</td>
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<td>Spalling on ceiling and walls.</td>
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Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.

Half broken lobby door found in doorway of Flat 96; post-flashover conditions.

Spalling on the ceiling and walls with structural damage to the ceiling noted in entry ways to each flat.

Door removed from hinge and appears to have some damage

Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.

Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.

Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.

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Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.

Spalling on the ceiling and walls with structural damage to the ceiling noted in entry ways to each flat.

Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.

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Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.

Spalling on the ceiling and walls with structural damage to the ceiling noted in entry ways to each flat.

Door has visible soot and fire damage.

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Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions.
PHASE 2 GRENFELL TOWER INQUIRY: ADEQUACY OF THE CURRENT TESTING REGIME

Prof. José L. Torero CEng, RPEQ, FREng, FRSE, FTSE, FIFE, FSFPE, FICE, FCI

January 4th, 2022
1. PHASE 2 INSTRUCTION

1.1. TOPIC OF THIS REPORT

1.1.1. I have been instructed by the Grenfell Tower Inquiry, as part of Phase 2 of the Inquiry, to undertake an analysis that includes:

a. Your final conclusions on the relative contributions of the cladding design and materials to the fire spread at Grenfell Tower, taking account of the findings made in the Phase 1 report. This work will include collaboration with Professor Luke Bisby in relation to a programme of experimentation aimed at understanding and quantifying the respective roles of the various materials and products that made up the cladding system at Grenfell Tower under a range of relevant fire conditions and system geometries. This work is to be undertaken by Professor Bisby with a team from the School of Engineering at the University of Edinburgh including Dr Angus Law and Dr Rory Haddon. The experimental work will be developed in on-going consultation with you and will aim to establish the manner and extent to which each component of the cladding system contributed to rate and extent of fire spread during the Grenfell Tower fire.

b. An analysis of the adequacy of the current testing regime.

1.1.2. Testing should be defined to fulfil a well specified purpose and this purpose is established by the laws of physics and by the information required from the test by the regulatory regime. Therefore, before discussing the adequacy of a test, it is essential to fully describe the physical processes involved, as well as to clarify the regulatory environment within which the test is being used. This information serves to contextualise the role that the testing regime is required to serve. It is only when the physical and regulatory context is clear that adequacy can be assessed.

1.1.3. The review of the regulatory environment in this report is not comprehensive because this has been done by Prof. Bisby. Where appropriate, his report will be referred to in this report.

1.1.4. Therefore, regulatory aspects of this report should not be read as a detailed analysis of current regulations and the regulatory environment, but as a statement of first principles. The purpose being to set out the relevant regulatory framework in order that it can be used to understand / contextualise what is expected from fire safety related tests.

1.1.5. This understanding will enable a clearer perspective on the value, appropriateness and validity of tests directly applicable to the performance of external wall systems such as that which was installed at Grenfell Tower. It will also enable those aiming to establish building compliance to assess which tests are relevant to particular Building Regulations.

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1 As described in a Technical Addendum to a letter from the Inquiry to Core Participants dated 23 April 2019 (INQ00014941)
2 Bisby, L. Grenfell Tower Inquiry Phase 2 – Regulatory Testing & the Path to Grenfell. (LBYP20000001)
1.1.6. This report comprehensively describes the physics that control the external spread of a fire and, within that description, identifies the main physical parameters controlling the process. Establishing these parameters and linking the physical processes to the potential outcomes of a fire enables the definition of key parameters that need to be quantified to deliver the information required by the regulatory regime.

1.1.7. By contrasting these key parameters with the information obtained from current testing regimes, it can then be ascertained if current testing regimes deliver the required information, and by extension, if the current testing regime is capable of delivering the outputs necessary for the correct implementation of the current Building Regulations.

1.1.8. This report emphasizes the manner in which the physical parameters should be used to determine the ultimate performance of a building.

1.1.9. This report also describes the manner in which different stakeholders (e.g. designers, builders, building approvals officers, building managers, etc.) should use these parameters while performing their roles.

1.1.10. This also serves to highlight the respective required level of competency of these stakeholders in order that they are able to make appropriate use of test information.

1.1.11. The analysis of the physical parameters controlling fire spread is used with key information extracted from the tests conducted by Prof. Bisby’s team\(^3\) to assess products of specific relevance to Grenfell Tower. This provides the basis for establishing the manner and extent to which each component of the cladding system contributed to the rate and extent of fire spread during the Grenfell Tower fire. Furthermore, this analysis enables identification of the limitations of existing testing regimes for delivering the information necessary for a comprehensive performance assessment of an external wall system.

1.1.12. The data collected and the detailed descriptions of the experiments\(^4\) conducted are not covered here. This information is provided in Prof. Bisby’s report.\(^5\) Nevertheless, I have actively participated in the planning of those experiments, I have been present while several of the experiments were conducted, and I have worked with Prof. Bisby and his team in the interpretation of the results. This report makes references to specific information in Prof. Bisby’s report where appropriate.

1.1.13. This report includes an extensive appendix where a thorough review of work that has been carried out globally following the Grenfell Tower fire is presented. This review primarily covers information that pertains to the key matters addressed in this report, nevertheless, it extends beyond these matters where necessary for context and completeness. The review

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\(^3\) Bisby, L. Phase 2 Experiments Work Package 2 – System Interactions, Grenfell Tower Inquiry. {LBYWP200000001}

\(^4\) For the purpose of this report the term ‘experiment’ will be used to describe a procedure carried out to support or refute a hypothesis. Experiments provide insight into cause-and-effect by demonstrating what outcome results when a particular factor is varied. The term ‘test’ will be used to describe a procedure intended to quantify a pre-established parameter or to determine the quality, performance, or reliability of something, especially before it is taken into widespread use. Tests can be ad-hoc or can be standardized, as a consequence, a ‘standard test’ is a standardized procedure that has the same objectives as test.

\(^5\) Bisby, L. Phase 2 Experiments Work Package 2 – System Interactions, Grenfell Tower Inquiry. {LBYWP200000001}
does not attempt to be comprehensive and therefore does not cover work that I considered had too weak of a link to the Grenfell Tower fire.

1.2. FIELD OF EXPERTISE

1.2.1. My name is José L. Torero. I am Professor of Civil Engineering and Head of the Department of Civil, Environmental and Geomatic Engineering at University College London. I also serve as Director of TAEC. Previously, I held the John L. Bryan Chair at the Department of Fire Protection Engineering and was the Director of the Center for Disaster Resilience at the Department of Civil Engineering at the University of Maryland, USA (2017-2019). Between 2012 and 2017 I was Professor of Civil Engineering and Head of the School of Civil Engineering at the University of Queensland, Australia. Before moving to Australia, I held the Landolt & Cia Chair for Innovation for a Sustainable Future at the Ecole Polytechnique Fédérale de Lausanne, Switzerland (2012) and the BRE Trust/RAEng Chair in Fire Safety Engineering at the University of Edinburgh (2004-2011). Between 2004 and 2011 I was also the Director of the BRE Centre for Fire Safety Engineering and in the 2008 to 2011 period I was Head of the Institute for Infrastructure and Environment, both at the University of Edinburgh. I have held other positions at CNRS (France), University of Maryland (USA), NIST (USA) and NASA (USA).

1.2.2. My field of expertise is fire safety; a field in which I have worked for more than 25 years. I was trained as a Mechanical Engineer obtaining a Bachelor of Science from the Pontificia Universidad Católica del Perú in 1989. In 1991 I obtained a Master of Science and in 1992 a PhD from the University of California, Berkeley, both in Mechanical Engineering with specialty in Fire Safety. I am a Chartered Engineer by the Engineering Council Division of the Institution of Fire Engineers (UK), a Registered Professional Engineer in Queensland and a full member of the Society of Fire Protection Engineers (USA).

1.2.3. I am a Fellow of the Royal Academy of Engineering, the Royal Society of Edinburgh, the Australian Academy of Technological Sciences and Engineering, The Institution of Civil Engineers, The Institution of Fire Engineers, the Society of Fire Protection Engineers and the Combustion Institute. In 2008 I was awarded the Arthur B. Guise Medal by the Society of Fire Protection Engineers (USA) and in 2011 the David Rasbash Medal by the Institution of Fire Engineers (UK) in recognition for eminent achievement in the education, engineering and science of fire safety. In 2016 I was awarded a Doctor of Science Honoris Causa from Ghent University, Belgium. I am the author of more than 500 technical documents in all aspects of fire safety of which more than 200 are peer review scientific journal publications. I have been invited to deliver more than 100 keynote lectures in conferences and professional fora worldwide of which more than 20 have been in the area of Fire Investigation.

1.2.4. I was the Editor-in-Chief of Fire Safety Journal (2010-2016), the most respected scientific publication in the field, Associate Editor of Combustion Science and Technology (1997-2008) and a member of the Editorial Board of Fire Technology, ICE Journal of Forensic Engineering, Fire Science and Technology, Case Studies in Fire Safety, Progress in Energy and Combustion Science and the Journal of the International Council for Tall Buildings. I am
one of the Editors of the 4th Edition of the Fire Protection Engineering Handbook of the Society of Fire Protection Engineers (USA) and an author of several chapters. I am regularly in the Scientific Advisory Boards of most conferences in the field and a member of the Committee of many professional organizations. I chaired the Fire Safety Working Group for the International Council for Tall Buildings and Urban Habitat and was the vice-Chair of the International Association for Fire Safety Science.

1.2.5. I have been involved in numerous fire investigations many of which have been landmark studies. Between 2001-2010 I was involved in an independent investigation of the World Trade Center buildings 1 and 2 collapses. I was involved in the fire and structural modelling of the World Trade Center building 7 collapse in support of litigation and conducted an independent investigation of the fire growth and structural failure of the Madrid Windsor Tower Fire commissioned by the British Concrete Institute. I conducted a cause and origin investigation of the Texas City explosion and subsequent fires as well as a damage correlation analysis. I conducted dispersion fire modelling supporting the litigation of the Buncefield Explosion and of the Sego mine explosion (USA). I supported the fire service investigation of the Ycu Bolanos supermarket fire in Paraguay to establish the cause of the fire and to analyse the reasons for the fatalities. I conducted the fire investigation of La Rocha prison fire in Uruguay where 12 inmates died where we developed analytical and numerical model of fire growth in support of the investigation. I conducted the fire investigation of the San Miguel prison fire in Chile where 26 inmates died where we developed analytical and numerical models of fire growth in support of the investigation. I worked with the Scottish Fire Service on the Balmoral Bar fire investigation. I conducted the post-fire structural assessment of the Abu-Dhabi Plaza fire in Kazakhstan, probably the biggest ever fire of a building under construction. Recently, I led the fire investigation of the Ayotzinapa 43 murder case driven by the Organization of American States that encouraged the Mexican government to reopen the investigation. (Science, 11 March 2016, vol. 351 Issue 6278, pp.1141-1143 and Science, 29 April 2016, vol. 352, issue 6285, p.499) and by the National Academy of Science (USA) (http://www7.nationalacademies.org/humanrights/). I served as advisor to the Attorney General of Mexico in the subsequent investigation. I have given expert testimony in several forensic fire investigations worldwide.

1.2.7. For more than 20 years I have been involved in the education and training of fire engineers, fire investigators and the fire service. I have developed training programmes on fire investigation for the Bureau of Alcohol Tobacco and Fire Arms (USA), fire investigators and fire brigades in the UK (University of Edinburgh short course in Fire Science and Fire Investigation, 2001-20012), the RAIB (UK) and the Police Scientifique of Lyon (France) among others. I have taught courses at Fire Service College Gullane, for the Queensland Fire and Emergency Services and for the fire services in numerous other countries (Costa Rica, Chile, Peru, Argentina, Singapore, Malaysia, etc.). I have developed curriculum and taught the Fire Protection Engineering programme at the University of Maryland, the Structural and Fire Safety Engineering course at the University of Edinburgh, the Civil and Fire Safety Engineering course at the University of Queensland and the International Masters in Fire Safety Engineering (Ghent, Lund and Edinburgh Universities). I was external examiner to the Fire Safety programme of Glasgow Caledonian University (UK) and I am on the Advisory Board of Worcester Polytechnic Institute (USA) Fire Protection Engineering programme. I am a Distinguished Visiting Chair Prof. in Fire Safety Engineering at the Hong Kong Polytechnic University.

1.2.8. In the period 2007 to 2010 I lead the development of the FireGrid project funded by the Department of Trade and Industry and in partnership with the London, Manchester, Strathclyde and Lothian and Borders Fire Brigades where a detailed study of the role of information on fire brigade emergency response was analysed. This project was featured in the 2007 BBC Horizon Documentary “Skyscrapers Fire Fighters” that has been shown in more than 30 countries. In 2010 I was awarded a GBP 2M grant by the Engineering and Physical Sciences Research Council UK to study the Real Fires for the Safe Design of Tall Buildings.

1.2.9. I have been involved in numerous advisory roles for industry and government many of them including the fire service. I was involved in the Nuclear Regulatory Commission (USA), PRIT Committee on Fire Modelling, a member of the Expert panel of the Fire and Resilience Directorate (Communities and Local Government, UK) and of the Forum of Chief Fire Officers of Scotland (SDAF). I was advisor to the Department of Transportation and Main Roads (Queensland, Australia), special advisor to the vice-President of Peru on the Utopia Club and Mesa Redonda fire investigations and a member of the CFOA Training Needs Analysis Gateway Review Group. I am currently special advisor to the Minister of Housing (Queensland) on issues of façade fires. I am a regular participant in standards development committees worldwide.

1.2.10. A full and up to date CV (current at the time of Torero’s initial instruction as Expert Witness) has previously been provided to the Inquiry’s Core Participants.
1.3. STATEMENTS

1.3.1. I confirm that I have made clear which facts and matters referred to in this report are within my own knowledge and which are not. Those that are within my own knowledge I confirm to be true. The opinions I have expressed represent my true and complete professional opinions on the matters to which they refer.

1.3.2. I confirm that I have made clear which facts and matters referred to in this report are within my own knowledge and which are not. Those that are within my own knowledge I confirm to be true. The opinions I have expressed represent my true and complete professional opinions on the matters to which they refer.

1.3.3. I was assisted in the production of this report by Dr Adam Cowlard – Director at Torero, Abecassis Empis and Cowlard Ltd. Dr Cowlard holds a PhD in Fire Safety Engineering and an MEng (Hons) in Civil Engineering from the University of Edinburgh. He has experience of a wide range of consultancy and research work encompassing development of fire safety strategies for a wide range of complex infrastructure, development of design fires and heat transfer modelling, and fire and evacuation modelling.

1.3.4. I confirm that I understand my duty to assist the Inquiry on matters within my expertise, and that I have complied with that duty. I also confirm that I am aware of the requirements of Part 35 and the supporting Practice Direction and the Guidance for the Instruction of Experts in Civil Claims 2014.

1.3.5. I confirm that I have no conflict of interest of any kind, other than any which I have already set out in this report. I do not consider that any interest which I have disclosed affects my suitability to give expert evidence to the Inquiry on any issue on which I have given evidence and I will advise the Inquiry if, between the date of this report and the Inquiry hearings, there is any change in circumstances which affects this statement.

Signed:

Dated: January 4th, 2022
2. EXECUTIVE SUMMARY

2.0.1. The application of testing for the purpose of fire performance assessment is an aspect of fire safety engineering that is inherently complex and is currently the subject of significant confusion within the construction industry.

2.0.2. Since testing for fire performance was initially formalized more than 100 years ago, it has always been characterized by a complex relationship between need, perceived importance and knowledge. This relationship has defined approaches to test development that strongly prevail today, but which are, in many cases, no longer justified.

2.0.3. Fires have existed through history, therefore the need to protect society from the ravages of fire has always been evident. The perception of need changes regularly and for numerous reasons. The most obvious reason is the occurrence of a major event.

2.0.4. Major fire events also increase the perceived importance of fire safety. They change the perception that the public has of their own safety and as a result people assign a higher priority to fire safety matters. This results in pressure for regulatory change.

2.0.5. Major fire events also affect the construction market, in particular, the introduction of new products and building systems. The barriers to market imposed by fire safety constraints are perceived as being more important after a major event than after a period of relative safety. This has been clearly evident following the Grenfell Tower fire.

2.0.6. Major events tend also to question the knowledge base used in delivering what is needed to assure fire safety. So, the manner in which knowledge is used is also complex.

2.0.7. The Grenfell Tower fire of June 14th 2017 is a major fire event that has highlighted weaknesses in the manner in which the provision of fire safety is assured by Building Regulations. Furthermore, it has emphasized the societal importance of fire safety, as evidenced by a strong demand for regulatory reform. It has also deeply questioned the knowledge framework underpinning our current Building Regulations. An area of particular emphasis has been that of fire performance testing.

2.0.8. It is unquestionable that improving the use of testing requires a deep understanding of the technical principles behind all processes involved. Nevertheless, in the case of fire testing, contextual matters are also of great importance because fire testing is firmly rooted in regulation and regulation cannot be separated from context and history.

2.0.9. To be able to improve fire testing, it is necessary to understand

- how fire tests have been developed and have evolved over time
- how fire testing is implemented and why specific testing procedures are used and
- what fire testing is used for and why it is appropriate and or necessary.
2.0.10. Building technologies / products are typically developed with specific functionalities / objectives in mind that are not necessarily related to fire safety. Therefore, from a fire safety perspective, novel building technologies have traditionally been perceived as the source of new challenges.

2.0.11. In the majority of cases, the fire safety challenges created by new technologies required technical knowledge that was not developed until several decades later, yet the need to ensure a societally defined minimum acceptable level of safety is ever present.

2.0.12. The introduction of novel technologies in spite of the lack of technical knowledge to adequately describe their performance might be perceived as inappropriate, nevertheless, it is a characteristic of competent engineering practice. Engineers, through the use of robust solutions and factors of safety,\(^6\) have, for many years, delivered solutions to problems that were not fully understood. It is the competency of the engineer that guarantees that the solutions, and associated factors of safety, adequately compensate for the gaps in technical knowledge.

2.0.13. The technical knowledge necessary to develop adequate testing methods has consistently lagged behind the need for such tests. Despite this, the continuous evolution of building technologies has not stopped generating a need for fire performance assessments that existing knowledge could not deliver at the time of the introduction of those technologies into the market.

2.0.14. Some pertinent examples are fire tests intended to regulate combustibility being developed three decades before ignition theory was resolved; surface fire spread tests being adopted to regulate the propagation of fires at least five decades before the controlling mechanisms of fire spread were elucidated and fire-resistance tests having existed for almost a century while to date, the fire engineering field has still not fully understood how structures behave when exposed to a fire.

2.0.15. It is remarkable that, despite having been developed decades before the technical knowledge that underpins their objectives was elucidated, many of these tests have remained almost invariant decades after that knowledge was finally established.

2.0.16. As a result, the basis for testing that has been used throughout the history of fire safety to characterize the performance of new building technologies, has not included a technical or scientific understanding of fire performance. So, key to understanding fire testing is the recognition that their development has been responsive and driven by extrinsic challenges. Furthermore, it has to be accepted that fire tests have been, by necessity, developed with insufficient technical knowledge.

2.0.17. A unique aspect of fire safety engineering of relevance to fire testing is the absence of a well-structured and regulated professional practice. Higher education in the discipline of fire

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\(^6\) A factor of safety is a means by which a solution is over-dimensioned to account for lack of knowledge and uncertainties in the derivation of the solution e.g. a structure might be prescribed by an engineer as requiring sufficient protection to achieve 90 or 120 minutes of fire resistance when in actuality, had they had the technical knowledge to understand the performance of the structural system with sufficient precision, they would have been able to establish / demonstrate that a fire resistance of 60 minutes was appropriate. Therefore, the structural fire protection is “over-dimensioned” to compensate for the gap in technical knowledge.
safety engineering is still poorly defined and unregulated. Without a well-defined engineering practice, our capacity to use the ‘engineering principles of robust solutions’ and ‘factors of safety’ to underpin the delivery of adequate fire tests in the absence of complete knowledge remains questionable.

2.0.18. In the absence of adequate technical knowledge and rigorous engineering practice, the development of fire testing has been driven by experiential knowledge. This experiential knowledge has been provided by many stakeholders including manufactures and the fire service. While research organizations have also provided advice, this advice has always been limited by the presence of significant technical gaps.

2.0.19. Historically, the fire service has been in charge of protecting society against the dangers of fire and therefore its role was the first one to be formalized. The experiential knowledge emerging from fighting fires and observing building performance in fires made the fire service the natural and presumed competent authority. As such, the fire service has provided significant advice to government on matters pertaining fire safety, including Building Regulations and, by extension, fire testing. This practise remains until today.

2.0.20. The level of effort deployed by different stakeholders to provide advice is intimately related to the importance assigned to the test in relation to the role of the stakeholder. Thus, the fire service will be very proactive at providing advice associated with water supply systems because water is of extreme importance to firefighting, while the plastics industry will be very proactive at providing advice on combustibility because combustibility is key to the market share of their products.

2.0.21. Given that advice is volunteered on the basis of stakeholder interest and that the knowledge base used to support such advice is experiential, it becomes essential to determine who is providing sound advice. In the area of fire testing, resolving which advice to accept is a matter that remains unresolved even today.

2.0.22. The lack of an adequate definition of competency and the fact that advice is inevitably interest driven makes it difficult for regulators to develop fire tests that adequately balance the relevant needs. As a result, there is clear confusion over what a fire test is meant to deliver and how to use the information emerging from the tests.

2.0.23. In the absence of a proper definition of competency and an independent advisory body, interest-driven advice prevails.

2.0.24. Test practices have become entrenched, and scientists and engineers have not been able to argue, on the basis of technical knowledge, why these practices should change. Common sense and experiential knowledge-based arguments have remained stronger than clear technical knowledge.

2.0.25. This is the case for performance testing, but also for testing and experimentation supporting fire investigation. The experiential and common-sense practice that drives the investigator immediately towards a large-scale fire-reconstruction has become the norm for major fire investigations. The result has been a series of inconclusive, and frequently misleading, investigation results emerging from the investigations of most of the major fires that have
occurred in the UK in the last twenty years. The conclusions, as inappropriate as they have been, have driven regulatory change and performance fire testing.

2.0.26. Nevertheless, our current capacity to learn from our mistakes is questionable, not because of lack of knowledge, but because of poor practise and unmanaged interest driven advice.

2.0.27. The reality of today is that science has caught up and that most of the knowledge and scientific principles needed to be able to adequately assess fire performance exist. Nevertheless, tradition and stakeholder interests are keeping the practice of fire safety operating under the same framework as it did more than one hundred years ago.

2.0.28. The appropriate scientific principles have been used in this report to establish the metrics necessary to assess the performance of building envelopes. This assessment has been done on a first principles basis and making sure that all relevant variables have been incorporated and that all necessary information is extracted.

2.0.29. While every effort has been made to purposely keep the assessment as simple as possible (and therefore it should not be taken as comprehensive and complete), it serves to demonstrate what it is possible to extract from testing the necessary information to assess the fire performance of building envelopes.

2.0.30. A first principles approach that focuses on understanding the different phenomena governing the failure of building envelopes has been used on systems relevant to the Grenfell Tower. The series of small-scale tests conducted at the University of Edinburgh were analysed to identify a sequence of failure and enabled the following fundamental conclusions to be reached:

- The main parameters defining self-sustained fire spread are the fire spread velocity ($V_S$) and the heating length ($L_h$).
- If the heating length is greater than zero ($L_h > 0$) then the flame will continue to spread and increase in size in an irreversible manner. Thus, if the small-scale tests show that the heating length is greater than zero ($L_h > 0$) then the small-scale tests are sufficient to establish that a system will allow for self-sustained flame spread at the building scale.
- Once self-sustained flame spread has been attained, it will continue to accelerate and the flames will continue to increase in size.
- The ignition conditions required to achieve self-sustained flame spread on an external wall system with characteristics consistent with that used at Grenfell Tower are much less onerous than those imposed by the external flames typical of most compartment fires.  

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7 When using the term compartment fire, this report refers to any fire that can be considered as ‘foreseeable’ within the context of a room in a residential unit. This could range from localized flames (like in the case of the Grenfell Tower fire) to a fully developed (post-flashover) fire. Given the significant probability of a fire attaining flashover in a residential unit, a fully
• Thus, in the event of a compartment fire in Grenfell Tower, it was inevitable that these systems would have supported uncontrolled external fire spread.

• The onset of self-sustained spread occurs when local breaches of encapsulation are followed by a generalized breach of the encapsulation.

• A generalized breach of the encapsulation provided by the aluminium plate to the core material will only occur in the presence of insulation forming part of the cavity with the Aluminium Composite Material (ACM). In the absence of insulation there is not sufficient heat feedback to fully detach the panel and the flame does not spread in a self-sustained manner.

• This behaviour is observed irrespective of the level of combustibility of the insulation.

2.0.31. The work carried out at the University of Edinburgh has demonstrated that it is possible to use a systematic set of small-scale tests to support an analysis of the system based on first principles, in order to gain sufficient understanding and obtain the necessary information to support the design and implementation of an external wall system that is compatible with a given Fire Safety Strategy.

2.0.32. In contrast, when using a first principles approach to analyse existing testing methods, it becomes clear that none of the current tests have the capacity to deliver the information that is necessary to assess the performance of building envelope systems.

2.0.33. A first principles classification is presented to try to determine the physical basis underpinning the objectives of the existing testing protocols. This allows the tests to be characterised by three different objectives:

• The first group, ‘scenario tests’, are those aiming to resemble reality and thus to assess performance under conditions deemed representative and realistic.

• The second group, ‘bounding tests’, are tests attempting to define a worst-case (or upper-bound) scenario, under which extreme loading, the performance of the test specimen can be established.

• The third group, ‘input tests’, attempts to extract quantitative information that can be used as inputs for an assessment framework or model.

2.0.34. As indicated above, the review of a large number of tests relevant to Grenfell Tower has showed that none of the tests were capable of providing the relevant information necessary to establish external fire spread performance. All tests were found to have serious weaknesses, independent of their objectives. Furthermore, many of them set performance developed fire is considered a ‘foreseeable’ event and therefore all systems supporting the fire safety strategy should be designed with this scenario in mind.

8 For the purposes of this report the term ‘encapsulation’ is defined as the full covering of a material that has a lesser fire performance with a material with a better fire performance. From a fire safety perspective, the purpose of encapsulation is to enable the use of materials in places where the required fire performance is higher than what the material can deliver.
targets that were misleading when considering the information necessary to assess the performance of these systems in the context of their application.

2.0.35. By setting misleading performance targets, that have no sound technical basis and are not linked to the end use application, these tests encouraged a culture, across all stakeholders, that ‘chased test performance targets’ instead of aiming to understand the true performance of these systems.

2.0.36. This archaic framework and approach discouraged all stakeholders from using technical knowledge, sound science and technical skill. The industry preference for reliance on ‘common sense’ and experiential knowledge in a quest to ‘chase test performance targets’ remains prevalent.

2.0.37. The above statements are not intended to discourage the use of common sense and experiential knowledge; these will always be useful and important. What is essential is for technical and scientific knowledge to be afforded the appropriate value in the assessment of fire performance. Fire is a complex physical phenomena that requires much more than ‘common sense’ and ‘experiential knowledge’ to be properly understood.

2.0.38. Among the many reasons why this is necessary is the introduction of outcomes-based regulation. This approach to regulating fire safety has made the use of the traditional prescriptive framework very difficult. If we continue to believe that outcomes-based regulation is the preferred path, then it is essential that the approach to testing for fire safety changes accordingly.

2.0.39. Other disciplines working in the built environment space have incorporated technical and scientific knowledge to develop new products, new systems and new methods of construction. These new methods are based on desired outcomes and based on technical knowledge. This knowledge-based approach has resulted in a collateral transformation of the challenges faced by fire safety. The current experiential-based/common-sense approach has proven ineffective at addressing these new challenges.

2.0.40. External façade fires represent a key new challenge. The Grenfell Tower fire, and failures that have preceded and followed this tragedy, are clear evidence of the difficulties our current fire safety practice is facing in its attempt to address this problem. The most powerful evidence is that while fires continue to happen, buildings globally are being stripped of their facades and occupants of these buildings are being negatively affected, but the technical response globally has been overwhelmingly small.

2.0.41. Society is still trying to find a response that is based on ‘experiential knowledge’ and ‘common sense’ and this response cannot be found.

2.0.42. To illustrate this, Appendix A of this report provides a short summary of the global technical response to the Grenfell Tower fire.

2.0.43. This problematic approach is in fact widespread across the fire safety engineering practice and testing practices supporting fire safety for buildings present an exceptionally good example that illustrates this problem. Thus, the subject matter within this report should also
be considered as indicative of the wider issues that are prevalent across all fire safety related practices associated to the built environment.

2.0.44. To understand the role of fire testing within an outcomes-based regulatory context, it is critically important to differentiate the concepts of conformity and compliance.

2.0.45. Conformity is a verification approach by which specific information is independently established as valid within the precision and uncertainty reported.\(^9\) An example of this is testing of a material to establish if it can be classified as non-combustible. The test, due to its specific design and characteristics, represents a specific definition of non-combustibility, thus the output of a test i.e. conformity to a classification of “non-combustible”, must be understood within that context.

2.0.46. Compliance, in an outcomes-based regulatory framework, is a verification process by which an outcome is independently established as having been demonstrated.\(^10\) An example of this is the demonstration that the outcome of the ignition of a façade panel does not lead to external fire spread that is incompatible with the fire safety strategy. The demonstration of that outcome may involve the competent engineer establishing that all materials should conform to the test definition of non-combustible, however the conformity in and of itself is not the demonstration of compliance.

2.0.47. Thus, conformity can be considered as one of many tools available to the competent professional when attempting to establish compliance.

2.0.48. As current regulation is outcomes based, it is written in terms that allow competent professionals to interpret the regulations and provide solutions. This approach towards regulation is intended to give flexibility to the professional. Nevertheless, it is the role and responsibility of the professional to demonstrate that the outcomes expected by the Building Regulations have been met. In the case of fire safety, the primary outcome is life safety.\(^11\)

2.0.49. The compliance process will independently establish that an adequate demonstration that life safety and other outcomes has been conducted. It is the role of the competent professional to present an explicit demonstration that life safety and other outcomes have been met so that the compliance authority can conduct an assessment.

2.0.50. Outcomes based regulation is typically accompanied by guidance. Guidance offers potential methods and solutions for the competent professional to use with the objective of demonstrating that the outcomes expected by the Building Regulations have been met.

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\(^9\) For the purposes of this report, conformity requires the independent verification of any values that serve to characterize a parameter. For example, a person can be characterized by height and weight with a specific level of precision (ex. nearest millimetre, nearest gram). These two parameters can be reported by the individual. So, conformity will be the independent measurement of the height and weight that serves to verify the values reported within the bounds of the desired precision.

\(^10\) For the purposes of this report, compliance is the verification that a material, product or system fulfils the function for which it is intended in the manner intended. For example, the flow rate of a sprinkler has to conform to the flow rate reported in its listing, but the sprinkler system has to comply with being able to control a fire of a magnitude considered to be characteristic of a specific building classification (i.e. comply with the objective).

\(^11\) This report constrains itself to this specific outcome while recognizing that other outcomes such as property protection, cost and practicality also require demonstration.
Following guidance is not evidence, in itself, of having appropriately demonstrated that the required outcomes have been met.

2.0.51. Needless to say, if the guidance is silent on any aspect, this is not evidence that this aspect does not have to be considered. It is the competent professional that is required to perform due diligence and deliver the necessary demonstration of outcomes in matters covered and not covered by the guidance.

2.0.52. The document used to describe all these demonstrations is a desktop study. Thus, the terminology is inherent to outcomes-based regulation. The terminology has been related to poor practice, nevertheless, this is a generic term that should have no negative connotations and just represents the written manifestation of an analysis conducted by a competent professional.

2.0.53. Current Building Regulations do not explicitly establish what the life safety outcome should be\(^\text{12}\) nor what method should be adopted to achieve it. These two key elements of the regulation therefore need to be defined by the competent professionals in consultation with all stakeholders. This is a fundamental point that remains implicit in the Building Regulations and that defines the first point of contention between the traditional (prescriptive) approach to fire safety and the current approach.

2.0.54. The means by which the desired outcome is defined is captured in the Fire Safety Strategy. The Fire Safety Strategy establishes all the individual provisions of fire safety, how they work together and how they will achieve the desired outcome. In the case of building fire safety, it is the Fire Safety Strategy, its demonstrated performance and correct implementation, that should be compliant with Building Regulations.

2.0.55. In the formulation of the Fire Safety Strategy, the competent professional needs to establish a clear desired outcome and provide the explicit demonstration of performance. This is the desktop study.

2.0.56. The first conflict in this process is often who is responsible for establishing the quantitative and overall measure of performance that represents the desired outcome. Given that the outcome is related to life safety, this is a complex decision to be made and one which, potentially, nobody wants to make.

2.0.57. The second conflict is who has the competency to establish what is an adequate Fire Safety Strategy. In the absence of a definition of competency, the latter decision cannot be resolved without conflict. This was analysed and discussed at great length in the Warren Centre Reports\(^\text{13}\) that are briefly described in Appendix A of this report.

\(^{12}\) A potential approach to establishing desired outcomes could be ‘the probability of a person to be in contact with smoke (defined by a light obscuration greater than 10%/m) and heat (defined by a maximum acceptable heat flux of 1 kW/m\(^2\)) shall remain below 10\(^{-6}\). This is just an example and advocating for any specific desired outcomes is beyond the scope of this report.

2.0.58. The natural consequence of the two conflicts addressed above has been to migrate the discussion away from the required outcomes and the Fire Safety Strategy into a discussion that focuses on the performance of components. The performance of the Fire Safety Strategy is no longer a point of discussion, instead, and for example, it is the performance of the smoke extraction system, the sprinklers or the façade system that becomes the primary driver of performance assessment. This can become even more granular and vague when terminology such as “adequately resist” or “inhibit” need to be quantified.

2.0.59. In a prescriptive framework, this is not a problem because prescriptive regulations, if adequate, deliver, as an ensemble, the desired outcomes. Given that all the components have to be as prescribed to achieve the outcome, then the focus can remain on the components. Guaranteeing that all the components are designed to prescription can lead to the conclusion that the overarching package will be a Fire Safety Strategy that delivers the expected outcomes. So, the tendency to revert to the traditional (prescriptive) approach is reinforced by the absence of desired outcomes and an explicit mention of the Fire Safety Strategy.

2.0.60. This is at the core of the current problem with the building envelope and the fire testing regimes that serve to characterize its fire performance.

2.0.61. The fire performance of building envelope systems is defined by a set of materials, products and systems that follow a sequence of assemblies until they become part of a building. Each element of these assemblies will have properties that are relevant to the overall fire performance of the system. At each stage of the assembly, all these properties need to be evaluated and then amalgamated into an analysis that quantifies a set of parameters that will then be used to characterize the next stage of assembly.

2.0.62. Any parameters that are deemed critical to attaining the required outcomes of the Fire Safety Strategy should be independently verified for conformity. The parameters are combined, through a desktop study to define either the performance of a sub-system or that of the building envelope. The fire performance of the sub-system or the building envelope also needs to be verified for conformity. The parameters describing the fire performance of the building envelope will serve as input to the performance assessment of the Fire Safety Strategy. Thus, the fire performance of the building envelope is not in itself compliant, but it can be deemed, by the competent professional, to conform with the fire performance expected of it by the Fire Safety Strategy.

2.0.63. Conformity can be verified off-site during the production of materials or the manufacturing of systems or products. Conformity can also be verified on-site during the construction and/or installation of assemblies. Conformity can be verified through inspection but also through testing or analysis.

2.0.64. Thus, a conforming building envelope is one where a set of key parameters have been quantified and independently verified. These parameters are the necessary inputs that the
competent professional needs in order to demonstrate that the Fire Safety Strategy has met the required outcomes.

2.0.65. To understand which key parameters have to be quantified and verified, it is essential to first establish what performance the Building Regulations expect from the building envelope. This performance will be part of, and will support, the overall Fire Safety Strategy.

2.0.66. In the context of external building components, current outcomes-based regulations use terminology such as “adequately resist the spread of a fire.” The word “adequate” allows for multiple approaches towards achieving such an objective. Nevertheless, the characterization of ‘what is adequate?’ should be explicitly defined by the Fire Safety Strategy.

2.0.67. The Fire Safety Strategy should amalgamate all the different fire safety provisions and define their relationships, assumptions, and performance in a manner such that the required outcomes are achieved. Thus, a specific definition of “adequate” is only valid for a specific Fire Safety Strategy.

2.0.68. In a building such as Grenfell Tower, where the Fire Safety Strategy introduces a set of very specific provisions, the definition of “adequate” is intimately related to the egress strategy. Given that a “stay-put” strategy is being utilized, and occupants remain in adjacent units, then “adequate” can only mean that ‘no external fire spread can be tolerated’.

2.0.69. Any building envelope that allows for any form of fire spread will not be consistent with a “stay-put” strategy. Depending on the design of the building, and the building envelope, different approaches can be considered, but all of them will have to guarantee that the fire will not spread beyond the unit where it originated.

2.0.70. Even if we recognize that a fire will potentially break out of the unit through a window, and that there is a risk that it could re-enter a different unit, also through a window, the condition of ‘no fire spread’ still remains for a “stay-put” strategy. This scenario, its probability and its consequences need to be addressed as part of the analysis of the potential failure modes of the Fire Safety Strategy. A competent professional will explicitly establish those scenarios, the risk level and the mitigation strategy.

2.0.71. An appropriate analysis of certain unavoidable risks can be used to caveat the interpretation of ‘no fire spread can be tolerated.’ Nevertheless, this will have to be done explicitly and the attainment of the desired outcomes would also have to be demonstrated.

2.0.72. From a physical perspective, the simplest parameter that can quantify the requirement of ‘no fire spread can be tolerated’ is the heating length ($L_h$). If the heating length is demonstrated to be zero ($L_h = 0$) then the building envelope delivers a level of performance consistent with the requirements of a Fire Safety Strategy that utilizes a “stay-put” approach to evacuation.

2.0.73. It is important to note that the principles associated with the requirement for the heating length to be zero ($L_h = 0$) can be extrapolated to the case where no combustible materials are present. This is the case when through deformations, poor design or detailing the ‘no
fire spread can be tolerated’ condition is breached and fire is capable of entering adjacent units before it has burnt-out in the unit where the fire originated.

2.0.74. Predicting the conditions that allow the ascertainment, with sufficient precision and robustness, of the heating length being zero \( (L_h = 0) \) is extremely difficult.\(^{14}\) This is particularly the case for systems as complex as those that are commonly used today in building envelopes. This needs to be considered when using a “stay-put” approach within the Fire Safety Strategy.

2.0.75. If the complexity of the building envelope cannot be resolved into a characterizable performance, it is necessary to give serious consideration to avoiding a “stay-put” strategy.

2.0.76. The tests conducted at the University of Edinburgh have shown that the condition of zero heating length, i.e. \( L_h = 0 \), could not have been attained with an external building envelope system with the characteristics of that used in Grenfell Tower. Thus, these systems cannot be used with a “stay-put” strategy. This is information that the designer/manufacturer (off-site) should have determined before bringing these products to the market, or even before subjecting them to any form of conformity assessment. This is the minimum information that could have been expected from designers/manufacturers (off-site) delivering products/assemblies with competence and moral integrity.

2.0.77. Contrastingly, if an egress strategy is defined and implemented on the basis of occupants evacuating, then it is the required time for evacuation that feeds into the definition of “adequately resist the spread of fire.”

2.0.78. The time required for occupants to safely evacuate is normally referred to as the Required Safe Egress Time (RSET) and it needs to be compared to the time that is available for them to evacuate, generally referred to as the Available Safe Egress Time (ASET). The rate of fire spread from unit to unit will define the available time for the occupants to safely evacuate.

2.0.79. In this scenario, “adequately resist” has to be demonstrated to enable the evacuation strategy to be successfully completed. A competent professional will require, as necessary information, all parameters that enable the quantification of the evolution of the rate of fire spread \( (V_S) \).

2.0.80. The rate of fire spread \( (V_S) \) is difficult to evaluate but nevertheless can be bounded by a conservative quantification. The tools necessary to do this exist and are accessible to competent professionals.

2.0.81. Currently, there is sufficient technical knowledge to support outcomes-based regulation. This technical knowledge needs to be used to understand the behaviour of all building components. This understanding then has to be used by competent professionals in support of demonstrating that the outcomes of the Fire Safety Strategy are achievable as a result of the performance of the provisions put in place by that strategy.

2.0.82. To enable the transition from experiential knowledge and stakeholder advice to technical demonstration of outcomes, it is essential to first establish a clear approach towards the

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\(^{14}\) This also applies to the case where only non-combustible materials are being used but it is necessary to quantitatively demonstrate that no fire spread beyond the unit of origin will occur until burn-out.
definition of what the desired outcomes of Building Regulations are. While these remain implicit, the goals of the Fire Safety Strategy will not be clear and therefore its explicit demonstration of performance impossible.

2.0.83. Once the desired outcomes are clear, it is essential to state that every fire safety analysis should include an explicit Fire Safety Strategy that defines how all components work together to deliver the required outcomes. With an explicit Fire Safety Strategy in place, what follows is a quantitative demonstration that this strategy meets the outcomes stipulated by Building Regulations.

2.0.84. Guidance on what a Fire Safety Strategy should include should be developed by independent parties with no commercial interests in the outcome.

2.0.85. Finally, a detailed and explicit definition of competency along the lines of what is suggested in the Warren Centre Reports is necessary to guarantee a smooth process of both conformity and compliance.

2.0.86. These actions will prompt change towards enhancing the value, respect and subsequent use of sound technical and scientific knowledge. Furthermore, it will encourage the development of technical knowledge so that it can keep pace with new technological challenges.

2.0.87. In relation to testing, a detailed understanding of product/system behaviour has a number of positive benefits including the enabling of improvements that prevent critical failure mechanisms. It also means that the value and validity of standardized testing practices can be questioned by means of correct and transparent information. This level of understanding is necessary and should be expected from designers/manufacturers (off-site) operating with competence and moral integrity, in particular when it comes to the safety of their products/systems.

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4. TESTING IN SUPPORT OF SAFE BUILDINGS

4.0.1. This report is primarily intended to convey a first principles understanding about the role of fire testing in support of construction and compliance with the Building Regulations.

4.0.2. By addressing the problem from its most fundamental principles, this report will also provide insight into the role of products, assemblies, testing and stakeholders as they pertain to the Grenfell Tower fire, hopefully therefore providing a better understanding and contextualisation of the large amount of information that has been produced as part of this inquiry.

4.0.3. To achieve the latter objective, this report provides additional background information that otherwise might be considered unnecessary. For those well versed in these matters, some of this information might seem trivial, nevertheless, the information provided is interconnected in such a complex manner that it is essential to present it all. This will enable some of the common misconceptions associated with testing and its role within the current regulatory framework to be avoided.

4.0.4. The first point that has to be addressed is: ‘what is testing?’ and how testing for the purpose of building performance assessment resembles or differs from other forms of testing. This fundamental discussion is important because it is apparent that there is a significant amount of confusion about how testing should be applied in regard to buildings.

4.0.5. In a similar manner, the principle of ‘demonstrating safety’ in the context of buildings will be discussed and how it differs from ‘demonstrating safety’ when referring to materials, products, systems or assemblies.

4.1. UNDERSTANDING TESTING

4.1.1. Figure 1 presents a schematic that aims to illustrate different aspects associated with building construction that affect the manner in which testing is conducted or interpreted. This figure is conceptual and deliberately simple and non-comprehensive, however it is presented here for illustration. Figure 1 focuses on aspects relevant to the Grenfell Tower fire, and it does not aim to cover all possible aspects relevant to building construction. A more comprehensive description is provided by ISO 9000.16

4.1.2. The most basic form of testing is material testing. Materials can be used in the manufacture of systems or products, nevertheless, before they can be used, they need to be characterized.

4.1.3. Some characteristics of materials are so well understood that they can be modelled using mathematical formulations that stem from first principles. For example, the density of a

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metal can be calculated from its molecular weight by using statistical mechanics and the methods of calculation are so well known that they can be found in many textbooks.

4.1.4. It is important to emphasize that if a mathematical model can describe, in a precise and quantitative manner, the parameter that needs to be characterized, this denotes a high level of understanding. If understanding is complete enough to enable a model, then modelling is considered the preferred option for quantifying the given parameter and quantification of the parameter can thus be achieved without testing.

4.1.5. Most material properties are too complex to be calculated, therefore they need to be measured. For this purpose, many well-defined tests have been developed. Mechanical properties (e.g. yield stresses, Young Modulus of Elasticity, density, etc.) as well as thermal properties (e.g. thermal conductivity, specific heat, etc.) can be estimated with significant precision and a very small level of uncertainty by means of very well-defined test methods. These test methods have been standardized, as have been the calculations used to derive the properties, the intrinsic errors and the uncertainty.

4.1.6. Some material properties can be very complex, not allowing a simple and unequivocal characterization. In these cases, the approaches used to characterize the properties can be varied and the errors and uncertainty are significant. Testing approaches can have defined boundaries of applicability and the methodologies and measurements can carry significant and poorly defined uncertainty. Fire related properties tend to fall in this category.

4.1.7. The objective of testing is therefore to quantify these properties (Figure 1, blue box). Quality control that involves the assessment of the test methods used, the adequacy of the application of the test methods, and the repeatability of the results (i.e. normally assessed by random sampling), gives certainty to the values reported. Quality control is thus a pathway to ensuring conformity of the reported values and the methods that deliver them; it is a process of verification.

4.1.8. Thus, in what pertains to material properties, manufacturers of those materials need to behave with competency and integrity in the use of the test methods and in the reporting of the data. The more complex the characterization of the properties, the higher the required competency. Furthermore, tracing errors becomes difficult, therefore the need for integrity in reporting results also increases.

4.1.9. In cases where the materials are deemed by themselves to pose a hazard, or if they are of exceptional value or importance, independent quality control might be necessary. In those cases, quality control should independently establish the conformity between the reported properties and the actual properties of the material. This is for example the case with diamonds where conformity is achieved by independent quality control of the reported properties.

4.1.10. The term conformity is used here to describe the process by which a reported value is verified and deemed to be correct within the bounds of the required precision and uncertainty.
4.1.11. Different materials can be combined to deliver a product or a system in the context of a production-line (green box in Figure 1). Here, a product, or a system, is defined as a combination of materials that are combined to perform a function. A product can be formed of a single material (e.g. a spoon), while a system generally includes several components (made out of a single or multiple material(s)) assembled to perform a function (e.g. a window). Products/systems are manufactured in an environment that is independent of the environment in which they will ultimately be used e.g. in a factory.

4.1.12. This definition of a product/system, when applied in the context of the construction industry, emphasizes a key characteristic which is that the product/system is manufactured and sold independently of its end use, and therefore has the potential to be used in many different ways / configurations.

4.1.13. For the purpose of this report, products/systems utilised specifically in the construction industry shall henceforth be referred to as ‘components’. Components can be very simple (e.g. steel beams, bricks, etc.) or can be very complex (e.g. fans, pumps, lifts, etc.).

4.1.14. The process of developing, testing and manufacturing of components, for the purpose of this report, is termed the ‘off-site’ process\(^\text{17}\).

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\(^{17}\) The term ‘off-site’ should not always be taken literally, in the case of some products/systems the components might be all manufactured ‘off-site,’ nevertheless they are assembled at the construction site. For example, this is the case with fire doors, that while they are considered as products/systems and thus are labelled here as ‘off-site,’ they require on-site assembly because they include the frame, hardware and self-closing mechanisms.
4.1.15. The above definitions and their implications are trivial when discussing cases like consumer products. Consumer products/systems are designed and built in a factory by combining multiple materials. The combination of materials is defined by designers and produced by the manufacturer. The designer needs to understand the environment in which these products/systems will be used so that a product/system can be designed in a manner that it fulfils its intended function in an adequate and safe manner.

4.1.16. Furthermore, the product/system designer needs to understand the user, the competency of the user and the variability of the environment of use so that they can deliver a product/system that will fulfil its functions adequately and safely under the full range of potential operating conditions.

4.1.17. Tests that characterize the capacity of a product/system to fulfil its function are used to ascertain that a product/system will work as intended. Consumer protection regulations define the rules that govern these testing regimes.

4.1.18. Testing regimes for products/systems are complex and they constantly evolve as technologies evolve, therefore the designer/manufacturer needs to fully understand the market that their product/system is entering. The designer/manufacturer takes responsibility for the performance of their products, including their safety. Therefore, significant investment in research associated with product development is expected and this investment is generally protected by law (i.e. patents, copyrights, etc.). This investment covers all functionality requirements of the products, including safety.

4.1.19. The designers/manufacturers therefore need to demonstrate high levels of competency and integrity in the assessment of the functionality requirements of their products.

4.1.20. Society can implement many different approaches towards quality control. Generally, these translate into markings (e.g. CE, UL, etc.), which mean that the manufacturer or importer affirm that the product/system conforms with specific health, safety, and environmental protection standards.

4.1.21. In the case of consumer products, the potential users are highly heterogeneous and therefore the presumed competency and proficiency expected in the use of the product/system needs to be assumed to be low or none. Product/system manufacturers need to be aware of this and are responsible for design and manufacture according to what is expected from the user.

4.1.22. Components are considered a specific sub-set of products/systems that are designed and manufactured to be used within a series of assemblies which are typically bespoke to the building in which they are ultimately installed.
4.1.23. The process of designing and combining components in order to produce a ‘building’ is, for the purpose of this report, labelled the ‘on-site’ process.

4.1.24. These assemblies are designed and built by the ‘on-site’ designers/builders, who are not the same entities as those designing and manufacturing components (the ‘off-site’ designers/manufacturers).

4.1.25. This handover is very important because the off-site designer/manufacturer produces a component that has a range of applications. The on-site design is a bespoke application that has specific needs defined by the designer/builder. The users of the components are therefore professionals who are expected to be competent and therefore are designed and manufactured with this level of competency in mind.

4.1.26. It is the responsibility of the off-site designer/manufacturer to adequately and competently represent the performance of the component when utilised on-site, but it is the responsibility of the off-site designer/builder to use this information in a competent manner. Competency is necessary at both ends and all parties are required to conduct their activities with integrity.

4.1.27. The off-site designer/manufacturer must have a very clear idea of the market so that a component with the correct characteristics and information can be delivered to the on-site designers/builders. This is the responsibility of the off-site manufacturer and applies to all functionalities of the product, in particular those related to safety.

4.1.28. The off-site designer/manufacturer carries this responsibility because no other stakeholder knows the product/system as well as the designer/manufacturer, in particular because some of the knowledge is proprietary and non-disclosure of certain information is frequently protected by the law.

4.1.29. The on-site designer/builder has to be competent enough to use the product and the available information appropriately. It is only the on-site designer/builder that knows and understands the needs for the specific building in which the component is to be utilised. In the case of fire safety, it is the on-site designer/builder that has created and is implementing the Fire Safety Strategy that will be used to meet the requirements of Building Regulations.

4.1.30. The on-site designer/builder is expected to be able to trust the information provided by the off-site designer/manufacturer, nevertheless, the on-site designer/builder is never exempt from due diligence. This is always the case because every particular application has the potential to bring challenges that might require additional, improved or reinterpreted information. In this case, on-site and off-site professionals are expected to establish a

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18 The ‘building’ is, for the purpose of this report, also considered to be a ‘product’, for which the design and manufacture process will also incorporate and rely on testing.

19 The term ‘on-site’ should not be used literally. In the case of some assemblies, the assembly might be manufactured ‘off-site,’ nevertheless the assembly is considered bespoke to the specific building and defined by the designer/builder and therefore is labelled here as ‘on-site.’ For example, the case with fireproofing of steel elements with intumescent paint. In this case the steel and paint are defined by the designer/builder for the specific needs of a construction site, and thus, are labelled here as ‘on-site’ assembly. Nevertheless, the steel elements might require off-site manufacture because of quality control.

20 The term on-site designer/builder covers all professionals participating in the design and execution processes. These can include architects, engineers, builders, construction managers, etc.
competent dialogue such that challenges particular to the building can be elucidated and resolved.

4.1.31. In matters that pertain to safety, verification that the different levels of assembly perform adequately might be required. This could be as required by regulations or conducted because the on-site designer/builder has identified the need for such verification. In this case, appropriate testing needs to be implemented to extract the performance of the assemblies for all their required functionalities. This generally covers all matters of safety but also covers other functionalities such as energy efficiency, comfort, etc.

4.1.32. Verifying the adequacy of assemblies of components will frequently require periodic inspections and analysis of performance test data. Different regulatory regimes have implemented different forms of inspection and verification. The delivery of this verification can range from self-certification by builders or clerks of works and, in the case of fire, by fire brigades, building certifiers or specially appointed authorities. Figure 1 does not explicitly show a verification and inspection path because of the many different approaches that can be taken towards this process.

4.1.33. The objective of this verification process is to guarantee that all the information required to ascertain the performance of all the assemblies against all necessary functionalities has been collected. Furthermore, this information has to be adequate and sufficient. This process is therefore still a process of establishing conformity.

4.1.34. All parties involved in this process will be handling complex information which requires professional competency and the understanding of complex testing methods and highly analysed data. Therefore, the exercise of competency needs to be done with integrity in a manner that is consistent with general principles of professional practice.

4.1.35. It is at the level of the final assembly that the role of testing ends. What follows is the appropriate use of the available information which is the responsibility of the on-site designer/builder and eventually, once the building is completed and handed-over, of the building owner / manager.21

4.2. UNDERSTANDING COMPLIANCE WITH BUILDING REGULATIONS

4.2.1. Building regulations are implemented to provide assurances that the building (as a complete product) fulfils its intended functions in a manner that can be deemed adequate. The term “adequate” varies from jurisdiction to jurisdiction but it amalgamates elements of performance as well as cost and feasibility.

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21 The term ‘building manager’ is used in a generic way to describe the organizations or individuals in charge of maintaining the performance and functionality of a building to levels consistent with what is required by Building Regulations. There are cases where such management does not exist, in those cases the building has to be designed and built to guaranty performance and functionality through the expected life of a building. For certain assemblies, the alternative is to empower the user to identify failures and have the capacity to correct them. As an example, this is the case with issues regarding lighting or plumbing.
4.2.2. If Building Regulations are outcomes-based, then it is the building that needs to explicitly satisfy the required outcomes. Compliance with the Building Regulations therefore pertains to the building, not its components or subassemblies, which instead are demonstrated to conform (to specific health, safety, or environmental protection standards for example).

4.2.3. It is a fundamental misconception in the field of fire safety that assemblies or individual components can be considered as ‘compliant’. This is a mind-set carried over from a period of strict prescriptive regulations where all individual components had to conform to specific sets of rules and therefore be deemed compliant with those rules.

4.2.4. In that regulatory environment, compliance of all individual components (without exception) implicitly meant compliance of the overall Fire Safety Strategy (in form and function) with its intended objectives. Therefore, whereas in a fully prescriptive environment, assemblies and products need to be compliant, this is not the case in an outcomes-based regulatory system, which as stated above, pertains to the building as a whole.

4.2.5. In the case of fire safety, the functionality requirements (i.e. the desired outcomes) for the building are delivered by means of an explicit Fire Safety Strategy. This is compiled by the on-site designer who determines / specifies the performance required of the component parts of the building (i.e. the individual products or assemblies) such that the ensemble delivers the desired outcomes and thus compliance.

4.2.6. Products that are selected for installation in the building must therefore conform to that specified level of performance / functionality. Testing provides a means to demonstrate that conformity to the on-site designer.

4.2.7. The output from conformity orientated testing may simply take the form of data or else be presented as a more formalised rating or classification. It is the responsibility of the on-site designer to demonstrate that the information gathered through the conformity processes (Figure 1) is correctly used in the development of a Fire Safety Strategy such that the overall strategy complies with the requirements of Building Regulations.

4.2.8. Thus, the Fire Safety Strategy and the building can be compliant with society’s expectations for safety, as defined by the Building Regulations. The Fire Safety Strategy addresses compliance as a technical concept that is explicitly demonstrated to fulfil the required outcomes and the building is then compliant as a product that is demonstrated to deliver the required outcomes.

4.2.9. This Fire Safety Strategy, produced by the on-site designer, which explicitly states the various requirements for conformity, can then be implemented by the builder and verified by the appropriate process or authority.

4.2.10. The regulatory framework might require inspection of the building and validation of the Fire Safety Strategy. Similarly, the on-site designer might also require further inspection to guarantee conformity such that all elements of the Fire Safety Strategy will perform as assumed by the design.

4.2.11. So, whether it is required by regulation or by the on-site designer, all necessary inspections need to be enabled through the building process. Without those inspections, conformity
cannot be established and there can be no guarantee that the Fire Safety Strategy will function as intended and deliver compliance.

4.2.12. During the construction process, all stakeholders endeavour to deliver a building that is consistent with the design. Any changes to the design need to be validated through dialogue between all parties until agreement that the altered Fire Safety Strategy still fulfils the requirements of the Building Regulations.

4.2.13. In constructing the Fire Safety Strategy, the on-site designer is expected to exercise competency and integrity. In delivering an adequate Fire Safety Strategy all parties (i.e. designer, builder, verification authority, etc.) need to exercise competency and integrity.

4.2.14. It is the role of the building owner / management to guarantee that the compliance which should be ascertained at the moment of handover of the building, remains during operation. For this purpose, those managing a building have to exercise their role with competency and integrity.

4.2.15. Having defined how testing fits within the delivery of a compliant building within the generalised context of outcomes-based regulations, the following section will focus specifically on Building Regulations, as applicable to Grenfell Tower, to establish how these principles can be applied and what the implications are for the adequacy of existing testing regimes as well as professional practice.
5. **BACKGROUND ON RELEVANT BUILDING REGULATIONS**

5.0.1. The principal objectives behind building regulation in the UK began to shift from property protection to life safety following the introduction of requirements for ‘means of escape’ in the Factory and Workshop Act 1901\(^{22}\), and later the Public Health Act 1936\(^{23}\). This was followed by the Building Regulations 1965\(^{24}\), which were the first set of national (England and Wales) prescriptive design regulations\(^{25}\).

5.0.2. The Building Act 1984\(^{26}\), marked the wholesale introduction of outcomes-based regulation for fire safety in the UK, with the adoption of a set of ‘functional requirements’ in the Building Regulations 1985\(^{27}\) replacing previous prescriptive rules and deemed-to-satisfy solutions. The rationale for this change in approach is discussed elsewhere,\(^{28}\) but it is important to stress that the underlying objective of this regulation was, and remains, life safety.

5.0.3. The diversity of infrastructure that these functional requirements are required to regulate means that, by necessity, they are stated in relatively ambiguous terms, using terminology such as “adequately resist” or “inhibit”. Since their introduction in 1984, the functional requirements that relate to the provision of fire safety have barely changed in this respect.

5.0.4. Any regulatory approach framed in these ambiguous terms therefore requires designers to demonstrate that the performance of their designs meets the intent set out in each functional requirement. Therefore, by necessity, the designers must define what constitutes “adequately resist” or “inhibit”, in effect deriving an explicit array of performance requirements, bespoke to the piece of infrastructure they are designing, and the Fire Safety Strategy being created for it.

5.0.5. A designer must then explicitly demonstrate, by means of appropriate performance metrics, that the design meets the performance requirements and thus, by extension, the intent of the functional requirements.

5.0.6. To assist designers in the process of achieving solutions that meet the functional requirements, practical guidance was provided by the Secretary of State in the form of Approved Document B\(^{29}\).

5.0.7. The first version of Approved Document B did not however address all of the functional requirements and mandatory prescriptive rules for ensuring means of escape were initially

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\(^{22}\) The Factory and Workshop Act 1901

\(^{23}\) The Public Health Act 1936

\(^{24}\) The Building Regulations 1965, Statutory Instruments 1965 No. 1373, (LABC0009446)

\(^{25}\) Bisby, L. Grenfell Tower Inquiry Phase 2 – Regulatory Testing & the Path to Grenfell. Section 9.2. (LBYP20000001)

\(^{26}\) The Building Act 1984, 1984 Chapter 55.

\(^{27}\) The Building Regulations 1985, Statutory Instruments 1985 No. 1065.

\(^{28}\) Bisby, L. Grenfell Tower Inquiry Phase 2 – Regulatory Testing & the Path to Grenfell. Section 11. (LBYP20000001)

maintained. Only with the introduction of the 1992 version of Approved Document B did all functional requirements (B1 – B5) become subject to guidance rather than prescription and/or deemed-to-satisfy solutions.

5.0.8. As pointed out by Dame Judith Hackitt, whose report endorsed the continued use of the outcomes-based approach, users of the Approved Documents, and specifically Approved Document B, have tended to treat / consider these documents as deemed-to-satisfy solutions, where it is assumed that following the ‘rules’ associated with each specific component leads to an adequate overall solution to the Fire Safety Strategy.

5.0.9. An even more complex problem in practice has been the assumption that when the guidance is silent, there is no need for further analysis or information. This is not a correct approach to the use of the guidance documents.

5.0.10. The result of this misuse is clearly evidenced by the realisation of the scale of use of polyethylene ACM cladding on many High-Rise Residential Buildings (“HRRBs”) around the UK since the Grenfell Tower fire, and by the subsequent discussion that has focussed on the adequateness of the ‘guidance’ in Approved Document B.

5.0.11. This report will explicitly address the manner in which the guidance in Approved Document B was used with respect to demonstrating conformity of external wall systems. It will aim to reaffirm that the guidance must be considered as a tool in the design process, presenting only information that a competent professional can use towards ultimately achieving adequate performance in the context of the Fire Safety Strategy.

5.0.12. This report will principally address the existing regime of physical testing (whether of materials, components, systems or assemblies) to ascertain if the tests are capable of evidencing the appropriate performance metrics directly, or else of providing information / data that supports the designer in determining whether these products/assemblies support the needs of the Fire Safety Strategy.

5.0.13. To do this, the required performance metrics must first be explicitly established. This report will step through this process, deriving the performance criteria that can be used towards establishing if the Fire Safety Strategy meets the intent of the functional requirements.

5.0.14. At this stage, the report focuses on the Fire Safety Strategy, although, as explained before, this is only the first step of compliance. The discussion then needs to move towards building compliance and management, and involve the process of delivering and maintaining the building.

6. PERFORMANCE ASSESSMENT OF EXTERNAL FIRE SPREAD ON HIGH RISE BUILDINGS

6.0.1. An ‘outcomes-based’ regulatory framework requires infrastructure to adhere to a ‘Fire Safety Strategy’\(^{34}\) that ensures the infrastructure in questions meets the societal expectations for fire safety. In the UK, the Fire Safety Strategy is implicitly represented by a set of functional requirements. These functional requirements must then be transformed into a set of explicit performance requirements that are bespoke to the building in question.

6.0.2. The explicit performance requirements will inevitably be a function of the performance of individual components/systems/assemblies through complex relationships. The understanding of these complex relationships represents the professional practice of Fire Safety Engineering. In matters of fire safety, the professional Fire Safety Engineer is therefore the on-site designer.

6.0.3. The on-site designer can then establish the necessary demonstrations of performance for each product/system/assembly. This requires the selection of the most appropriate way of demonstrating that performance, whether that be by physical testing, analysis, computational modelling or otherwise.

6.0.4. It is the analysis of available data by the designer that is generally labelled a desktop study. Desktop studies are an unavoidable feature of an ‘outcomes-based’ regulatory framework. Desktop studies analyse, organize and present the quantitative evidence that supports the Fire Safety Strategy.

6.0.5. The following section will use the implementation of over-cladding of the Grenfell Tower as an illustration of the process by which performance requirements should be assessed. The analysis will be centred around the Fire Safety Strategy as the key target for compliance.

6.1. ADEQUATE PERFORMANCE AS A FUNCTION OF THE FIRE SAFETY STRATEGY

6.1.1. At the time of the over-cladding of the Tower, the applicable Building Regulations are understood to have been the Building Regulations 2010.\(^ {35}\) Part B of Schedule 1 of the Building Regulations sets out the functional requirements that relate to fire safety. As previously stated, the primary overall objective for the ‘Fire Safety Strategy,’ that is implicitly defined by these functional requirements, is life safety.

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\(^{34}\) It is important to note that in current Building Regulations, and in those applicable to the design and refurbishment of Grenfell Tower, the ‘Fire Safety Strategy’ is an implicit concept. This report carries the use of this terminology from my Phase One report as a concept that is overarching to the functional requirements. Accepting that the objective of Building Regulations is life safety, inevitably requires all functional requirements to be structured around a Fire Safety Strategy that is focused on delivering life safety. Therefore, the use of the term ‘Fire Safety Strategy’ should not be interpreted as language specific to relevant Building Regulations, guidance or practice.

\(^{35}\) The Building Regulations 2010, Statutory Instruments 2010 No. 2214. (LABC0008228)
6.1.2. The Fire Safety Strategy represents how these functionality requirements are being interpreted and organized to deliver the overall objective of life safety.

6.1.3. The role of the Fire Safety Strategy will be illustrated through a simple example. This example, while based on reality and using appropriate quantifications, is purely intended for illustration. Therefore, the options described throughout this section should not be taken as implicit endorsement of any specific approach or as a thorough analysis of the events that unfolded during the Grenfell Tower fire.

6.1.4. The example to be developed here will look specifically at relationship between requirements B1 and B4.(1). Requirement B1 states that:

“The Building shall be designed and constructed so that there are appropriate provisions for the early warning of fire, and appropriate means of escape in case of fire from the building to a place of safety outside the building capable of being safely and effectively used at all material times.”

While requirement B4.(1) establishes:

“The external walls of the building should adequately resist the spread of fire over the walls, and from one building to another, having regard to the height, use and position of the building.”

6.1.5. As written, the requirements state that the provisions for early warning and means of escape have to be “appropriate” and that the external wall reaction to the fire has to be “adequate.”

6.1.6. There are clearly two components to the latter requirement; (1) to adequately resist the spread of fire over the walls, and (2) to adequately resist the spread of fire from one building to another, both contextualised by the height, use and position of the building in question.

6.1.7. This example will specifically address the first of these components i.e. what constitutes to “adequately resist the spread of fire over the walls,” in the context of the fire at Grenfell Tower and considering the provisions implemented to satisfy requirement B1.

6.1.8. The Fire Safety Strategy in place in Grenfell Tower at the time of the fire utilised a “stay-put” strategy, whereby only the occupants of the flat of fire origin were alerted to the presence of the fire by the detection and alarm system in their unit.

6.1.9. Requirement B1 is therefore implemented using an alarm system that notifies the occupants of the first unit of the presence of the fire and by providing a clear path for these occupants to escape the building, i.e. these are the “appropriate provisions for the early warning of fire, and appropriate means of escape in case of fire.”

6.1.10. All other occupants were expected to be able to remain indefinitely and safely, in their respective units with any fire contained to the unit of fire origin by fire-resisting construction

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36 Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019. (INQ00014818)
(Requirements B3.(3) and B3.(4)), until that fire has either consumed all available fuel, or has been extinguished by firefighter intervention.

6.1.11. As established during Phase 1 of the Inquiry, the fire at the Tower was first detected at approximately 12:55am in the kitchen of Flat 16. Evidence shows that it had spread to the cladding system by approximately 01:06am. By approximately 01:15am, the fire was established on the external face of the cladding system, and subsequently spread vertically, reaching the architectural crown of the building at approximately 01:30am. Analysis puts the average rate of vertical external fire spread at approximately 4m per minute.\(^{38}\)

6.1.12. The fire then spread laterally around and then vertically down the Tower.

6.1.13. As per the Fire Safety Strategy, the majority of the occupants of the Tower initially remained in their respective units or else moved to those of a neighbour, and continued to be instructed to do so, until full evacuation was ordered at 02:47am.\(^{39}\)

6.1.14. As was documented in Phase 1 of the Inquiry,\(^{40}\) the fire resulted in 72 deaths, principally attributed to the spread of fire over the external wall system, which enabled the fire to circumvent internal fire-resisting construction, endangering the lives of those occupants that remained within the building. Thus, the external wall system did not “adequately resist” the spread of fire over the walls for a building of this specific use (high-rise residential) with this specific Fire Safety Strategy. This was clearly stated in the Phase One Report where Grenfell Tower was deemed as non-compliant.\(^{41}\)

6.1.15. It is important to add, given that the objective of the Building Regulations as a whole is one of life safety, the Fire Safety Strategy implemented at Grenfell Tower was also not compliant because the ‘stay-put’ strategy is inherently inconsistent with vertical external fire spread.\(^{42}\)

6.1.16. The link to the Fire Safety Strategy is more clearly illustrated by considering the potential outcome from the same fire event, had an alternative Fire Safety Strategy been in place. The alternative postulated here assumes an idealised simultaneous evacuation strategy,\(^{43}\) supported by appropriate detection and alarm infrastructure, initiated by the first detection event, with occupants having been made aware of the need to evacuate upon sounding of a relevant alarm, and appropriate provisions for means of egress that include provisions for occupants classified as Persons with Reduced Mobility (PRM). This would have also included pre-planned response with emergency services. This alternative Fire Safety Strategy is

\(^{37}\) Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019. [INQ00014818]

\(^{38}\) Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. [JTOR00000001]

\(^{39}\) Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019. [INQ00014818]

\(^{40}\) Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019. [INQ00014818]

\(^{41}\) Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019. [INQ00014818]

\(^{42}\) Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. [JTOR00000001]

\(^{43}\) The practicalities of implementing such an evacuation strategy in this manner in a HRRB are acknowledged but set aside for purpose of this example.
therefore formulated upon a different interpretation of the word “appropriate” in Requirement B1.

6.1.17. The Phase One report\textsuperscript{44} states that “in the early stages of the fire (before around 01.50) there was a marked difference between conditions in the lobbies and conditions on the stairs; generally, the smoke in the stairs was less dense than in the lobbies, allowing 168 people to escape the tower by 01.50.”

6.1.18. The above suggests that conservatively, evacuation was achievable before approximately 1:50 am.\textsuperscript{45}

6.1.19. Simplistic calculations that only consider perfectly able occupants enable baseline times for egress to be established.\textsuperscript{46} These estimates are not presented to indicate that these should have been the times of egress during the Grenfell Tower fire but are presented just for the purpose of illustrating the hypothetical example described above.

6.1.20. On the basis of that caveat, and considering a conservative travel time of 1 minute is required to evacuate one floor, given that the Tower had 24 floors, the travel time from the uppermost floor can be conservatively approximated as ±25 minutes. This results in ±35 minutes left to include any unforeseeable delays and pre-movement (reaction) time and will still allow all occupants sufficient time to escape. Occupants from the upper floors would have reached the lower half of the tower by 1:20 am and thus not been hampered by the smoke reported after this time in the upper levels.

6.1.21. Indeed, successful evacuations of this nature have taken place in fires with extensive external vertical fire spread. See Appendix A for details and references related to the information available in the multiple compilations of past-events that have been published before and after the Grenfell Tower fire.

6.1.22. In this scenario, the overarching life safety objective could have been achieved, and thus logically, so would the Fire Safety Strategy have met the functional requirements of the Building Regulations. In this scenario, the over-cladding system could have been considered to have “adequately resisted” the spread of fire i.e. the fire spread would have not directly impacted the life safety of the occupants. If there were no occupants in the building when the means of egress were compromised, then “adequately resist” could be interpreted as “it is not required to resist.”

6.1.23. These contrasting examples serve only to illustrate that the definition of what is “adequate”, is inherently tied to the manner in which all functionality requirements are structured

\textsuperscript{44} Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019, Vol 4, p.573. (INQ00014817)

\textsuperscript{45} Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019, Vol 4, p.573. (INQ00014817)

\textsuperscript{46} The simple calculation of one minute per floor comes from taking average data for displacement velocities from the SFPE Handbook for Fire Protection Engineering (SFPE, 2016) and standard maximum egress distances. It is just a reference value used for rapid estimation that should not be considered as an accurate representation of what the potential egress times would have been during the Grenfell Tower fire.
around an overall Fire Safety Strategy for the building, and in this case, specifically, in relationship to the word “appropriate” in the context of the evacuation policy.\(^{47}\)

6.1.24. It is once again essential to note that this is not an endorsement of this interpretation but a simple example that illustrates how extreme interpretations can still remain within the bounds of the ambiguity embedded in the Building Regulations.

6.1.25. Different fire safety strategies allow for different interpretations of the functionality requirements without altering the overall outcome. This is the advantage of the ambiguity embedded in the language used in the Building Regulations. While this ambiguity can give the designers freedom it can also result in inappropriate interpretations if the designer does not carefully assess the interplay of all requirements within the Fire Safety Strategy.

6.1.26. A further issue of great relevance here is whether the designer has sufficient or adequate information to make the necessary assessments and where that necessary information has to come from. This therefore reintroduces the purpose of testing and the competency associated with the interpretation of test results in the context of the Fire Safety Strategy.

6.2. **EXPLICIT DEFINITION OF ADEQUATE PERFORMANCE**

6.2.1. The above comparison presents two bounding approaches to the Fire Safety Strategy which will be further discussed and developed here to define explicit performance requirements that could be used in the design process to establish compliance with the Building Regulations. These approaches are defined as follows:

- **Approach 1.** A Fire Safety Strategy that supports a *controlled evacuation* strategy
- **Approach 2.** A Fire Safety Strategy that supports a *stay-put* strategy

6.2.2. In the case of Approach 1, the Fire Safety Strategy will require that evacuation of each sector of the building occurs before the fire compromises this sector or its corresponding means of egress. The sector can be a unit, a floor or the whole building.

6.2.3. To demonstrate that this objective has been met it is possible to establish and compare two sets of characteristic times:

- **I.** The first set corresponds to the time required for evacuation of each sector, this could be the evacuation of a unit, the evacuation of each floor or the evacuation of the entire building. These are generally referred to as the Required Safe Egress Time or RSET

- **II.** the second set of times corresponds to the period before the fire manages to breach any egress path and prevent any occupants from egressing any sector of the building. This time is commonly referred to as the Available Safe Egress Time or ASET.

\(^{47}\) It is important to note that this postulation is not advocating for the use of simultaneous evacuation in high-rise residential buildings but simply postulated to illustrate the inherent link between the Fire Safety Strategy and interpretation of the functional requirements of the Building Regulations.
6.2.4. Fire spread can therefore be tolerated so long as:

I. It does not compromise a unit before everyone has been evacuated from that unit

II. Each floor, and then the building as a whole, has been evacuated before the egress paths have been compromised

In effect, whether looking “locally” or “globally”, for Approach 1 to be compliant with the Building Regulations, the ASET must always be larger than the RSET.

6.2.5. It is important to note that in the evaluation of the ASET there are many provisions that can be explicitly incorporated to isolate external fire spread from the means of egress and therefore to extend the ASET. All those provisions (e.g. smoke management, compartmentalization, etc.) must be explicitly designed in accordance to the solicitations imposed by Approach 1.

6.2.6. Given the uncertainties associated with human behaviour and the need to treat all occupants equally, it is essential to establish a robust and conservative approach to the characterization of time. Thus, it is important to guarantee that the RSET must not just be smaller than the ASET, but significantly smaller.

6.2.7. To summarise, in the specific case of a controlled evacuation (Approach 1), external fire spread over the façade can be tolerated. The performance criteria for what constitutes “adequately resist” can be explicitly established by defining an allowable rate of fire spread. The allowable rate of fire spread will emerge from comparing the time necessary to compromise a sector or the egress paths enabling evacuation from a sector (ASET) to a conservatively estimated time for egress (RSET).

6.2.8. If appropriately implemented such that all occupants can safely evacuate the building, then should the external fire continue to envelop the rest of the building, such an outcome, from a life safety perspective, would be acceptable.

6.2.9. An important consideration is fire brigade response. Approach 1 can only be implemented in coordination with the fire brigade and under the recognition that the fire brigade might not have the capacity to safely fight the fire ensuing from external fire spread.

6.2.10. So, for Approach 1, in what concerns the over-cladding, the parameter to be quantified is the rate of fire spread.

6.2.11. The ‘stay-put’ strategy (Approach 2) has as its fundamental premise that only the occupants of the flat of fire origin are alerted and required to evacuate. All other occupants are expected to be able to remain indefinitely, safely, in their respective units.

6.2.12. Therefore, a fundamental and essential performance objective, critical to instigating a ‘stay-put’ strategy, is that fire is contained within the unit of origin and does not spread to other units where occupants remain.
6.2.13. As shown in my Phase One report and as exemplified by the Grenfell Tower fire, the occurrence of any form of external vertical fire spread undermines / disables all of the provisions of the Fire Safety Strategy (internal separation, firefighter intervention, smoke control, egress etc.) and therefore external vertical fire spread cannot be tolerated.

6.2.14. Thus, this firmly establishes the performance criteria for the functional requirement in the context of a stay-put strategy (Approach 2) as no amount of external fire spread can be permitted and there is no tolerable error and/or acceptable uncertainty in this regard.

6.2.15. As opposed to Approach 1, time ceases to be a performance metric and this performance criteria must be sustained for the duration of the fire event.

6.2.16. In what concerns over-cladding, the performance criteria when following Approach 2 is therefore, a “no fire propagation condition” for the duration of the event.

6.3. ESTABLISHING THE RELEVANT PERFORMANCE METRICS

6.3.1. Once the relevant performance metrics have been clearly defined for both approaches, then it is necessary to explore the process of fire spread to establish what characterizes both fire spread velocity and the no fire spread condition.

6.3.2. Whether the performance criteria of compliance with the functional requirement is “no fire spread” or “an allowable rate of fire spread”, appropriate performance metrics need to be established from which subsequently, an explicit demonstration of performance can be made.

6.3.3. By explicitly defining these performance metrics, it will then be possible to assess the current testing methodologies to determine if they are capable of adequately capturing these performance metrics and are therefore fit for purpose in the context of this application.

6.3.4. Clearly, for Approach 1, the expected rate of fire spread over an external wall system must be explicitly established.

6.3.5. With regard to Approach 2, given that the duration of the event cannot be defined in a robust manner, it is essential to implement a precise definition of how long it would be necessary for the compartmentation to remain intact. There are two options:

I. Establish a response time for the fire service and the associated performance metrics for fire fighting

II. Guarantee compartmentation that performs beyond burn-out of the fire

6.3.6. For option 1, where the response time is used, the design must ensure that fire and smoke cannot migrate outside the unit of origin before the fire service have extinguished the fire. This will include a robust, conservative, explicit determination for the time of arrival of the fire brigade, the time required to reach the seat of the fire, and the time required to

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extinguish the fire. In addition, and for robustness, this will require the evaluation of an alternative strategy in case the fire brigade fails to meet any of these pre-defined times.

6.3.7. For option 2, where the integrity of the compartment must be guaranteed beyond burn-out, it is essential to quantify the behaviour of the compartment boundaries (including the external wall) for the duration of the fire. The duration of the fire is determined by the geometry of the unit and the amount of fuel available. Thus, the time to burn-out will be defined by the geometry of the building and the amount of fuel accumulated within a unit. The amount of fuel needs to be conservatively assessed. The means to do this include inspections or statistical determination of a typical distribution of fuel loads.

6.3.8. The case of no fire spread requires that any external flaming that originates from within the unit, throughout the quantified duration of the internal fire, has to extinguish before flaming can be established on the external façade materials. It is potentially acceptable that materials forming part of the external wall could ignite, although they should extinguish as soon as the external flame is extinguished without compromising any additional units. Thus, the relevant performance metrics in this instance require the understanding of ignition and extinction.

6.3.9. In summary, the appropriate performance metrics for assessing performance of an external façade in respect of the functional requirements are the potential for ignition, the rate of fire spread and the tendency to extinction. All tests used to provide data to make this assessment must provide output that is relevant to addressing/demonstrating these performance metrics.

6.3.10. The following section of this report describes these performance metrics in detail and breaks them down in order to establish the exact parameters that must be derived from the output of any testing regime that is to be used to this end.
7. **BREAKDOWN OF RELEVANT PERFORMANCE METRICS**

7.0.1. In the previous section, the relevant metrics for assessing the performance of an external façade system in regard to its ability to adequately resist the spread of fire have been identified as the potential for ignition, fire spread rate and the tendency to extinction.

7.0.2. Logically, it is necessary for any testing regime that is used to assist in the assessment of performance via these metrics, to provide information/data relevant to establishing these metrics. Such testing might involve a direct assessment of these metrics or establish a component of the processes that these metrics represent.

7.0.3. To assess if a testing regime can therefore capture these metrics (processes) or components of them, it is first necessary to explicitly describe the processes and their component parts.

7.0.4. This section will also describe in detail the process of ignition, a process which inherently links flame spread and extinction, and is critical to understanding both.

7.1. **IGNITION**

7.1.1. The flame spread process can be considered as a sequence of individual, incremental ignitions, following the initial ignition that first resulted in the flame. Extinction occurs when a single ignition in that sequence is prevented from occurring, thus breaking the sequence.

7.1.2. Ignition requires the surface of the combustible material to be heated by an external source of heat until it reaches a critical temperature. At that temperature, the combustible solid material undergoes chemical decomposition into a fuel vapour which is released into the air next to the solid surface.

7.1.3. This fuel vapour mixes with the air (containing oxygen) to form a combustible mixture which can then be ignited by the external source of heat. If the external heat source is a flame which is sufficiently close to the combustible mixture to ‘come into contact with it’ and ignite it directly, this is termed “piloted ignition”.

7.1.4. If the flame is not sufficiently close to cause a piloted ignition, it can heat the combustible mixture from a distance by radiation until such a point as it undergoes ‘auto ignition.’ While physically possible, in most common situations flame spread by auto ignition is very uncommon and therefore this mechanism is not discussed any further.

7.1.5. When discussing external building envelope fires, it is very likely that the external heat source will be a flame projecting from an opening (i.e. window) of a compartment fire. Flames originating from fires external to the building (e.g. waste bins) are also possible. Characterization of the potential ignition sources is essential, although it is important to be
aware that flame projections from fully developed fires can reach more than $100 \, kW/m^2$.\textsuperscript{49} Accordingly, when assessing the performance of combustible materials, it has to be assumed that they could potentially be exposed to such heat fluxes.

7.1.6. There are many possible approaches to the characterization of ignition, however the most common is by establishing the critical temperature that defines the onset of chemical decomposition of the solid fuel (‘ignition temperature’ or $T_{ig} [\degree C]$) and time taken to reach this temperature. It is regularly assumed that the onset of solid decomposition signals the onset of potential for ignition, therefore the time taken to reach the ignition temperature is often referred to as the ignition delay time ($t_{ig} [s]$).

7.1.7. The ignition delay time depends on how much external energy is being supplied to the material ($q''_e [kW/m^2]$) and some key material properties. The most commonly used approach (and the assumptions embedded within the analysis) are summarized in the SFPE Handbook for Fire Protection Engineering.\textsuperscript{50} This approach uses a heat transfer analysis to obtain an expression that links, via the aforementioned key material properties, the external heat supply and the ignition delay time. This expression is as follows:

$$ t_{ig} = \frac{\pi}{4} \frac{k \rho C}{(T_{ig} - T_\infty)^2} \left( \frac{1}{q''_e} \right)^2 $$

\textit{Equation 1}

7.1.8. The term ‘$k\rho C$’ is typically referred to as the thermal inertia and consists of the product of the thermal conductivity ($k [kW/m.K]$), the density ($\rho [kg/m^3]$) and the specific heat ($C [kJ/kg.K]$) of the material. All three are properties of the material that relate to the capacity of the material to absorb heat. A material with high thermal inertia will require a lot of heat to increase its temperature.

7.1.9. $T_\infty$ denotes the ambient temperature. The ambient temperature is always recorded in standardized testing as a reference value, thus is a known quantity.

7.1.10. From Equation 1 it can be observed that ignition can be delayed by increasing the thermal inertia ($k\rho C$), increasing the ignition temperature ($T_{ig}$) or decreasing the external heat supply ($q''_e$).

7.1.11. The relationship governing the phenomenon of ignition, presented in Equation 1 uses ignition delay time ($t_{ig}$) as a surrogate for ignition. Faster ignition is generally equated as greater hazard.

7.1.12. Equation 1 is only valid if the external heat flux ($q''_e$) is greater than a critical heat flux for ignition ($q''_{0,ig}$), the latter being the minimum external heat flux necessary to bring


combustible material to its ignition temperature. If the material cannot reach its ignition temperature, it will never ignite.

7.1.13. Therefore, the main variables controlling ignition are as follows in Table 1:

Table 1: Material properties, inputs and outputs associated to ignition.

<table>
<thead>
<tr>
<th>Equivalent Alternative</th>
<th>Type of Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition temperature, $T_{ig}$</td>
<td>Critical Heat Flux for Ignition, $\dot{q}''_{0,ig}$</td>
</tr>
<tr>
<td>Thermal Inertia, $k p C$</td>
<td>Material property</td>
</tr>
<tr>
<td>External heat-flux, $\dot{q}''_e$</td>
<td>Input</td>
</tr>
<tr>
<td>Ambient temperature, $T_\infty$</td>
<td>Input</td>
</tr>
<tr>
<td>Ignition Delay Time, $t_{ig}$</td>
<td>Output</td>
</tr>
</tbody>
</table>

7.1.14. Accurate and reproducible standard testing protocols (e.g. ASTM-E-1321\textsuperscript{51})\textsuperscript{52} which exploit the relationship in Equation 1 have been developed. By measuring the inputs and corresponding outputs shown in Table 1, the data can be used to establish the corresponding material properties, i.e. ignition temperature, and thermal inertia, and also establish the critical heat flux for ignition if required.

7.1.15. It is important to note that in all tests, simplifications and idealizations are introduced and the user of the data needs to be well versed on these simplifications and idealizations. Only a knowledge of the test will enable the appropriate use and extrapolation of the test output to scenarios different to the test. The literature associated with the standard test will generally explicitly state all these simplifications and idealizations.

7.2. FLAME SPREAD

7.2.1. As stated previously, flame spread can be thought of as a series of individual ignitions which when viewed as a sequence, form a continuous process by which a flame creeps over the surface of a combustible material.

7.2.2. For simplification, the description in this section will focus on a single mode of flame spread. Upward flame spread over a continuous combustible material is chosen to illustrate the main variables that control flame spread due to its particular relevance to the subject matter of this report.


\textsuperscript{52} In this analysis, reference to international standard tests has been deliberately made, not because there are no equivalent British standard tests, but to avoid confusion with the discussion on each standard test that will follow later in the report.
7.2.3. A similar approach can be followed for downward flame spread or lateral flame spread. The mechanisms controlling the rate of spread are the same for the three modes of flame spread although downward and lateral flame spread are much slower than upward flame spread.

7.2.4. Lower rates of flame spread represent a lesser hazard, so upward flame spread is also the more dangerous and persistent mode of flame spread. Given this, and similarities between the three modes, downward and lateral flame spread will not be discussed further in this report.

7.2.5. The diagram in Figure 2 shows an idealised slice of a flame established in the air, immediately adjacent to a vertical surface of a burning material. This diagram highlights the important characteristics necessary to describe the process of upward flame spread.

7.2.6. The gases produced by the burning flame are hotter than their surroundings and so rise upwards. Colder air is naturally drawn in from below. This process is continuous and therefore creates a general flow of air and combustion gasses in the upwards direction (shown in Figure 2).

7.2.7. The burning flame is also hotter than the combustible material therefore heat is transferred from the flame to the combustible material, whether it is burning or not. The heat flux from the flame to the surface of the combustible material is shown in Figure 2 as $\dot{q}_f$. This heat flux will vary along the length of the flame, nevertheless here it is represented by this single variable.

7.2.8. Where the material is already burning (the burning length, $L_b$), the heat from the adjacent flames keeps the material in this region above the critical ignition temperature, and so it continues to chemically decompose, releasing fuel vapour from its surface (shown as a brown arrow in Figure 2).

7.2.9. This fuel vapour mixes with the air which is continually being drawn in from below (blue arrow). As this air contains oxygen, the resulting mixture of air and fuel vapour is combustible. The flame, which is continually present, is therefore ideally located to ignite this combustible mixture.

7.2.10. Some of the heat produced by this combustion reaction feeds back into the burning material, resulting in the release of yet more fuel vapour, which is then also ignited by the flame and so the flame self-perpetuates as a seamless series of ignitions.
Figure 2: Schematic of upward (or forward) flame spread over a continuous combustible material.
7.2.11. The general upward flow of air causes the mixing of fuel vapour and air to occur not just immediately above the burning surface, but also further ‘downstream,’ in this case above the burning length. Wherever a combustible mixture is created in this air stream, it can be ignited, creating a flame that extends beyond the burning length. Thus, it is the airflow that gives the flame its elongated shape and its overall length, ‘$L_f$’.

7.2.12. When combustion takes place above the burning length, the heat flux from the flame (\(\dot{q}_f\)) also heats the unburnt surface of the material. This results a length of material being heated by the flame. This will be called the heated length and is labelled in Figure 2 by $L_h$.

7.2.13. The length of material heated is typically referred to as the heated length, ‘$L_h$’. The flux of heat from the flame along the heated length is typically more intense closer to the end where the burning is already taking place, becoming gradually less intense towards the tip of the flame.

7.2.14. The surface of the material in the region of the heated length will therefore rise in temperature. The uneven flux of heat to the heated length will create a temperature gradient along the surface where the unburnt material is hottest at location (a) in Figure 2 (where it is just arriving at the critical temperature for ignition), getting gradually cooler until location (c) (where it is only just beginning to be heated).

7.2.15. Because of this, a small length of the surface immediately above location (a) will be the first portion of the heated length to reach the critical temperature for ignition. This length is shown in Figure 3 as ‘\(\Delta L_b\)’. When it reaches the ignition temperature, it will start to chemically decompose and release fuel vapour which will mix with the air and be ignited by the flame. It will thus become part of the burning length and the flame can be said to have spread.

7.2.16. The result is that there is now a bigger overall burning length, ‘$L_b + \Delta L_b$’. If the time it takes for this change to occur is described as $\Delta t$, then the flame spread velocity, ‘$V_s$’, can be described as the distance travelled by the flame front divided by the time taken for it to travel that distance, or:

$$V_s = \frac{\Delta L_b}{\Delta t}$$

7.2.17. The above essentially describes an incremental ignition of a small length of combustible material caused by an existing flame. As described at the beginning of this section, the process of continuous flame spread can be thought of as simply a continuous sequence of the above.

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53 $\Delta$ is a mathematical symbol used to represent a non-specific amount of change, so $\Delta L_b$ represents a change in $L_b$. 
Figure 3: shows the same flame as Figure 2 but $\Delta t$ seconds later. It has spread slightly up the vertical surface so that the burning length has increased by $\Delta L_b$. The speed at which the flame is spreading, $V_S$, can thus be expressed as $V_S = \Delta L_b / \Delta t$. 
7.2.18. While the explanation provided above is based on a single fire spreading, in many instances the heat flux originating from the flame \( \dot{q}_{f} \) can be assisted by heat coming from other flames or hot smoke, as shown in Figure 2 by \( \dot{q}_{e} \). This is very common in compartments where the accumulated hot smoke can deliver heat that is comparable to the heat flux coming directly from the flame.

7.2.19. Other examples where the flame spread is assisted by a significant heat flux are cavities with multiple combustible materials. If more than one combustible material is burning within a cavity then the flame from one material will assist the spread of a flame over the surface of another material.

7.2.20. Defining the potential heat flux that can assist flame spread is a complex process that requires very detailed understanding of the fire dynamics within the region adjacent to the flame. This will be explored in greater detail later in this report, but at this point it will simply be referred to as an external heat flux \( \dot{q}_{e}[kW/m^2] \).

7.2.21. As described above, flame spread over combustible materials tends to be idealised as a continuous process by which the flame creeps over the surface of the material (Figure 3). The continuous nature of the combustible material potentially differentiates it from the more all-encompassing term ‘fire spread’ which does not require a continuous combustible surface, and where it is possible for a flame to ‘jump’ over gaps with no combustible materials (Figure 4 (b)).

Figure 4: Schematic of vertical flame spread showing three different conditions (a) flame spread over a continuous combustible material (b) flame spread over a discontinuous combustible material (c) Arrested flame spread by means of discontinuities in the combustible material
7.2.22. In this case the fire will only spread if the flame can heat a nearby combustible material until it starts producing combustible gases and the flame is close enough that it can still act as an ignition source. This is the scenario depicted in Figure 4 (b). If the non-combustible material extends beyond the heated length (Figure 4 (c)), then the flame will not be able to cause ignition of the nearby combustible material. This is a first scenario where the ‘no fire spread’ condition can be attained and is exemplified in practice by the use of non-combustible spandrels/panels.

7.2.23. As hopefully is clear thus far, flame spread is controlled by: 1) the material (or product or system)’s characteristic properties that lead to its decomposition into combustible gases (fuel vapour), 2) the production rate of those combustible gases, and 3) the propensity for the combustion of those gases to transfer sufficient heat so as to not only perpetuate the flame, but also ignite adjacent combustible material.

7.3. IDENTIFYING THE PARAMETERS CONTROLLING THE FLAME SPREAD VELOCITY

7.3.1. When a flame is established over a portion of a combustible material, the total rate of production of further fuel vapour ($\dot{m}_f [kg/s]$), can be defined as the product of the fuel production rate per unit area that is burning ($\dot{m}'_f [kg/s.m^2]$), multiplied by the area burning ($A [m^2]$).

7.3.2. The area that is burning can be expressed as the burning length ($L_b [m]$) multiplied by the burning width ($w_b [m]$). Therefore, per unit width of flame i.e. $w_b = 1 [m]$, the total rate of production of fuel vapour can be expressed as:

$$\dot{m}_f = A. \dot{m}'_f = L_b \dot{m}'_f$$

EQUATION 3

7.3.3. As described previously, the fuel produced will migrate towards the air flow, where the air and fuel will chemically react resulting in products of combustion and heat. The heat produced per unit mass of fuel is termed the heat of combustion ($\Delta H_C [kJ/kg]$) and the total energy released per unit time is the rate of heat released ($\dot{Q} [kW]$). Therefore, the rate of heat release is given by equation (4)

$$\dot{Q} = \Delta H_C \dot{m}_f$$

EQUATION 4

7.3.4. The heat of combustion is a property of the combustible material, but also of the burning conditions.

7.3.5. The heat release rate is a very important variable because it determines the temperature of the flame, and ultimately, the heat being transferred towards the solid to enable the spread of the flame. As described, the temperature of the flame is highest when closest to the fuel and it decays as the flame moves away from the burning surface. Figure 3 shows two locations on the flame, (f) and (g). The temperature in location (f) will be greater than the temperature in location (g).
7.3.6. Furthermore, the temperature in location (g) has decreased so much that the chemical reaction stops; this is the critical flame temperature for quenching \( T_{\text{crit}} \) [°C]. It is common and appropriate to assume that \( T_{\text{crit}} \approx 1600 - 1700 \degree C \)\textsuperscript{54} and therefore this value does not need to be ascertained. Nevertheless, this value serves to determine where combustion quenches and therefore the value of the flame length \( L_f \) [m]. Anywhere else in the flame the temperature will be denoted as the flame temperature \( T_f \) [°C] and it will be higher than the critical temperature \( T_f > T_{\text{crit}} \).

7.3.7. It is important to note that the flame temperature is not the temperature of the hot gases \( T_g \). Fires are turbulent flows and therefore flames are intertwined with reactants and products. The reactants and products are colder than the flame so the overall gas temperature (i.e. the average of flames, reactants and products) is much smaller than the flame temperature \( T_f \approx 1500 - 1700 \degree C \)\textsuperscript{55} and therefore this value does not need to be ascertained. Nevertheless, this value serves to determine where combustion quenches and therefore the value of the flame length \( L_f \) [m]. Anywhere else in the flame the temperature will be denoted as the flame temperature \( T_f \) [°C] and it will be higher than the critical temperature \( T_f > T_{\text{crit}} \).

7.3.8. Nevertheless, it is the flame temperature that defines the temperature of the gases and therefore the gas temperature follows the same trends as those described for the flame temperature in the paragraph above. It is the overall gas temperature \( T_g \) that will define the heat flux emerging from the flame.

7.3.9. It can therefore be concluded that the heat release rate \( \dot{Q} \) determines the flame temperature \( T_f \) which in turn determines the temperature of the gas \( T_g \). It will also determine the flame length \( L_f \) and the heat being transferred from the flame to the combustible solid \( \dot{q}''_f \). In turn the heat release rate \( Q \) depends on the burning length \( L_b \), the burning rate per unit area \( \dot{m}''_f \) and the heat of combustion \( \Delta H_C \). The sequence of processes is schematized in Figure 5.

7.3.10. The heat of combustion \( \Delta H_C \) can be determined by means of multiple standard tests of which the cone calorimeter (ASTM-E-1354\textsuperscript{55}) and the bomb calorimeter\textsuperscript{56} are the most commonly used. It is important to note that in both tests the heat of combustion obtained will be slightly less than the theoretical (or ‘idealised’) value based on the known chemical composition of a material, therefore this limitation needs to be taken into consideration.

7.3.11. Most combustion books will tabulate heats of combustion obtained by means of these tests for many combustible materials.\textsuperscript{57,58} Tabulated values generally provide the ideal heat of combustion, which is the maximum amount of energy that a material can release under idealized burning conditions. In most cases the conditions are not ideal and therefore combustion is deemed incomplete, and its heat of combustion is less than the tabulated values.

7.3.12. An important variable affecting the heat of combustion is the air supply to the flame. If excess air is supplied (more than what is necessary for complete combustion), it is common for the heat of combustion to approach the ideal value. If the supply is not sufficient for complete combustion, then the combustible gas does not release all its energy and the heat of combustion is less than the ideal value. It is possible to evaluate, by means of testing, what the effective heat of combustion is, although the test would have to accurately replicate the real burning conditions and be properly instrumented.

7.3.13. The determination of the burning rate per unit area ($\dot{m}_f''$) and of the burning length ($L_b$) is a much more complex process because these are not material properties but rather are a function of complex heat exchange processes.

**Figure 5:** Sequence of processes defining the rate of spread of a flame (green). In black are the main parameters, in brown independently measured material properties and in blue parameters that are independent of the flame spread process.
7.3.14. The nature of the airflow will influence the way in which heat is being transported. As such, the direction and magnitude of the air flow will have a significant effect on heat transfer. In turn, the size of the flame can determine the magnitude of the airflow induced by buoyancy; therefore, these processes are difficult to uncouple.

7.3.15. In a similar manner, other sources of heat \( \dot{q}'' \) can add to the flame heat flux. The characteristics of each heat source will determine the area being heated \( (L_h) \) (Figure 2) and if, and if so, how fast, the temperature of the combustible material is raised from that of ambient to the ignition temperature to enable the flame to spread.

7.3.16. The more heat is being transferred, the shorter the ignition delay time, just like in the ignition process. The larger the region being heated \( (L_h) \) the larger the area that will ignite and therefore the faster the spread rate. As can be seen from Figure 5, external heat flux, flame heat flux and air flow will define \( L_h \).

7.3.17. Having described many of the overlapping relationships between these parameters, what follows is to establish how all these parameters can be used to determine the rate of spread of the flame. Numerous formulations have been proposed in the literature and among the simplest one is proposed by Quintiere\(^{59}\) and shown in Equation 5 below:

\[
V_S = \frac{\phi}{kpC(T_{tg} - T_{\infty})^2} \quad \text{Equation 5}
\]

7.3.18. The parameter \( \phi \) is known as the flame spread parameter and represents the energy delivered to heat the combustible solid material from the ambient temperature \( (T_{\infty}) \) to its ignition temperature \( (T_{tg}) \). \( \phi \) can be expressed as follows:

\[
\phi = (\dot{q}''_f + \dot{q}''_e)L_h \quad \text{Equation 6}
\]

7.3.19. Equation 5 provides an expression for the flame spread velocity \( (V_S) \). It is important to note that this expression utilizes the same material properties necessary to characterize ignition (i.e. ignition temperature: \( T_{tg} \) and thermal inertia: \( kpC \)) which is logical when having conceptualised the flame spread process as a series of ignitions.

7.3.20. Beyond the properties characterized for ignition, the only additional material property necessary to characterize flame spread is the flame spread parameter \( (\phi) \). The flame spread parameter can also be determined using standard testing (ASTM-E-1321)\(^{60}\) following Quintiere’s theoretical approach.\(^{61}\)

7.3.21. Each column in Figure 5 shows the different set off processes ultimately leading to the flame spread velocity \( (V_S) \). While the number of material properties necessary to characterize the


flame spread velocity can ultimately be limited to three \((\phi, T_{ig}, kpC)\), flame spread has many more processes than ignition and each of these processes creates intermediate parameters (all terms to the left of \(\phi\) in Figure 5). Equation 5 lumps all these parameters into a single term, \(\phi\), which can be quantified by a specifically developed standard testing procedure\(^62\).

7.3.22. Having ascertained \(\phi\) from this standardised test along with the material properties \((T_{ig}, kpC)\) from standardized ignition tests,\(^63\) a characteristic flame spread velocity can be calculated from Equation 5.

7.3.23. Following this approach, the main variables controlling flame spread can be summarised as follows in Table 2:

<table>
<thead>
<tr>
<th>Equivalent Alternative</th>
<th>Type of Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition temperature, (T_{ig})</td>
<td>Critical Heat Flux for Ignition, (\dot{q}^\prime)_0,ig</td>
</tr>
<tr>
<td>Thermal Inertia, (kpC)</td>
<td></td>
</tr>
<tr>
<td>Heat of Combustion, (\Delta H_C)</td>
<td></td>
</tr>
<tr>
<td>Flame spread parameter, (\phi)</td>
<td>(L_h) as obtained from modelling that includes (\dot{q}^\prime)_e, (\dot{q}^\prime)_f and airflow plus additional modelling that allows to calculate (L_f) and (T_f) from the heat release rate ((\dot{Q})). Heat release rate, (\dot{Q}) plus modelling Burning rate ((\dot{m}_f)) as obtained from (\dot{m}_f) and (L_p) plus modelling</td>
</tr>
<tr>
<td>External heat-flux, (\dot{q}^\prime)_e</td>
<td></td>
</tr>
<tr>
<td>Ambient temperature, (T_{\infty})</td>
<td></td>
</tr>
<tr>
<td>Flame Spread Velocity, (V_S)</td>
<td></td>
</tr>
</tbody>
</table>

7.3.24. Needless to say, the testing conditions and their influence on the results have to be carefully assessed before any extrapolation is conducted. Given the complexity of the processes and the simplicity of the approach, the capacity for extrapolation is somewhat limited.

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7.3.25. It is essential to emphasize that using the parameter $\phi$ obtained by means of standard testing to assess in-use performance of a real material or system implies that the conditions of the test must be representative of reality for all parameters (given in Figure 5). Where changes in environmental conditions matter then those changes need to be incorporated by means of analysis.\textsuperscript{64}

7.3.26. Furthermore, as illustrated in Figure 5 and Equation 2, the flame spread velocity ($V_s$) defines the burning length ($L_b$), therefore the feedback loop also needs to be carefully considered.

7.3.27. This simple approach can only be used for the performance assessment of very simple systems and in a very conservative manner, to the point that some will claim that it is only useful for the relative rankings of materials and cannot be used for understanding the performance of systems.\textsuperscript{65}

7.3.28. Alternative approaches seek to increase relevance and precision by evaluating intermediate parameters that could have a significant impact on the flame spread velocity, through additional standardized testing and modelling. The more parameters which are independently assessed, the more precise and robust the extrapolation to in-use conditions. Nevertheless, the increase in parameters also results in an increase in complexity of the assessment process and thus in an increased presumption of competency for those individuals conducting the assessment.

7.3.29. If one wanted to evaluate the flame spread velocity from first principles it would be necessary to start with an initial calculation ($t = 0$ seconds) from the furthest left column of Figure 5 and first evaluate the burning rate per unit area ($\dot{m}_f$) and the burning length ($L_b$). With that information any model of the process being used then needs to progress from left to right through all the intermediate parameters until the flame spread velocity can be calculated. The flame spread velocity obtained can then be fed back to the left most column to obtain a new burning length ($t = \Delta t$ seconds, Equation 2) and then all calculations would need to be repeated.

7.3.30. The evaluation of all these parameters by means of models has been attempted in the past by many\textsuperscript{66} but has proved only to be possible for very simplified scenarios. Furthermore, it still required strong assumptions and the use of an enormous amount of computational resources. It is therefore clear that, from the outset, it is necessary to rely on tests to estimate many of the different terms.

7.3.31. One attempt to achieve this approach to modelling has been provided, in the context of Grenfell Tower, by Dréan et al. Their analysis, assumptions, simplifications and limitations are discussed in Appendix A of this report.

7.3.32. A commonly used intermediate approach aims to eliminate the need to assess the terms in the first two columns of Figure 5 and to determine the heat release rate directly via testing. Standardized methodologies have been defined for this purpose and enable the evolution of the heat release rate ($\hat{Q}$) in time to be ascertained. It is also possible, through the determination of the heat release rate, to obtain the burning rate ($\dot{m}_f$), an average burning rate per unit area ($\dot{m}_{fr}$) and an effective heat of combustion ($\Delta H_c$).

7.3.33. The main problem with this approach is that it does not recreate the feedback loop between the flame spread velocity ($V_S$) and the burning length ($L_b$), thus major assumptions have to be made which relate the flame spread velocity to the heat release rate. The standard test will therefore only deliver the heat release rate ($\hat{Q}$) and does not address any relationship between this parameter and the flame spread velocity.

7.3.34. It is important to clarify the use of terms such as effective or average. These terms are necessary because the tests cannot provide all the detailed information and instead deliver approximate values that are intended to represent appropriate estimations for use in practice. Furthermore, the tests are conducted under very specific conditions, so any extrapolation requires a careful and competent analysis.

7.3.35. The heat release rate can be inputted into mathematical models that can deliver the different parameters described in the subsequent columns towards the right of Figure 5. Once again, these models range from empirical correlations for simplified scenarios, to complex computational models. In all cases additional simplifications and assumptions are necessary to enable a prediction of the flame spread velocity. Perusal of the literature shows the complexity of these analysis, the significant potential for error, and the high level of competency necessary from those using these tools.

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7.4. **EXTINCTION AND THE NO FLAME SPREAD CONDITION**

7.4.1. Extinction is the result of what is mathematically called a ‘bifurcation.’ A bifurcation is a condition by which minute perturbations lead to a very different outcome. Under certain conditions the system will support burning and the spread of flame. However, under slightly different conditions, a system could struggle to continue to burn and instead tend to extinction of the flame.

7.4.2. A good example of small variations influencing the potential outcome is the degree of exposure of polyethylene core at the edges of ACM cladding panels. Depending on how much of the core is exposed, it could anchor a flame that will persist until conditions change (e.g. an aluminium face delaminates) which allows the fire to spread. Slight alterations in the size and nature of the edges can result in an insufficiently robust burning process that cannot self-perpetuate.

7.4.3. When these bifurcations are examined by means of testing, they require great attention. Very small changes in a scenario test can lead to dramatic changes in the result.

7.4.4. The ‘no fire spread’ condition is inherently coupled with extinction because if a flame cannot continue to spread, it will eventually consume all available fuel and thus extinguish. Given the complexity of the flame spread process, assessing the tendency to extinction requires detailed and explicit treatment.

7.4.5. While the previous section described how to calculate the flame spread velocity, ‘\( V_s \),’ it did not discuss the conditions necessary to prevent the flame from spreading. Based on the structure of Equation 5, an expression for calculating flame spread velocity, the aim of preventing a flame from spreading i.e. making \( V_s = 0 \), can be achieved if the denominator is extremely large.

7.4.6. In Equation 5, the denominator consists only of material properties. The thermal inertia (\( kpC \)) can vary significantly and result in slow flame spread but will never achieve the no-flame spread condition.

7.4.7. In contrast, if a material is non-combustible, it will not ignite, no matter what the surface temperature is, therefore can be considered the equivalent of \( T_{ig} \to \infty \). In this case there will be no ignition and no flame spread.

7.4.8. Thus, a condition of there being no flame spread is that the material is non-combustible. Physically demonstrating the condition of \( T_{ig} \to \infty \) is clearly problematic, therefore standard tests will introduce sufficiently high threshold temperatures (in the case of BS 476-4\textsuperscript{72} and

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\textsuperscript{71} From an ethical perspective, dealing with bifurcations opens the door to advice. Advice can be provided by personnel of testing facilities to clients to guide them towards the development of systems that will require very minor modifications to meet the testing requirements. The guidance can be ethical, when it leads to true improvement of the system’s fire performance, or it can be unethical when the guidance is intended to help pass a test with no real performance gain or when the changes move the system away from it being representative of the actual building envelope whose performance is being assessed. This is of critical importance in Scenario Testing.

the threshold is set at 750°C) which could be deemed as equivalent to non-combustible.

7.4.9. Focusing on the numerator in Equation 5, i.e. the flame spread parameter $\phi$ which is expressed more fully in Equation 6, the absence of both a flame and an external heat-flux will result in $\dot{q}^f + \dot{q}^e = 0$ which is the equivalent of not achieving ignition.

7.4.10. Given that compartment fire heat fluxes can be of the order of 100 kW/m², not achieving ignition under those heat fluxes implies that the material will not ignite when its surface temperature has exceeded approximately 750°C and thus again, is non-combustible.

7.4.11. The final condition that leads to no propagation is when there is no heated length, i.e. $L_h = 0$. This condition requires for the flame length to be smaller than the pyrolysis length ($L_f \leq L_p$). As will be discussed later in this report, this is a very important condition/phenomenon which is not currently assessed as part of any testing regime.

7.4.12. If this condition is valid then heat will not be transferred ahead of the flame and the flame will extinguish with no flame spread after the fuel in the burning region has been fully consumed. To establish this condition, the heated length, $L_h$, needs to be estimated explicitly by either measurement or modelling.

7.4.13. Modelling tools will have to model all terms affecting $L_h$, as presented in Figure 5. The capacity to accurately estimate the evolution of $L_h$ by modelling, as indicated above, requires major assumptions and simplifications as well as enormous computational resources. Currently, no model has demonstrated adequate first-principle predictions of the heated length, $L_h$, therefore, the only possible characterisation is currently, once again, by means of testing.

7.4.14. On the basis of the above, the main variables controlling the non-flame spread condition are set out in Table 3.

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Table 3: Material properties, inputs and outputs associated with no flame spread.

<table>
<thead>
<tr>
<th>Equivalent Alternative</th>
<th>Type of Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition temperature, $T_{ig} \rightarrow \infty$</td>
<td>Non-combustible</td>
</tr>
<tr>
<td>Thermal Inertia, $kpC \rightarrow \infty$</td>
<td>Not physically possible</td>
</tr>
<tr>
<td>$\dot{q}''_f + \dot{q}''_e = 0$</td>
<td>Non-combustible</td>
</tr>
<tr>
<td>Heated Length, $L_h = 0$</td>
<td>$L_h$ as obtained from modelling that includes $\dot{q}''_e$, $\dot{q}''_f$ and airflow plus additional modelling that allows to calculate $L_f$ and $T_f$ from the heat release rate ($\dot{Q}$).</td>
</tr>
<tr>
<td>Non-Flame Spread, $V_S = 0$</td>
<td></td>
</tr>
</tbody>
</table>

7.5. SUMMARY

7.5.1. This section has described in as simple a manner as possible the process of fire spread over a combustible material. Wherever possible, processes and parameters have been simplified to their minimum expression. Thus, this section does not pretend to be comprehensive, instead it is simply illustrative of how complex processes can be reduced to measurable parameters through an understanding of theory.

7.5.2. Two processes have been identified as being essential to a quantitative estimation of “adequately resist the spread of a fire.” The processes are as follows:

a. Approach 1 - (controlled evacuation) requires the quantification of the fire spread velocity, $V_S$

b. Approach 2 – (stay-put strategy) requires either the use of non-combustible materials or the quantification of the heated length, $L_h$, to demonstrate that the heated length is zero, $L_h = 0$.

7.5.3. Table 1 summarizes all the properties necessary to characterize ignition as a building block towards the characterization of fire spread. Table 2 summarizes the properties necessary to characterize the fire spread velocity and Table 3 the properties required to characterize the conditions that enable $L_h = 0$.

7.5.4. Figure 5 summarizes all the different processes that need to be calculated to achieve the necessary predictions.
7.5.5. It is important to emphasize that while all these processes are extremely complex, methodologies have been developed to make appropriate estimations of the fire spread velocity. These methodologies include calculations and standardized test results. These estimations will carry significant error and imply major assumptions, nevertheless they can be used by competent professionals for the purpose of assessing the validity of Approach 1.

7.5.6. In a similar manner, the same methods can be used to evaluate the heated length, $L_h$. For materials that support any form of combustion $L_h = 0$ is the necessary condition that enables Approach 2. Nevertheless, if the materials support any form of combustion, there is no test methodology that enables quantification of when and how the critical condition of $L_h = 0$ has been attained. As the ‘no fire spread’ condition is a bifurcation, precision is essential because very small changes can result in major differences in outcome. This makes the definition of this condition even more difficult and complex.

7.5.7. The following section discusses additional elements of complexity that have been introduced as products/systems have been developed. This additional complexity increases the difficulties already established in this section and further challenges the current capacity of our methods to quantitatively characterize the variables necessary to support a specific Fire Safety Strategy through testing.
8. SYSTEM COMPLEXITY AND TESTING

8.0.1. The evolution of products/systems used for construction is determined by many drivers associated with architecture, sustainability, cost and constructability. It is these drivers that encourage manufacturers to innovate in order to achieve better performance in regard to as many of these drivers as possible. This is how most current products/systems entering the construction market respond to multiple requirements of functionality.

8.0.2. Multi-function systems tend to increase complexity, thus building envelopes formed of single materials are no longer the reality for the construction industry. Building envelope systems have multiple layers, multiple materials and complex geometries.

8.0.3. This section introduces some complexities that have become a common occurrence in components used in modern building envelopes. Some of these complexities have been introduced to meet functionality requirements not related to fire but others have been incorporated directly in response to fire safety regulatory requirements.

8.1. ENCAPSULATION

8.1.1. Encapsulation is probably one of unique complexities that has been introduced to attain a desired performance for several specific objectives. Two key performance drivers are reducing heat transfer between the building and the environment and achieving fire performance targets. Insulating a building in a practical and cost-effective manner encourages the use of combustible polymers, while fire safety requirements represent barriers towards their use. It is therefore important to discuss encapsulation using the fundamental principles presented in the previous section.

8.1.2. In a context where ‘no fire spread’ is required and the conditions listed in Table 3 can neither be met nor evaluated, an alternative approach has been adopted by product developers. The alternative approach uses non-combustible materials to cover combustible materials in a manner that allows for the conditions of Table 3 to be met. This is normally referred to as encapsulation.

8.1.3. Full encapsulation will require the combustible material to be covered on all sides by a layer of non-combustible material which is capable of withstanding the level of insult of a fire that is consistent with its intended use and as a result, will not breach any of the conditions listed in Table 3. A fully encapsulated system is shown in Figure 6 (a).

8.1.4. The key to encapsulation is that it needs to meet the same requirements as those established in Table 3, but these conditions are achieved by the ensemble of a non-combustible barrier and a combustible core material. Exposure of the combustible core material will inevitably breach the conditions of $T_{ig} \to \infty$ and $\dot{q}_f^\prime + \dot{q}_e^\prime = 0$ but do not necessarily breach the condition of $L_h = 0$. Therefore, partial encapsulation (Figure 6(b)) is possible if the exposed material does not result in a heated length and thus, $L_h > 0$. 
8.1.5. Non-combustible materials such as aluminium have very high thermal conductivity and therefore will dissipate any heat from an external source that may be impinging on the exposed core material at the product edge very effectively. If this energy is dissipated very rapidly then the combustible material might not reach its ignition temperature. This could potentially allow exposed edges to be present in the cladding panel without breaching the $L_H = 0$ condition.

![Diagram of encapsulation types](image)

**Figure 6**: The concept of encapsulation (a) fully encapsulated (b) partially encapsulated and (c) single side exposure encapsulation.

8.1.6. In a similar manner, insulation can be directly mounted against non-combustible wall assemblies resulting in heat exposure only being possible at the one exposed side. In this case only single side encapsulation will be necessary (Figure 6(c)). It is important to note that for any single side exposure it is still necessary to consider the possibility of heating of the exposed shorter edges, as the $L_H = 0$ condition still needs to be met.

8.1.7. If encapsulation fulfils its function, then the system can be treated as non-combustible and there is no further need to evaluate the potential for flame spread. Nevertheless, the complexity of the system introduces additional performance metrics, because continued attainment of “effective non-combustibility” relies on the continued functionality of the encapsulation.

8.1.8. The new performance metric that emerges therefore is that the encapsulation exhibits adequate thermo-mechanical system performance as it receives heat from a fire that is deemed to be realistic. Factors that influence this type of performance in these systems include, but are not limited to:

- individual performance of each material, degradation, thermal expansion, deformation, melting, dripping, etc.
- relative performance of the ensemble, relative deformation (e.g. splitting, cracking because of restraint, peeling because of relative deformations, etc.)

- performance of any adhesive

- temperature gradients, as they pertain relative deformations, localized stresses, etc.

Figure 7: Failure of encapsulation (a) Sequence of failure of an aluminium composite panel showing how the aluminium plate is first adhered to the core, but as it heats-up it splits forming a gap that eventually leads to ignition (b) failure of insulation encapsulated by cementitious rendering.

8.1.9. Figure 7 shows two examples of breaches of encapsulation. Figure 7(a) shows the splitting of the aluminium plate as a result of a combination of heating, temperature gradient induced relative deformations and adhesive failure. The splitting sequence leads eventually to ignition of the combustible core material.

8.1.10. Figure 7(b) shows the cracking of a cementitious render induced by relative thermal deformations between the polymeric insulation and the cementitious rendering leading to pyrolysis of the insulation and eventual ignition. In both cases the result is $L_H > 0$ and thus failure to meet one of the conditions of Table 3.

8.1.11. It is important to note that thermo-mechanical modelling of the failure of encapsulation assemblies is even more complex than the modelling of flame spread, because it incorporates all the parameters described in Figure 5, plus all the new parameters associated with the thermo-mechanical behaviour of the system. Thus, performance assessment requires detailed and comprehensive testing that can elucidate the different forms of failure and the conditions that induce them.
8.1.12. The more complex the system, the more the influence of variables on the rate of spread needs to be assessed. This generally implies the use of multiple tests, complex models and extensive measurements.

8.2. COMPLEX SYSTEMS

8.2.1. Figure 26 of my Phase One Report\textsuperscript{76} is reproduced here in Figure 8. As explained in that report, the effect on flame spread of flow velocity, external heat fluxes, material properties, etc. have been analysed extensively.

8.2.2. As explained in the previous section, adequate models for simple scenarios such as vertical flame spread over a flat surface have also been studied, but less attention has been given to the spread of flames within cavities.\textsuperscript{77} It has been found that the width of the cavity (“W” in Figure 8) plays a fundamental role in the rate of flame spread.

8.2.3. Considering the extremes, if “W” is large, radiative feedback and buoyantly driven chimney effects disappear with flames spreading at similar rates to those in the case of a single, fully exposed surface. Conversely, if “W” is very small, thermal expansion of the gases interrupt the general air flow (blue arrow in Figure 2) and the flames cease to spread internally, remaining outside the cavity.

8.2.4. Accelerated spread can be explained by the presence of open vertical channels, inducing chimney effects associated with their width (“W”) and also by preferential burning of specific combustible materials.

8.2.5. It is often the case that when construction systems are developed, little attention is given to the extreme complexity introduced. Figure 8 shows a very simplified schematic of the different processes occurring during the spread of a flame within a simplified version of the external wall system used in Grenfell Tower.

\textsuperscript{76} Torero, J.L., Grenfell Tower Fire Public Inquiry, Phase One Report, 2018.

8.2.6. In a system of such complexity, many other processes are introduced beyond simple effects such as the role of “W” (i.e. the cavity width). The low melting temperature and high thermal conductivity of aluminium results in complex heat transfer from external flames into the combustible core of the panel. Furthermore, melting of the aluminium is possible, so the loss of protection needs to be accounted for. The polyethylene core of the panel will also melt at low temperatures, while the temperature gradients between the inside and the outside will result in differential deformations of the aluminium plates. This can lead to splitting of the plates and exposure of the polyethylene\textsuperscript{78,79}.

8.2.7. Inside the cavity, the insulation might pyrolyze, char and burn but also potentially burn-out. Insulation generally has a very low thermal inertia\textsuperscript{80} and it is treated so that charring is promoted. A low thermal inertia favours a fast flame spread rate, nevertheless its tendency to char results in small fuel production and therefore short flame lengths. Charring therefore has a detrimental effect on the rate of fire spread.

8.2.8. The outcome of these two competing effects is determined by the radiative exchange between the insulation and the ACP; thus, the way the ACP burns defines the way the

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insulation will spread a flame. Furthermore, the way the insulation burns will then affect the rate at which the ACP will degrade, melt and burn. Faster degradation induces further melting and thus might reduce spread rates but increase the rate at which molten debris falls. The interactions between the two materials are therefore difficult to uncouple.

8.2.9. These are only a few of the complexities introduced in these systems. When the systems are utilised in construction, a multiplicity of other complexities are introduced (e.g. cavity barriers, complex geometries, other materials, intumescent sealants, etc.). The level of complexity is such that a very careful analysis is necessary to establish the fire performance of such a system.

8.2.10. Previous sections of this report highlighted the enormous complexity associated with determining the ‘no fire spread’ condition, as well as the ‘flame spread velocity ($V_s$)’ for simple configurations such as a single, isolated combustible surface. The added complexity associated with encapsulation was also highlighted. Finally, this section of the report highlights the additional complexities associated with complex systems with multiple components arranged in intricate configurations, such as those present in Grenfell Tower.

8.2.11. At each stage of the flame spread analysis, a series of parameters could be isolated and a table with those parameters could be produced. But at this point i.e. at the point that these systems are applied in construction, this is no longer possible. The list of parameters is not only too extensive but will change with each specific configuration. Different arrangements will introduce different parameters and therefore understanding a system requires a bespoke approach.

8.2.12. There is a strong perception that, given the complexity of such systems and the impossibility of modelling their performance on the basis of first principles, the only way to achieve any measure of performance is to conduct a large-scale test that is representative of any potential worst-case event. While there is some merit in such large-scale tests because they can reproduce some of the conditions present in a real fire, these tests are extremely complex to interpret due to the aforementioned number of processes that occur simultaneously and interactively.

8.2.13. It is therefore fundamental to have a detailed understanding of the processes involved and the means by which failure of a system occurs before formulating the characteristics of a large-scale test. Furthermore, given the processes that need to be characterized and the parameters that need to be quantified, it is imperative to introduce appropriate measurements. Only through appropriate measurements can the necessary quantification be achieved.

8.2.14. The next section will attempt to characterize the systems used in Grenfell Tower as a way to highlight the information that can be gathered by detailed small scale tests, but also to illustrate the complex behaviour of systems of this nature.
9. UNDERSTANDING THE FAILURE MODES OF THE GRENFELL TOWER CLADDING SYSTEM

9.0. INITIAL OBSERVATIONS

9.0.1. This section provides a brief set of observations regarding the tests conducted at the University of Edinburgh as part of Phase 2 of the Inquiry’s investigations. These tests are described in detail by Prof. Bisby in a separate independent report. In this section of this report, I have attempted to explain the understanding that is necessary before any attempt can be made to establish a performance assessment of a cladding system.

9.0.2. Despite the complexity of the systems to be analysed, the factors which influence the principle of ‘no-fire spread’ remain those as already listed in Table 3 of this report. This involves first characterizing the different components and then the ensemble.

9.0.3. A series of ignition tests were conducted with the Aluminium Composite Panels (ACP) and the different types of insulation (i.e. Celotex/Kingspan). The encapsulated and non-encapsulated combustible materials were exposed to a constant heat flux. In the case of tests with encapsulation, the encapsulation was allowed to fail exposing the plastic core of the ACP and resulting in ignition. Only the ACP and thermal insulation were tested because they correspond to the key combustible materials present in the cladding system at Grenfell Tower.\textsuperscript{81}

9.0.4. This series of ignition tests provided information about the basic behaviour of the different products, as well as the heat of combustion ($\Delta H_c$) and the ignition properties listed in Table 1.

9.0.5. An equivalent approach is presented in the University of Queensland (‘UQ’) Cladding Material Library.\textsuperscript{82} This library consists of a database of different material properties covering a wide range of products used in building envelopes. The library was commissioned by the Queensland Government as part of their response to the Grenfell Tower fire. Details of the library are provided in Appendix A.

9.0.6. The UQ Cladding material Library contains detailed protocols that deliver ignition properties and the heat of combustion for an extensive group of materials identified in building envelopes in Queensland. Furthermore, it provides a database and a series of identification tests that enable the materials present in different products to be established.

9.0.7. If a material can be identified as being in the database, then the properties have already been established and no further tests are necessary. The library provides a methodology that uses a series of tests that deliver the key properties that characterizes a material. Nevertheless, the materials library is only a database, and is only intended as information for competent engineers, so if a manufacturer labels more than one material with the same identification, then the database will provide the same properties for these materials. While


\textsuperscript{82} https://claddingmaterialslibrary.com (accessed 04-12-2021)
the methodology will be able to differentiate these materials, the user doubting the composition will have to submit the material for testing.

9.0.8. Non-encapsulated polyethylene has a critical heat flux for ignition of less than $12 \, kW/m^2$, and PIR and phenolic foams range between $10 - 15 \, kW/m^2$ and $20 - 22 \, kW/m^2$ respectively.

9.0.9. When encapsulated by an aluminium plate only retained in place by the adhesive (i.e. no mechanical fixation), the critical heat fluxes for ignition of the ACPs tested were within the same ranges as those reported from similar independent tests ($18 \, kW/m^2 < q''_e < 25 \, kW/m^2$).

9.0.10. PIR and phenolic foams are generally covered by a thin layer of non-combustible material e.g. a foil facer. When heated, this layer stops adhering to the foams mainly due to degradation of the polymer at the interface. Once the thin layer separates it tends to break very easily creating a direct path for the heat to reach the foam, i.e. the encapsulation is breached. For the PIR and phenolic foams the encapsulation breach was followed by ignition for heat fluxes below $25 \, kW/m^2$. These values are consistent with values previously presented in the published literature.

9.0.11. Therefore, the results consistently showed that ignition could be attained at heat fluxes significantly below those possible when compartment fires break through windows (i.e. $q''_e > 100 \, kW/m^2$) for both ACP and insulation. So, whether the combustible materials are encapsulated or not, they will ignite under many fire conditions, including that representative of the conditions present in the initial stages of the Grenfell Tower fire.

9.0.12. Thus, the only condition left that could result in ‘no-fire spread’ will be a zero heating length, $L_h = 0$ (see Table 3).

9.0.13. The required conditions for failure of the system leading to a zero heating length, $L_h = 0$, requires a more detailed exploration. Thus, the main objective of the subsequent tests conducted at the University of Edinburgh is to characterize the circumstances which would lead to breach of this condition.

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9.1. CONDITIONS THAT LEAD TO SELF-SUSTAINED FLAME SPREAD

9.1.1. A series of preliminary tests served to establish the minimum conditions that will breach the ‘no-fire spread’ requirement. By establishing the minimum conditions that will breach the ‘no-fire spread’ requirement it is possible to determine what size of an ignition fire is necessary to breach the zero-heating length condition \( L_h > 0 \) for a specific cladding system. Once this condition has been breached, flame spread proceeds only by means of the energy released by the system and not by the ignition source. So, if the cladding system can independently support a flame where \( L_h > 0 \) at the laboratory scale then it will continue to do so at larger scales, and there is no need to extend testing to the large scale.

9.1.2. Comparison of these minimum heating conditions to those created by possible real fire scenarios will determine whether the specific assembly is susceptible to breaching the ‘no-fire spread’ requirement and thus, should not be used.

9.1.3. The first stage of testing consisted of identifying the smallest ignition flames necessary to initiate the sustained burning of the polyethylene. Two parameters were identified; (1) the minimum size of the flames, and (2) the minimum duration of impingement necessary to initiate sustained burning followed by self-sustained flame spread.

9.1.4. The heat release of the initial ignition flames is \( 8 \, kW \) (Figure 9(a)). They are placed immediately under the ACM and need to remain in place, heating the ACP, for a period of 4: 00 minutes. A smaller flame and a shorter heating duration will result in no flame spread over the ACP.

9.1.5. As can be seen in Figure 9(a), the ignition flames are very small when compared to a typical flame emerging from a compartment fire (flames emerging from a compartment fire are generally of the same size as the windows) and the heating period required is very short when compared to a typical compartment fire duration (generally compartment fires last for more than 15 minutes).

9.1.6. As part of the ignition study, it was established that the ignition burner was capable of initiating flame spread on the ACP, nevertheless, once removed, the ACP will continue to burn for a few minutes but eventually extinguish. Through this period molten polyethylene continue to drip and burn. If the molten polyethylene fire was extinguished or allowed to burn far away from the ACP, then it did not influence burning and extinction would naturally follow.

9.1.7. The heat from the incipient flames was found not to be sufficient to breach the aluminium encapsulation by itself, therefore, the condition of zero heating length, \( L_h = 0 \), remained.

9.1.8. A series of follow-up tests were conducted to understand the process by which the polyethylene melts, ignites, and drips, producing a small fire below the ACP. It was observed that with the heat input from the molten polyethylene fire the ACP will support self-sustained spread.

9.1.9. The results of the preliminary tests established that the melting polyethylene pooling underneath the assembly delivers the additional heat input that is necessary to challenge
the zero heating length condition. Nevertheless, the pool width necessary is much smaller than the dimensions of a typical windowsill.

9.1.10. These series of tests demonstrated that the conditions necessary to breach the zero heating length condition ($L_H > 0$) and thus, the ‘no-fire spread’ requirement, would have been attained in most fully developed compartment fires. And therefore, a fire of the characteristics of the Grenfell Tower fire\(^{90}\) would have certainly breached the ‘no-fire spread’ requirement for the specific assemblies utilized in Grenfell Tower.

9.1.11. In summary, if the ignition flames are placed under the ACP (Figure 9(b)) they cause the melting and dripping of the polyethylene. The dripping polyethylene will eventually ignite (Figure 9(c)) and result in a pool fire that provides further heat to the ACP (Figure 9(d)). This heat leads to a series of processes that require more detailed exploration. Details of the test protocols followed can be found in Prof. Bisby’s report.\(^{91}\)

Figure 9: (a) Image from the back of the panel showing the ignition flames before being placed under the ACM (b) Close-up showing the ignition flames immediately after being placed under the ACM (c) Closer close-up showing the ignited melted polyethylene being collected by the small tray placed under the ACM (d) image from the back of the panel showing the ignition flames placed under the ACM and the flames burning over the polyethylene pool formed on the tray.

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\(^{91}\) Bisby, L. Phase 2 Experiments Work Package 2 – Systems Interactions, Grenfell Tower Public Inquiry. {LBYWP20000001}
9.2. SELF-SUSTAINED FLAME SPREAD ($L_h > 0$)

9.2.1. The following descriptions correspond to a single test, but nevertheless, most of the processes described are consistent through the tests. The presentation here is a qualitative presentation intended only to illustrate the critical mechanisms leading to the breaching of the zero-heating length condition, $L_h > 0$, that defines the onset of self-sustained flame spread. The report by Prof. Bisby provides a more detailed description of these mechanisms but also a more comprehensive review of all the tests conducted.\textsuperscript{92}

9.2.2. Figure 10 shows the evolution of the heat release rate (see Equation (4)) as a function of time. The smaller inserted graph shows the full evolution while the main figure zooms into the area of particular interest. The first 4:00 minutes correspond to the period where the ignition flames are in place underneath the ACM. Initially only 8 kW of heat release is recorded, but rapidly (after about 15 seconds) it almost doubles as the polyethylene melts and starts to ignite.

9.2.3. The heat release rate then remains almost constant until about 2:30 minutes. Until this point the melted polyethylene is burning at almost the same rate as it is dripping and therefore the flame does not change. It is at this point that the first transition happens and the heat release rate starts increasing in time.

9.2.4. This change in regime is defined by the first pieces of aluminium dropping off and exposing the surface of the polyethylene core. As these surfaces ignite the flame spreads and the heat release rate increases. While the fire is bigger, it is still not self-sustained and the removal of the igniter will result in a decay and ultimate extinction of the fire.

9.2.5. Figure 11 shows this first transition in detail. At 2:30 minutes the fall-off of the first aluminium plate is observed. This is characterised in the measurements by a change in slope in the heat release rate (Figure 10) and a sudden increase in mass in the tray (bottom right image and data) (Figure 11).

9.2.6. The result of the exposure of the polyethylene surface and corresponding increase in heat release rate is a systematic increase in the flame length. The increase in flame length provides sufficient heat to lead to the eventual ignition of the insulation surface (top left photographs (Figure 11)). Once the polyethylene has been exposed, the heat provided by the polyethylene flames is greater than the critical heat flux for ignition (i.e. $\dot{q}_e > \dot{q}_{\text{ig}}$). As shown in Table 1 this is a condition for ignition.

9.2.7. It is important to reiterate that the critical heat flux for ignition varies with different types of encapsulation and therefore the size of the flames necessary to deliver sufficient heat will also vary.

\textsuperscript{92} Bisby, L. Phase 2 Experiments Work Package 2 – Systems Interactions, Grenfell Tower Public Inquiry. (LBYPW200000001)
Figure 10: Evolution of the heat release rate as a function of time showing five different stages in the burning process.

9.2.8. The increase in burning surface area of the polyethylene enhances dripping until the pool fire covers the entire surface of the tray. The larger flames result in a stronger draft on the cavity side, sucking the flames from the igniter into the cavity (see the images on the top right of Figure 11). Before this transition the flames appear on both sides of the ACM, while after 2:30 minutes they are only visible on the side of the cavity.

9.2.9. At approximately 3:45 minutes, the vertical aluminium plate starts splitting from the surface of the polyethylene, allowing the flame to start spreading on the vertical surface. As this occurs the magnitude of the heat release rate increases. As the igniter is removed (4:00 minutes) the heat supply decreases and there is a short period where the rate of increase of heat release rate slows down. This is the first of two further transitions ((A) and (B)) that will be discussed here.

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93 The term draft is used here to describe the flow induced by the buoyancy generated by the heat from the flames. The larger the flame, the more heat is released and the stronger the draft.
9.2.10. Figure 12 shows a magnification of a section of the heat release rate data presented in Figure 10. In this figure, two further transition points can be observed; a first transition labelled (A) between 3:45 minutes and 4:45 minutes and a second one, labelled (B), between 5:15 minutes and 5:30 minutes.

9.2.11. The first transition marks the point where igniter assistance is no longer required for burning. The second transition marks the full failure of encapsulation and the failure of the zero heating length condition (i.e. $L_h > 0$). Unrestricted flame spread follows which is characterized by a very rapid increase of the heat release rate (Figure 12).

9.2.12. The mass of the ACP, as well as the mass of the tray underneath the ACP, have been recorded and are presented in Figure 13. The upper curve shows the mass of the ACM and the lower curve the mass of the tray. As can be seen, in the first 2:30 minutes the ACP is observed to experience a slight mass loss at an almost constant rate, while the tray seems to maintain a constant mass. Thus, the mass dripping on the tray is being consumed by burning. This is consistent with the constant heat release rate described above.
Figure 12: Detail of the heat release rate curve showing the two further transitions. The first, transition (A), corresponds to the change between igniter assisted spread and self-sustained spread. The second, transition (B), corresponds to the transition between a regime where spread is limited by the effects of the aluminium plate encapsulating the polyethylene and maintaining the zero-heating length ($L_h = 0$) condition. The final stage corresponds to free spread of the flame over the polyethylene surface ($L_h > 0$).

9.2.13. At 2:30 minutes there is a sudden increase in the mass of the tray and a similar sudden decrease in the mass of the ACP because a section of the aluminium encapsulation falls from the ACP into the tray. With a larger surface of polyethylene exposed, the flame spreads and the mass loss rate for the ACP increases. This, once again, is consistent with the increase in heat release rate described above. Eventually, the burning rate on the tray increases sufficiently to compensate for the increased dripping and the mass of the tray reaches a steady period.

9.2.14. Figure 13 shows transition (A) in detail. Initially, the aluminium plate is attached to the surface of the polyethylene, not allowing for combustion to occur between the polyethylene and the plate. At approximately 3:45 minutes the plate starts to move away from the polyethylene surface. The gap being formed then allows the flame to ignite and start spreading over the vertical polyethylene surface. This can be clearly seen in the images in the bottom right of Figure 13. The plate has fully split by 4:15 minutes. Once the flame is established behind the aluminium plate, the burning rate of the ACM and the overall heat release rate increase (i.e. steeper slopes in the graph).
9.2.15. Figure 13 (data on the top right) shows that a dip in the heat release rate occurs when the igniter is removed. This dip is then followed by a period of recovery where the heat release rate increases at a similar rate to that during the period between 3:45 minutes and 4:00 minutes (when the igniter is removed).

9.2.16. Figure 13 also shows images of a back view and a side view (images on the top left) corresponding to this period. The images show how the flame shrinks and then recovers.

9.2.17. The transition (B) is presented in Figure 14. The aluminium plate facing the cavity has separated from the polyethylene at the bottom of the panel but remains attached halfway up. The polyethylene is burning in the lower region, but spread cannot progress until the aluminium plate fully separates from the polyethylene surface.

**Figure 13**: Characteristics of the transition (A).
9.2.18. The complete separation of the plate from the polyethylene occurs between 5: 15 minutes and 5: 30 minutes. The images at the bottom right of Figure 14 show how the bottom part of the plate moves back towards the polyethylene surface as the top of the plate separates, allowing the flame to spread through the full extent of the panel. At this point it can be established that the zero heating length condition has been breached, $L_h > 0$ and that flame spread will therefore proceed uncontrolled.

9.2.19. The period where the plate is moving delivers a transient and small reduction in the heat release rate. While some variability was observed, the characteristics of these transitions repeat themselves for all experiments and are always related to the deformation of the aluminium plate.

9.2.20. Figure 10 shows that after this transition, the heat release rate reaches its peak (i.e. there is full involvement of the entire panel) very rapidly. The flame rapidly increases in size and it is expected that flames of this nature will continue to spread over these panels essentially unrestricted.
9.2.21. It is of significant importance to note that this final transition (B) will only occur in the presence of insulation forming a cavity with the ACM. In the absence of insulation there is not sufficient heat feedback to fully detach the top of the panel and the flame does not spread. Thus, it is possible to state that, in the absence of this heat feedback, the zero-heating length condition \((L_h = 0)\) would have been attained. Furthermore, the heat feedback required to enable \(L_h > 0\) does not require the insulation to burn, so non-combustible insulation will deliver the same results. This is discussed in detail in Prof. Bisby’s report.\(^{94}\)

9.3. SUMMARY

9.3.1. A series of small-scale tests have served to establish the manner by which a cladding system of the type used in Grenfell Tower leads to self-sustained fire spread. The main parameter defining self-sustained fire spread is the heating length \((L_h)\). If the heating length is greater than zero \((L_h > 0)\) then the flame will continue to spread and increase in size in an irreversible manner. Thus, if the small-scale tests show that the heating length is greater than zero \((L_h > 0)\) then the small-scale tests are sufficient to establish that a system will allow for self-sustained flame spread at the building scale.

9.3.2. Once self-sustained flame spread has been attained, it will continue to accelerate, and the flames will continue to increase in size. Therefore, a system that supports self-sustained flame spread to happen at the small scale will never be compatible a Fire Safety Strategy that relies on the ‘no flame spread’ condition.

9.3.3. The ignition conditions required to achieve self-sustained flame spread on a system of characteristics consistent with the ones used at Grenfell Tower are much less onerous than the conditions typical of most compartment fires. Thus, in the event of a compartment fire in Grenfell Tower, it was almost inevitable that these systems would have supported uncontrolled external fire spread.

9.3.4. Self-sustained flame was achieved as a consequence of ignition, melting and dripping of the core material. The ignited molten polyethylene produces a small fire underneath the ACP that generated enough heat to enable sufficient deformation of the aluminium panels of the ACP. This resulted in exposure of the core and the subsequent spread of a flame. The onset of self-sustained spread occurs when local breaches of encapsulation are followed by a generalized breach of the encapsulation.

9.3.5. A generalized breach of the encapsulation provided by the aluminium plate covering the core material will only occur in the presence of insulation forming part of the cavity with the ACM. In the absence of insulation there is not sufficient heat feedback to fully detach the top of the panel and the flame does not spread in a self-sustained manner.

9.3.6. The determination of what size of an ignition fire could have resulted in self-sustained fire spread on the ACP for different configurations (e.g. different cavity dimensions, absence of insulation, etc.) is beyond the scope of this study, nevertheless, if different arrangements

\(^{94}\) Bisby, L. Phase 2 Experiments Work Package 2 – Systems Interactions, Grenfell Tower Inquiry. {LBYWP200000001}
are to be explored, the approach followed in the tests described here can be used to establish the relevant information, in particular that related to the zero heated length \( L_h \).

9.3.7. The sections that follow will describe relevant standardized testing practices. However, it is important to state here that the form of testing presented in this section provides information that is very difficult to obtain from standardized testing. The form of testing described above was specifically conceived in order to understand the product, not to qualify the product or establish conformity with parameters that describe its behaviour.

9.3.8. Tests conceived to understand a product require a trial-and-error approach, flexibility in the manner in which the tests are conducted, and the introduction of measurements as required by observation of the results. None of these things are possible when conducting standardized tests. Nevertheless, the value of the testing approach presented here is very significant because it enables the performance of a system under fire loading to be explicitly established.

9.3.9. These tests have shown that the condition of zero heating length, i.e. \( L_h = 0 \), could have not been attained with an external building envelope system of the characteristics of those used in Grenfell Tower. Thus, these systems cannot be used with a ‘stay-put’ strategy.

9.3.10. This is information that the designer/manufacturer (off-site) should have determined before bringing these products to the market, or even before subjecting them to any form of conformity assessment testing. This is the minimum information that should be expected from designers/manufacturers (off-site) delivering products/assemblies with competence and integrity.

9.3.11. Given that fire safety is a key functionality of building envelopes, it is necessary to conduct this form of assessment before any product enters the market, independently of the regulatory testing regimes required to establish conformity. This form of product development is consistent with most other functionalities and represents a key responsibility of product/system designers and manufacturers (off-site).

9.3.12. Conducting this form of assessment before products enter the market enables the designer/manufacturer to understand the behaviour of their products/systems. It is this understanding that allows the generation and delivery of information necessary for the development of further assemblies and for compliance assessment by the designer/builder (on-site).

9.3.13. In a similar manner, the designer/builder (on-site) intending to use these products/systems for a building where the Fire Safety Strategy includes a ‘stay-put’ policy should have asked the designer/manufacturer (off-site) for information that guaranteed that the condition of zero heating length, i.e. \( L_h = 0 \), could be achieved for a range of fire conditions consistent with the application. Furthermore, the designer/builder (on-site) should have established that any further assemblies (e.g. the introduction of a variation of the system on the crown of the building) would have not altered this conclusion.

9.3.14. The detailed understanding of product/system behaviour facilitates improvement of the products by preventing critical failure mechanisms and also allow the value and validity of standardized testing practices to be questioned by generating correct and transparent
information. This level of understanding is necessary and is to be expected from designers/manufacturers (off-site) operating with competence and integrity, in particular when it comes to the safety of their products/systems.

9.3.15. The approach illustrated in this section is not unusual in the context of design/manufacturing (off-site) of products or systems. This approach is regularly applied in the characterization of many of the product/system’s other functionalities. What is suggested here is that among those functionalities that need to be characterized, safety should be included. Even when it comes to building products/systems, the understanding and quantification of their functionality is not unusual in the development process. **What is particularly unusual is the absence of a process by which product/system development introduces understanding of performance in matters that pertain fire safety.**

9.3.16. The following section aims to describe why it is considered acceptable practice to ignore the understanding of product/system performance in matters that pertain fire safety. This will be presented in the context of current approaches to conformity and compliance.
10. THE DEVELOPMENT OF A TESTING TRADITION

10.0.1. The previous section established the key performance parameters that support different approaches to the Fire Safety Strategy. Furthermore, it established a manner by which these parameters can be assessed. The complexities and limitations were highlighted, and a testing approach was presented and used on external cladding systems consistent with that installed at Grenfell Tower. A simple and unquestionable conclusion could be drawn that those systems should never have been used in conjunction with a Fire Safety Strategy that uses a ‘stay-put’ egress strategy.

10.0.2. While this conclusion was clear in hindsight, the previous section provides a method by which this conclusion could have been reached in a quantitative and unequivocal manner at the time of design. Furthermore, it provides relevant information on the behaviour of the systems that could have been of use to the designer/builder (on-site) for the purpose of demonstrating building compliance.

10.0.3. The previous section also highlights that the approach followed is consistent with the manner by which the performance of many other functions is assessed by testing, including many components used in the construction industry.

10.0.4. This leaves the question of why this is not the approach that is currently followed in matters pertaining fire safety. This section aims to address this issue further.

10.1. THE TIMELINE OF KNOWLEDGE AND REGULATION DEVELOPMENT

10.1.1. To understand the characteristics of the current approach to testing, it is important to first establish a timeline of when different fire safety related regulations were introduced, including tests related to regulations. Here only a few highlights are presented as greater, more comprehensive, detail is provided in Prof. Bisby’s report.95

10.1.2. This timeline of test development will be contrasted with key activities that mark the state of knowledge and state of professional competency.

10.1.3. The timeline is presented in Figure 15 and shows how knowledge and testing practices have evolved since the 1800’s. The information is intended to be indicative rather than comprehensive.

95 Bisby, L. Grenfell Tower Inquiry Phase 2 – Regulatory Testing & the Path to Grenfell. Part II: The Path to Grenfell. (LBYP200000001)
Figure 15: Chronology of knowledge testing practices and key regulation.
10.1.4. While fire safety has been a concern throughout history, technical knowledge has not always been available to support society’s approach towards fire safety. This concern has been constantly exacerbated by dramatic events that have resulted in major loss of life and property. These events have been consistent throughout history.

10.1.5. Lessons have been learned as a function of these events, many times resulting in significant changes in the approaches followed by society towards controlling the hazard posed by fires.

10.1.6. In parallel, response practices have also evolved as a function of these events. Some form of fire fighting has existed for centuries, but it did not evolve into a professional practice until 1824 in Edinburgh and 1833 in London (Figure 15), in both cases due to James Braidwood.\(^{96}\)

10.1.7. The formalisation of the fire brigades occurred before the most basic fire science was developed and made available, thus protocols and procedures created to fight fires were mostly based on experience and basic knowledge acquired through training and firefighting. James Braidwood himself had knowledge of building materials that he carefully applied to firefighting protocols.

10.1.8. Thus, from the outset, the fire brigades have been presumed to be the competent authority and their experiential approach to the acquisition of knowledge has been taken as the norm. It is no surprise that senior fire brigade officers have served as advisors to government from the onset of fire safety legislation and continue to do so even today.

10.1.9. Furthermore, the approach towards the management of fire safety is defined from its onset as a responsive approach. Through experience, common sense, and very rudimentary technical knowledge, solutions have been provided to problems arising due to the evolution of other disciplines such as the construction industry. Governments, with advice from multiple stake holders, have then required these solutions to be implemented through legislation and imposed as constraints.

10.1.10. The first scientific evidence of fire research was conducted by Faraday, who in 1848 attempted to explain the behaviour of a candle. His explanations were based on sound principles of thermodynamics but only managed to explain some of the simplest processes. Not only were these explanations developed much later than they were needed in practice, but they were still too rudimentary to provide answers to the very basic questions.

10.1.11. Combustion is the fundamental scientific discipline that underpins fire research, and it was only formalized in 1928 at the First International Symposium on Combustion. Needless, to say, the science presented at this symposium was far removed from the practical needs of fire safety.

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\(^{96}\) James Braidwood (1800-1861) was a Scottish firefighter credited with the foundation of the first municipal fire service in Edinburgh (1824). He was later director of the London Fire Engine Establishment which was later to become the LFB. On 22\(^{nd}\) June 1861 he died; being crushed by a collapsing wall while fighting the Tooley Street fire at Cottons Warf. The principles explained in his books “On the Construction or Fire Engines and Apparatus” (1830) and “Fire Prevention and Fire extinction” (1866) are still used by many fire brigades.
10.1.12. By the same year, Government had already implemented the Royal Commission marking the onset of modern Building Regulations (Figure 15). Tests to provide an assessment of physical concepts that were very poorly understood, such as combustibility, had already begun being developed in 1915 (Price’s test on combustibility) despite the absence of scientific knowledge at the time. Furthermore, complex testing frameworks, such as the ‘Fire Resistance’ concept had been implemented (1928) as a response to the new demands of high-rise construction.

10.1.13. Progress in combustion science was very slow in the period after the first combustion symposium, principally because of the complexity of the problem, exemplified by the scientists working in combustion receiving Nobel prices for their work. For example, Hinshelwood and Semenov shared the Nobel prize for Chemistry in 1956. The second symposium only happened in 1937 and included works by these authors.

10.1.14. Of particular importance is the work by Semenov who constructed the first physical model that described the process of ignition (1940). So, while scientists were beginning to understand ignition at the end of the 1930’s, government regulations had already adopted the principles of ‘fire resistance’ (1930) and published BS 476. This version of BS 476 included testing approaches for combustibility and fire resistance.

10.1.15. It was only in 1957 that Emmons postulated the first theory of condensed fuel burning applicable to fire problems. The first fundamental study on flame spread was not published until 1969 by John de Ris and the mechanisms controlling flame spread were not summarized until 1983 by Fernandez-Pello and Hirano. Understanding of the ‘no spread condition’ was only published in 2002. Nevertheless, testing procedures that incorporated surface fire spread and aimed to address both spread rates and the no spread condition were first introduced in BS 476 in 1945.

10.1.16. All of the above reaffirms the significant time lag between the need to guarantee fire safety while incorporating ever evolving technologies and the development of useful scientific knowledge to explain the relevant issue.

10.1.17. By the end of the 1920’s, the USA had a Fire Protection Engineering higher education programme, and the Institution of Fire Engineers had been formalized in the UK recognizing the need for professional practice. Both organizations were driven by experiential knowledge and common sense and strongly influenced by the fire service.

10.1.18. In contrast, in what concerned the recognition of fire as a scientific and technical discipline, the Combustion Institute was not formed until 1954 and the International Association for Fire Safety Science in 1985. Thus, the role of science in the professional development of fire safety is minimal.

10.1.19. In 1956 the University of Maryland launched its Fire Protection Engineering programme, once again, mostly based on experiential knowledge and strongly influenced by the fire service. The first educational programme based on scientific and technical knowledge started at the University of Edinburgh in 1972. The development of this programme was strongly driven by Frank Rushbrook, Chief Fire Master for Edinburgh. Rushbrook recognized
that technical knowledge was essential for the development of the fire brigades and that the construction industry needed technically competent Fire Safety Engineers that had an equal professional standing as those in other engineering disciplines. Professor David Rasbash, an experienced scientist from the Fire Research Station (FRS), was appointed as the first Professor of Fire Safety Engineering in 1974. This was the first time that technical knowledge, need, and experiential learning converged.

10.1.20. New construction technologies were creating new challenges and driving the need for new solutions. Technical publications began appearing, first driven by technological needs (Fire Technology Journal (1965)), then by the use of new materials (Fire and Materials Journal (1976)) whereas only in 1977 did scientific based knowledge begin to be published through the creation of Fire Safety Journal.

10.1.21. By the end of the 1950s, the pattern of responsive reaction to new technological problems had been strongly solidified and was only exacerbated in the two decades that followed. The time lag between necessary testing practices and relevant technical knowledge was very significant and thus science had a very mild influence on the evolution of testing.

10.1.22. A good example illustrated by Prof. Bisby\(^{97}\) are the changes implemented to BS 476-11 under the auspices of Dr. Phillip Thomas (a key scientist in the field of fire safety). In essence, the test remained the same but added improved methods to measure the temperature.

10.1.23. Objective-based regulations were introduced in 1984 with the assumption that there was no need to reformulate professional practice. The structure of Approved Document B still retains its fundamental principles that are primarily based on experiential knowledge. There is no recognition that transferring prescriptive information into guidance\(^{98}\) requires a very different form of professional practice. Details on the necessary evolution of professional practice can be found in the Warren Centre Reports.\(^{99}\)

10.1.24. By the time the test that would become BS 8414 and the Euroclasses were formalised around 1999 - 2000, the process of developing new testing approaches was very well defined. This process was not based on identification of a fundamental technical understanding of a problem and the development of an adequate testing solution. Instead, it continued to be based on the evolution of existing practices driven by experiential knowledge and influenced by many stakeholders.

10.1.25. Testing has remained a vehicle to implement regulatory constraints and therefore designers/manufacturers have not been encouraged to use testing as a means to understand the performance of their products. Furthermore, off-site designers/manufacturers have been encouraged to see these tests as barriers that are necessary to be overcome in their attempt to enter a market.

\(^{97}\) Bisby, L. Grenfell Tower Inquiry Phase 2 – Regulatory Testing & the Path to Grenfell. Section 11.4. (LBYP20000001)

\(^{98}\) Bisby, L. Grenfell Tower Inquiry Phase 2 – Regulatory Testing & the Path to Grenfell. Section 11.3. (LBYP20000001)

10.1.26. Given the absence of a technical basis for the testing regimes, there is no incentive for off-site designers/manufacturers to acquire the technical knowledge necessary to adequately understand the behaviour of the components they produce.

10.1.27. While this analysis is not comprehensive and cases do exist where thorough technical principles have been used for the development of testing practices, this is not the current norm, and not a representation of the majority of our current testing practices.

10.2. CATEGORISATION OF TEST TYPES

10.2.1. Given that fire tests have not been developed from first principles and their design is not truly defined by technical knowledge, it is difficult to discuss individual tests without a structure to group them on the basis of some common characteristics.

10.2.2. The characteristics of these tests are mostly determined by need and the balance between experiential and technical knowledge used in their development. Large scale tests tend to be defined more on the basis of experiential knowledge and need, and small-scale tests can generally be better related to technical knowledge, even if at the point of their original conception, this technical knowledge was not necessarily used.

10.2.3. When assessing fire performance by using fire test data, different approaches to testing have been used. Here a classification is proposed on the basis that the fundamental objective of a test is to collect useful information. This useful information is to be used by a competent professional for the purpose of delivering an adequate and well characterized component or a compliant building. This approach is consistent with an outcomes-based regulatory system.

10.2.4. Other classifications are possible, nevertheless, this one has been chosen because it is aligned with the objectives of this report i.e. analysing testing in support of outcomes-based regulation. By classifying the tests as a function of the type of information they deliver, it is possible to assess individual tests to establish if they are capable of delivering the information necessary to support the implementation of a viable Fire Safety Strategy.

10.2.5. While all tests do not always fall strictly in one or another classification, it is useful to provide these classifications to establish how different tests should be used or interpreted.

**INPUT TESTS**

10.2.6. Input Tests are designed to deliver, in an indirect or direct way, input data that a qualified engineer, using mathematical models, can use to predict the performance of a material or

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100 Prof. Bisby, in his report (Bisby, L. Grenfell Tower Inquiry Phase 2 – Regulatory Testing & the Path to Grenfell. Part I – The Purpose of Testing [LBYP20000001]) uses a different approach to this classification. This approach is equally valid but is driven by a very different objective. As stated in his report, “the purpose of testing is to allow an individual or an organisation to use the results of a test to make a claim about how a material, product, or system will perform in a real “in-service” situation.” If this is the objective, then, tests can be used to proof, i.e. “proof test.” If “proof tests” are not possible or practical the testing can be “geared towards standardised metrics,” i.e. standardized tests.
system. These tests are useful when there is a robust and adequate mathematical representation of a component or system.

10.2.7. Examples of direct input tests are standardized tests that deliver material properties, for example, thermal conductivity, density, yield stress, etc.

10.2.8. Examples of indirect tests are the Lateral Ignition and Flame Spread Test (i.e. ASTM-E-1321\textsuperscript{101}) or the Cone Calorimeter Test (i.e. ASTM-E-1354\textsuperscript{102}), where measurements are made of visible variables (such as the moment of ignition or the oxygen concentration of the exhaust) to obtain, by means of mathematical models, parameters (such as ignition temperatures and heat release rates) that can then be used by engineers to assess fire performance.

10.2.9. The parameters obtained have limitations associated with the way the tests are conducted, but they are also limited by the assumptions inherent in the interpretation tools.

10.2.10. Input tests are generally the type of tests that are most influenced by technical knowledge.

**BOUNDING TESTS**

10.2.11. Bounding Tests are designed to deliver performance on the basis only of the test results. There is no mathematical representation of the required fire performance, and the test results are the sole variable used to quantify the required performance.

10.2.12. These tests are bounding tests because they assume that the conditions under which performance is assessed in the test are worse than any condition which is deemed to be realistic i.e. that can be encountered in practice.

10.2.13. A good example of a bounding test is the “Fire Resistance” Test (ISO-834\textsuperscript{103}) where the standard temperature vs. time curve is deemed to be the worst possible fire. By subjecting structural elements to this condition and establishing a conservative failure criterion, it is possible to determine if a structural element will survive any realistic fire.

10.2.14. If the “worst case” condition is deemed as adequate and robust, these tests generally require minimal interpretation.

10.2.15. Bounding tests are generally defined on the basis of experiential knowledge, nevertheless, they can incorporate elements of technical knowledge to justify the validity of approach used for testing as well as the adequacy of the “worst-case” condition assumption.

**SCENARIO TESTS**


10.2.16. Scenario Tests are similar to the “Bounding Tests”, but they do not represent a “worst case” scenario and instead they represent a “scenario” that is deemed to be realistic. The data and information obtained from the test can be extrapolated to establish fire performance in conditions different to those in the test.

10.2.17. Scenario Tests are required in cases where mathematical representations of the processes involved are so complex that the use of data from Input Tests is not sufficient to describe the evolution of a fire. In this case the Scenario Test data incorporates components of the processes to a greater extent.

10.2.18. Scenario Tests are highly dependent on the realism of the test conditions, but also on the resemblance of the tested system to the real system. Any variation in either will have to be carefully interpreted because fire performance is defined by using the test to represent the real conditions and the tested system to represent the real system. These tests also tend to have very simple performance outcomes.

10.2.19. Examples of Scenario Tests are the Room Corner Test\textsuperscript{104}, The Single Burning Item Test\textsuperscript{105} and the BS 8414\textsuperscript{106} Tests.

10.2.20. The use of the data and information obtained from Scenario Tests requires great attention and a highly competent professional.

10.2.21. It is important to note that the more complex the system, the more data that is necessary to be able to characterize it and the clearer the objectives of the test need to be. Furthermore, if Scenario Tests are to be used, the more complex the system, the more data is necessary to establish that the fire and system tested are consistent with the scenario that is being represented. Great rigour needs to be applied to demonstrate the validity of the Scenario Test.

10.2.22. Scenario tests tend generally to be developed on the basis of experiential knowledge with very minor technical inputs.

\textsuperscript{104} ISO 9705-1:2016, Reaction to fire tests — Room corner test for wall and ceiling lining products — Part 1: Test method for a small room configuration (BSI00001906)

\textsuperscript{105} The Single Burning Item Test, EN 13823:2014. (BSI00001908)

\textsuperscript{106} BS 8414-2:2015+A1:2017, Fire performance of external cladding systems. Test method for non-loadbearing external cladding systems fixed to and supported by a structural steel frame, BS1, 2015. (BSI00000165)
10.3. SUMMARY

10.3.1. The above has explored the historical progression of testing practices in the UK and to some extent globally. The evolution of testing practices has been described in the context of the evolution of technical knowledge pertaining fire safety.

10.3.2. The comparison has clearly established that need has been the primary driver of testing and regulatory practice while technical knowledge has generally lagged decades behind.

10.3.3. Testing and regulation has thus typically developed on the basis of common sense and experiential knowledge and has been heavily influenced by many stakeholders, in particular the fire service. The fire service undertook, from the very beginning, control of fire safety needs and thus naturally evolved as presumed holder of all necessary knowledge. This approach to testing and regulation still prevails today.

10.3.4. This historical perspective has clarified why fire safety related testing does not follow the technically sound approach used in previous sections of this report.

10.3.5. When it comes to testing, this approach is inconsistent with outcomes-based regulation, because testing is not designed to provide technically sound information that enables designers/builders to deliver compliant buildings. Furthermore, this approach discourages designer/manufacturers to embark in a coherent and technically based performance assessment of their products/systems.

10.3.6. The following sections will address individual tests and assess their potential to deliver useful information.
11. UTILISATION OF TESTING WITHIN THE UK REGULATORY APPROACH

11.0.1. In order to contextualise the assessment of adequacy of the current testing regime in the UK, this report has defined what information provided by testing needs to enable (assessment of adequate performance), and the specific performance metrics that testing needs to provide in that regard.

11.0.2. It is also necessary to establish why, and to what ends, the current regulatory system and approved guidance (which is a key component of the overall testing regime) in the UK advocates the use the various testing protocols contained within these documents.

11.0.3. The following section therefore aims to establish:

(i) What tests are specified for establishing adequate performance of external wall systems by UK regulations and guidance?

(ii) What aspect of performance each test that is specified is expected to establish?

11.0.4. The following analysis of the various testing protocols enables conclusions to be drawn as to:

(i) Whether these tests are capable of delivering the performance information expected of them by UK regulation and guidance, and are therefore being specified appropriately

(ii) To what extent the specified tests account for the performance metrics required

(iii) To what extent the output from the tests

   a. Is standalone in delivering the performance metrics, or else

   b. Requires interpretation by a competent individual to establish adequate performance in the way UK guidance expects it to behave

11.1. THE BUILDING REGULATIONS

11.1.1. As previously summarised and discussed in the report by Prof. Bisby,\(^\text{107}\) the Building Regulations are an outcomes-based system of regulation and require a designer/builder to demonstrate that their design “performs” appropriately such that it achieves the specified outcomes.

\(^{107}\) Bisby, L. Grenfell Tower Inquiry Phase 2 – Regulatory Testing & the Path to Grenfell. Section 11.1. {LBYP20000001}
11.1.2. As previously illustrated, these outcomes are expressed in the form of functional requirements and the broad range of potential application of the Building Regulations means that these functional requirements, by necessity, must be expressed in relatively inexact language.

11.1.3. The onus is placed on those individuals applying them to interpret them correctly in respect of the characteristics of the particular piece of infrastructure under consideration so that they can develop an appropriate performance demonstration.

11.1.4. Again, as previously illustrated, the specific Fire Safety Strategy implemented for a piece of infrastructure can dramatically change the interpretation of what level of performance is necessary for any particular component of that infrastructure to meet the relevant functional requirement.

11.1.5. Thus far in this report I have focused primarily on matters associated with external fire spread and have therefore considered Requirement B4.(1). I have also discussed the added complexities associated with fire spread through cavities which is often considered part of Requirement B3.(4) which states:

“The building shall be designed and constructed so that the unseen spread of fire and smoke within concealed spaces in its structure and fabric is inhibited.”

11.1.6. The solution to satisfying this requirement in the context of external wall systems is typically trivialised to the provision of cavity barriers within the external wall system; in effect, strict adherence to the guidance in Approved Document B108 and / or BR 135.109

11.1.7. If approached in accordance with the analysis conducted in sections 5 to 7 of this report, in the context of a HRRB with a stay-put strategy, this requirement is interpreted almost identically to Requirement B4, i.e. that fire spread through these concealed spaces must be inhibited to the extent that fire cannot spread between units.

11.1.8. Therefore, a “no fire spread” condition applies equally as a performance criterion for Requirement B3.(4), albeit with the added complexity associated with flame spreading through a concealed space.

11.1.9. As seen during the fire at Grenfell Tower and described in the report by Prof. Bisby110, when considering an external wall system, the flame spread processes, whether external or internal, are influenced by the complex heat feedback processes that involve all components of the external wall system, internal and external to the cavity.

11.1.10. It is therefore impossible to arbitrarily separate an analysis of the performance of the external wall system into that which is required to meet Requirement B4.(1) and that

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required to meet Requirement B3.(4). In this context, the whole external wall system must be assessed as an ensemble for its ability to achieve a no fire spread condition.

11.1.11. Beyond these functional requirements in Part B of Schedule 1, I am not aware of any requirements within the Building Regulations that were considered directly applicable to the fire performance of the external wall system. Further, neither of these requirements explicitly requires the use of any testing protocols for the purpose of demonstrating an adequate performance outcome.

11.1.12. In more general terms, Regulation 7 of the Building Regulations 2010, addresses materials and workmanship, and provides that:

“7. Building work shall be carried out-

(a) With adequate and proper materials which-

(i) Are appropriate for the circumstances in which they are used,

(ii) Are adequately mixed or prepared, and

(iii) Are applied, used or fixed so as adequately to perform the functions for which they are designed; and

(b) In a workmanlike manner.”

11.1.13. While this discusses materials in a general sense, there is no specific reference to external wall systems, nor to testing in any context. Thus again, at the time of the design and construction of the over-cladding system at Grenfell Tower, there was no explicit requirement for material, product or system testing in the Building Regulations.

11.1.14. I do not consider this in itself as being unusual in an outcomes-based system of regulation such as that provided by the Building Regulations.

11.1.15. After the Grenfell Tower fire, as described by Prof. Bisby\textsuperscript{111}, The Building (Amendment) Regulations 2018\textsuperscript{112} made various amendments to the Building Regulations 2010\textsuperscript{113} including:

I. In Regulation 2, adding further detail / clarity concerning what constitutes the definition of an external wall;

II. In Regulation 7, stating where materials which become part of an external wall must have specific reaction to fire properties save for specific exceptions to this requirement.

\textsuperscript{111} Bisby, L., “Grenfell Tower Public Inquiry, Phase 1 - Expert Report,” 20\textsuperscript{th} Oct 2018. (LBYS00000001)

\textsuperscript{112} The Building (Amendment) Regulations 2018, Statutory Instruments 2018 No. 1230.

\textsuperscript{113} The Building Regulations 2010.
11.1.16. A part of the addition to Regulation 7 states that:

“Subject to paragraph (3), building work shall be carried out so that materials which become part of an external wall, or specified attachment, of a relevant building are of European Classification A2-s1, d0 or A1, classified in accordance with BS EN13501-1:2007+A1:2009 entitled “Fire classification of construction products and building elements. Classification using test data from reaction to fire tests” (ISBN 978 0 580 598616) published by the British Standards Institution on 30th March 2007 and amended in November 2009.”

A similar addition is made to Regulation 6 in regard to works that constitute “a material change of use”.

11.1.17. This amendment represents the first prescriptive use of physical testing with regard to an external wall system since the introduction of blanket outcomes-based regulation in 1985.114

11.1.18. Beyond this, all other references to physical testing for the purpose of demonstrating adequate performance of the external wall system are contained in guidance documents. The following section will therefore assess that guidance and specifically that provided by Approved Document B, to ascertain its reliance on, and utilisation of, testing protocols, so as to contextualise the expectations placed on these tests in regard to conferring compliance of external wall system with the aforementioned functional requirements of the Building Regulations.

11.2. APPROVED DOCUMENT B

11.2.1. This assessment of Approved Document B will specifically address the guidance that is given in respect of Requirement B4.(1). In the period of time since the fire at Grenfell Tower, the guidance contained in Approved Document B about external fire spread has changed. While some clarity has been added, and some details have been changed, the general approach is fundamentally the same. For the sake of completeness, both the latest (2019+2020 Amendments)115 and previous (2013)116 versions are discussed here.

11.2.2. There are two principal objectives when it comes to meeting Requirement B4.(1) which can be summarised as:

Objective 1. “Resisting fire spread from one building to another”

Objective 2. “Resisting fire spread over external walls”

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11.2.3. These are two fundamentally different objectives that emerge from two fundamentally different scenarios. These objectives represent two very different problems:

- a low risk, very well-defined problem (Objective 1)
- a high risk, ambiguously defined problem (Objective 2)

11.2.4. The provisions for addressing Objective 1 are not discussed in significant detail here, except to say that for this particular hazard, there is a sufficiently detailed understanding of the mechanisms controlling performance (i.e. individual material flammability and radiative heat transfer from adjacent buildings).

11.2.5. In the case of Objective 1, there is a comprehensive characterization of the relevant physical phenomena, and related parameters, that determine the processes controlling performance. Quantification methods for the key flammability parameters (critical heat flux for ignition) have been established. Furthermore, the various methodologies and measurements to be used to quantify all relevant parameters have been developed, standardized and quantified.

11.2.6. Of note however is that one critical underlying assumption of all of the calculation methodologies for determining performance in regard to Objective 1 is that the source of the radiation i.e. the fire that may pose a risk to adjacent buildings, comes from a single compartment. Clearly, the radiation from a multi-compartment fire will be greater and therefore, there is an assumption underlying all calculation methodologies that the external wall system will not provide a means by which fire can spread between compartments.

11.2.7. In addressing Objective 2 (resisting fire spread over external walls), both the 2013 and 2019 editions of Approved Document B, essentially present two distinct paths to meeting this external fire spread objective:

Route 1. The “linear route” where the majority of materials/products incorporated into the external wall system have specified ‘reaction to fire’ performance criteria, or

Route 2. The “alternative route” where the external wall system is specified so as to “meet the performance requirements given in BRE Report BR 135 for external walls using full-scale test data from BS 8414-1 or BS 8414-2”.

11.2.8. As stated, Route 1 utilises a range of reaction to fire classifications to ascribe adequate performance to external wall systems. The actual specifications vary between versions of Approved Document B and are summarised here so that the adequacy of the testing protocol...
for delivery of the performance implied by their utilisation in Approved Document B can be established.

11.2.9. With regard to tall buildings i.e. over 18m in height (not specifically residential buildings) the 2013 version of Approved Document B specifies:

(i) Reaction to fire properties for the “external surfaces of walls” depending on height and distance to the boundary. These classifications are expressed in both European and National classes and are summarised in Table 4.

(ii) Insulation or filler materials should be of “limited combustibility”.

11.2.10. It is of note that these classifications are irrespective of purpose group and therefore any expectation of Fire Safety Strategy and/or egress strategy. They are solely a function of the height of the building and its distance from a “relevant boundary”. It is therefore left to the user of the guidance to decide if these classifications are appropriate for the infrastructure in question.

Table 4: Reaction to fire properties for external surfaces of walls of buildings more than 18m in height specified by Diagram 40 of Approved Document B 2013.

<table>
<thead>
<tr>
<th>HEIGHT</th>
<th>DISTANCE TO BOUNDARY</th>
<th>NATIONAL CLASS</th>
<th>EUROPEAN CLASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any</td>
<td>&lt; 1m</td>
<td>Class 0</td>
<td>B-s3, d2 or better</td>
</tr>
<tr>
<td>&lt; 18m</td>
<td>&gt;1m</td>
<td>Index I &lt; 20 in BS 476-6</td>
<td>C-s3, d2 or better</td>
</tr>
<tr>
<td>&gt; 18m</td>
<td></td>
<td>Class 0</td>
<td>B-s3, d2 or better</td>
</tr>
</tbody>
</table>

11.2.11. Approved Document B introduces a classification of ‘Class 0’ which is not the direct product of a specific testing protocol, but rather can be achieved according to classification results defined in Approved Document B. Class 0 is effectively achieved in one of two ways:

(i) By being of limited combustibility when tested according to BS 476-11 (as described in section 12.3). It is important to note that limited combustibility is not a direct outcome of the test.
itself, but an interpretation of the output of the test stated in Table A7 in Approved Document B (2013)\textsuperscript{118}.

(ii) Is rated Class 1 according to BS 476-7 and has a fire propagation Index $I < 12$ and sub-index $< 6$ according to BS 476-6.

11.2.12. These tests are described and discussed in this context in section 12.3 of this report.

11.2.13. The most up-to-date version of Approved Document B at the time of writing (2019 with 2020 amendments\textsuperscript{119}) utilises the same approach but with more stringent classification criteria and with reference to the aforementioned update to Regulation 7 of the Building Regulations. All classifications are European Classifications only.

11.2.14. Similar to Approved Document B 2013, reaction to fire criteria are specified for both the external surface of the wall and insulation and filler materials. Filler materials are clarified in this latest version of Approved Document B as “such as the core of metal composite panels, sandwich panels and window spandrel panels but not including gaskets, sealants and similar).

11.2.15. In the context of a HRRB, the classification for the external surface of the wall is specified as Class A2-s1, d0 or better, regardless of distance to a boundary. The classification specified for insulation products or filler materials is A2-s3, d2 or better.

11.2.16. However, this is in conflict with Regulation 7(2) which requires that all materials which become part of an external wall or specified attachment achieve a classification of A2-s1, d0. As Regulation 7 is prescriptive, it will supersede the requirements in Approved Document B and therefore any building with a storey 18m or more above ground level containing 1 or more dwellings will have to comply with this requirement.

11.2.17. These classifications and the tests that determine them are described and discussed in section 12.4 of this report.

11.2.18. As discussed in paragraph 11.2.7, both versions of Approved Document B offer an “alternative approach to assessing adequate performance which requires subjecting the external wall system to large-scale testing. In both cases, the external wall system should meet the performance requirements given in BRE Report BR 135 for external walls using full-scale test data from BS 8414-1 or BS 8414-2.

11.2.19. Again however, this guidance is superseded by the prescriptive requirement of Regulation 7 in the case of a building with a storey 18m or more above ground level containing 1 or more dwellings which, regardless of performance in this test, will still require all materials which

\textsuperscript{118} Table A7 of Approved document B classifies a material as being of limited combustibility if of density greater than $300\text{kg/m}^3$ and when tested to BS 476-11, does not flame or cause a rise in temperature in the gas phase temperature of more than $20^\circ\text{C}$.

\textsuperscript{119} Approved Document B, Fire Safety, Volume 2: Buildings other than dwellings, 2019 edition incorporating 2020 amendments. (INQ00015026)
become part of an external wall or specified attachment to achieve a classification of A2-s1, d0 or better (A1).

11.3. SUMMARY

11.3.1. The guidance provided by Approved Document B, both at the time of the over-cladding of Grenfell Tower, and following its evolution in the wake of the fire, provides two routes to “demonstrating compliance” with the Requirement.

11.3.2. The first (the ‘linear route’) relies on reaction to fire classifications of individual components. The second relies on large-scale testing of a representative external wall system assessed against performance criteria defined in the BR 135 guidance document.

11.3.3. This guidance is now somewhat superseded by the introduction of the 2018 amendments to the Building Regulations which have effectively created a single prescriptive performance requirement for HRRBs in excess of 18m i.e. that all materials that become part of an external wall system achieve a minimum classification of A2-s1,d0.

11.3.4. It is not clear how this requirement is expected to sit within the wider outcomes-based framework. In particular it is not clear if this overriding requirement is assumed to deliver a system that “adequately resists the spread of fire over the walls” or whether there is still an onus on the designer to provide adequate demonstration of performance in the circumstances that this regulation applies to.

11.3.5. It is notable that neither Regulation 7 nor the approved guidance frame any of the requirements / “recommendations” in terms of the (expected / implied) Fire Safety Strategy of a building. The baseline for establishing adequate performance for the purpose of ensuring life safety therefore takes no account of whether occupants are expected to be present or not, and if so, for how long.

11.3.6. It is therefore incumbent on the competent professional to understand the different assumptions and relationships associated with the provisions described in the Approved Document and Regulation 7. Furthermore, it is incumbent on the competent professional to understand how their design decisions and interpretations fit within these assumptions and relationships.

11.3.7. The following sections of this report will assess whether the aforementioned specifications, along with the BS 8414 / BR 135 testing and assessment protocol, are capable of directly delivering the necessary level of performance, or else the information necessary to indirectly establish if a system is compliant.
12. TESTING RELEVANT TO THE PERFORMANCE OF EXTERNAL WALL SYSTEMS

12.0.1. The following section aims to assess the adequacy of various testing protocols that are deemed relevant to the performance of external wall systems and therefore to the ultimate outcome of the fire that took place at Grenfell Tower.

12.0.2. Some background specifically relevant to testing is provided along with a general classification of testing protocols which is intended to provide context to the objectives behind the tests assessed here.

12.0.3. This section then discusses all testing regimes in the context of their ability to deliver the performance metrics discussed in Section 7, which are necessary to assess if a level of performance equivalent to compliance with the Requirement has been attained.

12.0.4. Where relevant, and where known, some historical context behind the development of the individual tests is also given.

12.1. GENERAL PRINCIPALS OF PERFORMANCE ASSESSMENT THROUGH TESTING

12.1.1. The key to understanding any testing methodology is to clearly establish both the objective(s) of that test and the value and/or limitations of the output information in demonstrating those objectives.

12.1.2. Prescriptive regulatory approaches that utilise testing protocols work on the assumption that the testing protocol can deliver a sufficiently accurate and robust assessment of the performance of the test sample / system, such that the result of that test will be representative of the performance of the actual product(s) once installed in a building.

12.1.3. In the case of façades of high-rise residential buildings such as Grenfell Tower, fire related testing of an external wall system needs to establish if the demonstration of performance observed in the test translates to that system performing adequately in situ.

12.1.4. Once incorporated in a completed design, all tested components should seamlessly combine to deliver an overall desired performance. Pre-completion inspections (whether by quantity surveyors or building control) and commissioning of the different systems provide additional confidence that the final system is adequately installed, containing all the relevant components, such that it will deliver its expected performance.

12.1.5. Parameters controlling physical phenomena such as fire spread (including those discussed in Section 7) can be quantified in different ways. Some of them can be calculated, others
need to be measured directly and some of them have to be inferred indirectly from testing via different forms of data analysis.

12.1.6. As an example, a height can be measured using a ruler but can also be inferred by measuring the time it takes for a falling object to hit the ground when dropped from this height. The former is a direct measurement, and the latter is an indirect inference that requires understanding of Newton’s first law of motion.

12.1.7. When parameters are either measured or inferred from tests, these tests have to be designed and implemented in a manner that enables quantification of the parameter but also provides an estimate of error and uncertainty. The appropriate design of the test therefore requires a clear understanding of the parameter that needs to be quantified, and if any inferences are to be made, of what the laws of physics are that control the phenomenon that the test aims to quantify.

12.1.8. A single test can be used to identify multiple parameters. Using a single test to quantify multiple parameters requires a detailed understanding of the phenomenon taking place in the test and the manner in which each parameter influences it. Specific measurements will therefore have to be selected so that they can then be used to infer the values of the multiple parameters. Once again, quantification of the parameters can only be attained if the relationships between parameters and measurements are known.

12.1.9. Furthermore, inferring a single set of results from the measurements requires assurance that the results are unique and have physical meaning. Complex systems are governed by complex relationships and frequently different sets of parameters can, when combined, give the same results. When inferred from experiments, in many cases, these parameters are only a product of the mathematical models used to calculate them and therefore have no physical meaning.

12.1.10. Furthermore, if only a single test producing a single set of measurements is to be undertaken, and the outcome needs to be inferred from the data, there needs to be certainty that the outcome would be the same if the test was to be repeated.

12.1.11. An example might be the use of a temperature measurement to indicate the location of flame in a flame spread test, where a temperature threshold criterion (e.g. 600°C) is used to indicate the presence of the flame having spread. Such a system may not be capable of distinguishing between a small flame close by or the smoke plume from a larger flame at a distance. Therefore, while a flame spreading to the measurement point will result in a measurement of 600°C, it cannot be guaranteed that a measurement of 600°C has resulted from the spread of a flame to the measurement point i.e. A will result in B, but B doesn’t necessarily always result from A.

12.1.12. Most complex problems, such as fires, exhibit complicated relationships between parameters and measurements and thus the same measurements can result from multiple and very different combinations of parameters.
12.1.13. For a test to be useful it is therefore necessary to:

I. Clearly establish the phenomenon that needs to be quantified and the tolerable error and uncertainty

II. Understand the relationships governing the phenomenon

III. Extract from these relationships the parameters that influence the phenomenon

IV. Determine the measurements necessary to define and infer the parameters

V. Demonstrate that all inferences are unique, and

VI. Understand errors and uncertainties

12.1.14. This report will therefore seek to contrast these principles with existing testing methodologies to establish their capability to deliver the information required to quantify fire spread or extinction to the level of accuracy, certainty, and consistency with the requirements of the Fire Safety Strategy.

12.2. BS 8414 AND BR 135

12.2.1. As discussed previously, when following the guidance in Approved Document B, the second route proffered for assessing performance of external façade systems such as that installed at Grenfell Tower, is through assessment according to BRE Report BR 135\(^{120}\) in conjunction with test data from a BS 8414\(^{121,122}\) test.

12.2.2. Both the test and the guidance have seemingly evolved in parallel since the 1980’s. The first edition of BR 135\(^ {123} \) in 1988 was informed by ad-hoc large-scale testing to understand the implications of the increased use of flammable insulation in building facades. BR 135 was subsequently conceived as an information document / research report for designers / specifiers of external wall systems for use as part of the design process.

\(^{120}\) BR 135, Fire performance of external thermal insulation for walls of multistorey buildings, 3rd Ed. BRE, 2013. (BRE000005555)

\(^{121}\) BS 8414 – 1:2020, Fire performance of external cladding systems, Part 1: Test method for non-loadbearing external cladding systems fixed to, and supported by, a masonry substrate, BSI, 2020. (BSI00001911)


12.2.3. The ad-hoc test protocol was iterated and formalised in the 1990’s, seemingly in response to the Knowsley Heights fire in Liverpool, UK in 1991\textsuperscript{124}. In 1999, the testing protocol was formalised and published by the Fire Research Station (a part of BRE) as Fire Note 9\textsuperscript{125}, having been previously described in a report produced for the Department of the Environment, Transport and the Regions as Fire Note 3\textsuperscript{126}.

12.2.4. It was subsequently decided that it would become a British Standard Test and used in conjunction with the BR 135 guidance and information, following a parliamentary inquiry and review into a multi-storey residential housing block fire in Scotland in 1999. Fire Note 9 was thus developed into BS 8414-1:2002\textsuperscript{127}.

12.2.5. The information contained in BR 135 was also reviewed due to the evolution of façade systems and their constituent materials. This resulted in the second edition of BR 135 being published in 2003. It contained a new annex that gave performance criteria and a classification method against which the output data from BS 8414-1:2002 could be assessed.

12.2.6. It was subsequently recognised that the development of lightweight framed wall structures had resulted in a scenario significantly different to that represented by the then current test scenario. Thus, the test rig was adapted and BS 8414-2: 2005\textsuperscript{128} was created, along with BRE Digest 501\textsuperscript{129} in 2007, which defined the corresponding performance criteria.

12.2.7. Finally, a third edition of BR 135, was developed and published in 2013, incorporating BRE Digest 501 as a new annex, together with information relating to up-to-date façade products and systems. Since then, there have been incremental updates to the BS 8414 tests, most notably in the 2020 revisions. This test, and aspects of its evolution are briefly described here to provide sufficient background for the analysis of the BR 135 approach which follows.

**BS 8414 Large-Scale Testing**

12.2.8. The 2020 BS 8414 testing setup is shown in Figure 16 (a). It consists of a ~9.7m high main wall and perpendicular wing wall. A “representative sample” of the façade system being tested is mounted to either a masonry wall (BS 8414-1) or a steel frame (BS 8414-2) structure. These two mounting structures exist to account for the two principle characteristic system types; insulation applied directly to a continuous masonry wall substrate, or a lightweight metal framed system hung from a steel structural frame.

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\textsuperscript{124} Bisby Phase 2 - Regulatory Testing & the Path to Grenfell. Section 12 (LBYP20000001).

\textsuperscript{125} Assessing the fire performance of external cladding systems: a test method, Fire Note 9, BRE 1999. (BRE000005595)

\textsuperscript{126} Test method to assess the fire performance of external cladding systems, Fire Note 3, BRE 1998. (BRE00005868)


\textsuperscript{128} BS 8414 – 2:2005, Fire performance of external cladding systems – Part 2: Test method for non-loadbearing external cladding systems fixed to and supported by a structural steel frame, BSI 2005. (BSI000000097)

12.2.9. There is an open-faced combustion chamber located at the base of the main wall approximately 2m high. Unlike other international fire tests of this kind, there is no specific guidance given on how the façade system should be constructed around the opening to the combustion chamber. A fire (typically a wood crib fire) is ignited in the combustion chamber and in time the fire plume spills through the opening and impinges on the external façade (Figure 16 (b)).

12.2.10. This setup evolved from the early bespoke testing carried out at the Fire Research Station (now BRE) and which was used to inform the guidance given in the 1st Edition of BR 135. This initial bespoke testing was a simpler configuration with a single main wall but no wing wall. The decision to incorporate a wing wall came as a result of the Knowsley Heights fire in Liverpool, UK in 1991.

12.2.11. BR 135 states, “The Knowsley Heights fire... suggested that a full-scale fire test method was necessary to fully understand the overall fire performance of the complete system as installed in these applications, using a representative fire scenario rather than relying solely on an elemental approach to try to control the overall fire performance of the system.”

12.2.12. Clearly therefore, the BS 8414 test was conceived as a scenario test. Section 6.1 of BS 8414-2: 2020 states that the following should be true of the test specimen:

a) “Is representative of the intended end use design and consists of all relevant components of the intended specification;

b) References the associated component manufacturer’s design specification and installation details; and

c) Is assembled and installed in accordance with the test sponsor’s instructions, as would be expected in practice.”

12.2.13. The fact that the sample must be representative of the end-use scenario specification, within the bounds of the constraints imposed by the testing geometry, is characteristic of a scenario test. This was the principal driver for having two versions of the test in order to better represent the typical classifications of systems being constructed.

12.2.14. The incorporation of a wing wall represents a real-world condition that resulted in a specific form of behaviour deemed important for the testing protocol to capture.

12.2.15. The fire scenario, and thus the thermal loading on the external façade in BS 8414 tests, directly reproduces the experimental fire source described in the 1st edition of BR 135. This document describes the fire source as providing:

i. “flames typical of a fully-developed building fire impinging on the façade up to 2m above the recess at least 20 minutes;

ii. heat flux on to the façade of at least 100kW/m².”
Figure 16: (a) BS 8414 testing rig diagram showing thermocouple locations and (b) Ignition and fire growth during BS 8414 testing\textsuperscript{130}.

\textsuperscript{130} Image from https://www.tecnalia.com/
12.2.16. Again, the language used (“flames typical of a fully-developed building fire”) identifies this as a scenario test, and the thermal loading corresponds to the upper end of the range identified in my Phase I report\textsuperscript{131,132} as a characteristic wall flame heat flux.

12.2.17. Another example related to the fire source, is that it is extinguished 30 minutes after ignition unlike in a bounding test such as BS 476:20-24\textsuperscript{133} where the thermal loading is indefinite and imposed until failure of the test sample. While not explicitly stated in the BS 8414 documentation (although described as such in the original BR 135 from which it is taken), 30 minutes is representative of a characteristic compartment fire burning duration. Extinguishing the fuel source simulates burn-out of the fire source and removal of the external flaming.

12.2.18. The implicit assumption is that if the fire is not capable of continued fire spread after burn-out of the original fire source (i.e. the crib), then it can be inferred that, in a real fire, the fire will not be able to spread beyond the time of burn-out of the compartment fire that originated the event in the first place.

12.2.19. Despite being clearly conceived as a scenario test, BR 135 states:

\begin{quote}
“The classification applies only to the system as tested and detailed in the classification report. The classification report can only cover the details of the system as tested. It cannot state what is not covered. When specifying or checking a system it is important to check that the classification documents cover the end-use application.”
\end{quote}

Thus, while the test was inherently designed as a scenario test, it is not assumed to directly correspond to the end-use scenario. This emphasizes the need for competent interpretation of the results of the test and has implications for how applicable the test output actually is.

12.2.20. Temperatures are measured during the test by various thermocouples, located in the air next to the external face of the façade (external thermocouples), and within the system at mid-depth of any insulation and cavities (internal thermocouples). External thermocouples are located at Level 1, a height of 2.5m above the opening to the combustion chamber, and both external and internal thermocouples are located at Levels 2 and 3, at heights of 5m and 7.5m above the opening to the combustion chamber respectively.

12.2.21. The test is deemed to have started when any external thermocouple at Level 1 rises more than 200°C above the initial temperature and sustains this for more than 30s. The test is run for a duration of 60 minutes, with the heat source extinguished 30 minutes post ignition. The test may be terminated prematurely if there is a risk to the safety of personnel or equipment or the flame spread extends above Level 3 (i.e. the top of the rig).

12.2.22. The addition of this 3rd level of thermocouples represents one of the most obvious changes to the testing protocol in the 2020 version. The other major updates involve a significantly

\textsuperscript{131} Torero, Grenfell Public Inquiry, Phase One Report, 2018. (JT00000001)
\textsuperscript{133} BS 476 : Parts 20-24 :1987 (BSI00001748); (BSI00001745); (BSI00001743); (BSI00000074); (BSI00000075)
increased focus on detailing of the test specimen (to ensure compatibility with the end-use condition), the post-test examination and reporting on observations and outcomes.

12.2.23. The latter are presumably to ensure that the engineer utilising the testing data has as much information as possible on which to base their analysis and to minimize interpretation by those conducting the test.

12.2.24. Finally, it is worth noting that there are no pass / fail performance criteria provided in the BS 8414 documents. The test exists solely to act as a visual demonstration of system performance in this scenario and collect data via the arrays of thermocouples shown in Figure 16(a). While performance criteria were provided in the original Fire Notes 3 and 9, these were later added to BR 135, rather than being included in the BS 8414 test documentation itself.

12.2.25. Finally, it is worth noting that, while the pass / fail performance criteria provided in BR 135 have been modified in the different versions of this document, the changes have retained the same fundamental principles since their first appearance in Fire Note 9 (1999).

DEVELOPMENT OF BR 135

12.2.26. The original (1988) BR 135 document describes the development of a bespoke research programme that incorporated large-scale testing. The objective was to, “identify the design principles on which constructional recommendations might confidently be based”, about the use of combustible insulation within an over-cladding system (i.e. a façade system retrospectively applied to the outside of a masonry walled building, typically HRRBs), in order to achieve improved thermal insulation.

12.2.27. The research would “...determine both the risk of flame spread over the surface of the building and the risk of progressive spread via a cavity within the cladding system or through a layer of combustible insulant to areas remote from the original fire.”

12.2.28. Upon inspection of this report, it becomes clear that this experimental series was originally devised as a scoping study and was not in any way intended to be the development of a test of these systems’ performance.

12.2.29. Furthermore, the focus is on risk of flame spread (surface and cavities), but it bears no relationship to the objective of supporting a Fire Safety Strategy. So, when the objectives indicate that the purpose is ‘to identify the design principles’ they relate to an undefined concept of ‘risk of flame spread.’

12.2.30. As a result, and from the outset, BR 135 and the research supporting it, leaves it to the interpretation of the competent professional to determine what the objectives of the test are and how to embed the concept of ‘risk’ of flame spread (surface and cavities) in the assessment and definition of the Fire Safety Strategy.
12.2.31. The experiments described in the first edition of BR 135\textsuperscript{134} looked at the following systems:

i. "A system with insulation sandwiched between rendering and a wall;

ii. An aluminium-faced cladding system incorporating expanded polystyrene, the extent of the ventilated cavity being limited by fire barriers;

iii. A traditional timber clad façade, at present accepted as meeting the provisions of the Building Regulations for low rise developments and included in the fire test programme as a basis for comparison."

12.2.32. Therefore, aside from the timber clad façade systems which were included simply as a point of comparison, there were no combustible materials in the two systems being assessed, other than the insulation products that were highlighted as the primary justification for performing this research. The external panels on the rainscreen systems were uniformly metallic and non-combustible.

12.2.33. The recommendations made in the first edition of BR 135\textsuperscript{135} as a result of the experiments carried out followed one of two distinct trends, one for each class of system. They can be summarised as follows:

i. For surface rendered insulation systems attached directly to a masonry substrate, preventing distortion / reinforcing of the surface render is essential to prevent the insulation becoming involved in the fire;

ii. For rainscreen type systems, provision of cavity barriers is deemed essential to limit the extent of spread over the exposed surface of the combustible insulation that faces into the cavity.

12.2.34. Both recommendations emphasize processes that are intimately related to the geometrical and thermo-mechanical characteristics of the specific systems studied.

12.2.35. The first category of recommendations was formed on the basis of observations made regarding the behaviour of the rendering material applied to the surface of combustible insulation. This product is essentially a form of encapsulation which, as explained in Section 8.1, is intended to allow an otherwise combustible material to meet the requirement of ‘no fire spread’ by delivering a non-combustible exposed surface.

12.2.36. While the surface render is intact, the insulation material achieves the first property associated with no flame spread listed in Table 3 i.e. $T_{ig} \rightarrow \infty$. However, if the surface render is not adequately supported, the thermo-mechanical behaviour of the rendered insulation

\textsuperscript{134} BR 135, Fire performance of external thermal insulation for walls of multistorey buildings, 1\textsuperscript{st} Ed., BRE, 1988, p2-3. (BRE00001077)

\textsuperscript{135} BR 135, Fire performance of external thermal insulation for walls of multistorey buildings, 1\textsuperscript{st} Ed., BRE, 1988, p6. (BRE00001077)
system can lead to a breach of the encapsulation, exposing the combustible insulation and enabling fire spread.

12.2.37. The second recommendation indicates that flame spread will be inhibited if access to further fuel is prevented by an effective barrier. This is a specific way to attain \( L_h = 0 \) in a manner that is not intrinsic to the combustibility of the materials involved but by means of a mechanical barrier (as shown in Figure 4(c) and described in Section 7.2.22).

12.2.38. Thus, both recommendations are specific to the systems studied and are not influenced by assessments of combustibility but by assessments of thermo-mechanical behaviour.

12.2.39. The second recommendation is important in the context of subsequent historical perception of the risk posed by rainscreen façade systems. As stated above, the external panels considered at the time were uniformly non-combustible; likely representative of the products on the market at the time judging by the scope of the document. Therefore, spread of flame over the external surface was not a possibility, would not have been observed, and thus was never addressed in this document.

12.2.40. The principal hazard identified was the elongation of flames contained within a cavity, and seemingly as a result of which, ever since the publication of this document, has historically been perceived as the most critical threat in regard to these systems. Thus, the provision of cavity barriers has remained the primary focus of industry and regulation and was typically the sole consideration when addressing the risk posed by rainscreen façades containing no combustible materials.

12.2.41. Given that cavity barriers are a mechanical means to guarantee \( L_h = 0 \), their performance relates specifically to the thermo-mechanical behaviour of the system. This puts a significant weight on creating a test system that has very similar thermo-mechanical behaviour as the one the building system will have. But there are no provisions in BR 135 to guarantee that this essential objective is attained.

12.2.42. Once again, the onus is on the competent designer/engineer to establish if the objective of mechanically achieving \( L_h = 0 \) by means of a cavity barrier or encapsulation in a specific building is demonstrated by means of this scenario test.

12.2.43. Later editions of BR 135 continue, almost exclusively, to focus on the threat of fire propagation through cavities. The only direct reference to the potential for flame spread over external panels of rainscreen façade systems in the most recent (2013) version of BR 135 is as follows:

“**Combustible** panels are typically based on vinyl or glass-reinforced plastic, although various new products are being developed in this area, some of which also contain insulation materials. These products generally have good surface spread of flame characteristics to prevent rapid fire spread across the surface of the system, but once the panels become involved in the fire, they have the potential to generate falling debris, add to the overall fire load, and provide a route for fire to propagate up the outside of the building.”
No methodology or list of considerations for determining / addressing the risk posed by any such external panel is proffered in these documents.

12.2.44. While this perception of the risk posed by modern façade systems may have changed in light of the external fire behaviour at Grenfell Tower, there is still a significant industry focus on the type, location, and orientation of cavity barriers. This is despite the fact that external fires of the nature of that of Grenfell Tower clearly spread over the external façade. A clear technical assessment of the role of cavity barriers in reducing or preventing external fire spread is currently not available. This again is demonstrative of the endemic perception in industry of where the risk lies when addressing rainscreen façade systems.

**EVOLUTION OF BR 135 AND PERFORMANCE CRITERIA**

12.2.45. Given that the first edition of BR 135 is not concerned with the development of a test, it does not develop any performance criteria related to the experimental setup that it describes. It simply provides advice based on observations of a scenario-based scoping study.

12.2.46. A detailed historical examination of BR 135 is presented by Prof. Bisby, thus only some highlights will be discussed here.

12.2.47. The first description of a formal testing protocol for façades and associated performance criteria comes in Fire Note 3 (1998). There is no description / discussion in Fire Note 3 or later in Fire Note 9 (1999), of the origin or strategy for development of the testing protocol that would become BS 8414, however it is clearly derived from the scoping experiment described in BR 135 (1st edition)\(^{136}\).

12.2.48. Further, there is no explanation or justification for why the performance criteria were chosen, or what they were deemed to represent. To my knowledge, these performance requirements were first published in Fire Note 3 in 1998 and remain verbatim in the 3rd edition of BR 135 in 2013.

12.2.49. The 2nd edition of BR 135 is, in reality, an entirely different document to the 1st edition, as opposed to an iterative revision. Rather than focussing on specific products that populated the market at the time, it provides generalised discussion of the two principal types of cladding systems ([1] rendered systems and [2] ventilated cavities) and describes some of the issues typical of each type as observed from large-scale testing.

12.2.50. In this regard, the 2nd edition states that, “Prescriptive solutions are not given as data from recent full-scale fire tests and feedback on earlier design guidance suggest that the rapidly changing market and wide range of applications over which external cladding systems are used do not lend themselves to this type of design solution.”\(^{137}\)

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12.2.51. Thus, issues relating to the two types of system are identified in a simple and generic manner for the benefit of the reader. Although these are consistent with the observations made in this report, it is not established why they are important or what impact they can have on the test results and the extrapolation of the extracted information to specific buildings.

12.2.52. The 2nd edition of BR 135 [at page 7] provides the following generic template for designers to follow when assessing cladding systems:

“The following general points should be considered when designing and specifying external cladding systems.

i. The installation and fixing methods employed should be sufficiently robust to withstand the potential thermal exposure and fire spread characteristics associated with this type of fire incident without exhibiting significant fire spread or system collapse such as:

- Loss of strength as the system is heated
- Forces generated by retained thermal expansion of fixings and components
- Movements and distortions arising from thermal expansion if unrestrained

ii. The external finish should not unduly support fire propagation.

iii. The systems should not prematurely delaminate or spall providing potential entry routes for fire to access unprotected cavities or combustible material within the system.”

12.2.53. This is followed by guidance relating to the two types of system. Thus, the onus for developing detailed solutions to ensure the adequate performance of a façade system is placed on the reader.

12.2.54. As described above, by way of Annex A to BR 135, and later (post-publication) BRE Digest 501\[138\], the reader is introduced to large-scale testing according to BS 8414. BR 135 does not state that it is necessary to perform the test, just that it provides “an alternative means of demonstrating fire performance for external cladding systems”. Annex A then provides a brief description of the testing protocol and a brief section titled, “Performance criteria and classification method”.

12.2.55. It states at page 3 that:

“The performance of the system under investigation is evaluated against three criteria:

- External fire spread

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12.2.56. The test is adjudged to have started when a temperature rise at a Level 1 thermocouple (see diagram in Figure 16(a)) equals or exceeds 200°C for at least 30s. The failure criteria are then as follows:

i. External fire spread: Failure is adjudged if an external thermocouple at Level 2 exceeds 600°C for 30s or more within 15 minutes of the start of the test.

ii. Internal fire spread: Failure is adjudged if an internal thermocouple at Level 2 exceeds 600°C for 30s or more within 15 minutes of the start of the test.

iii. Mechanical Performance: No failure criteria. Details of system collapse, spalling, delamination, or flaming debris should be noted in the test report and this should be taken into consideration by the cladding designer.

12.2.57. Beyond this, this document provides nothing for the purpose of assessment and classification of the test specimen beyond these failure criteria. There is no classification system presented in the document nor in any related document. Further, the Building Regulations and guidance in Approved Document B do not refer to any such system classification in relation to these tests.

12.2.58. Neither do any of these documents relate the pass/fail criteria to the issues identified in the main body of BR 135, or to the requirements of the Building Regulations or the guidance in Approved Document B do not refer to any such system classification in relation to these tests.

12.2.59. This interpretation is made more complex due to the lack of description of the rationale behind the chosen failure criteria; what they represent, and how they specifically relate to the three chosen performance criteria or the requirements of the Building Regulations.

12.2.60. The 3rd edition of BR 135 is essentially an iteration of the 2nd edition, providing an expanded description of the general issues surrounding insulated façade systems in the main body of the document, and adding BRE Digest 501 as Annex 2. The content of the Annexes remains unchanged and the disconnect between the Annexes and the main body of the guidance also remain. Thus, the difficulties associated with identifying adequate performance of a façade system based on its performance in the test are exactly the same.

RELEVANCE OF BR 135 AND BS 8414 TO HIGH-RISE RESIDENTIAL BUILDINGS

12.2.61. BR 135, and the protocols described therein, were conceived as directly applicable to addressing Requirement B4 in the context of a HRRB, and specifically the part of Requirement B4 that relates to the prevention of external flame spread over façade materials. It states in section 2.1 that:
“the performance standard set out could be adopted where the implications of rapid fire spread by way of the external cladding system are considered to be unacceptable, such as tall buildings (above 18 m) that may be out of the reach of conventional firefighting techniques, and areas where people sleep, when external fire spread may present an unacceptable risk to the occupants.”

Therefore, the BS 8414 test and associated BR 135 performance criteria are considered, in an implicit manner, in the context of the Fire Safety Strategy for a HRRB, as described previously in this report.

12.2.62. As has already been discussed, the process of interpreting the performance requirements defined by ambiguous statements in the Building Regulations must be inherently linked to the Fire Safety Strategy of a building. Whereas a Fire Safety Strategy with a controlled evacuation can allow for a conservatively defined degree of external flame/fire spread, a fire strategy with a stay-put policy in place cannot allow any.

12.2.63. As described, testing according to BS 8414 in conjunction with BR 135 essentially applies a single pass/fail criterion based on the measurement of a single temperature two storeys (5m) above the fire compartment within 15 minutes of the start of a test. According to the test, fire can be established on the façade and spread, so long as it does not spread to an extent that the temperature failure criterion is met (internally or externally) two storeys above inside a 15-minute window.

12.2.64. It logically follows that a façade system can meet the BR 135 performance criteria and yet still be entirely incompatible with the Fire Safety Strategy of a HRRB with a stay-put policy in place.

12.2.65. Further, the information provided by the thermocouple arrays do not establish (per Table 3):

I. If the ignition temperatures of the products forming the system are sufficiently high i.e. $T_{ig} \rightarrow \infty$ that these products / materials can be considered non-combustible;

II. The length-scales of any flames established on the external face or within any cavities such that once the ignition source (the crib fire) is extinguished, any flame established on the external wall system tends to extinction i.e. $L_h = 0$

12.2.66. With regard to a controlled evacuation strategy, and in accordance with Table 2, there is no provision for the measurement of:

I. The actual rate of external or internal flame spread

II. Length-scales of any flames established or spreading on any external or internal surfaces

III. Material properties such as $T_{ig}$, $kpc$, or $\Delta H_c$

The test output data cannot be assessed against a calculated permissible rate of fire spread.
12.2.67. Again therefore, it follows that a façade system can meet the BR 135 performance criteria and yet be entirely incompatible with the Fire Safety Strategy of a HRRB that incorporates controlled evacuation.

12.2.68. The only potential for usable data comes from a failure to meet the performance criteria of BR 135 which clearly identifies the test specimen as inadequate for use in a building with a stay-put policy.

12.2.69. If a scenario test result does not account for the nuances in the requirements of the Fire Safety Strategy, because a façade that passes or fails the performance criteria may or may not be adequate, the responsibility for assessing the implications of the test result falls entirely on the competent designer / engineer.

12.2.70. The BS 8414 test was conceived as a scenario test, but the scenario that it attempted to represent related only to the characteristics of the initiating fire event. The fire reproduced by the test does reflect the typical conditions of a compartment fire, where heat fluxes to the external façade above the compartment of fire origin exceed $100 \, kW/m^2$ and decay in a manner consistent with scientific data on fire plumes. The period allowed for the crib to burn (30 minutes) is also consistent with the time to burn-out of a typical fully developed residential fire ($15 - 30 \, minutes$). Thus, the thermal conditions which the test imposes can be deemed as conforming to a scenario that could be expected from an HRRB.

12.2.71. The authenticity of the test scenario is however limited to the aforementioned thermal conditions imposed by the fire. Neither the test output nor supporting guidance provide the user with any instruction or means to adequately characterise and/or account for the similarities (or lack of) between the test system and the as-built system. Such unaccounted-for disparities include but are not limited to:

(i) The effects of further openings vertically above the fire compartment

(ii) What influence the wing-wall plays in the observed fire spread

(iii) The mechanical consistency between the test system and the as-built system

(iv) the change in thermal loading at the surface due to any contribution from the combustion of cladding system materials, or

(v) the effect of the façade geometry on the shape/dimensions of the impinging flame

12.2.72. The BR 135 / BS 8414 approach is presented by Approved Document B 2019 as an alternative to following the more simplistic alternative that restricts material combustibility. In spite of this, the BR 135 assessment does not translate data from the test to a classification of combustibility that could be used to assess the adequacy of a system.

12.2.73. Combined with the lack of geometrical constraints (i.e. spandrels) in approved guidance, the BR 135 / BS 8414 approach provides no assessment of external vertical fire spread and therefore responsibility for assessing the design in this regard again falls entirely to the competent designer / engineer.
12.2.74. Finally, no classification system, or even failure criterion is given with regard to the third performance objective, “mechanical performance.” This is once again left to the competent designer/engineer.

12.2.75. An example of relevant mechanical performance was provided in the 1st edition of BR 135 with regard to rendered insulation systems, where relative differential deformation of the external render and insulation support structure leading to a breach of the protective render was considered to be the primary failure mechanism. This led to exposure of the flammable insulation components and passage of fire into cavities behind the insulation.

12.2.76. In respect of rainscreen systems, deformation of such systems, as described in the main body of the BR 135 report (2nd edition), can lead to the creation of gaps that allow flame penetration behind and through the façade system and directly into the unit above. The absence of another opening above the fire compartment in the BS 8414 test makes even a visual assessment of the propensity for such a compartmentation failure to occur almost impossible. Thus, failure by deformation of the system is not an aspect which is assessed by BS 8414 / BR 135.

12.2.77. In the absence of an adequate failure criterion or performance classification system, the designer/engineer must, once again, assess the system’s performance in this regard based purely on direct observations. Thus, the manner in which the testing facility, the manufacturer and the competent designer/engineer share information is critical to the usefulness of the test.

12.2.78. Given the statements made above, it is a very simple exercise to find weakness and flaws in the manner in which BS 8414 was designed and is used. For example, criticisms can be made about:

- the manner by which the scenario that the test is intended to represent is defined
- the manner in which BR 135 characterises its use and application
- the measurements and observations extracted from the test
- the relationships between manufacturers, testing facilities and competent designers/engineers

But any such exercise will give an incomplete picture and ultimately will not be helpful to deliver a measure of relevance or appropriateness for this testing approach.

12.2.79. As previously indicated, for a scenario test of this nature to be useful it is necessary to:

I. Clearly establish the phenomenon that needs to be quantified and the tolerable error and uncertainty.

In the case of HRRB’s with a stay-put strategy the phenomenon is clearly defined by $L_h = 0$, with no tolerable errors and uncertainties. Therefore, any assessment of these phenomena needs to provide a conservative and robust result. Furthermore, given the presence of
combustible materials, $L_h = 0$, is to be attained purely on the basis of adequate mechanical behaviour.

II. Understand the relationships governing the phenomenon.

The relationships governing this phenomenon consist of a complex combination of combustibility and mechanical deformations leading to $L_h > 0$. Yet it is clear that BS 8414, because of its configuration, characteristics and associated measurements, cannot provide and cannot be expected to provide, the necessary information. In circumstances where the phenomena involved are so complex, Scenario Tests in the nature of BS 8414 are not intended to deliver this information.

III. Extract from these relationships the parameters that influence the phenomenon.

While Approved Document B defines BS 8414 / BR 135 as an alternative means to demonstrate performance, it is only set as a mechanism to deliver data to be interpreted by a competent professional. Given the narrow scope of the test, the poor instrumentation and the impossibility of fully capturing mechanical behaviour, it would be impossible for a competent professional to understand solely from these tests (BS 8414) the relationships and parameters that influence the phenomenon ($L_h > 0$). For each system, a bespoke protocol of further experimentation and analysis that enables an understanding of the different relationships leading to $L_h > 0$ is required.\(^{139}\) Depending on the complexity of the system, this could be done first at the product level, then at the system level and finally potentially verified by means of BS 8414.

IV. Determine the measurements necessary to define and infer the parameters.

V. Demonstrate that all outcomes are unique.

VI. Understand errors and uncertainties.

12.2.80. Finally, as explained in this report, the need for this bespoke protocol is very clear when addressing the systems put in place at Grenfell Tower. The responsibility for the preparation of these protocols, the required measurements, the uniqueness of inferences, the management of errors and uncertainties, as well as the execution of the required tests remains the responsibility of the competent professional. In this case, these competent professionals not only involve the engineer/designer but should also involve individuals working for the manufacturers as well as the testing facilities.

12.2.81. It can therefore be concluded that BS 8414 cannot quantify any relevant parameters influencing $L_h$. Furthermore, it cannot quantify any of the relevant parameters with sufficient precision and robustness.

\(^{139}\) The type of testing suggested here relates to typical approaches followed in product development. These tests intend to understand the behaviour and failure modes at a scale that enables systematic study using multiple test conditions. This approach is consistent with the description of the tests conducted by Prof. Bisby (Bisby, L. Phase 2 Experiments Work Package 2 – Systems Interactions, Grenfell Public Inquiry) (LBYWP200000001).
SUMMARY

12.2.82. The BS 8414 testing protocol is conceived as a scenario test directly applicable to HRRBs.

12.2.83. As such, the test reproduces a fire scenario that is relevant to a single compartment fire breaking through a window. The relevance is clear both in intensity, characteristics and duration of the fire.

12.2.84. Even in the case of HRRB’s with heights above 18 m and a ‘stay-put’ strategy, the test is proposed as a means to allow the use of combustible materials. Furthermore, the test was conceived in order to establish if a façade will “adequately resist the spread of fire” and therefore its main purpose is to deliver information that could be used by a competent designer/engineer to quantify $L_h$ and allow them to establish if the required condition of $L_h = 0$ can be attained.

12.2.85. For buildings with a Fire Safety Strategy that involves a controlled egress strategy, the test is required to deliver information that allows the competent designer/engineer to evaluate the flame spread velocity, $V_s$.

12.2.86. No direct measurement of flame spread is made, nor is any characteristic measurement or classification delivered that could be used directly to establish a rate of flame spread or the required assessment of $L_h$.

12.2.87. An inherent weakness in the overall protocol is the failure criterion used. The failure criterion of an external (or internal) thermocouple at Level 2 exceeding 600°C for 30s or more within 15 minutes of the start of the test does not relate to the objectives of the test.

12.2.88. During a test, a fire capable of directly penetrating the fire compartment above can be established on the façade and spread vertically and yet the system being tested could still pass the test. The failure criterion is therefore incompatible with the requirements of a façade system used on a HRRB with a stay-put policy.

12.2.89. BS 8414 cannot reproduce the mechanical constraints associated with the interactions between the building and the façade system, therefore the information it can deliver about encapsulation failure, the performance of cavity barriers or penetration of fire or smoke into adjacent units requires very competent scrutiny. Any extrapolation of performance will have to be strongly supported based on detailed observations conducted by a competent professional.

12.2.90. The details of the assembly will have a significant impact on the outcome of the test and therefore, for the test to enable extrapolation of information that can be used towards the design of a building, it is essential that all detailing is clearly described and justified. This requires a transparent transfer of information between the testing facility, those commissioning the test and those using the output.
12.2.91. Thus, the relationship between all parties has to be clear and transparent and all parties have to have demonstrated competency consistent with the complexity of the problem and of the systems being evaluated.

12.2.92. The characteristics of BS 8414 and the complexity of the phenomena that it is intended to quantify results in the interpretation of the information collected relying heavily on the competency of all those involved in the assessment process (i.e. manufacturers, testing facility, designers/engineers) and the clear and appropriate definition of the relationships between all parties.

**INTERPRETING BS 8414 BY DESKTOP STUDIES AND BS 9414: 2019**

12.2.93. As described earlier, the use of testing to establish the performance of systems to be used in buildings potentially requires multiple levels of analysis. Parameters of verified magnitudes can be introduced into models and potentially combined with different approaches to performance testing so as to determine if the system, in the context of its application, fulfils the requirements of the fire safety strategy. This information has to be analysed by a competent professional and delivered through a desktop study. Thus, a desktop study is an inherent component to the practise of fire engineering.

12.2.94. Any parameters that are deemed critical to attaining the required outcomes of the Fire Safety Strategy should be independently verified for conformity. The parameters are combined, through a desktop study to define either the performance of a sub-system or that of the building envelope. The fire performance of the sub-system or the building envelope also needs to be verified for conformity. The parameters describing the fire performance of the building envelope will serve as an input to the performance assessment in the Fire Safety Strategy. Thus, the fire performance of the building envelope is not in itself compliant, but it can be deemed, by the competent professional, to conform with the fire performance expected of it by the Fire Safety Strategy. The vehicle by which these assessments are presented and recorded are the desktop studies. The assessment of a fire safety strategy might incorporate several desktop studies.

12.2.95. In cases where performance can be established in a simple manner, well defined parameters and formulas can deliver the required performance metrics. These parameters and formulas can be standardized into prescriptive calculation methods for implementation by a competent professional. This is very rare in the case of fire performance metrics because of the inherent complexity of the processes involved.

12.2.95.1. When the systems are more complex, it is common for the parameters to be less defined and more prone to error. In addition, the testing options will frequently be insufficient or characterized by major weaknesses in their definition or implementation. In this case, the role of the competent professional becomes more significant, because it is the competent professional who is called-upon to interpret all available information.
12.2.96. It is important to clarify that in these complex systems, tests are sources of information for competent professionals. Thus, the competent professional is expected to sieve through the tests to extract any information that might be necessary for the required performance assessment. In some cases, the competent professional might require further testing to be carried out if the information available is insufficient.

12.2.97. The more complex the system, the more complex the information, the more limited the tests and, as a consequence, the greater the burden on the professional to provide an assessment of adequacy. The means by which the professional explicitly provides the demonstration of adequacy is through the desktop study.

12.2.98. Throughout this report extensive analysis has demonstrated the immense complexity of cladding systems such as those used in Grenfell Tower. Furthermore, the significant limitations of all testing protocols, including BS 8414, have been highlighted. Thus, when it comes to the assessment of fire performance of cladding systems, the burden on the competency of the professional conducting the desktop study is extremely onerous.

12.2.99. In the period following the Grenfell Tower fire, an additional British Standard (BS 9414:2019) has been published to provide guidance on interpreting and extending the results of BS 8414 testing to proposed systems whose characteristics depart from those that were actually subjected to physical testing. The purpose of BS 9414:2019 in this respect is defined by its scope as follows:

“This British Standard specifies procedures and rules used to evaluate variations and changes to products and systems which have been tested in accordance with BS 8414-1:2015+A1:2017 or BS 8414-2:2015+A1:2017, and, where appropriate, defines options and limits for preparing reports based on the direct and extended application criteria provided.”

12.2.100. This scope is expanded upon in the introduction section that states:

“There are a number of practical limitations on the size and design of construction elements that can be evaluated by a standard method of test. For example, if these elements are larger or of a modified design or type, it is necessary to be able to confirm that the integrity of the test result would be maintained if such changes to the system were implemented.”

“This British Standard is concerned with evaluating the scope of the results obtained from the BS 8414-1 and BS 8414-2 tests, defining the parameters which can or cannot be varied and to what extent. It provides direct application (DIAP) rules for a system which has been subjected to a single BS 8414-1 or BS 8414-2 test and interpolation for systems which have been subjected to multiple tests.”

“This British Standard relates only to the extension of results of an external facade system which has previously been tested in some form in accordance with BS 8414-1:2015+A1 or BS

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140 BS 9414:2019, Fire performance of external cladding systems – The application of results from BS 8414-1 and BS 8414-2 tests, BSI. (BSI00001934)
8414-2:2015+A1. It does not provide a means of assessing external facade constructions which incorporate multiple cladding systems.”

12.2.101. Thus, there is a fundamental assumption that the BS 8414 test result provides adequate information for a baseline assessment of performance (or, as BS 9414 phrases it, “the fire performance characteristics”) of the tested external wall system. The BS 8414 tests’ status as a useful / adequate / fit for purpose test is never questioned or addressed. Even more important, BS 9414 implicitly assumes that BS 8414 tests produce results that are ‘standalone’ in nature and do not require the interpretation of a competent professional. This is in contradiction with BR 135 and with the integrity of the analyses presented in this report.

12.2.102. This is further exemplified by the following statement:

“In the specific case of external cladding systems, such predictions are based upon the need to abide strictly with the fundamental principle that the fire performance of the modified system would be equal or better if it were to be subjected to a BS 8414-1 or BS 8414-2 test.”

12.2.103. The main body of the document presents a series of tables setting out an extensive range of changes to typical external wall system components that an assessor potentially might need to consider the impact of e.g. changing the substrate from one type of brick to another, or substitution of the insulation for a different variant etc. It then provides a series of statements about each of these potential changes. The majority of statements follow the format “The test result shall be deemed to be valid when / for…” [Page 15], which repeats the flawed assumption that the BS 8414 tests are the appropriate and sole mechanism to produce the information necessary to demonstrate performance of the reference external wall system.

12.2.104. The document is intended to be generally applicable to any tested system within the range of specified categories (e.g. rainscreen systems, external thermal insulation composite system etc.) and therefore the advice for what is permissible (or not), is independent of any actual tested system. What is deemed permissible are simply changes that are perceived as not having the potential to negatively impact the “fire performance characteristics” of any prospective system. Thus, while the introduction claims that the standard, “is concerned with evaluating the scope of the results obtained from the BS 8414-1 and BS 8414-2 tests”, in actuality, use of this document never addresses the process by which the user actually establishes how the tested system is performing, nor quantifying or even qualifying the impact of any proposed changes. Again, this reinforces the flawed presumption that the baseline 8414 test is in itself an adequate mechanism for establishing performance.

12.2.105. This is in contradiction with the principle that the test should provide appropriate information so that a competent professional can conduct a performance assessment of a system in the context of its application. Figure 1 presents a flowchart where at each stage of the assessment process decision making is required to follow the procedure for

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141 BS 9414:2019, Fire performance of external cladding systems – The application of results from BS 8414-1 and BS 8414-2 tests, BSI, p.7.(BSI00001934)
performing an “application evaluation.” First, all the cladding components are defined, then
the flowchart requires the user to “establish the evidence needed to perform the application
evaluation for the defined external cladding system/product components.” Establishing the
“evidence needed to perform the application evaluation” can only be done through a
desktop study and by a competent professional because determining the “need” for
evidence requires explicit and justified demonstration of that need.

12.2.106. The flow chart then requires comparisons of what is needed against Clause 5. While it is
possible that, in some very simple cases, the comparison between systems might be trivial,
given the complexity of these cladding systems this will generally not be the case. Table 1\textsuperscript{142}
can be taken as a very simple example of the potential complexities. In the case of the first
item, the variation from masonry substrate (BS 8414-1) test to a board faced steel framed
system (SFS) (BS 8414-2) test is considered not permissible. First, this is an arbitrary
assessment because it does not take into consideration how these products will affect fire
spread in the context of the application, nor does it address how the variation would affect
the heated length ($L_h$). Most problematically, the reverse situation is considered permissible
i.e. the variation from a board faced SFS (BS 8414-2) test to a masonry (BS 8414-1) test is
said to be appropriate in Table 1 provided additional evidence is available in the form of: 1. Temperature in insulation layer, 2. Fire resistance of substrate and 3. Thickness of brick,
block or concrete. But an explicit assessment of these parameters can only be conducted by
a competent professional by means of a desktop study. The assessment of these parameters
involves establishing acceptable limits for temperature, fire resistance and thickness,
but it also requires an assessment of their relevance and appropriateness. In many applications
these parameters might be irrelevant or inappropriate to the assessment of fire spread.

12.2.107. The same analysis can be conducted for any of the decisions required by the flowchart
presented in Figure 1. Therefore, at every stage of the process, BS 9414 requires a desktop
study and an assessment by a competent professional. Nevertheless, the method proposed
by BS 9414 substitutes a desktop study which should be conducted by competent
professionals with simple tables. Given the complexity of these systems and the extensive
weaknesses of the testing protocols used for the assessment of fire performance, this is a
fundamentally flawed approach. While intended to deliver an outcome, this outcome
cannot be comprehensive, does not provide sufficient or appropriate information and still
requires decisions to be made by a competent professional.

12.2.108. As set out earlier in this report, it is clear that the BS 8414 + BR 135 protocols for establishing
external wall system performance do not provide any meaningful measure of assessment of
the relevant performance metrics pertaining to establishing compliance of an external wall
system with Requirement B4(1). Thus, by not recognizing the unavoidable role of the
competent professional in the assessment of the information obtained from BS8414 + BR135
and not questioning the intrinsic value of this test output, the basic premise of the BS 9414
document is flawed. BS 9414 is therefore establishing a list of permissible changes to tested
systems whose “fire performance characteristics” are still unquantified/unqualified because

\textsuperscript{142} BS 9414:2019, Fire performance of external cladding systems – The application of results from BS 8414-1 and BS 8414-2
tests, BSI, p.8.(BSI00001934)
no competent professional assessment is defined and this is also compounded by the limitations of the test that provides the input data.

12.2.109. In summary, BS 9414 is a document that follows a long tradition of attempting to ignore the need for professional competency by substituting the need for professional assessment by means of over-simplistic, non-comprehensive and flawed prescriptive rules. When Tables 1 to 6 of BS 9414 establish whether a proposed variation is permissible or not, this assessment is many times incorrect. Furthermore, in most cases, the Tables will also indicate the need for additional and competent professional assessment. Therefore, this new standard is not only flawed in its technical content, but it attempts to hide the need for the professional competency that the standard itself invokes.

12.3. UK (NATIONAL) REACTION TO FIRE CLASSIFICATION AND TESTING

12.3.1. The principal approach of what is often referred to as the ‘linear route to compliance’ is essentially the specification of reaction to fire classifications that materials or products incorporated into an external wall system should conform to. Traditionally this has been expressed via various clauses in Approved Document B, however more recently, as stated previously, prescriptive regulations have been added to the Building Regulations which incorporate reaction to fire classifications.

12.3.2. The current Approved Document B (2019 + 2020 amendments) and most recent amendment to the Building Regulations (2018) both utilise the European reaction to fire classification system and associated testing protocols, however the version of Approved Document B current at the time of the Grenfell Tower over-cladding product gave the option of both National and European classes.

12.3.3. The principles, selection, role and application of national class reaction to fire testing is described in BS 476-10\textsuperscript{143}. In an earlier section, this document discusses the relationship between reaction to fire tests and building fires. It states that:

“The BS 476 reaction to fire tests were basically developed to rank products and materials in terms of specific performance characteristics. The outputs of BS 476-4, BS 476-6, BS 476-7, BS 476-11 and BS 476-12 are simply a classification of a derived parameter that has no real physical meaning, other than comparison of one material or product with another. These tests do not provide data that can be related to real building fire performance in a quantitative sense or that can be used as input parameters to modelling approaches.”

12.3.4. From this statement therefore, it is clear that the output from these tests is not intended to deliver data against which material, system or product performance can be established in the context of an outcomes-based system of regulation. This therefore accentuates the need

\textsuperscript{143} BS 476-10:2009 Fire tests on building materials and structures – Part 10: Guide to the principles, selection, role and application of fire testing and their outputs, BSI. (BSI00001757)
for any utilisation of the test data in this respect to be performed by a competent professional.

12.3.5. There is a degree of contradiction in the document with regard to the function of reaction to fire testing. In contextualising the principle of these tests, section 5.1 states that “Reaction to fire tests are used to characterize the performance of construction products and/or materials in terms of their contribution to the initiation and growth stages of a fire, leading up to flashover.” This would appear to be unrelated to the scenario of fire impinging on or spreading over an external wall system.

12.3.6. In section 5.2 of BS 476-10 however, individual reaction to fire tests are discussed including BS 476 parts 4, 6, 7 and 11 which are discussed later in this section. In each case, it is stated that these tests “can be used for classifying the performance of” or “assessing the performance of” “external surfaces of buildings”.

12.3.7. Later however, when directly addressing “external fire performance” of facades, BS 476-10 discusses only the BS 8414 tests and BR 135 guidance, not mentioning any role to be played by reaction to fire testing in this regard.

12.3.8. This latter section also states that “the relationship between these systems [those tested to BS 8414] and typical building fires is heavily based on individual system scenario analysis”, therefore again stressing the need for the involvement of a competent professional to translate observations in the test to performance in-situ.

12.3.9. It appears apparent therefore that national class reaction to fire testing protocols, despite being cited by Approved Document B (2013), are not intended to be used to establish performance of external wall systems, either directly or indirectly, and at most, are intended to provide some degree of comparison between products.

**BS 476-4 – NON-COMBUSTIBILITY TEST FOR MATERIALS**

12.3.10. The National (British Standard) test for non-combustibility is described in BS 476-4:1970\(^{144}\) and is the National equivalent of the European classification test BS EN ISO 1182 which has ultimately replaced BS 476-4 in UK regulation. The foreword of the standard [piii] describes the protocol as follows:

“... a continuous recording of the furnace temperature is made and requires observations as to whether a sample produces a flame. Materials are classified as combustible or non-combustible by identifying those which make little or no thermal contribution to the heat of the furnace and do not produce a flame, and by calling the remainder “combustible”.”

12.3.11. In accordance with this description, the test involves placing a sample of a “building material” in the centre of a tube-shaped furnace at a temperature of 750°C for a period of

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\(^{144}\) BS 476-4:1970, Fire tests on building materials and structures – Part 4: Non-combustibility test for materials, BSI. (CTAR000000014)
20 minutes. Air is allowed to flow through the furnace to enable any combustion of fuel vapours should they be released by the specimen and be capable of forming a combustible mixture and ignited. A schematic of the test equipment is shown in Figure 7.

12.3.12. Therefore, as per the first row of Table 3, the test ostensibly seeks to establish the material property of non-combustibility using the proxy that the ignition temperature is extremely high i.e. \( T_{ig} \to \infty \).

12.3.13. As alluded to earlier, it is an assumption of the testing protocol that a temperature of 750°C will be in excess of the auto-ignition temperature of the vast majority of combustible materials, therefore can be considered as an adequate proxy for \( \infty \) i.e. very high.

12.3.14. As points of reference, some example ranges of auto-ignition temperatures for materials given by Babrauskas\textsuperscript{145} are 349 - 457°C for Polyethylene or 422 - 523°C for fire retarded high impact polystyrene. Some typical ignition temperatures provided for a range of types of wood are in the 300-450°C range.

12.3.15. The test utilises both visual observations of flaming and temperature measurements via the placement of two thermocouples, one in the gas phase in the furnace to monitor and maintain the furnace temperature, and a second placed at the centre of the sample.

12.3.16. Thus, the surface temperature of the tested material is not directly measured and therefore an ignition temperature (\( T_{ig} \)) is not directly generated.

12.3.17. It may be possible on the basis of some assumptions and knowledge of other properties of the material (e.g. \( k_{pc} \)) to extrapolate an approximate surface temperature at the point of ignition (should it occur) via modelling, but the testing protocol itself is not designed to measure or generate this directly.

12.3.18. The material is deemed non-combustible if the tested specimen does not:

(i) Cause the temperature reading in either thermocouple location to rise more than 50°C above the initial furnace temperature

(ii) Flame continuously for 10s or more inside the furnace

12.3.19. It is therefore important for the user of this test data to understand that a designation of “non-combustible” in this test does not equate to a completely inert material. This therefore puts an onus on the user of the test output to use this outcome appropriately and consider if the phenomenon (non-combustibility) has been adequately established for the particular application being considered.

12.3.20. In the context of the flux of heat incident on an external façade system due to impingement of external flaming from a fully developed fire, these heat fluxes can reach more than 100 kW/m\(^2\). There is no direct measurement of the heat-flux applied to the surface of the tested material (\( q''_e \)) therefore the onus is placed on the user of the output to assess if the thermal

condition experienced in the tube furnace is sufficiently conservative in comparison to the 100kW/m² figure to ensure the non-combustibility condition is realised in-situ.

12.3.21. Therefore, it is my opinion that the measurements are not sufficient to define and infer the necessary parameters when using this test in the context of external facades, and therefore place the onus on the competent professional for their appropriate interpretation in this context.

12.3.22. The non-combustibility testing protocol is repeated three times using oven dried specimens of dimensions 40mm x 40mm x 50mm (width x breadth x height) which should be at ambient temperature when placed into the furnace.

12.3.23. While the test is intended to classify a “building material” (the scope of the document states that the “test is intended for building materials whether coated or not, but it is not intended to apply to the coating alone”), it is recognised that not all materials within building products can conform to the sample size and thus there are provisions made to allow testing of thinner materials or composite materials.

12.3.24. In the case of thin building materials, “...each [test] specimen shall be made of a sufficient number of layers to achieve this thickness.” i.e. layers of the material are stacked until the sample thickness is achieved.

12.3.25. In the case of composite materials the standard states:

“For composite materials of a thickness such that an integral number of layers cannot be put together to give a specimen of the specified size (see Clause 3), the specimen shall be prepared to the required thickness by adjusting the thicknesses of the different components so that their proportions in the specimen shall be the same as those in the material. If it is not possible to follow either procedure in the preparation of the specimens, tests shall be performed on the individual component layers of the material and reported accordingly.”

12.3.26. This test is therefore clearly not intended to assess a product such as an encapsulated material in its ultimate (in-situ) form, but rather assess the individual component materials of that product.
Figure 17: General arrangement of the tube furnace used in the non-combustibility test in BS 476-4.
BS 476-11 – METHOD FOR ASSESSING THE HEAT EMISSION FROM BUILDING MATERIALS

12.3.27. Test standard BS 476-11 is the national test method for assessing the heat emission from building materials. It has been replaced by European Standard EN ISO 1182, the non-combustibility test that has also replaced BS 476-4.

12.3.28. The foreword to this standard test states:

“The behaviour of materials or combinations of materials in a fire depends on the characteristics of the fire, the method of use of the materials and the environment to which they are exposed. A method such as is described in this standard deals only with a simple representation of a particular aspect of the potential fire situation typified by a defined heat source, and it cannot alone provide any direct guidance on behaviour or safety in fire. This test is not intended to assess the effect of materials on fire growth and for that purpose other fire tests in the BS 476 series are more appropriate, but a test of this type may be used for comparative purposes or to ensure the existence of a designated level of performance considered to have a bearing on fire performance generally. It would be wrong to attach any other meaning to performance in this regard.”

12.3.29. From the outset therefore, it is made clear that “this test is not intended to assess the effect of materials on fire growth” and therefore it is apparent that the output is not intended to inform an assessment of propensity for flame spread.

12.3.30. The scope states that “this method is applicable to simple materials or mixtures of materials, either manufactured or naturally occurring, that are reasonably homogeneous and from which it is possible to obtain specimens representative of the material as a whole. It is also applicable to non-homogeneous materials providing that irregularities... are not disproportionately large compared with the size of the specimen”.

12.3.31. It goes further stating that, “this method is not normally suitable for assessing combinations of materials, such as those that are surface coated surface coated, veneered or faced or that contain discrete layers of materials that have been fixed or glued together as laminates. However, providing that sufficiently representative specimens can be produced, the individual discrete materials may be assessed separately”.

12.3.32. It is evident therefore that this test is not applicable to an encapsulated product such as an ACM panel unless each component material of the product is extracted and tested in isolation.

12.3.33. The scope of the test standard describes the test as “a method for assessing the heat emission from building materials when inserted into a furnace at a temperature of 750°C”. It is therefore, in principle, a similar test to the non-combustibility test and utilises essentially the same equipment setup as that shown in Figure 17, with minor variations in dimensions and electrical equipment specified.
12.3.34. Temperature measurement is again provided in the gas phase near to the furnace wall, and at the geometrical centre of the test specimen, with an additional third thermocouple measuring the temperature of the furnace wall.

12.3.35. While there is a difference in the shape of the sample itself (which is to be cylindrical with height 50mm and diameter 45mm) this equates to an almost identical volume of material as that used in the non-combustibility test.

12.3.36. In this test, the pre-conditioned sample is lowered into the furnace which is at a temperature of 750°C and remains there until the specimen temperature has passed a peak and then both the gas phase temperature and the specimen temperature have reached an equilibrium temperature. If no such peak in temperature occurs, then the test is run for 120 minutes and then shut off. Examples of temperature profiles are given in Figure 8 of the test standard which is reproduced in Figure 18.

12.3.37. The test results are expressed as the difference between the peak (max) temperature and final equilibrium temperature, recorded by and calculated for both the furnace gas phase and specimen thermocouples. These temperature differences are averaged for the five tested specimens. The diagrams in Figure 18 indicate the temperatures that are to be used in this calculation.

12.3.38. Other information recorded in the test are the sum of the recorded durations of sustained flaming, the density of the sample before testing, and loss of mass of the sample. Again, all of these values are averaged for the five samples tested.

12.3.39. Other than the reporting of these measurements and temperature differences, there is no classification or designation applied to the material tested on the basis of the test standard itself. Such designations are specified by other documents.

12.3.40. Table A7 of Approved document B classifies a material as being of limited combustibility if of density greater that 300kg/m³ and when tested to BS 476-11, does not flame or cause a rise in temperature in the gas phase temperature of more than 20°C. This is the performance necessary to achieve classification as Class 0.

12.3.41. It is of note therefore that, in accordance with paragraphs 11.2.9. – 11.2.11 and Table 4, Approved Document B 2013 suggests that an entire external wall system can be classified as appropriate for use on a high-rise residential according to this single test, despite the disclaimer quoted in paragraph 12.3.29 and the relationship between testing and real-world performance stated in BS 476-10 (see quote in paragraph 12.3.3 of this report)

12.3.42. Likewise, in addition to the use of the non-combustibility test (BS 476-4 previously) Approved Document B also utilises BS 476-11 output to attribute non-combustibility status if the tested sample does not flame or produce any rise in temperature in any of the thermocouples.
Figure 18: Examples of temperature profiles of gas phase temperature ($T_f$) and sample temperature ($T_c$) in the BS 476-11 test. The plots show example equilibrium conditions that signal the end of the test.
12.3.43. Again, this is not a direct outcome of the testing protocol itself, and it is also of note that, given the similarities of the tests, this test actually represents more stringent criteria for non-combustibility than that of the non-combustibility test (BS 476-4) which sets a limit of temperature rise of 50°C and continuous flaming of 10s as the threshold for non-combustibility.

12.3.44. While apparently more stringent, this result is still limited by the fact that the exposure conditions are limited to 750°C and there is no direct means provided in terms of direct measurement to compare this with the expected range of exposure of an external wall system i.e. up to 100kW/m².

12.3.45. Therefore, there is no guarantee on the basis of this classification that a material that meets this criterion will not ignite and contribute to heat release when deployed in an external wall system. Similarly, to the non-combustibility test, this protocol also does not directly measure or aim to quantify the ignition temperature of the tested material should it ignite.

12.3.46. In light of the above, this testing protocol cannot therefore be considered to provide adequate information for assessing the no flame spread performance metric.

12.3.47. While being titled as a test to establish the heat emission from materials, this test does not as the title might suggest, actually aim to measure the heat of combustion \( \Delta H_c \) of the tested material. As stated in paragraphs 7.3.3 – 7.3.5, the heat of combustion is a material property that is used to define the heat release rate of a material (per Equation 4) which is an important component in establishing the propensity for a flame established on that material to both self-perpetuate and provide heat to the unburned material \( L_h > 0 \) such that the flame can spread.

12.3.48. Therefore, establishing the heat of combustion is a necessary component material property, alongside the aforementioned ignition temperature, for assessing the propensity of a material to support flame spread (see Table 2).

12.3.49. Irrespective of the intended range of use of the test output, this test cannot be considered to provide any information that is useful in regard to establishing a characteristic rate of spread performance metric.

**BS 476-6 – METHOD OF TEST FOR FIRE PROPAGATION FOR PRODUCTS**

12.3.50. BS 476-6\(^{146}\) is the method of test for fire propagation for products. It is one of the tests used to establish if a product can be classified as Class 0 according to the definition in Approved Document B 2013 (see paragraph 11.2.11). This test has, in more recent times, effectively been superseded in the UK regulatory approach by the Single Burning Item test (EN 13823) which is discussed in section 12.4.

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12.3.51. Air is allowed to flow into the base of the furnace and hot gases allowed to vent through a chimney at the top of the furnace. A thermocouple is positioned to record the temperature of the gases leaving through the chimney. There is no measure of thermal exposure (either temperature or heat flux) experienced by the surface of the sample.

12.3.52. The furnace is heated at a variable rate during the test, using a combination of both gas burners and electrical heating elements. The former is run throughout the test at a constant rate while the latter is introduced part way through, and the output varied in time. The furnace is initially at ambient temperature and therefore the temperature in the furnace is not a constant value at any point. The total time for the test is 20 minutes.

12.3.53. The test is initially run for a calibration material (calcium silicate board) and once cooled, is repeated for 3 test specimens. If any of these test specimens deform to the extent that they block airflow through the chamber or impair the heating elements, the test is discarded and rerun. A maximum of 5 attempts are permitted from which 3 “good” tests must be conducted.

12.3.54. The test is very much geared towards assessing only the surfaces of the products that will be exposed in-situ. It states that any faces that can be exposed in use within a room, cavity or void should be tested. However, where materials are encapsulated, or covered by a flame-retardant coating, the specimen is to be mounted / presented in such a way as to prevent direct ignition of these underlying layers / faces.

12.3.55. Tested samples are “board shaped” (225mm square and a maximum of 50mm thick/deep), and when in position, will overlap the opening to the furnace, effectively closing it (forming the last wall), supported by the sample holder. Where products to be tested are more than 50mm thick, they are to be cut away from the non-exposed face, reducing them to the max allowable thickness whilst not impacting the surface which will be typically exposed in their practical use.

12.3.56. The output of the test is a Fire Propagation Index. The Fire Propagation Index is based on the difference in temperature rise in the effluent gases between the tested samples and the calibration material. These temperature differentials are essentially time averaged for each period of time in which the heating rate of the furnace varies for each sample. These values are then averaged again to give a single value for each sample. These values for each sample are then summed to give the Fire Propagation Index.

12.3.57. The derivation of the Fire Propagation Index is essentially extremely convoluted and the values themselves have absolutely no correlation to real world performance or to any specific material property. There is thus no value in trying to describe in detail the derivation process here and the reader is referred to the standard should greater clarity be required.
Figure 19: Diagrammatic representation of the BS 476-6 Method of test for fire propagation apparatus.
12.3.58. The scope of this test describes it as “a method of test, the result being expressed as a fire propagation index that provides a comparative measure of the contribution of the growth of a fire made by an essentially flat material, composite or assembly. It is primarily intended for the assessment of performance of internal wall and ceiling linings”.

12.3.59. The foreword adds that “whilst this test has been designed to give information on the performance of a product in the early stages of a fire, it should not be considered or used by itself for describing or appraising the fire hazard of a materials, composite or assembly under actual fire conditions or as the sole source on which a valid assessment of hazard pertaining to fire propagation can be based.”

12.3.60. It is clearly stated therefore that, as is essentially the raison d’etre of all reaction to fire tests, the test was never designed to provide a means to enable performance assessment in an outcomes-based regulatory system, but rather to provide a means for comparing different products. Concurrent with this objective, no classification or explanation is applied to the resulting Fire Propagation Index by the test standard.

12.3.61. Some interpretation is provided in Paragraph 12 of Appendix A of Approved Document B 2013, which specifies what are considered to be acceptable fire propagation indices from BS 476-6 that will “restrict the use of materials which ignite easily, which have a high rate of heat release and/or which reduce the time to flashover”. The objective for the use of this very limited test is therefore very wide ranging and assumed to cover a huge array of physical processes that are in no way covered in the test itself.

12.3.62. The combination of variability in heating rates, variability in heating mechanisms, and any combination of flaming or soot production from the specimen itself, coupled with the lack of diagnostic sensors, means that establishing the thermal exposure \( (q'' + q''_e) \) of the sample is not possible. Its performance cannot therefore be related to any design scenario and assessed in this context.

12.3.63. The moment of ignition, should it occur, is also not noted therefore establishing a critical heat flux for ignition or an ignition temperature is not possible.

12.3.64. The method of securing the sample in a sample holder will obscure any edge effects and therefore the test output can only be considered relevant to the exposed surface material. This has implications for encapsulated products such as those described in Section 8.1, as unless such a product experiences burn through of the outer encapsulation material, the test output will be blind to the presence of any combustible material behind.

12.3.65. Further, any thermo-mechanical behaviour that might indicate if there is a propensity for any encapsulated combustible material to be exposed will not be captured due to the size of the sample and securing of it in the sample holder.

12.3.66. Differences in soot production between tested products may also serve to block radiative heating from the heating elements to different extents and therefore it is not even possible to claim that the heat exposure experienced by each sample will be consistent. This therefore calls into question the suitability of the output of this test for drawing comparisons
between different products which, as stated, is ultimately the principal objective in reaction to fire testing.

12.3.67. This test therefore cannot provide any of the relevant information/data for establishing any of the performance metrics described in Section 7.

BS 476-7 – METHOD OF TEST TO DETERMINE THE CLASSIFICATION OF THE SURFACE SPREAD OF FLAME OF PRODUCTS

12.3.68. BS 476-7\(^{147}\) is the method of test to determine the classification of the surface spread of flame of products. Like standard test BS 476-6, it is one of the tests used to establish if a product can be classified as Class 0 according to the definition in Approved Document B 2013 (see paragraph 11.2.11).

12.3.69. An image of a test being carried out is shown in Figure 20 (a). On the left side is a radiant panel, and on the right, at 90° to the face of the panel, is a test specimen secured within a metal specimen holder such that the edges of the specimen are not exposed to the incident heat flux from the radiant panel.

12.3.70. Once the test specimen is swung into position, the radiant panel provides a pre-calibrated external heat flux (\( \dot{q}''_e \)) to the exposed surface of the test sample. The flux of heat ranges from 32.5 kW/m² @ 75mm from the face of the vertical edge closest to the radiant panel, dropping to 5kW/m² at the distant end of the sample.

12.3.71. A pilot flame is placed near the lower corner closest to the radiant panel such that if a combustible mixture is formed by heating of the sample to its ignition temperature by the radiant panel, it can be ignited.

12.3.72. If a flame is then established, it may spread laterally along the sample. In accordance with the description of flame spread in section 7.2, a flame can spread so long as the heat transfer to the unburnt material adjacent to it can be heated to its ignition temperature. In this case, due to the orientation of the flame relative to the direction of spread, the length of the test sample heated by the flame (\( L_h \)) is very short.

12.3.73. The unburnt fuel is however being heated by the radiant panel as well as the flame (\( \dot{q}''_f + \dot{q}''_e \)), therefore it is this sum that must be greater than the critical heat flux for ignition of the sample in order for the flame to continue spreading.

\(^{147}\) BS 476-7: 1997, Fire tests on building materials and structures, Part 7: Method of test to determine the classification of the surface spread of flame of products, BSI, 1997. (CTAR00000017)
Figure 20: (a) Still image taken from a video\textsuperscript{148} of a BS 476-7 test showing the test setup of radiant panel on the left perpendicular to the exposed face of the product sample in the sample holder. (b) shows the limits of the classifications relative to the radiant panel (right), defined as follows: Blue -> Class 1, Red -> Class 2, and Green -> Class 3. Dotted lines represent allowable limit of spread after 1.5 minutes, full lines represent allowable limits of spread after 10 minutes. Any sample exceeding the limits of Class 3 is classified as Class 4.

\textsuperscript{148} Still from video of a BS 476-7 test uploaded by Warrington Fire. Last accessed on 29/07/2021 at the address: https://www.youtube.com/watch?v=7a4gCLpOAY
12.3.74. If this summed incident heat flux falls below this critical value, the unburnt material will not be heated to its ignition temperature and the flame will no longer be able to spread. Under a set of very specific assumptions, the value of \( \dot{q}''_e \) calibrated at the point of ignition can be assumed to be comparable to the critical heat flux for ignition of the sample.

12.3.75. From the moment at which the test sample is exposed to the radiant panel, the test is run for 10 minutes. The outcome is classified based on how far the flame has spread by 1.5 minutes and 10 minutes after the first exposure of the sample to the panel. The distances that correspond to each classification (Class 1 to Class 3) are shown in Figure 20 (b). If flame is able to spread beyond the limits for Class 3, it is classified as Class 4.

12.3.76. The document’s scope describes BS 476-7 as: “a method of test for measuring the lateral spread of flame along the surface of a specimen of a product orientated in the vertical position under opposed flow conditions, and a classification system based on the rate and extent of the spread of flame. It provides data suitable for comparing the end-use performances of essentially flat materials, composites or assemblies, which are used primarily as the exposed surfaces of walls or ceilings.”

12.3.77. Drysdale\(^{150}\) notes that the results of tests such as BS 476-7 are “strongly apparatus dependent, and cannot yield quantitative data on material performance”. Further, in discussing standards tests from different European countries that effectively correspond to

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\(^{149}\) BS 476-7: 1997, Fire tests on building materials and structures, Part 7: Method of test to determine the classification of the surface spread of flame of products, BSI, 1997. (CTAR000000017)

this setup, Drysdale references Emmons in saying that they gave “wildly different orders” when ranking a given set of materials.

12.3.78. It is clear therefore that 1) this test is not intended to be used for extrapolation of material properties or processes to in-situ performance, and 2) the physical measurements are very sensitive to the apparatus that the tests are performed on, thus products are only comparable when subjected to the exact same testing protocol.

12.3.79. Consistent with point 1, it is not appropriate to directly extrapolate observed flame spread rates or derived material properties such as critical heat flux for ignition for the purposes of assessing in-situ performance. Therefore, this test cannot be used to establish any of the performance metrics required to establish the existence of performance compliant with the requirement.

12.3.80. As discussed above, the test utilises lateral (opposed flow) flame spread rather than upward (concurrent flow) flame spread. Concurrent flow flame spread is the primary relevant scenario for facades. It occurs more readily that opposed flow spread and therefore it is distinctly possible that a material which may struggle to spread laterally will be perfectly capable of spreading vertically, even in the absence of an external source of heat flux.

12.3.81. Indeed, this was observable at the Grenfell Tower fire where the flames spread readily upwards without noticeable lateral fire spread. Spread around the tower was due to pooling of molten polyethylene at parapet level which then flowed over the roof and dripped down the building, igniting fires which subsequently spread back up the building.

12.3.82. Also, external fires on building facades can impose a heat flux of up to 120kW/m² within the heated length\textsuperscript{151}. This compares to the range of external flux of heat flux imposed in this test of 5 – 32.5 kW/m².

12.3.83. It is therefore clear that any rating in this test is meaningless in terms of in-situ performance. Even a Class 1 rating which was previously used as a component to establish a Class 0 rating.

12.3.84. Finally, it should be noted that the sample holder obscures all edges of the sample, exposing only the surface. This has implications for encapsulated products such as ACM panels. In such a test, only the outer most surface is exposed to the heat flux from the radiant panel and thus the output will only ever be a measure of this component of the product. It will be effectively blind to the impact that any encapsulated materials might have.

\textsuperscript{151} Torero, J.L. Grenfell Tower: Phase One Report, 23\textsuperscript{rd} May 2018, p5 {JTOR00000001}
12.4. EUROPEAN REACTION TO FIRE CLASSIFICATION AND TESTING

12.4.1. The standardised European reaction-to-fire classifications are set out in EN 13501-1:2007 +A1:2009 – Fire classification of construction products and building elements – Part 1 Classification using data from reaction to fire tests\(^{152}\).

12.4.2. EN 13501 utilises a number of reaction-to-fire tests in order to establish a reaction-to-fire classification, with different combinations of these tests utilised to demonstrate different classifications.

12.4.3. The test standards themselves only describe the methodologies for producing data / output. The correlation between the output and the classification is solely given in EN 13501.

12.4.4. This section will briefly describe the conceptual development of the classification system, and the characteristics of the tests and the data / information that they produce, in order to assess their applicability to defining the performance of external wall systems.

(BS) EN 13501-1 – THE EUROPEAN REACTION TO FIRE CLASSIFICATION SYSTEM

12.4.5. The reaction to fire classification system was developed in response to Annex 1 of Council Directive 89/106/EEC\(^{153}\) which set out “essential requirements” for works and constituent products to be considered “suitable for construction works which are fit for their intended use”.

12.4.6. The specific “essential requirement” that resulted in the development of the reaction to fire classification system states, “the construction works must be designed and built in such a way that in the event of an outbreak of fire... the generation and spread of fire and smoke within the works are limited.” “The (construction) works” is defined as both buildings and civil engineering works.

12.4.7. Article 1 of Commission Decision 94/611/EC\(^{154}\) states:

\[\text{"When the end-use condition of a construction product is such that it contributes to the generation and spread of fire and smoke within the room of origin (or in a given area), the product will be classified on the base [sic] of its reaction-to-fire performances..."}\]

\(^{152}\) BS EN 13501-1 2007 (+A1 2009), Fire classification of construction products and building elements – Part 1: Classification using data from reaction to fire tests, BSI, 2009. (BSI00001738)


12.4.8. Further, it states that:

“Products will be considered in their end-use conditions”, and

“Table 1 applies to the following cases:

- Products for walls and ceilings including their surface coverings,
- Building elements,
- Products incorporated within the building elements,
- Pipes and duct components
- Products for facades/external walls”

12.4.9. Thus, it can be concluded that the intention was that the classification should qualify a product’s contribution to the “generation and spread of fire and smoke” whether that be within the room of origin or in a given area. Further, it was explicit that for the purpose of regulation, this system of classification was intended, at the outset, to be developed for application to individual components of external wall systems.

12.4.10. Section 4.2.3 of the interpretive document\textsuperscript{155} titled “Safety in the Case of Fire” describes the objective behind the aforementioned essential requirement as:

(i) “To retard the speed of fire development and spread of fire and smoke in the works so as to enable occupants near and/or remote from the origin of fire to have sufficient time to escape”

(ii) “To enable the fire brigade / rescue teams to control the fire before it has grown too large”

12.4.11. Objective (i) can therefore be considered directly applicable to the impact of the spread of fire over an external wall system as observed at Grenfell Tower.

12.4.12. The interpretative document states that these objectives may be achieved by the following sub-objectives:

(i) “Prevention of initial ignition”

(ii) “Limitation of the generation and spread of fire and smoke within the room of origin”

(iii) “Limitation of spread of fire and smoke beyond the room of origin”

12.4.13. Again therefore, it would appear that the objectives behind the classification system should be applicable to the scenario of fire spread via an external wall system.

12.4.14. It should be noted however that these three sub-objectives represent very different scenarios and therefore include a wide range of physical processes (e.g. heat loss/gain, piloted/auto-ignition, concurrent/opposed flow flame spread etc.), taking place under an equally wide range of environmental conditions (e.g. ambient conditions, evolving compartment fire, external spill plumes, wall cavities etc.).

12.4.15. Indeed, Section 4.3.1.1. of the interpretive document states that “the relevant performance criteria are considered to be ignitability, rate of heat release, rate of spread of flame, rate of smoke production, toxic gases, flaming droplets/particles and/or a combination of these”.

12.4.16. As illustrated here, this goal of creating a single system of classification to capture such a broad range of physical processes is ultimately embodied/epitomised by the range and complexity of the resulting testing protocols and classification system. The final classification system was published in Commission Decision 2000/147/EG\textsuperscript{156} and the summary table of this system from EN 13501-1 (page 38 of EN 13501-1\textsuperscript{157}) is reproduced in Figure 22.

12.4.17. The sub-objectives expressed in the quote in paragraph 12.4.12 refer to the principal stages of a reference scenario on which this classification system is based. The reference scenario is a compartment fire (a fire developing within a room). The evolution in time of a compartment fire event can be separated into the following stages:

(i) An ignition of a single item resulting in a flame that self-perpetuates and then spreads over that item

(ii) Secondary ignition of an adjacent item(s) due to a flux of heat from the initial burning item, and subsequent spread over this adjacent item(s)

(iii) A fully developed fire that involves the entire compartment, threatens the integrity of the compartmentation, and is capable of breaking out through openings such as windows and therefore spreading to sources of fuel outside the compartment

12.4.18. The transition between stages (ii) and (iii) is characterised by an exponential growth in fire size due to ignition of all fuel sources within the compartment. This transition is commonly referred to as “flashover”.

12.4.19. The reaction-to-fire classifications were intended to enable specifiers to prescribe products / materials that prevent or slow the first two stages such that flashover and the resulting third stage are either prevented or sufficiently delayed, depending on the requirements of a


\textsuperscript{157} BS EN 13501-1 2007 (+A1 2009), Fire classification of construction products and building elements – Part 1: Classification using data from reaction to fire tests, BSI, 2009. (BSI00001738)
particular building’s Fire Safety Strategy. The result should be that occupants are afforded sufficient time to escape the building.

12.4.20. Prior to the creation of this classification system, this information could be derived from the ISO 9705 Room Corner (RC) Test\(^{158}\). The RC test essentially involves lining a “full-scale” compartment with a product, igniting it with a burner in the corner of the compartment, and monitoring the rate of development of the fire. The burner output is 100kW for the first 10 minutes of the test, and then increase to 300kW for a further 10 minutes.

12.4.21. In developing the reaction-to-fire protocols, many of the associated testing protocols were adopted and adapted from existing tests, however one test was developed with the specific objective of replicating the results of the RC test but on a smaller scale. This test became known as the Single Burning Item test\(^{159}\).

12.4.22. A round-robin study of 30 products was conducted to see if the SBI test could repeat the results of the RC test. According to Messerschmidt\(^{160}\), when the 30 products were tested in the RC test, it was found that the outputs could be grouped into four principal classifications:

I. Those that went to flashover within 2 minutes of exposure (at 100kW)

II. Those that went to flashover between 2 and 10 minutes of exposure (at 100kW)

III. Those that went to flashover between 10 and 20 minutes of exposure (now at 300kW)

IV. Those that never went to flashover

12.4.23. A schematic of this result is presented in Figure 23. It is taken from EN 13501\(^{161}\) and augmented with information from Sundstrom\(^{162}\). It shows relationships between Heat Release Rate (a surrogate for fire size,\(^{163}\) described in section 7.3) and time from the initiation of the RC test. The lines represent the boundaries between the aforementioned four categories of behaviour. Passing above the red line, within the duration of the experiment, represents a flashover event.

\(^{158}\) ISO 9705-1: 2016, Reaction to fire tests - Room Corner Test for wall and ceiling lining products – Part 1: Test method for a small room configuration, ISO. (BSI00001906)

\(^{159}\) BS EN 13823:2010+A1:2014, Reaction to fire tests for building products – Building products excluding floorings exposed to the thermal attack by a single burning item, BSI, 2014. (BSI00001908)


<table>
<thead>
<tr>
<th>Class</th>
<th>Test method(s)</th>
<th>Classification criteria</th>
<th>Additional classification</th>
</tr>
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<tbody>
<tr>
<td>A1</td>
<td>EN ISO 1162 ²</td>
<td>ΔT ≤ 30 °C; and Δm ≤ 60 %; and Δt = 0 (i.e. no sustained flaming)</td>
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<td></td>
<td>EN ISO 1716</td>
<td>PCS ≤ 2.0 MJ/kg ³ and PCS ≤ 2.0 MJ/kg ³ and PCS ≤ 1.4 MJ/m² ⁴ and PCS ≤ 2.0 MJ/kg ⁹</td>
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</tr>
<tr>
<td>A2</td>
<td>EN ISO 1162 ⁵</td>
<td>ΔT ≤ 50 °C; and Δm ≤ 60 %; and Δt ≤ 20 s</td>
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<td></td>
<td>or</td>
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<tr>
<td></td>
<td>EN ISO 1716</td>
<td>PCS ≤ 3.0 MJ/kg ⁶ and PCS ≤ 4.0 MJ/m² ⁷ and PCS ≤ 4.0 MJ/m² ⁷ and PCS ≤ 3.0 MJ/kg ⁷</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>EN 13823</td>
<td>FIGRA ≤ 120 W/s and LFS &lt; edge of specimen and THR&lt;sub&gt;200&lt;/sub&gt; ≤ 7.5 MJ</td>
<td>Smoke production ¹ and Flaming droplets/particles ⁹</td>
</tr>
<tr>
<td>B</td>
<td>EN 13823</td>
<td>FIGRA ≤ 120 W/s and LFS &lt; edge of specimen and THR&lt;sub&gt;200&lt;/sub&gt; ≤ 7.5 MJ</td>
<td>Smoke production ¹ and Flaming droplets/particles ⁹</td>
</tr>
<tr>
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<td>F&lt;sub&gt;N&lt;/sub&gt; ≤ 150 mm within 60 s</td>
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<td>Smoke production ¹ and Flaming droplets/particles ⁹</td>
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<td>F</td>
<td></td>
<td></td>
<td>No performance determined</td>
</tr>
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</table>

² For homogeneous products and substantial components of non-homogeneous products.
³ For any external non-substantial component of non-homogeneous products.
⁴ Alternatively, any external non-substantial component having a PCS ≤ 2.0 MJ/m², provided that the product satisfies the following criteria of EN 13823: FIGRA ≤ 20 W/m² and LFS < edge of specimen, and THR<sub>200</sub> ≤ 4.0 MJ, and s₁ and d₀.
⁵ For any internal non-substantial component of non-homogeneous products.
⁶ For the product as a whole.
¹ In the test phase of the development of the test procedure, modifications of the smoke measurement system have been introduced, the effect of which needs further investigation. This may result in a modification of the limit values and parameters for the evaluation of the smoke production.

Figure 22: European reaction to fire classification criteria.
12.4.24. The four categories of behaviour were assigned classes. The no-flashover condition was further subdivided adding a further division that corresponds to very limited contribution to the fire. A final category was added for products that made no contribution to the fire.

12.4.25. With this set of groupings established, smaller scale tests could then be specified (and in the case of the SBI test created) that could be used to approximately categorise building products into these categories, without the need to run the large-scale RC test.

12.4.26. In the case of an A1 rating for example (products that make no contribution to the fire), two small scale tests (a test to establish non-combustibility of a material (ISO 1182\textsuperscript{164}), and a test to determine the heat output due to combustion of a material (BS EN ISO 1716\textsuperscript{165}) were adopted and utilised under the assumption that if the component materials of a product were “almost” inert and produced very little heat when themselves heated, it could be assumed that any product made of these materials would not contribute to the fire in an RC test.

12.4.27. Thus, laboratory-scale test methods were specified to correspond to each category of behaviour observed in the RC test. Most of the laboratory-scale test methods already existed, the only exception being the Single Burning Item (SBI) test that was developed specifically to fill a gap that was identified in this method of classification.

12.4.28. Levels of performance in each of these tests were then derived to distinguish between the performance corresponding to each classification, thus ultimately anticipating the equivalent performance in the RC test.

12.4.29. Classifications other than Class A1 are given as three components e.g. A2-s1, d0. According to van Mierlo\textsuperscript{166}, the main part of the classification (A1 – F) can be thought of as an indication of propensity for heat release, the second a smoke production classification, and the third a classification of falling flaming droplets and particles.

12.4.30. The classification boundaries for the main aspect of the classification for each component testing protocol are summarised in the table in Figure 22.

\textsuperscript{164} BS EN ISO 1182:2002, Reaction to fire tests for building products – Non-combustibility test, BSI, 2002. (BSI00001905)
\textsuperscript{165} BS EN ISO 1716:2018, Reaction to fire tests for products – Determination of the gross heat of combustion (calorific value), BSI, 2018. (BSI00001909)
\textsuperscript{166} Reproduction of Figure 1 from R. van Mierlo, The Single Burning Item (SBI) test method – a decade of development and plans for the near future, HERON, Vol 50, No 4 (2005).
Figure 23: Schematic plot showing the relationship between the heat release rate and time in the room corner test for materials/products with behaviour characteristic of each of the European classifications.
12.4.31. ISO 1182:2002 Reaction to fire test for building products – non-combustibility test\(^{167}\), is the European reaction to fire equivalent of the BS 476-4 test. The introduction states that:

"This fire test has been developed for use by those responsible for selection of construction products which, whilst not completely inert, produce only a very limited amount of heat and flame when exposed to temperatures of approximately 750 °C."

12.4.32. Unlike BS 476-4 therefore, it is explicit about the fact that a classification of non-combustible does not necessarily equate to an inert material.

12.4.33. The scope of the standard defines that this test “specifies a method of test for determining the non-combustibility performance, under specified conditions, of homogeneous building products and substantial components of non-homogeneous building products”.

12.4.34. The introduction states “The limitation of the field of application to testing homogeneous products and substantial components of non-homogeneous products was introduced because of problems in defining specifications for the specimens. The design of the specimen of non-homogeneous products strongly influences the test results, which is the reason why non-homogenous products cannot be tested to this standard.”

12.4.35. A homogeneous product is defined as “a product, consisting of a single material, having uniform density and composition throughout the product”.

12.4.36. Again, unlike the BS 476-4 equivalent, this test is more explicit about the nature of the products it should be applied to.

12.4.37. While the material is not tested in a particular configuration or as a product, it is still considered as a scenario test because of the nature of what is being assessed, i.e. the material is either ‘non-combustible’ or it isn’t. The premise is that under the given heating scenario (which is deemed representative of a fire) the material will or will not contribute to a fire, irrespective of the configuration it is ultimately used in.

12.4.38. The recommended apparatus is essentially the same as that used to the BS 476-4 non-combustibility test described previously in section 12.3 and shown in Figure 17. Thermocouples are provided for measuring the furnace temperature and the furnace wall temperature. The standard allows the use of additional thermocouples if the specimen surface temperature and the specimen centre temperature are required by the end user.

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12.4.39. The test requires testing of five pre-conditioned, cylindrical specimens of 45mm diameter and 50mm height, “taken from a sample which is sufficiently large to be representative of the product”.

12.4.40. The products are placed into a tube furnace that has been pre-stabilised at a temperature of 750°C for 10 minutes. The specimen is left in the furnace for a minimum of 30 minutes and then only removed if the furnace temperature has reached an equilibrium state for a period of 10 minutes. If this state isn’t reached then the specimen will be removed after 60 minutes in the furnace.

12.4.41. The results recorded are:

(i) Percentage loss in mass of the specimens

(ii) The temperature difference between the maximum gas phase temperature and the temperature in the final minute before the test is shut off

(iii) Total duration of any sustained flaming (flaming lasting more than 5s)

12.4.42. Despite the title of the test standard, there are not actually any criteria specified for defining if a material can be classified as non-combustible. The purpose of the test is therefore simply to provide data to feed into the reaction to fire classification system specified in EN 13501-1.

12.4.43. Unlike the BS 476-4 test, this test does allow for the addition of extra thermocouples, one of which can be applied to the surface of the specimen. This measurement, if prescribed by the user, will provide a means for establishing a ballpark ignition temperature of the specimen, should it ignite. If however the specimen does not ignite under the 750°C “thermal loading” condition, this material property will not be established.

BS EN ISO 1716 – DETERMINATION OF THE HEAT OF COMBUSTION

12.4.44. ISO 1716168 “specifies a method for determination of the gross heat of combustion of products at a constant volume in a bomb calorimeter”, where a product is defined by the standard as “material, element or component”. The intended output of this test is therefore an actual material property rather than a classification.

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12.4.45. BS 13501-1 considers that the output from this test should be considered independent of the products end use. The test standard adds that the test determines the absolute value of the heat of combustion and “does not take into account any inherent variability of the product”.

12.4.46. The test set up (a bomb calorimeter) is shown in Figure 24. A sample of material of known mass (shown in red) is burned in an atmosphere of oxygen in a sealed volume (shown in yellow). That volume is enveloped by a sealed vessel containing a known volume of water (shown in blue) at a known initial temperature. This vessel is insulated to minimise heat losses.

12.4.47. Heat produced by the combustion of the test sample transfers to water causing its temperature to rise. The water is stirred to ensure an even temperature which is measured.

12.4.48. The rise in temperature of the water can thus be used to establish the heat energy produced by the complete combustion of the test sample. By knowing the initial mass, the amount of heat that is produced by the combustion of 1kg of material ($\Delta H_c$) is thus established.

12.4.49. Adjustments are made for heat losses and additions not associated with the test sample i.e. the ignition wire, but as stated previously, this value will always be slightly less than theoretical maximum value for $\Delta H_c$.

12.4.50. In order to assess a product, the test should be run for each of the product’s component materials. Material samples are to be dried and ground into a fine powder and mixed with benzoic acid for testing. The intention is to ensure that complete combustion of the sample is achieved. Each sample is placed in a sample holder (No 8 in Figure 24) and ignited by means of a resistance wire (No 10).

(BS EN) ISO 11925-2 – Ignitability of Building Products Subjected to Direct Impingement of Flame

12.4.51. The ISO 11925-2 test\textsuperscript{169} is shown in Figure 25. In this test, a small flame is applied to the flat surface of an essentially flat product. “Product” is defined by the test standard as a material, element or component. If, when in use, edges of the product are to be exposed, the flame will also be applied to the edge of the product.

12.4.52. The duration of exposure of the test sample to a 20mm flame is either 15s or 30s, and is specified by the test sponsor depending on the classification being sought for the product. If applied for 15s, the total test duration is 20s. If applied for 30s, the total test duration is 60s.

12.4.53. The test records whether during the test, ignition is achieved, and if so, whether the flame can spread 150mm from the point of flame application. If this occurs, the time at which this is achieved is also recorded.
Figure 24: Diagram of a bomb calorimeter reproduced from BS EN ISO 1716. Colours added.
12.4.54. This test is therefore designed to simulate the initiation of a compartment fire event, to establish if a very localised, small heat source can ignite a product or material within the compartment, and if ignited, the flame can be sustained and spread away from the initiating flame.

12.4.55. This is therefore a “scenario test”. As a scenario test, the scenario is far removed from the initiating event associated to ignition and spread of flame over an external wall system due to the scale of the source of ignition.

12.4.56. The introductory text in the test standard is informative when considering the test as a means to derive information or data that may be used by a competent individual to make a performance assessment. It classifies the test as:

“a method of test for determining the ignitability of products by direct small flame impingement under zero impressed irradiance using vertically oriented test specimens. Although the method is designed to assess ignitability, this is addressed by measuring the spread of a small flame up the vertical surface of a specimen following application of a small (match-sized) flame to either the surface or edge of a specimen for either 15 s or 30 s.”

12.4.57. Thus while deemed to be a test of “ignitability”, it does not measure the ignition temperature, the ignition delay time or critical heat flux for ignition. While $q''_c = 0$ is established by the test conditions, the heat exposure from the small flame ($q'_f$) is not explicitly defined or measured. This test does not require the measurement of the thermal inertia of the product /material being tested so therefore fails to define any of the parameters associated with ignition as specified in Table 1.

12.4.58. The time of ignition is apparently not recorded as part of the testing protocol, therefore the time-taken for a flame to spread 150mm vertically is not established, and a characteristic velocity for flame spread in this test configuration cannot be derived from the recorded results alone. Length scales of any flames established on the material are not recorded therefore this test does not provide any of the parameters associated with establishing a flame spread velocity.

12.4.59. The test specimen itself is intended to be representative of the product in its final form and the test is principally designed for flat products, though can be applied to some extent on non-flat products.

12.4.60. The required specimen size is 250mm x 90mm (height x width) and up to a depth of 60mm. Where a product has to be cut to make it thin enough in depth to fit in the sample holder, the cut surface is not to be subjected to flame impingement.
**Figure 25:** (a) An image\(^{170}\) of a sample just prior to undergoing an ISO 11925-2 test. (b) Side elevation schematic of the test setup corresponding to Figure 7 in the same document.\(^{171}\)

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12.4.61. This has implications for application to encapsulated products as if the enclosed material is not intended to be exposed when in use, then it will not be subjected to direct flame impingement in this test.

12.4.62. Further, the level of thermal insult is small and localised so burn through of an outer surface intended to act as encapsulation in a fully developed fire scenario is very unlikely.

12.4.63. Finally, due to the nature of the sample size and sample holder, it is unlikely that any thermo-mechanical behaviour of the product will be captured.

12.4.64. If applied to an encapsulated product therefore, the test output can only be considered to be applicable to the outer encapsulation material.

(BS) EN 13823 – BUILDING PRODUCTS EXCLUDING FLOORINGS EXPOSED TO THE THERMAL ATTACK OF A SINGLE BURNING ITEM

12.4.65. The EN 13823\(^{172}\) test is commonly referred to as the Single Burning Item (SBI) test. A schematic of the test is presented in Figure 26. Many reviews of the SBI test have been published since its implementation. One of the most pertinent, which discusses the basis for, and process of, its development, is that of Messerschmidt\(^ {173}\).

12.4.66. The SBI test is a ‘scenario test’ intended to establish the performance of building materials under conditions representative of a fire within a compartment. It is intended to act as a scaled version of the “full-scale” room corner test (ISO 9705\(^ {174}\) ) and was developed such that results in this scaled down version would be largely indicative of the results in the full-scale test.

12.4.67. In her review, Messerschmidt notes that when considering the use of this test within regulatory systems, it is important that the link to the reference scenario is maintained such that the test and its output are used appropriately and thus, the safety objective being sought by their use is adequately met.

\(^{172}\) BS EN 13823:2010+A1:2014, Reaction to fire tests for building products – Building products excluding floorings exposed to the thermal attack by a single burning item, BSI, 2014. (BSI00001908)


\(^{174}\) ISO 9705-1: 2016, Reaction to fire tests - Room Corner Test for wall and ceiling lining products – Part 1: Test method for a small room configuration, ISO. (BSI00001906)
Figure 26: (a) The Single Burning Item testing apparatus. (b) A diagram of the specimen and specimen holder arrangement in plan view from Figure 2 of EN 13501.
12.4.68. The scaled-down SBI test maintains the scenario of a fire in a corner of a compartment but limits the extent of application of the test product to two walls that meet in a corner, labelled 5 in Figure 26 (b). The main wall is 1m long and the wing wall 0.5m long. Both walls are 1.5m high. Specimens can be a maximum of 200mm deep, with thicker products to be cut away from the non-exposed sides.

12.4.69. Tests are to be mounted / supported in accordance with their end-use application and the test standard is explicit in that the test results are only valid for that application. Significant attention is paid in the standard to the mounting of specimens reflecting the expected significance of this variable to the correlation between performance in the test and performance in the application.

12.4.70. A box burner is placed at floor level in the corner between the two “walls” of test specimen (labelled 6). The box burner delivers a heat release rate of 30 kW for ~20 minutes.

12.4.71. This setup is mounted on a trolley which is installed in a test compartment which has openings to allow entrainment of air and a smoke extract system to remove the combustion products.

12.4.72. A ‘rate of heat production’ from the specimen is determined by means of measurements taken within the smoke extract duct. It is expressed in a range of forms that include the average heat release rate, the total heat released, the total heat released in the first 10 minutes, and the fire growth rate index FIGRA (see paragraph 12.4.88).

12.4.73. Propensity for lateral (opposed flow) flame spread is measured by means of a single visual observation of whether sustained flames reach the far end of the main face (1m long) at any time during the test. The rate of progression of the flame is otherwise not recorded as part of the test protocol.

12.4.74. The propensity to produce flaming droplets is to be recorded only within the first 10 minutes of exposure and only droplets that fall out with the area around the burner are to be recorded.

12.4.75. Like the rate of heat production, the propensity for smoke production is also established by means of measurements taken within the smoke extract duct. It is also expressed in a variety of forms, including the average smoke production rate, the total smoke production (during both the whole test and the first 10 minutes), and another index titled SMOGRA which is a measure of the rate of increase of smoke production.

12.4.76. Like the other tests forming part of this reaction-to-fire protocol, this test is a scenario test. It represents stage (ii) of the reference scenario as defined in paragraph 12.4.17 where

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175 The RC test clads the ceiling and 3 walls in the test specimen.
secondary items and linings are “exposed to the thermal attack by a single [i.e. the initial] burning item”.

12.4.77. The rate at which the fire is able to grow due to ignition of the product being tested is considered indicative of the product’s propensity to bring a fire from its insipient stages to the point of flashover.

12.4.78. While the reference scenario for this test is not the scenario of interest when defining the performance of an external façade system, the major role of this test in defining reaction to fire classification means it cannot be discounted without a more detailed analysis.

![Figure 27: Surface heat fluxes measured during an SBI test showing a maximum exposure of 35 kW/m².](image)

12.4.79. The test delivers temperature measurements and heat release rate measurements. The temperature measurements allow the temporal evolution of the flame spread velocity ($V_f$) to be established and the oxygen concentration measurements are conducted in the extraction duct to infer the heat release rate ($\dot{Q}$). Both the heat release rate and the flame spread velocity are parameters of interest as described in Figure 4 of this report, thus the information derived by the test is potentially of value.

12.4.80. Another important characteristic of the test when considering its application to an external wall system is the thermal exposure of the sample. The burner delivers a nominal heat release rate of 30 kW which translates to a maximum heat flux input on the samples of less than 40 kW/m² (Figure 27).

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12.4.81. This is very important, because this value is much smaller than that which an external fire plume will impose on a facade for the scenario of relevance (greater than 100kW/m²). Therefore, a poor performance in the SBI can equate to a poor performance in the event of an external fire, but not the opposite. A good performance in the SBI could still result in an inadequate performance in an external fire.

12.4.82. A final observation regarding the scenario depicted by the SBI is the presence of the compartment. The compartment will have a very different heat feedback profile to an external fire and therefore, as the test progresses, flame spread velocities will accelerate due to increased levels of external heat flux on the sample.

12.4.83. Although this could be seen as a progression towards a more relevant environment, this is not actually the case. At the stage of the test at which conditions in the test chamber have become sufficiently hot / smoke logged etc. such that an increased level of external heat flux is being received by the sample, the flame on the sample will already have spread over its full height.

12.4.84. Thus, any remaining flame spread that may be influenced by this increase in external heat flux will be limited to horizontal (opposed flow) flame spread. As described in earlier sections of this report, horizontal fire spread is a less onerous condition than vertical fire spread and thus a less relevant scenario.

12.4.85. Despite the inconsistencies between scenarios, this test can provide useful information on fire spread velocities that could be used by a competent professional when assessing the performance of a façade system.

12.4.86. The one aspect of the test that cannot be used are the classifications emerging from the SBI test. The classifications are based on specific measurements obtained during testing. These are mostly physical measurements such as temperature rises in the duct which intend to represent the contribution of the sample to the overall heat release rate.

12.4.87. As described above, in some cases these measurements are converted into indices that are intended to represent the contribution of the material. The most relevant index is the FIGRA, which is presented in Equation 7 below.

\[
FIGRA = 1000 \times max \left( \frac{\dot{Q}(t)}{t - 300} \right)
\]

\textbf{Equation 7}
12.4.88. The FIGRA is intended to represent, in a standardized manner, how fast a fire spreads over the sample. It does not have a physical meaning beyond the fact that if the fire reaches a large heat release rate in a short period of time it delivers a large FIGRA.

12.4.89. The SMOGRA parameter represents a similar concept but for smoke, rather than heat, production.

12.4.90. Given the significant differences between the reference scenarios for external façade fires and the SBI, the test specific nature of the parameters measured to define the classifications, the lack of direct correspondence of the parameters measured to $V_s$ and $L_H = 0$, and the abstract nature of some parameters like the FIGRA, it is clear that the classifications resulting from the test have no relevance or meaning when addressing the performance of façade systems.

12.4.91. Like other scenario tests, the representation of the edge conditions is important, especially when assessing the performance of layered or encapsulated products. Bottom and top edges of the samples are clamped in place and therefore shielded from exposure. The junction is similarly held securely in place by a metal section.

12.4.92. Therefore, the only edges of the samples that may be exposed are joints within the pieces of test specimen forming the walls (which must be included if they are present in the end use application), and the far ends of the samples (which can be shielded if not exposed in the end use application).

12.4.93. Thus, while considered a scenario test, the limited representation of the reduced-scale corner arrangement around the burner means that the test cannot meaningfully attempt to reproduce any real installation conditions. This test is not intended to, nor can it, produce any data that reflects the thermo-mechanical behaviour of the systems being tested.

12.4.94. The commentary by Messerschmidt\textsuperscript{177} notes that during the Round Robin, “when comparing the test results from the SBI test with those from the ISO 9705 test based on the FIGRA parameter a good correlation was found between the two test methods for 26 of the 30 products”.

12.4.95. The remaining four products were deemed “exotic products” and their results were not taken account of in defining classification limits for the SBI test. Three of these items were complex in shape (pipes, cables etc.) and one was an encapsulated product (a steel-clad expanded polystyrene sandwich panel).

12.4.96. This latter panel was reported to result in a flashover in the RC test however “more than half the laboratories reported a very low heat release rate in the SBI test”. This result

\textsuperscript{177} B. Messerschmidt, The Capabilities and Limitations of the Single Burning Item (SBI) Test, Fire & Building Safety in the Single European Market, FireSeat, 2008. (INQ00014960)
demonstrates the complexity in trying to assess the behaviour of complex products and systems in small- to medium-scale test scenarios.

12.5. SUMMARY

**NATIONAL CLASS REACTION TO FIRE TESTING AND CLASSIFICATION (BS 476)**

12.5.1. The objective behind the development of the national class of tests is apparently far simpler than that of the European system. It is made clear in all documents relating to national reaction to fire classification that they should not be used for assessing the performance of a material or product under real fire conditions. They are simply intended as a method for comparing how different products might contribute to a (typically compartment fire) fire scenario. The usefulness of their output in this regard is not the subject of this report.

12.5.2. Specification of reaction to fire classifications that should equate to adequate performance of materials / products used in external wall constructions of buildings of specific heights, uses and positions, have, since the advent of wholesale outcomes-based regulation, come from Approved Document B. I am not however aware of any documented explanation about how these classifications (or combination of classifications in the case of designating a material as class 0) were determined as being capable of ensuring adequate performance of an external wall system for any purpose group or Fire Safety Strategy implemented within it.

12.5.3. While the UK system of regulation puts the responsibility on the competent practitioner to demonstrate an appropriate, compliant, outcome, those practitioners have also been provided with guidance that recommends (in language indicative of prescriptive regulation) the use of testing protocols to be used out of context. There is an expectation that the practitioner should rely on this guidance, despite a lack of reference to any appropriate justification / information being provided, whilst the practitioner simultaneously maintains responsibility for the outcome.

12.5.4. A notable example of this is the application of this testing approach to encapsulated or partially encapsulated materials. As described, tests BS 476-6 and -7 are strictly applied to the surfaces of products that are expected to be exposed, and the sample holders ensure that any edges are protected from thermal effects, and thermo-mechanical behaviour nullified.

12.5.5. It is clear therefore that a Class 0 rating achieved using these two tests by an encapsulated material such as an ACM panels will only be meaningful to the outmost material (the aluminium sheet in the case of the ACM). Nevertheless, the product as a whole will be assigned this rating if achieved.
12.5.6. It is therefore left to the competent professional to understand the details of these test methods, understand that they are not a reliable measure of the performance of such a product, and investigate by other means the likely thermo-mechanical behaviour and its implications for the performance of the product in an external wall assembly.

12.5.7. Finally, irrespective of the incompatibility between the original objective of the BS 476 tests and the manner in which they are used by regulation, it is also clear from analysis of the test protocols and outputs that they are incapable of providing any of the parameters associated with the relevant performance metrics of ignition, flame spread, and tendency to extinction.

EUROPEAN REACTION TO FIRE TESTING AND CLASSIFICATION

12.5.8. The initial objective behind Council Directive 89/106/EEC was to create a unified classification that could be applied to all construction products including those utilised in external wall systems (per paragraph 12.4.8). The development of the classification system however was based on a specific reference scenario and the choice of associated scenario orientated testing protocols was intended to capture specific characteristics of that scenario e.g. the primary ignition event, or the growth over the secondary ignited items.

12.5.9. The emphasis of the testing protocols for Classes B – F (and in part A2), as shown in the table in Figure 22, are scenario tests on products. As described in section 10.2, the fundamental premise of a scenario test is that it is representative of that scenario in which that product is to be utilised.

12.5.10. The scenarios of a compartment fire and an external wall fire are sufficiently different that it is extremely difficult to extrapolate performance in one scenario to the other with any degree of certainty.

12.5.11. It is therefore my opinion that any Class B – F classification through the European reaction-to-fire protocols should not be stated in the Approved Documents or Building Regulations as providing a demonstration of adequate (compliant) performance of an external wall system or product used for this purpose.

12.5.12. Similarly, it might appear reasonable to specify a Class A2-s1, d0 product for use in an external wall system of a building with a controlled evacuation egress strategy. In this strategy, a limited amount of external fire spread is deemed to be acceptable and a Class A2 product is deemed to not contribute significantly to growth of a fire.

12.5.13. The scenario tests used to define this performance however utilise a small (20mm) flame or a 30kW box burner, the latter of which has been demonstrated to impose a heat flux on the tested product of less than 40kW/m². This is in contrast with the reference scenario for an external wall that can experience heat fluxes of three times this amount.
12.5.14. It is therefore not possible to directly infer that the performance of an A2 product (“does not contribute significantly to growth of a fire”) will be reproduced in the external wall scenario without a very careful analysis.

12.5.15. This conclusion is reached even before considering that the limited scale of the testing means that global performance (thermal + thermo-mechanical) of the as-built external wall system can never be captured by these tests. This is a critical deficiency given that it is the complete performance of the entire as-built system that is required to deliver performance pursuant to the Requirement.

12.5.16. This is particularly important considering the amendment to Regulations 6 and 7 of the Building Regulations where a prescriptive requirement has been introduced into an outcomes-based system to define the performance requirement for all materials to be included in the external wall system of a building over 18m in height containing at least one dwelling i.e. HRRBs, as A2-s1, d0.

12.5.17. Following the guidance in Approved Document B when developing a HRRB will implicitly formulate a Fire Safety Strategy utilising a stay-put strategy. As defined in Section 6, this necessitates that the performance requirement for the external wall system must be “no fire spread”.

12.5.18. While products composed of Class A2-s1, d0 materials may not ultimately result in extensive or rapid fire spread, it is by no means clear that external wall systems composed of these materials will exhibit “no fire spread” and therefore result in a safe and compliant system. Even Class A1 does not equate to a truly non-combustible material i.e. where $T_{ig} \to \infty$. This is made explicit in the ISO 1182 test standard.

12.5.19. Testing for classes A1 and A2 will require one or both of the non-combustibility and determination of gross heat of combustion tests and therefore will always test all component materials of a composite panel.

12.5.20. From Class B downwards however, it is possible to test an encapsulated product without ever exposing any combustible material that may be encapsulated within it, assuming the encapsulation can withstand the heat exposure provided by the tests.

12.5.21. None of the tests will capture thermo-mechanical behaviour which is a critical performance metric for these complex products.

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\textsuperscript{178} And was of course never intended to having not been the original reference scenario.
13. LARGE SCALE RECONSTRUCTION TESTS FOR FORENSIC FIRE ANALYSIS

13.0.1. Testing can have many objectives, one of which is testing to support forensic analysis. Testing for this purpose commonly forms part of post-fire forensic investigations and has been evident following the Grenfell Tower fire with the aforementioned small-scale tests carried out at the University of Edinburgh\(^\text{179}\) and medium- to large-scale tests carried out by BRE Global\(^\text{180}\).

13.0.2. In accordance with the definition of testing, the main purpose of these tests is to demonstrate or illustrate a specific process or hypothesis. Before a large-scale test is conducted, the process or hypothesis needs to be established and understood and thus it is necessary to explore in sufficient detail the problem at hand and what remains to be demonstrated ("unknowns"). What remains to be demonstrated defines the objectives ("objectives") of the test to be conducted.

13.0.3. Once the objectives have been defined, it is essential to explore the literature to establish if existing knowledge and tools can respond to all unknowns and thus satisfy the objectives. This will correspond to the “analysis” of the scenario that is the subject of the forensic fire investigation. My Phase One Report description of the evolution of the Grenfell Tower fire represents such an analysis. The analysis utilizes all existing literature and tools to deliver, in as precise a manner as possible, explanations to all the relevant questions.

13.0.4. An analysis of this nature, if all the appropriate information and tools are available, can satisfy the objectives. If this is the case, then a “demonstration” can be performed. This demonstration is intended to confirm the analysis and demonstrate that the objectives have been met. The demonstrations may consist of multiple different tests and may target material, component or system behaviour. In all cases they need to be instrumented in a manner that enables collection of the information that is required to establish if the objectives have been met. Large-scale fire tests can be considered as system behaviour demonstration tests.

13.0.5. If the available information is not sufficient to respond to all the objectives, then additional analysis is necessary. This additional analysis can involve “experimentation” as well as “modelling”. Experimentation provides previously unavailable data and also enables the observation of new phenomena that might not have been accounted for previously. Modelling delivers a mathematical representation of the problem that can be used to better understand or quantify the relevant phenomena.

\(^{179}\) Bisby, L. Phase 2 Experiments Work Package 2 – Systems Interactions, Grenfell Tower Inquiry.\{LBWP200000001\}.

\(^{180}\) Crowder D. and Holland, C., Grenfell Tower Fire Investigation – Reconstruction, 24 May 2019 (MET00040237)
13.0.6. A combination of modelling and experimentation at multiple scales (from small or “bench” scale to full-scale replication) can be conducted to respond to the unknowns and thus fulfil the objectives set by the investigation. Experimentation needs to define and obtain the measurements necessary to respond to the unknowns with the necessary precision, and so measurement uncertainty needs to also be managed appropriately.

13.0.7. The more complex the experimentation, the more difficult it will be to obtain the necessary measurements and to manage uncertainty. Thus, it is always prudent to start with smaller and simpler experiments. Complementing experiments with modelling, at all stages, is also an effective approach towards adding value to experimentation. Modelling allows for uncertainty to be managed, but also enables the practitioner to better define the more complex experiments and their instrumentation. A final contribution of modelling is to resolve individual unknowns. In this case, the next level of experimentation enables the verification of the performance of the model, and thus represents some form of demonstration.

13.0.8. Large-scale fire tests are extremely complex, they raise problems of repeatability, and they are very difficult to instrument. Therefore, they cannot be used as a means to understand complex phenomena and should instead be utilised as a demonstration of a process or hypothesis that is already well understood.

13.0.9. In some cases, large-scale fire tests are necessary to answer unknowns that are related to complex large-scale system behaviour. This is the case when smaller experiments or models are not able to provide the necessary answers because multiple component interactions need to be described, thus in such instances, without the large-scale fire tests, the answers required to meet the objectives cannot be obtained. In this case, before undertaking a large-scale fire test, it is essential to first exhaust all possible means to reduce the uncertainty and to answer all unknowns that can be addressed by other means.

13.0.10. A good example of such large-scale experimentation for a forensic fire application is the testing conducted during the investigation of the collapse of the World Trade Centre Towers. In this case, a computer model of the fire was used to establish the heat being delivered by the fire to the structure. To model the fire, it was necessary to input data about the burning of workstations. Workstations are combinations of different materials in a complex geometrical configuration where system behaviour (i.e. the interaction between all the individual instances of burning items that comprised the overall workstation) dominates the outcome.

13.0.11. Computer fire models used at that time were incapable of modelling each individual interaction between the discreet components of the workstations as they “burned” with sufficient precision. Instead, it was postulated that if the evolution of the heat release rate of a workstation as a whole (of similar characteristics to those present in the World Trade Centre) could be used to characterise the evolution of the heat release rate, then this characterization could be used as an input for the model i.e. model the workstation as a
single burning entity rather than a collection of individual burning items e.g. chair, desk, computer etc.

13.0.12. Given the understanding of what was required as an input, a large-scale experiment with appropriate instrumentation was designed and the required output measured. The empirically established evolution of heat release rate enabled the model to quantify the heat being delivered by the fire to the structure.

13.0.13. This form of large-scale fire experimentation should not be confused with a forensic large-scale fire reconstruction. The objective, in this case, was not to recreate the way the fire burned but rather to establish a credible thermal input to a computational model of the structural system of the World Trade Center towers.

13.0.14. The concept of a forensic large-scale fire reconstruction can be illustrated by the King’s Cross Fire Investigation. This investigation serves to illustrate how the process of experimentation and modelling can be used for the purpose of meeting the objectives of a fire investigation. Furthermore, it illustrates how large-scale fire testing can be used as a demonstration that these objectives had been met.

13.0.15. As described by Drysdale, the existing body of knowledge was not capable of explaining the manner by which the fire accelerated:

“It was not immediately clear how the fire had developed at such a speed and in such a way as to trap so many people, when it had been perceived to be non-threatening for some considerable time after 1930 hrs. Several mechanisms were proposed, all of which took into account the fact that the exposed surfaces of the escalator, as well as the advertising hoarding on the side wall of the shaft, were of wood. Consideration was also given to the possible role of the multiple layers of paint on the curved, concrete lined ceiling of the escalator shaft. However, none of the mechanisms was capable of explaining the characteristics of the fire as reported by the eyewitnesses.”

13.0.16. The objectives of this fire investigation were well defined and included two key aspects:

“(i) to suggest the most probable ignition mechanism, and (ii) to explain the subsequent rapid growth of the fire and the so-called flashover into the ticket hall that had caught people unaware.”

13.0.17. Objective (i) was attained by means of a series of small-scale experiments that enabled investigators to collect all the necessary data as well as eliminate potential contributors to the fast growth of the fire.

13.0.18. The available knowledge required to address objective (ii) was found to be lacking. Previously developed flame spread models were not capable of reproducing the rates of spread observed during the fire. Extensive analysis indicated that the slope of the escalator

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181 Drysdale, D.D., Special Issue devoted to the King’s Cross Underground fire, Editorial, Fire Safety Journal 18 (1992) 1-2
had a significant impact on the airflow, which in turn seemed to affect the rate of fire spread. None of the existing modelling tools was capable of characterizing the airflow induced by the fire. The understanding was deemed insufficient to enable the definition of large-scale experimental studies and it was concluded that it was first necessary to conduct extensive computational fluid mechanics modelling together with small-scale experiments.

13.0.19. Computer simulations were performed by a large number of experts. These numerical simulations identified a new phenomenon, “the trench effect.” Further simulations confirmed that analytical formulations for fire spread could be used if the model accounted for the airflow correctly and that scaling laws normally used to reduce the size of fire experiments were applicable. These simulations provided a plausible explanation for the rate of fire spread that incorporated new physical phenomena, enabled definition of the nature of experimental verification and also served to advance the state of the art of computational simulations.

13.0.20. Following the numerical studies, a series of small-scale and intermediate-scale experiments were conducted to verify the “trench effect.” These experiments further demonstrated that the effect could be studied using scaling laws and enabled the definition of a series of large-scale fire demonstrations.

13.0.21. During late January and early February 1988, six full-scale fire growth tests were undertaken on a six-step length of escalator at the HSE Laboratory in Buxton. The demonstrations served to illustrate the rapid growth of the fire and the so-called flashover into the ticket, thus satisfying objective (ii). The King’s Cross Investigation is thus an example of the very successful use of large-scale fire reconstruction tests in support of fire investigation.

13.1. REQUIRED DEMONSTRATIONS AND Unknowns Identified in the Grenfell Tower Fire Investigation

13.1.1. The analysis presented in my Phase One report\textsuperscript{182,183} used the available information in existing literature and the evidence collected after the Grenfell Tower fire. The quality, precision and uncertainty of that information only warranted an analysis of a consistent level of crudity. Thus, the conclusions of my Phase One report are all derived from the simple analysis presented in the body of the report and Appendix A. A more detailed analysis was conducted for verification purposes and was presented in Appendix B. The more detailed analysis used the zone model called CFAST and the Computational Fluid Dynamics model called FDS. The results were consistent between all three approaches. I was therefore

\textsuperscript{182} Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, 3. Stage One: Breaching of the Compartment, pp.30-54. (JTOR0000001)

satisfied that the simple analysis was the most appropriate means to derive the necessary conclusions.

13.1.2. Given the simplicity of the analysis, the uncertainties introduced by the model were very significant and therefore the results could only be presented as a range of possible outcomes. This constrained the precision and nature of the conclusions, nevertheless, this was not considered a limitation because the information that emerged from the fire scene was of similar level of uncertainty. The limited detail inherent in the available evidence meant that the more detailed output from the more complex modelling analyses could not be adequately validated through comparison with the aforementioned evidence.

13.1.3. The analysis conducted allowed the use of material properties extracted from the literature for products similar to those used in Grenfell Tower. Testing of the specific materials used in Grenfell Tower was therefore not considered necessary. Significant testing was conducted by BRE Global and the results of these tests, when applicable, confirmed the assumptions of my Phase One report. Additional material characteristics were extracted from Professor Bisby’s Phase One Report as referenced in the description of the analysis.

13.1.4. There are several components of my Phase One report that can be verified using test results. Firstly, in my Phase One report I established the fire size that was necessary to damage the uPVC and, once the uPVC had fallen, to ignite the insulation and aluminium composite panel.

13.1.5. In my Phase One report I stated that: “a fire originating from appliances will ignite and then spread through the different combustible materials within the appliance, thus the fire will grow in time. Appliances with significant mass of combustible materials (e.g. refrigerators) can release heat beyond 1000 kW, while those with less mass of combustible materials (e.g. electrical stoves) might never reach 300 kW.”

13.1.6. Tests conducted by BRE Global indicated that the free burning of a refrigerator similar to that in Flat 16 at Grenfell Tower released up to 1.94 MW which was consistent with the statement above. This experiment serves to establish that, given the location of the refrigerator in the kitchen of Flat 16, and my observations that indicated that: “Flames have higher temperatures than the smoke accumulating below the ceiling of a room. Therefore, an unobstructed fire of 300 kW placed at a maximum distance of 3.1 m from the window would have been sufficient to ignite any of the combustible components of the façade system” and that: “If the fire was obstructed (i.e. there was an obstacle between the fire and the window) then a 300 kW fire would have had to be placed less than 1 m from the

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184 BRE Global Test Reports, (MET00040020) to (MET00040045), 2019.
186 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 3. (JTOR00000001)
187 Crowder D. and Holland, C., Grenfell Tower Fire Investigation – Reconstruction, 24 May 2019, Fig F15, page 222 (MET00040237/223)
188 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 3. (JTOR00000001)
combustible materials of the window if those materials were to ignite”, 189 the refrigerator had the capacity to be the origin of the fire. This is also consistent with all statements regarding cause and origin presented in the Grenfell Public Inquiry Phase One report. 190

13.1.7. In my Phase One report I also indicated that: “A fire placed further away, capable of igniting combustible materials in the window, would have most likely brought the room to flashover” 191 unless ventilation was restricted. Given that the evidence showed that the fire in the kitchen of Flat 16 never reached flashover, the test results demonstrate that ventilation had to be restricted and therefore confirms that the door to the kitchen had to be closed as described in the Phase One Report. 192

13.1.8. The above described “experimentation” and “modelling” support the important conclusion that a fire originating from the refrigerator would have been capable of damaging the uPVC and therefore of igniting the combustible components of the cladding. This, therefore, supports the Chairman’s statement that “A kitchen fire of that relatively modest size was perfectly foreseeable,” 193 which in turn enables me to conclude that: “the cause and origin of this fire is of minor importance to the outcome. To complete an investigation, it is important to understand how and where the fire started. Nevertheless, the precise cause and origin of this fire is, on one respect, irrelevant to the event which subsequently occurred. From a design perspective, a fire of 300 kW occurring in a residential kitchen, and in the proximity of the window, should be considered to have a probability of one. In other words, a fire of this nature will happen in a residential unit and therefore the building is required to respond appropriately.” 194

13.1.9. The output from the modelling and experimentation allowed me to establish and confirm that the conditions present in the kitchen of Flat 16 were sufficient to cause deterioration of the uPVC and ignite the combustible materials within the cladding system. Nevertheless, the behaviour of the systems was not verified, thus the following objectives remain unaddressed:

- “The geometry of the uPVC elements and approach used for their fixation would have resulted in the eventual fall-off of these elements. The failure of the uPVC leaves all other combustible components of the façade system exposed.” 195

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189 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 3. {JOR00000001}
190 Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019. {INQ00014814} {INQ00014815} {INQ00014816} {INQ00014817} {INQ00014818}
191 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 3. {JOR00000001}
192 Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019, p.12. {INQ00014814}
193 Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019, p.12. {INQ00014814}
194 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 3. {JOR00000001}
195 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 3. {JOR00000001}
“Once any of the combustible components of the façade ignited, their proximity and complex arrangement would have inevitably resulted in the ignition of other components leading to external flame spread.”

“The development of a testing protocol that will allow for comprehensively determining the influence that each material, components and geometry had on the spread of fire on the Grenfell Tower will also be a fundamental aspect of Phase Two. It is my firm view that only on the basis of this new approach can recommendations for future designs be made.”

13.1.10. An attempt to reconstruct the initial fire that occurred in Flat 16 was conducted by BRE Global. Flat 16 including its furnishings and external cladding were reconstructed as faithfully as possible. The following analysis of this reconstruction does not intend to assess the reconstruction comprehensively, but rather to establish if the objectives and results of this reconstruction affect any of the conclusions of my Phase One report.

13.1.11. The BRE Global report states that:

“This report details the findings of the reconstruction itself. Analysis of the actual fire in Grenfell Tower has been limited to that which is necessary to plan and provide initial validation of the reconstruction. The interim conclusions of this report are therefore limited to those conclusions which can be drawn from the reconstruction itself.”

13.1.12. Given the complexity of fire growth in the context of Grenfell Tower, it is not possible to establish that the characteristics of the reconstruction correspond to those of the actual fire without the support of a comprehensive analysis such as that presented in my Phase One report. Thus, given its purpose, it is unlikely that this reconstruction can complement or challenge any of the findings in my Phase One report.

13.1.13. Furthermore, the analysis presented in my Phase One report enabled me to establish a set of clear objectives. On the contrary, the BRE Global report lists a series of generic objectives that cannot be addressed by a fire reconstruction in isolation. A broad set of objectives is presented in the Executive Summary and expanded in the body of the report.

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196 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 3. (JTOR00000001)
197 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 64. (JTOR00000001)
199 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. (JTOR00000001)
The additional detail does not alter the main objectives, thus only the objectives listed in the Executive Summary will be discussed here.

13.1.14. The first objective indicated in the report is:

“To recreate as closely as is reasonably practicable and scientifically possible the conditions of the fire so that development and spread of the fire within Flat 16 and to the cladding could be observed.”206

13.1.15. Given that a large-scale fire reconstruction is a single event, the characteristics of the event and its evolution in time should have already been defined by means of experimentation and modelling. This would have enabled a clear set of testing parameters as well as the required measurements to be established. Otherwise, all that is being tested is one potential scenario of very many that are possible and therefore there is no guarantee that the data collected reflects the flat fire scenario of interest.

13.1.16. A test can reproduce the flat and its contents in as faithful a manner as possible, nevertheless, a test cannot faithfully reproduce the evolution of the fire, where very minor changes in variables such as ventilation or fuel content and location can result in very different outcomes.

13.1.17. The next objective is stated as:

“To test hypotheses that had been developed as a result of work carried out in other work packages, in particular the route(s) by which the cladding became involved in the fire.”207

13.1.18. Given that a large-scale fire test only corresponds to a single scenario, it will only exhibit one possible route by which the cladding could have become involved in the fire. Therefore, the large-scale fire reconstruction is meant to test a single hypothesis that should be clearly stated as the objective of the test.

13.1.19. The next objective is stated as:

“To examine mechanisms of initial fire development of the cladding when exposed to (a best approximation of) the actual compartment fire that occurred (as opposed to the idealised wood crib source used in “standard” cladding tests and the cladding experiments).”208

13.1.20. A large-scale reconstruction cannot have as objective to “examine mechanisms.” The examination of possible mechanisms needs to be done under conditions where the parameters affecting the cladding and leading to the uncontrolled spread of the fire are studied in a systematic manner. The process required to adequately address this objective

206 Crowder D. and Holland, C., Grenfell Tower Fire Investigation – Reconstruction, 24 May 2019 p.3 (MET00040237/4)
is exemplified by the experimental programme conducted at the University of Edinburgh and described previously in this report.

13.1.21. The final objective is stated as:

“To examine the mechanisms by which external (cladding) fire spread back through the construction of windows into flats.”

13.1.22. Consistent with the statements above, a single large-scale fire reconstruction cannot be used for the objective of examining the mechanisms by which external (cladding) fire spread back through the construction of windows into flats.

13.1.23. Firstly, given that windows are not intended to represent barriers to fire spread, this objective does not address a meaningful issue. Furthermore, during the Grenfell Tower fire it was observed that there were many mechanisms by which fire re-entered the building. These are all described in my Phase One report. Since a reconstruction represents a single scenario, only one of the multiple pathways of re-entry will be observed. This pathway will correspond to the particular conditions of the reconstruction and does not invalidate any of the others.

13.1.24. These aforementioned objectives of the reconstruction conducted by BRE Global are ill-defined and therefore are inconsistent with the three remaining objectives emerging from my Phase One report (see paragraph 13.1.9). The lack of appropriate objectives and the absence of a complementary analysis diminishes the value of the reconstruction and its potential to deliver useful information.

13.1.25. In the BRE Report, the definition of the scenario took careful consideration of all evidence available regarding the geometry of Flat 16, the furnishings and the potential ventilation (doors and windows). Detailed descriptions are provided in the report. The report also considers firefighting intervention as much as it is possible, recognizing that certain conditions could not be reproduced.

13.1.26. As indicated in Table 5 of the BRE report, the heat detector activated at 07:04 minutes, flames were observed exiting the window at 07:48 minutes and a firefighter opened the kitchen door at 08:58 minutes. Therefore, in the reconstruction, from the activation of the heat detector to external flaming there is 00:44 minutes and to the opening of the kitchen door there is a period of 01:54 minutes. The door was closed 00:04 seconds later and remained closed until 21:25 minutes (14:21 minutes after heat detector activation) and the fire was suppressed at 22:15 minutes (15:11 minutes after heat detector activation).

210 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 77-85. (JTOR00000001)
211 Crowder D. and Holland, C., Grenfell Tower Fire Investigation – Reconstruction, 24 May 2019, Section 5, pp.94-96. (MET00040237)
Significant flames were observed coming out of the kitchen window at 13:15 (06:11 minutes after heat detector activation) and subsequently there was evidence of significant visible external flaming on the cladding.

13.1.27. In contrast, the set protocol based on the timeline of the Grenfell Tower fire that is presented in Table 4\textsuperscript{213} sets the activation of the heat detector at 00:00 minutes. The reaction time of Mr. Kebede is set at 30 seconds, resulting in the opening of the kitchen door at 00:30 minutes and then closing of this door after 2 seconds (00:32 min). The door then remained closed until 20:38.

13.1.28. Therefore, in Grenfell Tower the fire burned for a period of 20:06 minutes with the kitchen door closed. This is in stark contrast with the actual 15:11 minutes of the full duration of the fire in the reconstruction. Furthermore, during the Grenfell Tower fire, flames were not observed outside the building until after the entry of the firefighters (i.e. after 20:38) into the kitchen, in contrast with the reconstruction fire where they were observed at 00:44 minutes. It is therefore clear that the reconstruction fire was completely different to the fire that actually occurred at Grenfell Tower.

13.1.29. A very important point that can be extracted from the analysis in my Phase One report is the role of the kitchen door. When the fire fighters opened the kitchen door at 08:58, the fire was already significant because 01:10 minutes earlier it had already appeared outside the window. Therefore, despite the brevity of the period where the door remained open (four seconds) it was potentially sufficient to vent all smoke allowing the continuing growth of the fire.

13.1.30. BRE report Figures 100,\textsuperscript{214} 101\textsuperscript{215} and 102\textsuperscript{216} show that in that test, the temperature increased very rapidly and the values were consistently above those typical of compartments that have undergone flashover.\textsuperscript{217} Thus, it is clear that the reconstruction attained flashover whereas it has been established that the Grenfell Tower fire did not.

13.1.31. While it is clear that the reconstruction and the Grenfell Tower fire are two very different events, it is not possible to establish why the behaviours were so different. None of the instrumentation utilized allows for the reasons behind the differences to be established. The conclusions extracted by the authors of the report might be correct for the reconstruction nevertheless they cannot be extrapolated to the Grenfell Tower fire.

13.1.32. An appropriate alternative approach will be to use the data obtained in the ‘reconstruction’ to verify a model output. This will enable them to use the model with confidence to attempt to reproduce the real scenario. Unfortunately, in the absence of a comprehensive set of

\textsuperscript{213} Crowder D. and Holland, C., Grenfell Tower Fire Investigation – Reconstruction, 24 May 2019, p.92 (MET00040237/93)
\textsuperscript{214} Crowder D. and Holland, C., Grenfell Tower Fire Investigation – Reconstruction, 24 May 2019, p.111 (MET00040237/112)
\textsuperscript{215} Crowder D. and Holland, C., Grenfell Tower Fire Investigation – Reconstruction, 24 May 2019, p.112 (MET00040237/113)
\textsuperscript{216} Crowder D. and Holland, C., Grenfell Tower Fire Investigation – Reconstruction, 24 May 2019 p.113 (MET00040237/114)
\textsuperscript{217} Typical flashover temperatures for a compartment are above 600°C. These can be slightly above or below and there is also spatial variation, nevertheless this value is generally used as a reference to establish that flashover has occurred.
modelling results obtained for the ‘reconstruction scenario,’ the value of the data is not significant.

13.1.33. In regard to the analysis presented in my Phase One report, the reconstruction provides no evidence / data that can be used to address any of the potential objectives identified as requiring a reconstruction (see paragraph 13.1.9). Given that the timelines of the fire are so different and that the reconstruction attained flashover, it is not possible to use this information to establish the validity of the results obtained from my Phase 1 modelling study discussed previously.

13.1.34. The temperatures in the reconstruction experienced a sudden transition from values close to ambient to values that exceeded the ignition temperature of the uPVC. This will have resulted in charring of the uPVC and therefore the uPVC would have not exhibited the deformations observed in the Grenfell Tower fire. In contrast, the modelling presented in my Phase One report clearly supports the following statement:

“*The temperature of the smoke accumulated below the ceiling of the kitchen is sufficient to heat the uPVC components of the window to temperatures that result in complete loss of mechanical properties (90°C). These temperatures would have been attained within an approximate period between 5-12 min which is consistent with the time available between the discovery of the fire (initial call to the fire brigade) and the first observation of smoke and burning debris external to the building.*”

13.1.35. Therefore, the reconstruction delivers a very different scenario and thus provides no evidence to validate or contradict statements like the following:

“The geometry of the uPVC elements and approach used for their fixation would have resulted in the eventual fall-off of these elements. The failure of the uPVC leaves all other combustible components of the façade system exposed.”

13.1.36. It is clear that, given the recorded gas temperatures were much higher than the ignition temperatures of all combustible materials present at Grenfell Tower, the reconstruction would support the following conclusion from my Phase 1 report:

“*Once any of the combustible components of the façade ignited, their proximity and complex arrangement would have inevitably resulted in the ignition of other components leading to external flame spread.*”

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219 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 3. (JTOR00000001)  
220 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 36. (JTOR00000001)  
221 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 3. (JTOR00000001)
13.1.37. Whether the fire was the same or different from that of Grenfell Tower, the reconstruction does provide yet another kitchen fire scenario that is consistent with the Chairman’s statement that

“A kitchen fire of that relatively modest size was perfectly foreseeable”\textsuperscript{222}

13.1.38. This in turn supports my conclusion that:

“the cause and origin of this fire is of minor importance to the outcome. To complete an investigation, it is important to understand how and where the fire started. Nevertheless, the precise cause and origin of this fire is, on one respect, irrelevant to the event which subsequently occurred. From a design perspective, a fire of 300 kW occurring in a residential kitchen, and in the proximity of the window, should be considered to have a probability of one. In other words, a fire of this nature will happen in a residential unit and therefore the building is required to respond appropriately.”\textsuperscript{223}

13.1.39. In contrast, the large-scale fire reconstruction\textsuperscript{224} only shows that, for that specific scenario, a fire ignites the façade system and spreads externally rapidly involving the unit above. The rate of spread and the different processes that influence it are very different to the initial stages of the Grenfell Tower fire and therefore do not enable us to establish the influence that each material, components and geometry had on the spread of fire on the Grenfell Tower.

13.1.40. Furthermore, the measurements and observations presented do not provide this information either. As a result, there is a remaining need for:

“The development of a testing protocol that will allow for comprehensively determining the influence that each material, component and geometry had on the spread of fire on the Grenfell Tower will also be a fundamental aspect of Phase Two. It is my firm view that only on the basis of this new approach can recommendations for future designs be made.”\textsuperscript{225}

13.1.41. Responding to this objective is therefore an important aspect of this report.

13.1.42. In summary, the fire reconstruction conducted by BRE Global\textsuperscript{226} delivers a fire scenario that is inconsistent with the available evidence. Despite the scenario being different, the

\textsuperscript{222} Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019, p.12. (INQ00014814)

\textsuperscript{223} Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 3. (JTOR00000001)

\textsuperscript{224} Crowder D. and Holland, C., Grenfell Tower Fire Investigation – Reconstruction, 24 May 2019 (MET00040237).

\textsuperscript{225} Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018, p. 64. (JTOR00000001)

\textsuperscript{226} Crowder D. and Holland, C., Grenfell Tower Fire Investigation – Reconstruction, 24 May 2019 (MET00040237).
observations made and measurements collected do not contradict any of the statements presented in my Phase One report\textsuperscript{227} or the Chairman’s Phase One report.\textsuperscript{228}

13.1.43. Unfortunately, the lack of background analysis and clear objectives led to an attempt to reconstruct the Grenfell Tower fire that does not deliver any information beyond what was presented in my Phase One analysis. Any further attempt to take the measurements and observations of the BRE Global reconstruction to provide explanations associated with the Grenfell Tower fire will likely result in misleading conclusions unless they are accompanied by a detailed and well supported analysis.

13.2. LARGE-SCALE FIRE RECONSTRUCTIONS AS A FLAWED APPROACH TO DEVELOP A FIRE INVESTIGATION – MISSED OPPORTUNITIES

13.2.1. A review of Professor Bisby’s report shows that the approach towards the use of large-scale testing followed by BRE Global in the case of the Grenfell Tower reconstruction is consistent with studies following numerous past fires of the last three decades. Many of the issues described above have led to limited outcomes from these fire investigations and as a result, opportunities to extract adequate lessons have been lost.

13.2.2. The first example pertains to the vague conclusions of the large-scale tests conducted to define the role of cavity barriers after Knowsley Heights, where variables such as the combustible nature of the rainscreen is not directly addressed despite indicating that “the effectiveness of the barriers [was] dependent on the nature of the cladding sheeting materials.”\textsuperscript{229}

13.2.3. It also seems to be the case that there is a consistent pattern of insufficient background experimentation, modelling or analysis conducted prior to establishing conclusions or conducting demonstrations. As Professor Bisby indicates in the case of the Garnock Court fire: “\textit{No effort was noted as having been expended to understand the heat of combustion, surface spread of flame, fire propagation potential, or other relevant reaction-to-fire properties of the GRP cladding used at Garnock Court.}”\textsuperscript{230} The conclusions regarding the need for a Class 0 classification are therefore limited by the lack of this background knowledge.

13.2.4. The investigations into the fire that occurred at The Edge Building in Salford in 2005 resulted in the presentation of conclusions relative to the role of wind in the spread of a fire. These conclusions are not backed by any modelling exercise. The use of computational models, as

\textsuperscript{227} Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. (JTOR00000001)
\textsuperscript{228} Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019. (INQ00014818)
\textsuperscript{229} (RCO00000001/43)
\textsuperscript{230} Bisby, Grenfell Tower Enquiry Phase 2 – Regulatory Testing & the Path to Grenfell, Section 13.5 (LBYP20000001)
described in the King’s Cross investigation, is very amenable to studying the role of the air flow. Professor Bisby thus concludes that “it is not clear what evidence is being used to support the fire spread hypothesis.”

13.2.5. A comprehensive review of the Lakanal House investigation shows a very similar approach to the one followed by BRE Global for the Grenfell Tower fire and therefore the same type of inconsistencies as those described above can be extracted from the analysis of the investigation report.

13.2.6. As a parallel to the Grenfell Tower reconstruction, it is important to discuss the six objectives set by the Lakanal House modelling and reconstruction fire report. The first objective was:

“1. Development of a possible reconstruction sequence of fire spread and development responsible for the observations that were witnessed and documented in the MPS and LFB timeline for the incident. This was to be achieved using a combination of data obtained from a reconstruction fire and computer modelling in conjunction with information received from MPS and LFB.”

13.2.7. The reconstruction fire for this case, as it did for the Grenfell Tower fire reconstruction, reproduced the characteristics of the flat where the fire had been presumed to start in a very faithful manner. Once again however, the sequence of the fire had not been explored in detail before the definition of the reconstruction fire. Modelling conducted before and after the reconstruction fire incorporated a diverse number of critical assumptions that could have significantly altered the outcome. At no point was the model used to define the reconstruction, nor did the characteristics of the reconstruction affect the assumptions made in generating the model. As a result, the progression of the fire during the reconstruction represents just one possible scenario.

13.2.8. A fire within the context of a flat such as the fires that occurred in Lakanal House and Grenfell Tower are much more complex than a fire such as the one that occurred in the King’s Cross station. Therefore, the preliminary analysis of the event has to be of a depth at least consistent with the efforts that were made to understand the King’s Cross fire. It is likely that, before a reconstruction can be attempted, the analysis required will be of a complexity and depth more extensive than that conducted for the King’s Cross fire.

13.2.9. Instead, the approach followed in these fire investigations was to jump directly to a reconstruction as if the reconstruction could provide all the required answers. The result is that (1) the reconstruction provides an event that is more likely to be inconsistent with the event it is meant to reconstruct, (2) that many of the phenomena cannot be explained, and (3) that the data obtained is very hard to use. This was the case for Lakanal House in as much as it was for Grenfell Tower.

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231 BRE Global, Lakanal House Fire Investigation - Computer modelling and reconstruction fire, 17 December 2010 (BRE00005878).
13.2.10. In the case of Lakanal house, given the uncertainties associated with the event, none of the five further objectives could be met by the fire reconstruction. The conclusions attained pertained uniquely to the scenario depicted in the fire reconstruction, with no guarantees that the fires in reconstruction and event were the same. A more extensive use of preliminary modelling could have enabled a better understanding of the possible fires and the expected conditions in a manner that would have been much more comprehensive than a single reconstruction.

13.2.11. Of the five further objectives, four were all associated with the performance of different building components. Given the temperature and conditions of the fire in the reconstruction, (those of a severe, fully-developed fire), the performance of all the components could have been established by smaller scale experimentation addressing each one of the components individually (i.e. ceramic board boxing, doors, panels above the flat front doors and window façade panels). This type of focused experimentation would have provided the understanding of the performance of these systems as well as producing data with much less uncertainty.

13.2.12. The final objective of the Lakanal House reconstruction was to:

“Investigate the size of the fires and amount of smoke that would have been necessary in Lakanal House in order to overwhelm the building bathroom extraction system and allow re-entry of smoke into bathrooms from that system.”

13.2.13. Given that the fire reconstruction would have been a single fire, this objective could not be attained. Furthermore, testing of the fan itself would have established pressure differentials and flow rates that could have clearly characterised the capacity of the fan. This information could have been used to establish the performance of a fan under a variety of fire conditions. This approach would have provided valuable information that a fire reconstruction could never deliver.

13.2.14. This report does not aim to conduct a detailed analysis of any of these fire investigations, but rather this section simply serves to illustrate that the approach followed during the reconstruction of the Grenfell Tower fire, while ineffective, is consistent with the practice of at least the last two decades.
14. CONCLUSIONS

14.0.1. In my opinion the existing testing approaches towards fire performance assessment of façade related systems are very limited and this is the case not only for systems incorporating combustible materials, but also for systems manufactured only from non-combustible materials.

14.0.2. It is the expectation of current Building Regulations that, in the case of façade systems, adequate interpretation of test data by competent professionals can deliver an appropriate assessment of fire performance. This assessment is intended to ensure the effectiveness of the Fire Safety Strategy in delivering an acceptable outcome in the event of a fire, whether it achieves this by means of controlled egress, or implements a ‘stay-put’ strategy.

14.0.3. However, the nature of current tests, current testing practices and the information they can deliver is so limited that proper assessment of performance for systems of the complexity of those currently implemented in buildings is not possible by these means.

14.0.4. Given that the assessment of test data by a competent professional is the means to establish compliance, the nature of current testing practices puts an enormous burden on the competency of all those participating in the development of façade systems and components. This includes component and system manufacturers, testing laboratories, those participating in the design and construction of building envelopes, building inspectors, and fire and rescue services. In simple terms, the available data is so limited and carries such uncertainty that the required extrapolations are enormous.

14.0.5. It is notable that despite the enormous reliance on the competency of the various participating stakeholders, inherent in the current outcomes-based approach to building regulation and associated testing protocols, at no point there been any definition (or apparently even consideration) of what is, or how to define, the necessary level of competency of the aforementioned stakeholders.

14.0.6. Current testing practices are poorly related to the key parameters that have to be quantified. In addition, they provide (in many instances due to the over-simplistic measurements) only a small fraction of the information required.

14.0.7. The systems to be addressed and the relevant scenarios are of such complexity that background information is necessary to enable a proper definition of what the appropriate set of tests are that would enable the phenomenon that need to be quantified to be clearly established, together with information about the tolerable error and uncertainty and the relationships governing the phenomena.

14.0.8. It is only then that tests and appropriate measurements can be defined to quantify the parameters that influence the phenomena in an unequivocal manner and taking account of the desired errors and uncertainties.
14.0.9. The tests conducted by Prof. Bisby provide the necessary background information in the case of the façade system used for Grenfell Tower. These tests enable the sequence of failures required to reach a condition such that $L_h > 0$ is established to be identified.

14.0.10. Furthermore, the tests identify the minimum size and duration of a fire that could still have been capable of initiating the observed sequence of failures. They show that this fire was an almost certain outcome of any fire scenario in a residential building. Furthermore, it is a fire of smaller size and duration to the one observed in the initial stages of the Grenfell Tower fire.

14.0.11. Finally, these tests enable the identification of the specific and unique roles that both the ACP and insulation had on the development of this sequence of failures. It is the melting and dripping of the polyethylene in the aluminium composite panel that sustains the initial burning, while it is the heat feedback to the ACP from the surface of the insulation in the cavity that enables the ultimate failure of the encapsulation and the attainment of the failure condition ($L_h > 0$).

14.0.12. Notably, it is not necessary for the insulation to be burning, because it is the heat feedback from the hot surface that results in the failure of encapsulation.

14.0.13. Once the failure condition is attained, the fire will continue to spread in an uncontrolled manner and therefore a ‘stay-put’ strategy is no longer viable.

14.0.14. Testimony provided during Phase Two by all those participating in the design, build, maintenance and operation of Grenfell Tower did not consider any of the issues raised in this report or the characteristics and failure modes of the systems used in Grenfell Tower. It is clear that all these considerations are essential to the design of any system that includes the additional risk of combustible materials. As a consequence, I have not been presented with any evidence that indicates that those participating in the design, build, maintenance and operation of Grenfell Tower could be involved in a recladding project that used anything but non-combustible materials.

14.0.15. Further, even if all materials had been non-combustible, a fire could have induced other forms of failure such as deformations, detachment of components, etc. that could have enabled the propagation of a fire into adjacent units. No analysis or consideration of any of these issues has been presented in evidence. Therefore, there would have been no guarantee that a ‘stay-put’ egress strategy would have been adequately supported by any building envelope that was designed, built and inspected by all those involved in these tasks for Grenfell Tower.

14.0.16. Whether the available information on system/product performance is adequate or limited, Building Regulations still require competent professionals to use the available test data to deliver a performance assessment that demonstrates the appropriateness of the Fire Safety Strategy. If the data is insufficient, or inadequate, reaching this conclusion still remains the responsibility of these competent professionals.
14.0.17. None of those participating in the design, assessment and build of the façade system understood the problem with sufficient rigour and therefore exhibited sufficient competency to be able to fulfil their functions in a manner that met the requirements of the Building Regulations. Furthermore, the competency exhibited by all those participating in the design, build, maintenance and operation of Grenfell tower was not consistent with what is the ‘presumed competency’ of anyone participating in the design, build, maintenance and operation of buildings using the applicable Building Regulations.

14.0.18. The complexity of the problem of fire spread generated by the use of systems with combustible materials, in complex arrangements such as the systems used in Grenfell Tower, is such that Building Regulations, approved guidance and standard testing do not, by themselves, deliver appropriate measures of performance.

14.0.19. Following the guidance provided by Approved Document B delivers only a fraction of the information and knowledge required to design a building to meet the functional requirements. None of the existing standard tests provides an assessment of performance and thus can only serve as data to be interpreted by highly competent professionals.

14.0.20. Accordingly, there is a very high dependency on the due diligence and competency of all professionals involved. None of those involved in the design, build, maintenance and operation of Grenfell Tower delivered that level of due diligence, nor exhibited the required level of competency.

14.0.21. The same conclusion applies to the London Fire Brigade who had no capacity to identify, via inspection, the key components of the building that enabled and promoted vertical fire spread. Thus, any inspection conducted by the London Fire Brigade would have failed to obtain the necessary information, because those conducting the inspection would not have understood the complexity of the problem and therefore would not have collected, through inspections, the necessary information that would have enabled them to conduct an adequate Risk Assessment.

14.0.22. With regard to those manufacturing and selling the products and systems, it is clear that they provided inappropriate assessments of the performance of their products and/or systems.

14.0.23. There is sufficient data in the open technical literature to establish that there are significant risks associated with the use of combustible materials in buildings. There is also evidence that thermo-mechanical behaviour can lead to the failure of encapsulation and to the breach of containment. Furthermore, there is technical and anecdotal evidence of the enhancement of those risks when these materials and/or products are used in complex assemblies and this was exhibited by numerous high-profile fires that have occurred both within and out with the UK prior to the fire at Grenfell Tower. Finally, there is sufficient evidence that any inappropriate combination of materials will dramatically challenge functionality requirement B4, with the resulting dismantling of the Fire Safety Strategy implicitly assumed in the applicable Building Regulations.
14.0.24. Manufacturers exhibited clear awareness of the risks but did not exhibit the will and necessary competency or due diligence necessary to appropriately and explicitly define the performance of their products and/or systems.

14.0.25. Those conducting testing were aware of the complexities and uncertainties intrinsic to the performance assessment of these products and/or systems. Nevertheless, none of them exhibited the competency to reach the conclusion that the current standardized testing procedures are unable to provide adequate performance assessment. Instead, the prevailing approach was to alter testing procedures to fit the apparent needs of particular products and/or systems.

14.0.26. While everyone seemed aware of the risks involved in these alterations, none of those involved in the testing and certification, whether manufacturers or regulatory/testing bodies, had the competency to understand the implications of these actions.

14.0.27. The development of BS 9414 exemplifies the chronic problem of attempting to substitute the competent professional by means of over simplistic, and many times inappropriate, prescriptive rules. In this particular case, and despite its limitations, using in an unchallenged manner the results of BS 8414. In the assessment of fire performance of complex systems, the role of the competent professional cannot be circumvented. Thus, BS 9414 falls in the trap of attempting to provide standardized outcomes while inevitably requiring an assessment by a competent professional at every step of the decision-making process.

14.0.28. The principles behind BS 9414 are fundamentally flawed and this document will continue to encourage an inappropriate process of fire performance assessment. Thus, it is my strong belief that this standard should not be used.

14.0.29. It has become a chronic problem that fire investigations turn immediately and almost exclusively to large-scale fire reconstructions as a basis for a fire investigation.

14.0.30. A large-scale fire reconstruction is a complex test, where measurements are very difficult and uncertainties are very high, therefore it should only be used to demonstrate phenomena that has already been characterized.

14.0.31. The process of characterization should entail a detailed and extensive combination of evidence and data collection, experimentation, small- and intermediate-scale testing and modelling. It is this characterization that should be used to develop the investigation.

14.0.32. Once the fire scenario that best fits the evidence has been identified and its evolution characterized in a quantitative manner, then a large-scale fire reconstruction can be conducted as a demonstration of that fire scenario.

14.0.33. Many of the major fire investigations conducted in the last two decades have neglected the need to develop comprehensive background information before a hypothesis can be tested by means of a large-scale reconstruction. Instead, they have jumped too fast to the large-
scale reconstruction as a means to produce a visible outcome credible to those lacking deep understanding of fire phenomena.

14.0.34. This neglect of the background information has resulted in incomplete and misleading information and lessons learned that nevertheless have deeply influenced Building Regulations. Thus, the changes in Building Regulations resulting from these forensic investigations have often been unnecessary or inappropriate. I consider these as missed opportunities to learn and extract societal value from the tragic circumstances of many of these fires.

14.0.35. The Grenfell Tower reconstruction conducted by BRE follows the same approach. The reconstruction was done without the necessary background information and characterization. As a result, the fire scenario resulting from the reconstruction is significantly different to that substantiated by the available evidence from the Grenfell Tower fire. These differences cannot be properly explained because of the complexity of the test scenario as well as the absence of key instrumentation.

14.0.36. While little information can be extracted from the Grenfell Tower reconstruction, this test does confirm many of the conclusions of the Chairman’s Phase One report. Furthermore, none of the information extracted contradicts any of these conclusions.
15. DEFINING AN ADEQUATE TEST REGIME

15.0.1. The conclusions presented above show that the current fire related performance assessment of materials and systems associated with the design and build of the building envelope is flawed.

15.0.2. The conclusions also indicate that the manner in which Building Regulations presume to deliver fire safety is also flawed. Building Regulations establish that “interpretation of test data by a competent professional” is the mechanism by which assurance is provided that the Fire Safety Strategy will be enabled and supported by the building envelope.

15.0.3. Nevertheless, the conclusions also indicate that:

- The understanding of the fundamental physical phenomena governing the attainment of the failure condition for modern building envelopes is insufficient and, by consequence, it is not clear what the required competency is for a professional to be able to establish the fire performance of a building envelope.

- Building envelopes are therefore currently designed in a manner that does not allow fitness for purpose to be established with any certainty.

- Existing testing practices have little capacity to deliver the necessary data for an adequate performance assessment. As a consequence, existing testing practices place an unrealistic expectation on professionals because they do not deliver appropriate and sufficient data for the required assessment.

- The expectation of competency as a guarantee to fire safety is wholly unjustified.

15.0.4. Thus, “interpretation of test data by a competent professional” is currently not possible.

15.0.5. While it might be believed that the answer to these problems is to ban combustible materials from the building envelope, the statements above also apply to failure induced purely by thermo-mechanical behaviour, regardless of the combustibility of the constituent materials. Furthermore, none of our current testing practices even address thermo-mechanical behaviour. Thus, even for façade systems made uniquely out of non-combustible materials, there is currently no means to conduct an adequate fire-performance assessment by way of testing.

15.0.6. Consequently, a ban will not solve the problem. Most importantly it will not set us on a path towards solving the problem, but instead deflects the problem in a direction where,

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232 Thermo-mechanical behaviour is the manner in which materials or systems deform when heated. Most materials used in construction will expand significantly when heated. When the expansion is restrained by any form of fixation, deformations can be very significant allowing elements to fall, gaps to be formed and elements to break. A typical form of thermo-mechanical is window breakage during heating.
eventually, technologies and solutions will be developed that once again, through optimization and cost-reduction, bring us back to the same place.

15.0.7. The true solution will require a complete reassessment of the manner in which fire safety is perceived by the construction industry. It is clear that these types of changes will take significant time, therefore it is essential that short term improvements are implemented before longer term ones can take effect.

THE SHORT TERM

15.0.8. As described throughout this report, the condition that dismantles the Fire Safety Strategy in the case of a ‘stay-put’ approach to egress is \( L_h > 0 \). This condition corresponds to a physical bifurcation that leads to extinction. Bifurcations are very complex to characterize and are extremely sensitive to any of the governing parameters. Thus, the transition from \( L_h = 0 \) to \( L_h > 0 \) will always be extremely difficult to predict with certainty.

15.0.9. Current testing practices and the prevailing professional competency do not enable us to make this characterization with confidence.

15.0.10. Thus, the abandonment of the ‘stay-put’ strategy for HRRBs is essential.

15.0.11. Controlled full evacuation of an HRRB will change the focus from the \( L_h = 0 \) condition to the characterization of the fire spread velocity \( (V_s) \). The speed at which the fire spreads is what determines the attainment of untenable conditions (RSET) and thus the time available for egress (ASET).

15.0.12. Conservative characterization of the fire spread velocity \( (V_s) \) is much simpler than quantification of no-fire spread \( (L_h = 0) \).

15.0.13. It is recognized that the processes involved are complex and their assessment requires significant effort, therefore accurate prediction of fire spread velocities in the context of façade systems is not possible. Nevertheless, conservative values of the fire spread velocity can be calculated with existing knowledge of fire science. The conservatism of the calculation will be consistent with the complexity of the solution i.e. simpler analyses will require more conservative solutions.

15.0.14. Changing the focus to establishing the fire spread velocity as a means to assess performance will require the appropriate modification to existing test procedures. The modifications will have to focus on:

- Understanding and quantifying the parameters controlling the flame spread velocity.
- The inclusion and quantification of parameters that govern thermo-mechanical behaviour.
- The inclusion of all measurements deemed necessary to quantify with sufficient certainty and robustness the different forms of fire spread.

15.0.15. While it is my belief that this can be done quite rapidly (months), it will require a significant effort to deliver the appropriate testing approach. Government should enable these developments to proceed as a matter of priority.

15.0.16. Together with the required changes, it is essential to develop a widespread programme that serves to equip professionals with the skills to interpret test data so that they can assess whether the performance of a system supports the Fire Safety Strategy.

15.0.17. It is important to establish that the use of sprinkler systems as a means to reduce the fire spread velocity will be supported by the change in focus towards the fire spread velocity. Sprinkler performance is intimately related to the size of the fire and the rate at which the fire grows. Therefore, if fire spread velocity is properly estimated, then sprinkler technologies specifically designed for the purpose of mitigating the risk of external fires can be appropriately designed.

15.0.18. In the absence of a quantitative estimation of the fire spread velocity, the assumption that conventional sprinklers will work appropriately remains speculation.

15.0.19. In the case of a ‘stay-put’ strategy, sprinklers are an inappropriate approach towards guaranteeing $L_h = 0$. There are several clear and simple reasons:

- A sprinkler system cannot be assumed to always be capable of controlling/extinguishing a fire. Sprinklers have high reliability but are not infallible, therefore in the case of failure of the sprinkler system the Fire Safety Strategy is still required to deliver the necessary safety. Thus, given that the condition of $L_h = 0$ is a bifurcation, failure of the sprinklers will inevitably result in full failure of the Fire Safety Strategy.

- If a sprinkler is meant to control a fire that has already penetrated an adjacent unit, not only will the ‘stay-put’ strategy already have been breached, but the sprinklers will have had to have been designed for the purpose of that performance outcome i.e. a multi-unit fire. Currently, sprinklers are not designed for this purpose and the development of the necessary design methods and performance assessment tools is as complex or more than development of a whole new suite of test methods to assess the performance of façade systems.

15.0.20. Accordingly, by moving the target towards the fire spread velocity, sprinklers will only be used to deliver a reduction in the fire spread velocity and thus their value is enhanced. Needless to say, their design and performance assessment will still need to be revisited with this objective in mind.
THE LONG TERM

15.0.21. Currently there is a conflict between attempts to promote a culture of competency and professional responsibility as embraced by technically quantified functional requirements (as per the Building Regulations), and guidelines that still rely on compliance testing. Compliance testing aims at delivering simple, high through-put and cheap measures of compliance that require little to no interpretation. This promotes a culture of ignorance and deflection of responsibility towards the tests and those who perform them.

15.0.22. The Grenfell Tower fire is a clear and painful representation of this conflict.

15.0.23. If the objective is to regulate fire safety through functional requirements that serve a Fire Safety Strategy, any long-term solution requires first:

- Making it a requirement for fire safety engineers to develop and present a clear Fire Safety Strategy, where objectives and the means to quantify them are clearly established. Current approaches do not require such explicit Fire Safety Strategies, and therefore enables those performing the fire safety analysis to hide behind the implied objectives of the Building Regulations or the information provided by the approved guidance. This, once again, promotes a culture of deflection of responsibility and where competency is not valued.

- Requiring the characterization of all products and materials in a manner which provide all the necessary information that a competent engineer needs to demonstrate that these systems explicitly meet the functional requirements as per the performance metrics required by the Fire Safety Strategy. This information should be delivered under strict rules of conformity. This will shift the responsibility of research and development to the manufacturers who will have to treat fire safety as a functional performance requirement. By doing so, the competitive nature of product manufacturing will result in a shift towards a culture of competency and responsibility.

15.0.24. New products are normally developed by manufacturers as a function of investment in research and development. This usually involves investing in a competent workforce which, through knowledge and initiatives, delivers new products that gain these industries a competitive edge. Thus, investment in education becomes an essential support mechanism for the manufacturers’ competitive edge. Most products improve and develop on the basis of this natural process of innovation.

15.0.25. The construction industry is no different. Many products enter the market on the basis of improvements in performance. Lighter weight structures have replaced heavy construction. Mass-timber is pushing its way into the market on the basis of its manufacturing precision, ease of assembly, sustainability credentials and speed of construction. Cellular plastic
insulation entered the market on the basis of its low thermal conductivity, light weight and ease of assembly. It is no secret that significant effort, resources and, in many cases, government incentives were spent on these developments.

15.0.26. These specific performance objectives have opened profitable markets and have become the drivers of the construction industry.

15.0.27. The industry demand for competent professionals has, in many occasions, transformed higher education, developed mechanisms for lifelong learning, changed the attitude of the professional institutions and even transformed higher education accreditation practices to embed these educational demands in curricula across the UK.

15.0.28. In parallel, the structure of our Building Regulations has evolved to do the same thing by implementing flexible functional requirements. Nevertheless, this has not been extended to testing practices where a prescriptive approach to performance has remained. This prescriptive approach has determined that fire safety is treated only as a constraint to be overcome.

15.0.29. Research and development results in products that meet functionality requirements that give a manufacturer a competitive edge. The final step is then to overcome fire safety constraints. The best possible outcome is therefore “immediate and at no cost.” Anything that results in a delay or implies a higher cost is perceived as a waste of resources. It is not a surprise that ignorance is therefore used as a vehicle for marketing, where the more ignorant the market, the faster the industry can circumvent the constraint. This extends to testing facilities, designers, approvals authorities and the fire service; the less they know, the less they understand their responsibilities and the more susceptible they are to accept means of persuasion other than true performance. This is the true ‘race to the bottom’ as described by Dame Judith Hackitt.233

15.0.30. There is no reason why functionality, when it pertains fire safety, cannot be explicitly defined. Furthermore, there is no reason why functionality, when it pertains fire safety, cannot be the product of research and development focused on delivering better fire safety to gain a competitive edge.

15.0.31. Like any other functionality, it is essential that the manufacturers understand the performance of their products and explicitly establish measures of performance.

15.0.32. This change needs to occur in parallel with a concerted effort to develop a coherent approach towards competency that encompasses the entire chain of activities associated with the delivery of fire safety. A detailed evaluation of this, and a proposal for its

implementation in Australia, was delivered by the Warren Centre Reports. It is recommended that a similar effort is conducted in the UK under the sponsorship of government and conducted by individuals independent to the main commercial interests.

\[\text{234 Professionalizing Fire Safety Engineering, Reports 1 to 9, the Warren Centre, University of Sydney, 2020. (see footnote 13)}\]
APPENDIX A: INTERNATIONAL RESPONSES TO THE GRENFELL TOWER FIRE

A1. INTRODUCTION

A1.1. The Grenfell Tower fire followed a sequence of events that correspond to a specific typology of fires that is referred to here as the external façade system fires. These fires have occurred globally and have continued to occur since the Grenfell Tower fire.

A1.2. In my Phase 1 Report, I conducted a brief literature survey of some of the fires of this typology that occurred before the Grenfell Tower fire. This list was not intended to be comprehensive, just to highlight some of the key features of these fire typology. Two more comprehensive lists provided by White and Delichatsios and Valiulis were referenced in my report. Following the Grenfell Tower fire, this fire typology has received a lot more attention and several new lists of events have been published. Among the new lists of events published, the most comprehensive are the one compiled by Bonner and Rein and that by Spearpoint et al.

A1.3. A simple review of qualitative aspects affecting façade system design and fire performance provided by Bonner and Rein suggests that an optimization approach that includes all functionality variables is essential for the fire safe design of façade systems. Through this work, it becomes evident that much of the key information necessary for this optimization is currently not available. This points towards the need for research on specific aspects of façade fire performance. Nevertheless, the paper also states that while a significant increase in fires of this specific typology has occurred over the last three decades, this has not resulted in an increased research activity. The paper concludes: “Unfortunately, the increased complexity of the problem has not been followed with an increased body of research, and many key aspects of façade flammability are not well understood. This is particularly true in regard to the additional complexities of constructing a real façade – how these systems behave when they are damaged, or include additional fixings and openings.”

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235 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. (JOR00000001)
236 White, N. and Delichatsios, M., “Fire Hazards of Exterior Wall Assemblies Containing Combustible Components,” June 2014, Fire Protection Research Foundation, Quincy, Massachusetts, USA.
237 Valiulis, J. Building exterior wall assembly flammability: have we forgotten the past 40 years? In fire Engineering Magazine, November 2015.
A1.4. Similarly, the role of the expert and expert opinion have also been questioned, not by a thorough assessment of the competencies required to deliver adequate solutions, but indirectly by the absence of uptake of expert opinion. A clear example is the decision-making tool – NFPA EFFECT– that was developed by NFPA and Arup\textsuperscript{241}, and uses expert opinion to enable performance assessment and decision making in matters pertaining to fire safety of façade systems. Users are able to input details of a building and will receive a corresponding risk rating. However, there is no evidence given to support the rating, and there is no way to understand the basis for how the rating is generated. For example, a different rating will be given depending on whether the wall cavity size is greater or less than 75 mm. This is an arbitrary limit based on the expert judgement of the panel of developers, and cannot be interrogated in any way. The tool has been rarely used to aid decision making and authorities have shown no interest in adopting it. The lack of uptake of such a tool represents clear evidence of the current lack of confidence in expert opinion.

A1.5. Given the magnitude of the Grenfell Tower tragedy, the consistent recurrence of external façade fires and the clear lack of confidence in the existing knowledge base and competency, it is extraordinary how limited the global research and education activity has been with regard to the external fire typology.

A1.6. This appendix explores the key activities that have emerged following the Grenfell Tower fire in matters concerning this typology of fires. These activities are in some cases a consequence of the Grenfell Tower fire, but not always. In some cases, like in Australia, the Grenfell Tower fire served to reinforce a set of actions that had already started because of the Lacrosse Building fire. In other cases, activities existed prior to the Grenfell Tower fire and continued thereafter.

A1.7. This appendix does not intend to be a comprehensive review of all activities, but rather selects a set of significant activities that characterizes the way in which society has responded to the Grenfell Tower fire. The focus is on research and regulatory activities associated with the characterization of fire performance. Significant attention has been given to the identification of knowledge and regulatory gaps that enabled the design of buildings in the manner that Grenfell Tower was designed.

A2. RESEARCH ACTIVITIES

GENERAL COMMENTS

A2.1. The scientific community has been exploring different aspects of façade fires for several decades, nevertheless the attention was mostly focused on material flammability and did not incorporate, in a comprehensive manner, studies on the behaviour of façade systems.\textsuperscript{242} Worth highlighting is a series of two conferences in 2013\textsuperscript{243} and 2016\textsuperscript{244} where perusal of the topics covered shows an emphasis on large scale test methods, flammability and some modelling. The topics discussed were very similar in both events.

A2.2. In January 2017 the scientific journal \textit{Fire Technology} published a special issue on Fire Safety of High-Rise Buildings\textsuperscript{245} where the Editors highlighted that “flammability of high-rise building materials” was the first issue of concern. Nevertheless, in the compilation of papers, there was only one paper that touches on the external façade system fire typology. Furthermore, this study touched on a very specific flammability issue, “Fire Performance of External Thermal Insulation Composite System (ETICS) Facades with Expanded Polystyrene (EPS) Insulation and Thin Rendering”.\textsuperscript{246} The tests assessed only the impact of imperfect rendering by means of the Single Burning Item test\textsuperscript{247} and standardized large-scale tests.\textsuperscript{248} The experimental results were accompanied by modelling using the Fire Dynamic Simulator (FDS) software developed in the USA by the National Institute of Standards and Technology.\textsuperscript{249,250} All other papers in this special issue addressed different aspects of fire safety for high-rise building which were not related to external façade system fire typology.

A2.3. The tools and approaches followed in early 2017 were very similar to those followed in 2013 and 2016. This was the case for both experiments and modelling. \textit{It is therefore clear that prior to the Grenfell Tower fire, the scientific community was not delivering significant and useful information that was capable of supporting a fire safe design of façade systems such as that which was implemented at Grenfell Tower.}

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\item 2\textsuperscript{nd} International Seminar for Fire Safety of Facades, Lund, Sweden, 11-13 May, 2016
\item FDS Version 5; User’s guide (2007) National Institute of Standards and Technology, Gaithersburg, Maryland, USA.
\item McGrattan K, McDermott R, Hostikka S, Floyd J. Fire dynamics simulator (version 6)—user’s guide. NIST Special Publication 2014.
\end{itemize}
\end{footnotesize}
A2.4. A different issue is the one of awareness. The fire safety engineering scientific community globally was aware of the external façade fire typology but nevertheless was incapable of securing the support necessary to conduct the research required to quantify the fire performance of façade systems. As an example, I am providing references to some of the many lectures that I delivered to scientists and professionals where this issue was discussed. These lectures all predate the Grenfell Tower fire and were delivered globally and correspond to a very small selection of those that were recorded. In a similar manner, the professional community was also aware of this problem. A good example is the presentation by O’Connor in the 2008 World Congress of the Council for Tall Buildings and Urban Habitat. By 2012, despite the many external façade fires that had occurred between 2008 and 2012, the Council had changed its approach and, in their keynote address, Li and Reiss do not discuss the external façade fire typology as a current fire risk despite the title of their presentation being Fire and Life Safety – Challenges in Sustainable Tall Building Design.

A2.5. In the aftermath of the Grenfell Tower fire, the scientific journal *Fire and Materials* published a special issue on façade fire safety. This special issue includes papers on test methods and modelling using more recent versions of FDS. Nevertheless, systems such as ETICS, EPS and XPS remain the focus of attention.

### POST-GRENFELL TESTING RELATED STUDIES

A2.6. The special issue of *Fire and Materials* is the first set of post-Grenfell research work published and two studies from this collection should be highlighted.

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251 Edinburgh, March 2011, [https://www.youtube.com/watch?v=cypliVb5C8c](https://www.youtube.com/watch?v=cypliVb5C8c) (accessed August 21\(^{st}\), 2021)
252 Edinburgh, March 2012, [https://www.youtube.com/watch?v=gb8iB3MYD0](https://www.youtube.com/watch?v=gb8iB3MYD0) (accessed August 21\(^{st}\), 2021)
253 Melbourne, October 2014, [https://www.youtube.com/watch?v=NvQbZyGctmI&t=1s](https://www.youtube.com/watch?v=NvQbZyGctmI&t=1s) (accessed August 21\(^{st}\), 2021)
254 New York, December 2015, [https://www.youtube.com/watch?v=syzehtz5PTg&t=680s](https://www.youtube.com/watch?v=syzehtz5PTg&t=680s) (accessed August 21\(^{st}\), 2021)
255 Chennai, May 2016, [https://www.youtube.com/watch?v=5Czy7-aTSx4](https://www.youtube.com/watch?v=5Czy7-aTSx4) (accessed August 21\(^{st}\), 2021)
256 Sao Paulo, October 2016, [https://www.youtube.com/watch?v=Yo9DDM5fr6g](https://www.youtube.com/watch?v=Yo9DDM5fr6g) (accessed August 21\(^{st}\), 2021)
257 Brisbane, January 2017, [https://www.youtube.com/watch?v=EOITC2znk8nM](https://www.youtube.com/watch?v=EOITC2znk8nM) (accessed August 21\(^{st}\), 2021)
258 Dubai, October 2008, [https://www.youtube.com/watch?v=kykwyKQpASg&t=1313s](https://www.youtube.com/watch?v=kykwyKQpASg&t=1313s) (accessed August 21\(^{st}\), 2021)
259 Shanghai, October 2012, [https://www.youtube.com/watch?v=eh_BnOkQJ3gQ](https://www.youtube.com/watch?v=eh_BnOkQJ3gQ) (accessed August 21\(^{st}\), 2021)
260 SP FIRE 105 Issue No: 5, Rev 1994-09-09, External Wall Assemblies and Façade Claddings, Reaction to Fire, SP Technical Research Institute of Sweden, {INQ00014964}.
A2.7. The first study addresses the thermal conditions imposed by different internal fire configurations using the SP Fire 105 test apparatus. The study contextualizes these conditions with different protection techniques used globally. The paper establishes "that facade solutions based on horizontal projections and upper facade set-back configurations result in comparable or better protection compared with a defined spandrel height." While this conclusion is qualitative and does not provide quantitative means of establishing protection, it still enables the authors to conclude that: "the positive effect of using horizontal projections or upper facade set-back configurations is underrated in a number of international building codes." The paper complements the experimental work with a numerical study using FDS. The authors conclude that FDS is a suitable tool when the facade is made of non-combustible materials. They do not explore or address the limitations of the tool when combustible materials are present.

A2.8. The second study worth mentioning is that by Guillaume et al. This study will be discussed in greater detail later, but of note here is the first paper published which aims to use testing and computational tools to attempt a reconstruction of the Grenfell Tower fire.

A2.9. Other modelling studies using the same tools have appeared in the literature, but all of them use very simple configurations and either address very specific issues such as fixation failure or provide very simple comparisons between models and experiments.

A2.10. In all cases the limitations of current modelling techniques are highlighted as a real impediment to the use of these tools to address realistic configurations or more complex systems.

A2.11. The fire performance of façade systems using testing is further addressed by several authors in subsequent studies. It is worth briefly summarizing the different approaches used and to highlight their different contributions.

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264 SP FIRE 105 Issue No: 5, Rev 1994-09-09, External Wall Assemblies and Façade Claddings, Reaction to Fire, SP Technical Research Institute of Sweden, \{INQ00014964\}.


A2.12. An earlier study by McKenna et al.\textsuperscript{270} recognizes the need to properly identify the different materials present in façade systems. For this purpose, they conduct a series of standardized tests that enable certain characteristic parameters to be established that can subsequently be used to identify different materials. While the testing approaches used for identification are state-of-the-art, the paper does not articulate why this identification is necessary. Furthermore, the identification data is not presented or discussed. Instead, the authors use the heat release rate per unit area of different materials and measured yields of species to attempt to characterize external fire spread and the potential of different materials to produce toxic products of combustion.

A2.13. The authors failed to recognize the role of encapsulation, configuration and scale in external fire spread thus their study does not encompass a comprehensive assessment of all variables affecting external fire spread.

A2.14. The authors imply that there is a good correlation between the heat of combustion per unit area and the peak heat release rate per unit area, as obtained from the cone calorimeter,\textsuperscript{271} with the test results published after the Grenfell Tower fire by the UK Government.\textsuperscript{272} The correlation between the BS 8414 test,\textsuperscript{273} the heat of combustion per unit area and the peak heat release per unit area suggested by the authors is only valid because of the unique characteristics of the systems they are describing. The materials used for the inner layer of the ACM produce much more heat than the insulation and therefore dominate the fire spread problem. This enables a simple correlation between qualitative performance and this single parameter. The two single cases where a “pass” was recorded correspond also to the two cases with a significantly lower heat release rate per unit area for the ACM, thus the correlation is expected. Finally, their assessment of toxicity ignores the role of compartmentalization in the Fire Safety Strategy as well as the fire dynamics leading to the production of combustion products. Thus, their analysis provides an incomplete characterization of the relationship between yields and toxicity.

A2.15. Further studies related to toxicity of the different materials used in façade systems have been published.\textsuperscript{274,275} These all suffer from the same shortcomings as the McKenna et al.
study.\textsuperscript{276} These studies have extended the discussion to long-term contamination after the Grenfell Tower fire\textsuperscript{277} and prompted an assessment led by the Office of the Government Chief Scientific Adviser (GCSA)\textsuperscript{278} that ultimately discarded the possibility of long-term contamination induced by the fire.

A2.16. The most extensive among all these studies is the University of Queensland Cladding Materials Library.\textsuperscript{279} This work was part of a comprehensive programme funded by the State of Queensland that aimed to address the assessment of risk posed by combustible cladding materials.\textsuperscript{280} The library followed a rigorous methodology that first provided methods of identification of the different components of façade systems.\textsuperscript{281} These methods used state-of-the-art diagnostics\textsuperscript{282} including many of the diagnostics used by McKenna \textit{et al.}\textsuperscript{283} The identification of the material was followed by a comprehensive set of small-scale flammability tests with the aim of extracting all relevant flammability properties. The properties aimed to enable engineers to use this information in models that could serve to predict the risk imposed by different materials used in façade systems. A series of tests aimed at providing further data in support of these models was also proposed.\textsuperscript{284} For this purpose, a professional development programme was designed to ensure that professionals conducting risk assessments had adequate competency to conduct these analyses. The professional development programme was assessed by means of examination and a certificate provided by the University of Queensland.\textsuperscript{285}

A2.17. This study is unique in that the Cladding Materials Library is based on the principle that each building design and each Fire Safety Strategy is unique and therefore the assessment of fire

\textsuperscript{276} McKenna, S.T., Jones, N., Peck, G., Dickens, K., Pawelec, W., Oradei, S., Harris, S., Stec, A.A., Hull, T.R., Fire behaviour of modern façade materials – Understanding the Grenfell Tower fire, Journal of Hazardous Materials, Volume 368, 15 April 2019, Pages 115-123. {INQ00014942}

\textsuperscript{277} Stec, A.A., Dickens, K., Barnes, J.L.J., Bedford, C., Environmental contamination following the Grenfell Tower fire, Chemosphere, Volume 226, 2019, Pages 576-586.

\textsuperscript{278} AECOM, Grenfell Investigation into Potential Land Contamination Impacts, Stage 1 Overarching Report Royal Borough of Kensington and Chelsea, Project number: 60595731 1 October 2019.

\textsuperscript{279} https://claddingmaterialslibrary.com


\textsuperscript{283} McKenna, S.T., Jones, N., Peck, G., Dickens, K., Pawelec, W., Oradei, S., Harris, S., Stec, A.A., Hull, T.R., Fire behaviour of modern façade materials – Understanding the Grenfell Tower fire, Journal of Hazardous Materials, Volume 368, 15 April 2019, Pages 115-123. {INQ00014942}


\textsuperscript{285} https://claddingmaterialslibrary.com
risk needs to be conducted by competent professionals. Following that principle, testing and analysis is limited to delivering qualitative descriptions of behaviour as well as quantitative data on parameters that can be used by a competent professional when conducting a performance assessment of a cladding system.\textsuperscript{286}

A2.18. Some of the small-scale material flammability tests described in the University of Queensland Cladding Material Library were used by Khan et al\textsuperscript{287} to assess the performance of Aluminium Composite Panels (ACP’s) with fire retarded cores. The results obtained are very similar to those presented for similar materials by the Cladding Materials Library.

A2.19. A further study of note is the study of the outcome of 252 commercial product tests conducted using the small scale Polish PN-B-02867 standard.\textsuperscript{288} These tests were used to create a data base (KRESNIK) that correlates the test results with the objective of providing data for designers. The authors claim that this type of test enables a better understanding of façade performance. Nevertheless, the specific test protocol is not adequately characterized, the fire source (a crib) is not benchmarked, the authors do not introduce additional measurements to add value to the results and the scientific basis for the specific configuration is not discussed. Thus, it is not possible to establish if their conclusions are a product of the nature of the test or of the tested sample. In summary, these tests suffer from the same limitations of all the tests discussed in the main body of this report.

A2.20. Several studies have attempted to reproduce the BS 8414 methodology, either at full scale or partial scale to assess different combinations of insulation and rain-screen materials in the context of specific façade systems.\textsuperscript{289} None of these studies addressed the fundamental limitations and shortcomings of BS 8414 or added any additional and meaningful measurements that could help supplement the test. Thus, while delivering data, the data is only of value if interpreted carefully by a competent professional, particularly if this data is to be used for specific building design. In this case, the competent professional needs to carefully extrapolate the data considering the context and objectives of the Fire Safety Strategy.


\textsuperscript{288} Bonner, M., Wegrzynski, W., Papis, B. K., Rein, G., KRESNIK: A top-down, statistical approach to understand the fire performance of building facades using standard test data, Building and Environment, 169 (2020) 106540. (INQ00014955)

A2.21. FM Global conducted a study of ANSI/FM 4880\textsuperscript{290} to establish the differences between this standard and NFPS 285.\textsuperscript{291} The study concludes that the conditions of NFPA 285 are such that several materials that pass this test failed the ANSI/FM 4880. The authors conclude that the thermal conditions created in the ANSI/FM 4880 test are more relevant to those typical of external flames. This study is particularly valuable in that it conducts some detailed measurements that help understand the nature of vertical fire spread. Thus, I reference some of these measurements in my Phase One report.\textsuperscript{292} The configuration (two parallel walls) is one intended to reproduce relevant thermal conditions and not a realistic façade assembly. Therefore, despite the value of these tests, the configuration is so unique that extrapolation of the results requires very detailed and careful interpretation.

A2.22. To my knowledge, the only case where testing was conducted considering the context and objectives of the Fire Safety Strategy was a series of four large scale tests conducted in India. The tests focused on a set of relevant variables and allowed the rate at which the fire breaches the unit above the compartment where the fire started to be established.\textsuperscript{293} While the assembly is very specific, and therefore the results cannot be generalized to other scenarios, the measurements and observations are focused on parameters of relevance to the Fire Safety Strategy. For example, it was established through measurement that the fire could progress externally (i.e. leap-frog). The initial fire will affect the compartment above in less than 3 minutes if combustible materials were present, while in the case of non-combustible systems the fire will most likely progress internally (through gaps produced by thermo-mechanical deformations). It was observed that it took approximately 6 min to breach the compartment. The time to breach the compartment varied as a function of the quality of the fire-stop at the characteristics of the interface between the structure and the façade system. These estimations are among the very few that permit the time available for occupants to escape the unit above the fire before compartmentalization is breached to be established. A final measurement of importance is the quantification of the heat-flux from the external fire to the façade system, confirming the estimates established in my Phase 1 report\textsuperscript{294} that indicated values greater than 100 kW/m\textsuperscript{2}.

A2.23. An attempt to analyse the shortcomings of the different test approaches used in the UK (mainly BS 8414) was conducted by Schulz \textit{et al}.\textsuperscript{295} This study aims to establish a critical assessment of the current testing regimes of relevance to façade systems. The authors correctly conclude that “\textit{The process by which combustible façades are permitted on tall...}”

\textsuperscript{290} Agarwal G. Research Technical Report: evaluation of the fire performance of aluminium composite material (ACM) assemblies using ANSI/FM 4880. FM Global, Norwood, MA02062, USA, December 2017. (INQ00014954)

\textsuperscript{291} NFPA 285. Standard fire test method for evaluation of fire propagation characteristics of exterior non-load-bearing wall assemblies containing combustible components. 2012. (INQ00014562)

\textsuperscript{292} Torero, J.L. Grenfell Tower: Phase One Report, 23\textsuperscript{rd} May 2018. (JTOR00000001)


\textsuperscript{294} Torero, J.L. Grenfell Tower: Phase One Report, 23\textsuperscript{rd} May 2018. (JTOR00000001)

buildings in England does not ensure fire safety” and insist that “a new and more robust approach is required.”

A2.24. The scope of the paper is limited to the BS 8414 testing protocol, the performance criteria in Annex A of BR 135, and the MHCLG sponsored tests. The analysis discusses details such as the ambiguities within the BS 8414 protocol, reproducibility, strong sensitivity of the outcomes to many variables and the lack of alignment of the criteria in BR 135 to any specific objectives of the Fire Safety Strategy. It is clear that reproducing realistic façade systems is very difficult in a test, so some degree of extrapolation will always be necessary. The authors use the MHCLG tests to illustrate this problem and how small differences can significantly alter the results. Finally, a series of recommendations are provided that correctly stipulate the need for more reproducibility, better measurements and more clear reporting and transparency in regards to objectives and motivation for the tests.

A2.25. While it is impossible to disagree with any of these statements, this study fails to establish the fundamental weaknesses of the test or to establish the key variables that will affect the quantification of external fire spread in a manner that supports the Fire Safety Strategy. Furthermore, the study provides no critical analysis of what is required for a correct extrapolation. A test delivers data and that data needs to be interpreted. Data that has more imperfections does not mean that the data is useless, it only means that a more complex interpretation is necessary. Without this critical analysis, this study does not enable any advancement towards a better compliance regime.

A2.26. Furthermore, by focusing on the weaknesses of the test, this study incorrectly exonerates the professional from deploying a sufficient level of competency in the analysis and extrapolation of the test results. This is in direct contradiction to BR 135296 which clearly addresses most of the shortcomings described in the paper as inherent to the approach: “This guidance document addresses the principles and design methodologies related to the fire-spread performance characteristics of non-loadbearing external cladding systems. Although various potential design solutions have been identified and discussed in this document, robust design details are not presented, as it has been found that generic solutions are not available to this rapidly changing market, where new products and novel design solutions are frequently presented. The illustrations and scenarios presented in this document are based on typical examples of current practice, but, as has already been identified, this field is subject to rapidly changing designs and materials, and so this guidance focuses on the issues surrounding the topic to enable designers and end users to understand better the parameters impacting on the fire-safe design and construction of external cladding systems.” As indicated in the above quote, the purpose of the guidance is to “enable designers and end users” not to reproduce the exact façade system details for a specific application or to deliver an analysis that is pertinent for a specific Fire Safety Strategy.

This is further reinforced by a later statement in BR 135 that emphasizes the role of the competent professionals: “This guide provides a basis for evaluating the fire performance of external cladding systems. It does not specify where this performance standard should be adopted; this is a matter for regulators and specifiers.” Thus, any study that ignores the need for extrapolation of the testing results and the key role of the competent professional needs to be treated with caution.

The issue of competency and its role in the adequate implementation of fire safety in the built environment is comprehensively addressed by the Warren Centre Project. The Warren Centre project focuses on the Australian context and was conceived before the Lacrosse Building and Grenfell Tower fires but finally emerged as a response to these events. This project delivered the following nine reports:

1. Regulation, Control and Accreditation Report
2. Education Report
3. Methods Report
4. Roles Report
5. Competencies Report
6. Professional Development Report
7. Accreditation and Regulatory Reform Report
8. Final Report (PDF, 13.3MB),
9. Comparison of FSE Guidance Documents and Assessment Criteria Report

The Warren Centre Reports analyse the relationships between regulation, competency and adequacy in the context of Fire safety Engineering design and finishes by delivering a pragmatic plan on a transition from the current state of fire safety engineering and design for Australia. It is my strong opinion that these documents are directly applicable to the reality of the situation in the UK and the process followed for their development is a very good example of coherent government, industry and academic collaboration towards the delivery of a common and pragmatic plan of improvement.

Post-Grenfell Modelling Related Studies

A2.30. Modelling of external fires over complex cladding systems is very difficult. It requires precise modelling of all gas phase processes (e.g. combustion, heat and mass transfer, buoyancy driven flows, turbulence, etc.) which demands sophisticated computational fluid mechanics models. Furthermore, if combustible materials are protected by non-combustible layers (i.e. encapsulation) or if combustible or non-combustible materials represent the solid boundaries to the burning areas, then thermally induced mechanical deformations and failure modes also need to be predicted in significant detail. These predictions require both complex pyrolysis and Finite Element Models. Finally, ignition and extinction also will need to be modelled to properly define flame spread and flame lengths.

A2.31. Models can occasionally be simplified by extracting data from experiments, however for this to be possible, experiments have to be well-defined and well-characterized by measurements that are consistent with the needs of the models.

A2.32. Notable among all the research work conducted after the Grenfell Tower fire is the combination of tests and modelling that was conducted by Efectis and published in a series of papers.\(^{298,299,300,301,302,303,304,305}\) A general review of the approaches taken, results and limitations will be provided here, but this review is not intended to be comprehensive and only aims to establish the elements from these studies that are relevant to the Grenfell Tower fire and thus need to be highlighted. In parallel with these journal publications there are also a series of conference papers that present similar information. These will not be

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discussed here because, in general terms, the information presented in the conference papers is included in the journal publications.

A2.33. In general terms these studies use state-of-the-art tools and follow an appropriate ‘building block’ approach that aims to provide elements of validation at each stage of the process. Furthermore, the results show general agreement with the observations presented in the Chairman’s Phase One report\(^{306}\) and allow the importance of some physical phenomena to be established. The results support the observation that cavity barriers will have little impact on the fire spread rate, which agrees with the descriptions presented in my Phase One report.\(^{307}\) The overall vertical fire spread rates are consistent with those reported in the Phase One report.\(^{308}\) Finally, and most importantly, these studies do not show disagreement with any of the conclusions presented in either my or the Chairman’s Phase One reports or the present report.

A2.34. Beyond these general qualitative observations, the tests and models presented cannot deliver information that can be used to address some of the questions raised in Phase One of the Grenfell Tower Public Inquiry. In particular, they cannot shed light on the relative contributions of the different materials to the onset of fire spread. This is the case because the computational cost of the models used is so high that some of the key phenomena needed to explore the exchanges between materials had to be eliminated and substituted by imposed values. By following this strategy, none of the observations related to the role of encapsulation and its failure can be introduced in the model. Thus, quantitative comparisons between these studies and the University of Edinburgh tests are not possible. Furthermore, the geometry of the cassettes needs to be significantly simplified eliminating necessary details of phenomena such as the gas flow within the cavities.

A2.35. The following paragraphs will look in detail at all the stages of these studies and will highlight all relevant aspects. The objective is to contextualize this research with the work of the Grenfell Tower Public Inquiry, highlighting where this research can add valuable information and where it cannot.

A2.36. An initial paper describes a series of tests that were conducted by Efectis and are reported by Guillaume et al.\(^{309}\) In these tests, an intermediate scale test (ISO 13785-1\(^{310}\)) is used to determine the flame spread capability of different façade systems (see Figure A1-1).

A2.37. The test utilizes a gas line burner (1200 mm by 100 mm) as an ignition source. This particular burner provides a heat flux to the façade assembly. The façade assembly is placed 250 mm

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\(^{306}\) Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019. [INQ00014818]

\(^{307}\) Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. [JTOR0000001]

\(^{308}\) Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. [JTOR0000001]


above the surface of the burner (Figure A1-1). The heat flux imposed by the burner on the façade system is not characterized and therefore it is not possible to establish the heat flux distribution imposed by the burner on the façade assembly.

A2.38. The test assembly has very unique features, such as an aluminium tray that fully envelopes the bottom edge of the façade system protecting the edges from the ignition source flames. This makes the characterization of the heat flux to the façade system even more difficult.

A2.39. The mechanical characteristics of all the components and their fixation is not described in the paper, thus deformations and mechanical failures cannot be studied.

A2.40. In contrast, the heat flux from a typical compartment fire has been well characterized. Thus, the target heat flux distribution for the real application is known. Figure A1-2 shows a typical distribution of heat-fluxes when a fire spills from a fully developed compartment fire. The heat-flux distribution is expected to be of the order of ~120 kW/m² at the leading edge and decaying to ~25 kW/m² beyond the pyrolysis zone and for the extent of the flames. A rapid decay towards zero will follow beyond the flame tip.

![Figure A1-1: Schematic of the ISO 13785-1 as per Guillaume et al.](image)

1. Position of Heat Fluxmeter
2. Back wall (support)
3. Draught screens
4. Test specimen back wall
5. Test specimen side wall
6. Ignition burner

A2.41. There are clear differences between the ignition source in the test and that of a real fire spilling from a fully developed compartment fire. Therefore, as is the case with BS 8414, any extrapolation of the results to a real-life performance assessment needs a detailed analysis.
A2.42. Whether these tests can be used to support modelling of a real-life scenario depends on which variables are calibrated by means of the test data and what the information is that the model seeks to establish.

A2.43. In the case of the experiments reported by Guillaume et al\textsuperscript{311} it is important to separate the processes that can be supported by this data from those which cannot be supported by the tests.

A2.44. Given a well-defined target, like in the case of heat-fluxes imposed by flames emerging from a fully developed compartment fire, the tests need to provide the appropriate data that will allow a relationship between the test and the scenario the test is trying to describe to be constructed.

A2.45. With regard to the burner used in the test, the following three cases are possible:

Case 1. The burner is characterized in a manner that it is demonstrated to replicate the heat flux from a typical compartment fire

Case 2. The burner is characterized in a manner that the data collected allows a model to be used to extrapolate the conditions of the test or the heat flux from a typical compartment fire

Case 3. The processes of interest are demonstrated to not be affected by the burner

A2.46. The lack of characterization of the burner and the aluminium shield does not allow the heat flux distribution on the tested system to be established. Therefore, the demonstrations required in the first two cases cannot be achieved.

A2.47. The initial sequence of failures that leads to the spread of a flame will fall within the first two cases, therefore the tests cannot be used to characterize the mechanisms that lead to the failure of the system, the subsequent ignition and the initial fire spread.

A2.48. Nevertheless, the data can be used to characterize the processes corresponding to the third case. While it is possible to estimate the region affected by the burners by means of simple calculations\textsuperscript{312} and to show that it is no greater than 0.5 m, calculating the corresponding heat fluxes is very difficult. Therefore, only the data produced by the test above the region affected by the burner (approximately 0.5 m) should be used for model validation or for extrapolation. Nevertheless, this statement has a very important caveat in that this will only be the case if it is possible to ascertain that the failure and onset of fire spread does not have


any impact on the subsequent spread of the fire. Unfortunately, the tests do not provide any insight on the sensitivity of fire spread to the input from the burner.

A2.49. Furthermore, there is no description of the sequence of failure; the images presented simply show the front view of the test with no explanation of what is happening with regard to the cladding and insulation. Images that describe the aftermath are also presented but these images do not provide any insight into the initiation event.

A2.50. The main measurements presented in the paper by Guillaume et al. are the heat release rate ($\dot{Q}$), temperatures (at five locations evenly distributed along the wall on each side of the test specimen (Side (4) and Side (5) on Figure A1-1)), a single heat flux measurement at the top of the sample and gas measurements.

A2.51. The temperatures enable a qualitative indication of the extent of propagation that is consistent with the photographic images. The actual quantitative values of the temperature are difficult to interpret in that they are influenced by many complex factors that remain undefined but that lead to complicated evolutions of the temperature in time. No analysis that aims at establishing fire spread rates is presented.

A2.52. The heat flux measurements at the top of the sample serves to confirm the values indicated in Figure A1-2, showing approximately $\sim 100 \ kW/m^2$ when the flames reach the sensor. The heat flux values could provide evidence for validation of computer models but they are only relevant once the flame is fully established. Only the cases with ACM panels with polyethylene (PE) cores provide such data.

A2.53. The authors conclude that there is “a very well-ventilated condition of combustion” from global measurements made at extraction. As a global measure of the overall system this is a correct statement. In the cases where the fire attains a large size, combustion is occurring mostly externally to the cladding, in which case it could be well ventilated and the products heavily diluted. In these cases, any combustion internal to the cavity might be under-ventilated, but as shown in the paper, fuel consumption within the cavity is small. Therefore, the products generated within the cavity will have a minor influence on the global measurements at the extraction system.

A2.54. In cases where the fire does not spread in a significant way, the heat release rate is at the lower limit of the resolution of both facilities used (200-300 kW), therefore, it is not likely that the measurements can accurately discriminate between under- or over-ventilated combustion. Nevertheless, the CO measurements indicate higher concentrations of CO for the smaller fires. This could be attributed to the fire retarded nature of the ACM infill or to less ventilated combustion. In these cases, the measurements do not provide information in regard to the local conditions of combustion.
Figure A1-2: Typical distribution of heat fluxes during fire spread. At the leading edge the heat-flux can reach values of approximately $\sim 120 \ kW/m^2$, decaying as the distance from the leading edge increases. Typical values in the heating region are of the order of $\sim 25 \ kW/m^2$.

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A2.55. The heat release rates can be related to the fire spread velocity through the evolution of the burning area in time. The heat release rate is approximately proportional to the evolution of the burning area in time ($\dot{A} [m^2/s]$), so, if the width of the burning sample is constant, then the Heat Release Rate will be proportional to the burning height. This will allow the fire spread rate to be established. The assumption that the entire width of the sample is burning is quite reasonable and therefore this calculation is possible and could be validated with the images obtained by the camera. The authors do not present such an analysis.

A2.56. The results instead focus on the differences between the different combinations of materials. This leads to the conclusion that the combustible material inside the ACM controls the outcome, independent of the insulation material used. This is an appropriate conclusion for the specific tests conducted but it is not a conclusion that could be extrapolated to other conditions / scenarios. The data available is not sufficient to allow for such extrapolation.

A2.57. A second series of tests were conducted by the same group\textsuperscript{314} using the LEPIR II facility.\textsuperscript{315} The test facility consists of two levels, and the lower part of a third level, built in open air. The fire source was a calibrated wood crib representing a fully developed compartment fire that approaches the standard ISO 834 fire.\textsuperscript{316} Two experiments are conducted using a non-combustible façade, one was used to calibrate a computational model using the Fire Dynamics Simulator (FDS) and the second one was used to validate the calibration. While the details of the model can be interrogated in significant detail, these are consistent with previous studies with non-combustible façades. The use of these models for the simulation of external fires emerging from fully developed compartment fires with no contribution to the fire by the façade materials has been demonstrated to be possible. Nevertheless, as the authors indicate: “these results cannot be extrapolated to other façade thicknesses, material or opening geometry.” This is particularly true in the case where combustible materials are used in the façade systems.

A2.58. In summary, this series of tests are not directly relevant to façade systems of the nature of those used in Grenfell Tower and are mostly a benchmark that enables confirmation that FDS can be used towards predicting the characteristics of a fire emerging from a fully developed compartment fire in the case where the façade is non-combustible.


\textsuperscript{316} ISO 834, BS EN 1363-1 (1999) Fire resistance tests: Part I - General requirements. (BSI00001750)
A2.59. Following the above experimental papers, Drean et al. present the results of a model using the FDS software. The model attempts to reproduce the experimental results of three tests (PE + PIR, PE + Mineral Wool and A2 + PIR) by simulating a simplified configuration. The model is limited by the mesh size in the gas phase (20 × 20 × 20 mm) but allows for a higher resolution in the solid phase. The model does not reproduce the interaction between the aluminium and the combustible infill and is not capable of addressing dripping and melting. The model uses a simple approach to combustion therefore is limited in its capacity to reproduce extinction and oxygen poor environments.

A2.60. The ACM is modelled solely as the combustible core (i.e. the aluminium elements are not included in the model) and the thermal properties, including an ignition temperature, are the only parameters affecting a one-dimensional heat transfer model. As the aluminium and its influence are not included, the role of encapsulation is not considered in the modelling process. This applies both to the protection provided by the aluminium, but also to the heat sink introduced by the aluminium that affects the burning rate.

A2.61. The destruction of the cladding is defined by the consumption of the combustible core, and is calculated by prescribing a burning rate from the literature. The burning rate can therefore not be modulated by the protective nature of the aluminium encapsulation or by the heat sink resulting from its high thermal conductivity.

A2.62. The authors conduct a careful and detailed assessment of the model parameters and the model predictions. The results show that despite the simplifications and assumptions, the model predicts the general trends appropriately for the cases where polyethylene is the material serving as the infill for the ACM. As the authors indicate, this is because “the justification of the chosen approach is based on the understanding of the materials in question and mostly on the very bad fire performance of PE.”

A2.63. A closer look at the comparisons validates this statement by the authors, however the predictions within the first 5 minutes of the test show significant discrepancies for all the measurements presented. As indicated above, the region influenced by the burner is not well characterized so, only predictions in the region above the area influenced by the burner are expected to be adequate. Furthermore, the model assumptions do not describe the failure mechanism leading to ignition or enable a prediction of the complex interactions between the burning materials, their encapsulation, and the burning molten material dripping from the ACM panels. All these factors are critical in the earlier stages of burning and none are described by the model.

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A2.64. Once the polyethylene becomes the dominant factor controlling flame spread and the protection provided by the aluminium encapsulation is no longer significant, then the model is capable of predicting temperatures and heat release rates with reasonable accuracy.

A2.65. The quality of the prediction is not as clear in the case of the A2 infill, where the contribution of the A2 infill is not as significant, in particular with regard to the heat release rate but also in the case of many of the thermocouple measurements used for temperature comparisons.

A2.66. In what concerns fire spread, Figure A1-3 shows that the rates of spread of the fire are not well predicted by the model after 4 min of the simulation. At this point the flames have already reached the top of the test facility therefore the experiments do not establish if the model can predict fire spread. The authors make no fire spread rate comparisons between the model and the experiments and therefore it is assumed that they recognize this comparison is not possible.

A2.67. In summary, the model proposed provides a reasonable tool to predict the heat release rate and temperatures in the immediacy of the flames once the burning of the combustible infill dominates. The model does not allow the early failure mechanisms leading to the involvement of the ACM and insulation, the early stages of the fire or the rates of fire spread to be explored.
**Figure A1-3:** Images extracted from Figure A-2 in Drean et al\textsuperscript{318} where significant discrepancies are observed between the model and the tests. In the tests the fire has emerged between the second and third panels at 3 minutes while this is only the case at 4 min with the model.

A2.68. Following this study, Drean et al\textsuperscript{319} undertook the modelling of three independent tests\textsuperscript{320,321,322}. Four models are presented, a first one following the method described in their previous study\textsuperscript{323} and three subsequent ones using a coarser mesh (125 × 125 × 125 mm).

A2.69. Along with the mesh, several differences between the previous medium scale validation and the present study can be noted. The first is that the failure mechanism for the ACM has been changed to the solid (aluminium element) disappearing if its surface temperature reaches 550°C. It appears that the combustible infill of the ACM panel still disappears after it has been fully consumed. This seems to be also used as a means to establish failure of the cladding (“when the mass contained in each solid cell is consumed, the solid disappears from the calculation cell by cell. This feature is used to account for the destruction of the cladding”). Not enough details are presented to precisely define the approach used and therefore it is not possible to ascertain how encapsulation is treated. It is important to note that these changes in approach could deliver very different results.

A2.70. The heat input from the crib was prescribed as a defined heat release rate and its use was validated (Appendix C of the paper) by a simple comparison with thermocouple measurements from a set of earlier tests using a non-combustible façade. As expected, and consistent with previous studies, the use of the FDS software to model an inert façade delivers appropriate results when describing the temperature conditions of the outer flames. Nevertheless, the coincidence of temperatures does not necessarily mean that the heat-flux (key parameter) to the surface is consistent.

A2.71. An important aspect of this work is the data presented in Appendices A and B that shows the sensitivity of the predicted heat release rate to the ignition temperature of the polyethylene and the insensitivity to the ignition temperature of the insulation. This clearly shows what was already observed in the medium scale validation, i.e. that the model is capable of predicting the heat release rate once the fire is dominated by the ACM’s PE core,

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\textsuperscript{318} Drean, V., Girardin, B., Guillaume, E. and Fateh, T., Numerical simulation of the fire behaviour of façade equipped with aluminium composite material-based claddings—Model validation at intermediate scale, Fire and Materials. 2019; 43:839–856. (INQ00014909)

\textsuperscript{319} Drean, V., Girardin, B., Guillaume, E. and Fateh, T., Numerical simulation of the fire behaviour of facade equipped with aluminium composite material-based claddings-Model validation at large scale, Fire and Materials. 2019; 43:981–1002. (INQ00014910)

\textsuperscript{320} Report N°B 137611-1037 issue 1.2 (DCLG test 1), BRE, 12th September 2017

\textsuperscript{321} Report N°B 137611-1037 issue 1.2 (DCLG test 5), BRE, 12th September 2017

\textsuperscript{322} Report N°B 137611-1037 issue 1.2 (DCLG test 2), BRE, 12th September 2017

\textsuperscript{323} Drean, V., Girardin, B., Guillaume, E. and Fateh, T., Numerical simulation of the fire behaviour of façade equipped with aluminium composite material-based claddings—Model validation at intermediate scale, Fire and Materials. 2019; 43:839–856. (INQ00014909)
but that the accuracy of these results is dependent on the protocol of defining an ignition temperature of the infill material and ignoring the presence of the aluminium components. The authors show that only a specific combination of ignition temperature and mesh size is appropriate. This is an unusual approach that would probably require much more detailed exploration.

A2.72. The authors conclude that when polyethylene is used as the infill material, 90% of the heat released is due to the polyethylene. Given that, in the conditions of the test, the ACM dominates over the release of heat, this is not a surprising conclusion. The authors nevertheless do not describe how the insulation contributes to the burning rate of the polyethylene. Heat transfer from the insulation to the polyethylene will enhance its burning rate as well as accelerate the damage of the aluminium encapsulation, thereby accentuating the discrepancy between the contribution to release of heat of the two components. The model is not capable of enabling such an analysis.

A2.73. Finally, the heat release rate appears insensitive to ignition temperatures in the first 5 minutes of the simulation. This shows that the crib as a fire source is so dominant (reaches more than 2 MW of heat release rate in less than 5 min) that it does not enable an observation of the initial failure modes with any clarity.

A2.74. The sensitivity analysis to the peak heat release rate shows the significance of the crib. A change in the crib heat release rate has a major effect on the temperature and the time evolution of the heat release rate of the simulated façade system. This observation is consistent with the analysis presented in this report.
Figure A1-4: Simulation results extracted from Figure 5 of Drean et al\textsuperscript{324} showing flames exceeding the limits of the experimental rig.

A2.75. As can be seen from Figure A1-4, at 5 min from ignition, the flames have already reached the top of the sample. The numerical results confirm this showing that the decay period for all the simulations started shortly thereafter. Therefore, this information shows that there is limited scope to use this data to look at predictions of fire spread as the effect of the crib on the observable flame spread rate cannot be differentiated.

A2.76. The temperature results for all cases show a reasonable agreement. The differences between experiments and models can be easily correlated with the assumptions made by the modellers. Even the ACM A2 + PIR model results show reasonable agreement when compared to the experimental data. Looking at the heat release rate model results, it is clear that for this configuration the contribution of the façade system to the fire is negligible and all that is being modelled is the fire output of the crib. There are no heat release measurements to compare, so the validation is limited to temperatures.

A2.77. In summary, the validation using the BS 8414 test results confirms that the model proposed provides a reasonable tool to predict the heat release rate and temperatures in the immediacy of the flames once the burning of the combustible infill dominates. No further information emerges from this study that leads to a conclusion that the model is capable of exploring the early failure mechanisms leading to the involvement of the ACM and insulation, the early stages of the fire or the rates of fire spread.

A2.78. Rightfully so, the authors do not explore fire spread or discuss in any detail the early failures leading to the loss of encapsulation or the ignition of the combustible insulation or infill.

\textsuperscript{324}Drean, V., Girardin, B., Guillaume, E. and Fateh, T., Numerical simulation of the fire behaviour of facade equipped with aluminium composite material-based claddings-Model validation at large scale, Fire and Materials. 2019; 43:981–1002. (INQ00014910)
A2.79. The previous study is followed by a final series of four papers directly related to the Grenfell Tower fire. The first of these papers is an analysis of images and the formulation of a series of hypotheses on the basis of observations. All of these hypotheses are reasonable in nature and consistent with the Chairman’s Phase One Report. Furthermore, vertical and horizontal fire spread is estimated from the images and shown to be consistent with the estimates of my Phase One report.

A2.80. The second paper uses the FDS modelling software to explore the different possible scenarios described in my Phase One report and the analysis is consistent with the approach used in Appendix B of that report, but it does not conduct a parametric study to establish the most comprehensive match with the evidence. Instead, the analysis introduces assumptions that enable a single computational model for each of the scenarios studied to be conducted. For example, a leakage area of 0.1 m x 2.0 m is introduced at the door and the kitchen window fan is modelled as a partial opening. None of those assumptions are necessary in a parametric study because these parameters are treated as variables with the objective of evaluating the sensitivity of the results to each of these parameters.

A2.81. The assumptions used in the models are reasonable, nevertheless lead to a specific result. The objective is therefore to illustrate a possible scenario, which is very different objective to that of the bounding analysis presented in Appendix B of my Phase One report. While some discrepancies can be found between the results of these models and those presented in my Phase One report, this can all be linked to the different objectives of the two studies, the inherent limitations of the models used and the input information available. Nevertheless, the fundamental conclusions are the same in that a significant fuel package close to the window will inevitably result in ignition of the façade system and the kitchen fire in Flat 16 never reached a flashover condition.

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331 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. (JTOR00000001)
332 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. (JTOR00000001)
333 Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. (JTOR00000001)
A2.82. In a similar manner, the paper illustrates possible paths for the fire to move into adjacent rooms in Flat 16 and adjacent units as well as illustrating the type of deformations that could be expected from the windows. The results are in general agreement with the sequence of events provided in my Phase One report\textsuperscript{334} as well as with the observations of damage presented.

A2.83. Extrapolation of the previous studies to the modelling of the external propagation in Grenfell Tower is very difficult and will always carry significant uncertainty. The limited information available makes only simple comparisons with images possible. Performing a numerical computation for such a large fire requires a much coarser mesh\textsuperscript{335} which results in further uncertainty and moves the model away from the previously validated range. The following study\textsuperscript{336} attempts to model the propagation of the fire for the Grenfell Tower fire. The authors use a mesh size of 0.25 × 0.25 × 0.25 m which is significantly larger than in their validation studies and means the model is unable to capture the detailing of cavities and other features of the façade system. Furthermore, many of the processes are much more complex than in the validation studies requiring the imposition of estimated inputs (e.g. input heat release rates, ignition temperatures, compartment fire heat release rates, the role of different infill materials (i.e. A2), etc.). Many of these are acknowledged by the authors.

A2.84. The complex assumptions and the limitations of the model do not enable the results from the model to be treated in a quantitative way. While comparisons with visual observations are made in the paper, many of them lack clear explanations. For example, the model seems to show a slowdown of fire spread between 01:16 am and 01:21 am, consistent with observations. The model, given the equations it is solving, has no simple mechanism to deliver this deceleration. The comparison with the scenario where the PIR is substituted by mineral wool (MW) adds further uncertainty to this observation. In this case, fire spread rates are almost identical, which is expected. Given the size of the mesh, the influence of the thermal properties of the insulation will be negligible and the results should be approximately the same. Surprisingly, the MW simulations do not show the region of

\textsuperscript{334} Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. (JTOR000000001)

\textsuperscript{335} In computational fluid mechanics the equations are solved by breaking the domain into many small volumes (‘the mesh’). These small volumes allow assumptions that simplify the computations to be made. Therefore, the size of these small volumes has to be consistent with the physical phenomena that need to be modelled. If the volumes are too large, certain physical phenomena cannot be reproduced. Nevertheless, the smaller the volumes used to discretize a particular domain the larger the computational cost. Therefore, a balance that enables modelling of the physics with sufficient precision while retaining manageable computational costs needs to be achieved. For fire problems this is very difficult because the domain (like in the Grenfell Tower) is very large, and therefore refined calculations have an unmanageable computational cost. Therefore, the volume needs to be increased to sizes that force the sacrifice of some physical phenomena. This is the case in the studies being discussed.

decelerated fire spread. Unfortunately, the authors do not provide an explanation that clarifies this point.

A2.85. In a similar manner, the authors show that the absence of cavity barriers results in significantly higher vertical fire spread as well as horizontal fire spread. Given the mesh size used, this observation needs to be treated with great caution because the entire façade system is within a single cell and as such the intricacies of the individual components are not captured. Any near surface mesh refinement (not explained in the paper) will affect the results of the model and will have to be analysed in much greater detail.

A2.86. In general terms this study agrees with the observations presented in the Phase One report\(^{337}\) and allows the importance of vertical shafts and internal ignition induced by the external fire to be explored.

A2.87. Nevertheless, this information, even if treated in a qualitative manner, is interesting and useful and shows that these two specific features can serve to enhance the rate of vertical fire spread. The observations that cavity barriers will have little impact on the fire spread rate is also in agreement with the descriptions presented in my phase one report.\(^{338}\) The overall vertical fire spread rates are consistent with those reported in the Phase One report.\(^{339}\)

A2.88. The final paper of the series\(^{340}\) addresses lateral fire spread. As explained in the comments above, this paper is in general agreement with my Phase One report,\(^{341}\) but nevertheless the results need to be treated with a significant degree of caution. Lateral fire spread is a very different mode of fire spread than vertical fire spread. It is much weaker and therefore the influence of encapsulation is far greater. The condition by which the burning of the ACM infill material dominates over all other aspects of the problem i.e. the only condition for which the model has been validated, is highly unlikely. The model does not address any of these features and therefore the results should simply be taken as an illustration of what could have potentially happened.

A2.89. The coincidence between the Grenfell Tower fire images and the model prediction is not fortuitous. The model does not have a sophisticated extinction mechanism and therefore will continue to sustain fire spread which will follow the natural trends defined by buoyancy. This applies to the model and to reality. Nevertheless, to be able to match the spread rate, some of the many variables of the model must have been calibrated and unfortunately the

\(^{337}\) Grenfell Tower Inquiry: Phase 1 Report, Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017, Chairman: The Rt Hon Sir Martin Moore-Bick, October 2019. (INQ000014818)

\(^{338}\) Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. (JTOR00000001)

\(^{339}\) Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. (JTOR00000001)


\(^{341}\) Torero, J.L. Grenfell Tower: Phase One Report, 23rd May 2018. (JTOR00000001)
paper does not discuss the manner in which this was done. This is acknowledged by the authors in the conclusions of the paper.

A2.90. The analysis of the crown does not consider the particular geometrical conditions of the crown, the formation of a pool fire underneath the ACM due to melting and dripping of burning polyethylene or the role of burning debris in secondary ignitions. All these features were deemed of importance in the Phase One report and have not been considered here.
A3. CHANGES IN REGULATION AND PRACTICE

GENERALITIES

A3.1. The Grenfell Tower fire has had a surprisingly small impact on the manner in which the world sees the effectiveness of fire safety design with regard to the external façade fire typology. Most countries have noted the Grenfell Tower fire and adopted a position that reflects high confidence in their own regulatory approaches towards fire safety. This has resulted in almost no change, even in countries where similar events have occurred and, in many cases, claimed lives. In some cases, where regulatory constraints already existed preventing the use of combustible materials in external façade systems (e.g. Hong Kong, France, Germany, China, etc.), the enforcement of these regulations has been strengthened.

A3.2. The submission by the NFPA\(^{342}\) represents a good example of the confidence described above. The NFPA is an organization that exercises a huge influence in the way fire safety is implemented in the USA and that has extraordinary confidence in their current approach to the external façade fire typology.

A3.3. Heavy reliance on enforcing NFPA 285 is the basis of that confidence and at no point has the capability of this testing protocol to properly assess external façade fires been questioned. Later in this report I have provided an analysis of the capabilities of this test protocol which perhaps serves as a contrasting opinion to the current confidence prevailing in the USA.

A3.4. The requirements imposed by NFPA 285 are deemed to be a “rigorous fire test”\(^{343}\) despite the dissenting opinions of some sectors of the insurance industry.\(^{344}\) As such, and when accompanied by adequate enforcement, it is considered a robust means to control the risk of external façade fires: “The potential risk of such façades systems can be controlled through requirements that limits the combustibility of the façade system by mandating certain test protocols such as NFPA 285 and proper understanding and enforcement of those requirements.”\(^{345}\)

A3.5. In addition, there is a recognition that specification and installation have to be “consistent”\(^{346}\) with the test. As described in the NFPA submission:\(^{347}\) “This can be one of the weakest points in façade fire safety as it requires a high skill level of designers, installers and inspectors. Especially for complex exterior wall systems, it is often minor details that can

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\(^{342}\) National Fire Protection Association, NFPA Response to Grenfell Tower Inquiry, 21 March, 2019. (USA00000001)

\(^{343}\) National Fire Protection Association, NFPA Response to Grenfell Tower Inquiry, 21 March, 2019. (USA00000001)


\(^{345}\) National Fire Protection Association, NFPA Response to Grenfell Tower Inquiry, 21 March, 2019. (USA00000001)

\(^{346}\) National Fire Protection Association, NFPA Response to Grenfell Tower Inquiry, 21 March, 2019. (USA00000001)

\(^{347}\) National Fire Protection Association, NFPA Response to Grenfell Tower Inquiry, 21 March, 2019. (USA00000001)
make a big difference in fire performance making it especially important to be vigilant through all steps of the construction, installation and inspection process.” Nevertheless, the practical meaning of “consistent” is not specified. This is similar to the approach taken in the UK and with potentially the same consequences.

A3.6. It is explicitly recognized that there is significant expert judgement in determining whether a test assembly is “consistent” with a real world system and that this expert judgement can have a significant effect on the results. In the USA, it is the enforcement professionals that have to be able to ascertain those differences and in many cases these enforcement professionals are not “consistent” in their judgement.\textsuperscript{348} “Some of the biggest differences may be found in the enforcement of the requirements.” To achieve an adequate level of consistency, significant weight is put on the competency of professionals, in particular the Authority Having Jurisdiction (AHJ) who is in charge of enforcement.

A3.7. In the USA there are rigorous accreditation processes and requirements for certification that allow the above statement to be justified. These requirements cover the whole range of technical professionals, from installers to design engineers and Authorities Having Jurisdiction (AHJ). The processes of accreditation and certification used in the USA are discussed in detail in the Warren Centre report.\textsuperscript{349}

A3.8. While it is possible to comment on the adequacy of these processes of accreditation and certification, it is clear that they provide a tangible basis for the confidence in the proper utilization of the existing regulation and testing practices. This is clearly reflected in the following statement:\textsuperscript{350} “In the majority of cases and jurisdictions, those involved in the design, construction and inspection processes are typically required to carry some form of certification, licensing, or similar credential that shows that they have achieved some level of competency in the area in which they work.”

A3.9. In the USA, the approach towards fire safety can be different in each State, and therefore there will be differences across the country. Nevertheless, NFPA represents a unifying standard that generally covers, with minor nuances, all fifty States. Thus, all statements made above can be considered as generally applicable across the USA.

A3.10. In Dubai, there was no explicit requirements for façade systems in the 2005 code, and even in 2011, the UAE Fire and Life Safety Code of Practice\textsuperscript{351} did not specify any fire spread limitations on external wall assemblies or any reaction to fire requirements for external components for buildings separated by more than 3 m. Some requirements were adopted

\textsuperscript{348} National Fire Protection Association, NFPA Response to Grenfell Tower Inquiry, 21 March, 2019. (USA00000001)


\textsuperscript{350} National Fire Protection Association, NFPA Response to Grenfell Tower Inquiry, 21 March, 2019. (USA00000001)

\textsuperscript{351} UAE Fire and Life safety Code of Practice, General Headquarters of Civil Defence Ministry of Interior, United Arab Emirates, 2011. (INQ00014966)
after 2012, when references to Euroclass A1\(^{352}\), ASTM E 84\(^{353}\) Class A and NFPA 285 were introduced in the UAE Fire and Life Safety Code of Practice. Detailed mention of these requirements only appears in the update to the Fire and Life Safety Code of Practice of 2018.\(^{354}\) A key change was the adoption of a fire-resistant spandrel for buildings above 15 m. This was in line with requirements already existing in many countries. While the 2018 Fire and Life Safety Code of Practice can be seen as a response to the Grenfell Tower fire, the effort appears to have started before and as a result of the numerous external façade fires that had occurred previously in the UAE. In this document a ban in the application of non-fire rated cladding assemblies is specified for mid-rise and high-rise buildings.\(^{355}\) This ban is accompanied by a ten-point action plan of which the three most relevant points are as follows:

- Core of the façade material shall be tested in naked flame form
- Façade panel as a product must be tested
- Façade system as well as assembly shall be tested (or listed as per test requirements of the code)\(^{356}\)

A3.11. The Fire and Life Safety Code of Practice of 2018\(^{357}\) relies on a very similar set of tests to those currently used in the UK and/or the USA. Nevertheless, the certification of products complements test results with adjudication by a “house of expertise.” The “house of expertise” corresponds to a group of selected fire and life safety consultant companies that “discuss, review and advise” the Civil Defence (AHJ equivalent in the UAE). No specification of the selection process for the “house of expertise” or the competencies that are required from the members is provided and, as indicated by the ten-point action plan, no specific fire safety competency is explicitly required:

“Consultants must have competent and qualified façade specialists in house or shall hire Civil Defence “House of Expertise” who have experience or expertise in façade consultancy for façade design, system selection and supervision of façade contractor.”\(^{358}\)

\(^{354}\) UAE Fire & Life safety Code of Practice, 2018. {INQ00014966}
\(^{355}\) Terence Ronald Jackson, Dubai Civil Defence, Statement to the Grenfell Tower Inquiry, May 1st, 2020. {DCD00000001}
\(^{356}\) Terence Ronald Jackson, Dubai Civil Defence, Statement to the Grenfell Tower Inquiry, May 1st, 2020. {DCD00000001}
\(^{357}\) UAE Fire & Life safety Code of Practice, 2018. {INQ00014966}
\(^{358}\) Terence Ronald Jackson, Dubai Civil Defence, Statement to the Grenfell Tower Inquiry, May 1st, 2020. {DCD00000001}
A3.12. Like in many other countries, enforcement and inspection of façade systems has been strengthened and changes to the regulatory framework have aligned the UAE to existing international regulations, particularly Europe, the UK and the USA. Nevertheless, the changes are in general minor and what is different in the approach taken by the UAE, as described above, is the full confidence in the Civil Defence Authority as the competent authority in charge of making all critical decisions.

A3.13. These are only two examples of the generalized attitude towards eternal façade fire globally, with the only remarkable difference being Australia. Australia will therefore be addressed independently.

THE AUSTRALIAN RESPONSE

A3.14. The Lacrosse Building fire that occurred in Melbourne on the 25th of November, 2014359 was the first external façade fire of significant magnitude to occur in Australia. This fire came together with several other failures that encouraged the Australian State and Federal Governments to undergo a series of studies on the state of the construction industry. The three main studies are the Lambert Report,360 the Shergold & Weir Report361 and the Warren Centre Reports.362 The Warren Centre Reports were a collaboration between the Australian State Governments and the fire safety engineering industry at large. While the Lambert Report was commissioned before the Grenfell Tower fire, the Shergold & Weir report was commissioned in August 2017 immediately after. The Warren Centre Reports had been in planning since 2012, although it was the impetus given by the Grenfell Tower fire tragedy that allowed the study to materialize. The study was officially launched in July 2018.

A3.15. While focusing on the Australian construction industry, these three reports present a deep introspection into professional practice in the construction sector that is applicable globally. These three reports have already had a profound impact in Australian construction and are worthy of detailed scrutiny.

A3.16. It is not the objective of this work to review these studies, because it is in the details of the analysis and recommendations that their richness and universality lies. I therefore respectfully suggest that these are incorporated as essential reference information for the Inquiry.

361 Shergold, P. and Weir, B., Building Confidence – Improving the effectiveness of compliance and enforcement systems for the building and construction industry across Australia, February 2018. {INQ00014963}
A3.17. The Australian response to the Grenfell Tower fire is probably the most comprehensive one globally. As a result of the multiple studies conducted, the Australian response is capable of addressing the problem of cladding fires more as a product of much more comprehensive and complex problems than as the problem in itself. Beyond the reports described above, the Australian response is mostly a State response. There are elements that transcend States and affect the National Construction Code and the Australian Building Codes, but mostly, it is comprised of weakly coordinated activities of three States: New South Wales, Queensland and Victoria.

A3.18. In 2016 and following the Lacrosse fire, Australia adopted a large-scale test for classification of façade systems. This test is the AS5113363 which is mostly identical to BS 8414364. This test was introduced as a complement to AS1530.1365 (Equivalent to BS 476-4166). Testing in compliance with this change had not become generalized when the Grenfell Tower fire occurred. Thus, the testing regime in Australia was very similar, but less developed, than in the UK. Generalized acceptance of desktop studies to establish comparative compliances was prevalent in Australia, in a similar manner as was in the UK.

A3.19. The Inquiry has received responses from all three States, New South Wales,367 Queensland368 and Victoria.369 Each State followed an independent approach but there are commonalities in the manner they address the problem. All three states refer to the Lambert and Shergold & Weir reports and many of the responses stem from the recommendations provided in these reports. In all cases, the Grenfell Tower fire was a catalyst for many of the actions reported.

A3.20. The actions conducted by all three states are extensive and they address the strengthening of enforcement, enhancing regulation, strengthening professional practice and improvement of system testing. All States implemented extensive inspection schemes to identify buildings that were deemed as hazardous, and enforced and encouraged extensive retrofit.

369 Department of Environment, Land, Water and Planning (DELWP) in collaboration with the Victorian Building Authority (VBA), Submission to the Grenfell Tower Inquiry on Victoria’s Response to Combustible Cladding, September 2020. (VIC00000001)
A3.21. All states introduced strong schemes to strengthen enforcement which had been perceived as one of the weakest processes in the Australian approach to construction.

A3.22. All states recognized the need to clarify competency at all levels, with New South Wales introducing the strongest regulatory changes in what concerns certification. Queensland had already implemented a clear certification process, the Registered Professional Engineer Queensland (RPEQ) that delivers certification for fire engineers in collaboration with the Institution of Fire Engineers (UK) and thus no further changes were made. The weakest response has been that of Victoria, where very few steps have been taken towards recognizing the need for professional certification.

A3.23. Victoria’s approach towards improving professional practice has been to develop a fire risk assessment tool that enables those auditing buildings to provide an output that then is assessed by an ‘expert panel’ to establish the level of hazard posed by a specific façade system for a specific building Fire Safety Strategy. While a tool of this nature might be useful as a first step towards conservatively identify buildings with potential problems, it is clear that it is no substitute to a competent professional assessment. It is important to note that Victoria strongly emphasizes expert opinion as a means to determine hazard, nevertheless it does not provide any clear definitions of what establishes expert knowledge or how the experts are selected / identified.

A3.24. Uniquely among all States was Queensland with a proposal to enable certified Fire Engineers, Building Certifiers and Building Inspectors to acquire the necessary knowledge to conduct adequate risk assessment of buildings with complex and combustible cladding systems. The necessary knowledge was delivered through a series of CPD courses that addressed the fundamental principles of fire safe design of high-rise buildings with complex and combustible façade systems.

A3.25. The State of Victoria took a much more centralized approach by concentrating a series of enforcement and regulatory powers around the Minister and the Victoria Building Authority that enabled them to conduct audits, assess them, and require and enforce rectification. Furthermore, the State of Victoria established Cladding Safety Victoria (CSV) in July 2019 to provide support and guidance to building owners and occupants of buildings with combustible cladding, particularly where rectification work was required to reduce risks to an acceptable level.

A3.26. Testing was only addressed by Queensland where the State Government commissioned the Cladding Materials Library which remains the most comprehensive proposition to assess performance of façade systems. The utilization of AS1530.1 and AS5113 still remains the

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370 https://claddingmaterialslibrary.com
main vehicle to address material and system performance respectively. All states eventually enacted bans on different materials.

A3.27. The Table A-1 attempts to structure the key information provided in the responses in the four groups described above. The text is taken verbatim from the submissions.
Table A1-1: Summary of different responses from Australia

<table>
<thead>
<tr>
<th>Strengthening Enforcement</th>
<th>New South Wales(^{373})</th>
<th>Queensland(^{374})</th>
<th>Victoria(^{375})</th>
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<tr>
<td><strong>A strengthened system for regulating certifiers is being introduced via the Building and Development Certifiers Act 2018 and an action plan for certifiers that aims to:</strong> improve certifier independence; clarify the role and responsibilities of certifiers; strengthen conflict of interest provisions; and enhance compliance and enforcement provisions. <strong>Amendments to the Environmental Planning and Assessment Act 1979 in November 2017 consolidated the provisions for building and subdivision certification. These provisions include new compliance powers, a revised occupation certificate regime and the introduction of subdivision works certificates. Major amendments were made to the Environmental Planning and Assessment Regulation 2000 in 2017, to improve fire safety in new and existing buildings. These were aimed at improving rigour and checking of the design, approval, construction and maintenance phases of the building life cycle related to fire safety. Building Products (Safety) Act 2017 (BPS Act) On 18 December 2017, the NSW Government introduced the BPS Act as part of its 10-point plan for</strong></td>
<td>The Non-Conforming Building Products Audit Taskforce completed an audit of all publicly owned buildings. Those identified as having combustible cladding are now undergoing detailed fire engineering assessment to determine the fire risk posed by the cladding and to identify the extent of remediation required. The majority of identified privately owned buildings are now in part three of the compulsory audit process. Engage a fire engineer to prepare a building fire safety risk assessment. This requires: (a) Testing to determine the composition of the cladding and identify the type of insulation material used. (b) Identifying the percentage of the building covered by the cladding. (c) Determining whether rectification is necessary (noting that rectification options will not be provided). (d) Identifying any short-term risk mitigation measures that should occur (such as prohibiting smoking and barbecues on balconies).</td>
<td>In 2015, a number of buildings were audited through a targeted, risk-based audit instigated by the Victoria Building Authority (VBA). This paper-based audit focused on high rise residential and public buildings in inner Melbourne that were built between 1 January 2005 and 30 April 2015. This process found that 51 percent of the buildings audited were assessed as clad with non-compliant external cladding. It was concluded that all but two of those buildings were still safe to occupy pending future rectification work because they were sufficiently protected by other fire safety features, with only two buildings requiring urgent remedial works. Following the Grenfell tragedy, the Victorian Government established the Taskforce to: (a) assess the extent of non-compliant external cladding on Victorian buildings; (b) advise on the rectification of non-compliant external cladding; and (c) recommend changes to the regulatory system. As at 31 December 2019, over 2,600 inspections have been conducted through the Statewide Cladding Audit (the Audit) and preceding audits. The government has also established the world’s first dedicated cladding rectification agency to coordinate</td>
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fire safety. The BPS Act is an important step in ensuring fire safety in high-rise buildings and provides enhanced powers to monitor and restrict the use of unsafe building products in NSW. The powers under the BPS Act promote the safety of residential, commercial and industrial buildings by:

- (a) giving the Commissioner for NSW Fair Trading (the Commissioner) the power to prohibit the use of a building product when satisfied on reasonable grounds that its use is unsafe,
- (b) enabling the Commissioner to identify buildings where building products have been used in a way that is prohibited (including buildings in which building products were used before the prohibition was imposed),
- (c) enabling councils or other relevant enforcement authorities to require building products to be rectified, by giving the relevant authority the power to issue a rectification order to eliminate or minimise the identified safety risk,
- (d) enabling the investigation and assessment of building products so that unsafe uses of building products can be identified and prevented.

a AUS600 million program of government funded rectification of privately owned residential buildings and AUS150 million for government owned buildings over the next five years.

Once a risk rating (Extreme, High, Moderate or Low) is determined, the ARP makes recommendations to the Municipal Building Surveyor (MBS), who is then required to make their own determination of how to proceed.

Using powers available under the Building Act, the Minister for Planning can designate the VBA as the MBS for a particular building.

Minister’s Guideline MG-14: Issue of building permits where building work involves the use of certain cladding products (MG-14) was published in the Victoria Government Gazette on 13 March 2018 and subsequently published on the VBA website. MG-14 is enforceable through action against building surveyors by the VBA. Building surveyors must ‘have regard for’ MG-14 and, if it can be shown that they have not done so, they can be subject to disciplinary action and financial penalties.

At the time that MG-14 was issued, legislation did not provide for a direct ban of specific building materials. The Taskforce recommended that the government restrict the use of aluminium composite panels with a polyethylene core and expanded polystyrene cladding on multi-storey buildings in Victoria. In response, the Building Act has been amended to provide the Minister with the power to declare a ban on the use of high-risk external cladding products. Section 192B of the Building Act was inserted by the Building Amendment (Registration of Building Trades
| **Enhancing Regulation** | The Queensland Government established the Non-Conforming Building Products Audit Taskforce in June 2017 to identify and make recommendations to government on the risks, remediation and performance-based solutions regarding non-conforming building products, particularly potentially combustible cladding including aluminium composite panels (ACP).

In October 2019, the Safer Buildings Taskforce was established in Queensland to build on the work of the former Audit Taskforce, with a focus on delivering the necessary policy and practice to ensure the safety of Queensland’s building infrastructure is maintained.

Victorian Government introduced legislation to provide for Cladding Rectification Agreements to enable owners to rectify dangerous cladding and pay it off via their council rates. The Cladding Rectification Agreements are modelled on Environmental Upgrade Agreements. The arrangement is designed to be between owners (or owners corporations), lenders and local councils – providing long-term (minimum of ten years) loans to pay for building work to rectify cladding. Owners would be charged via their council rates over a minimum period of ten years, with costs transferred with the property if sold.

Despite interest from lenders, owners and some local councils, no owners have yet entered into a Cladding Rectification Agreements to date.

In October 2019, the government announced that it will, under some circumstances, pursue building practitioners on behalf of owners of apartments covered in combustible cladding.

The government has established an expert advisory panel to assist with review of the legislation, which was formally commenced in December 2019.

| **Strengthening Professional Practice** | Queensland has a framework that enables practitioners to act as a group of self-determinative and autonomous professionals. The role and duties of engineers are outlined within the Professional Engineers Act 2002, and overseen by the Board of Professional Engineers of Queensland.

Taskforce (the Taskforce) was established as a dedicated team of experts working across

Risk Assessment Tool: The Tool was developed to assess the danger to life and property arising from fire safety issues associated with the presence of combustible cladding. The tool includes two sections – one which assess the risk of fire ignition and spread, and one which assess the ability of occupants to safely egress in the event of a fire. |
<table>
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<tr>
<th>Requirement categories of building practitioners who are defined as ‘building designers’ to formally declare that plans, specifications and performance solutions they provide are compliant with the Building Code of Australia (BCA), and that builders declare that buildings are built according to the declared plans.</th>
<th>Introduce a new registration scheme for ‘building designers’. These reforms were aimed at improving the quality of checks made throughout the design, approval, construction and maintenance phases of fire safety systems. Part of these reforms require certain functions to be undertaken by a competent fire safety practitioner.</th>
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<td>government departments to accelerate our approach, to guide our building industry, its professionals and private building owners and to create a call to action across the State. The Taskforce has also been involved in augmenting industry capability through the continuing professional development activities for Fire Engineers and other professionals. A professional engineer practises in the field of fire engineering (also called fire safety engineering) and must have an appropriate (approved) qualification. There is also an experience requirement which, if properly attained, should provide a fire engineer with the requisite knowledge to apply scientific and engineering principles to their evaluation and design of fire safety strategies. Appropriate fire safety strategies will protect a building (and ultimately people and their environment) from the consequences of a fire. Fire engineers must demonstrate a base competence, maintain ongoing professional development and registration, and are legislatively obligated to comply with a code of practice. They must be involved if a building design proposal includes a fire safety related, performance-based assessment. The identified need for continuing professional development (CPD) for fire engineers culminated in the establishment of a dedicated five-day full-time course titled 'External Fire Spread Risk in Tall Building Design'. The need to provide professional development for building surveyors and the broader industry professionals culminated in the establishment of a</td>
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<td>While safety has been the immediate focus of the government’s response, work has also been undertaken to bring practitioners to account. As at 31 December 2019, the VBA has suspended two building practitioners (one builder and one building surveyor) in relation to installation of non-compliant cladding and has issued nine show cause notices, which are the initial stage of disciplinary action against registered practitioners.</td>
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dedicated two day full-time CPO and general information course titled ‘Safer Buildings for Queensland - Assessing Buildings with Combustible Cladding’, a collaboration between the Queensland Government and the University of Queensland.

The Queensland Government and its partner institutions were acutely aware that in providing design solutions for buildings, competent fire engineers needed to possess the understanding of fundamental processes regarding Fire Safety Strategy, cladding design, and the interactions between the façade cladding and the building in the event of a fire. All of these issues were included in the development of the CPD curriculum.

**Improving System Testing**

A comprehensive scheme for unsafe building products under the Building Products (Safety) Act 2017 has been introduced.

On 15 August 2018, the Fair Trading Commissioner published a building product use ban for ACP comprised of a core of greater than 30% polyethylene in any external cladding, external wall, external insulation, façade or rendered finish in certain multi-storey buildings, subject to specific exceptions (the cladding ban). The Commissioner considered a broad range of sources when making the cladding ban, such as the public submissions, expert advice, relevant national and international reports, and NSW Cladding Taskforce data.

Queensland actively pursued and supported the NCC amendments to introduce AS5113, it also recognised that the time and cost associated with large-scale facade tests could be problematic for owners seeking assessment of the cladding products on their building and also expert advice on whether cladding rectification was required.

In 2017 the Taskforce has worked with experts from the University of Queensland to develop a cladding materials library. The library will be used as a reference and catalogue for fire hazardous building products so that the industry and the public can ascertain if a cladding product is safe to use.

In July 2019 Queensland instated a combustible cladding ban. The combustible cladding ban would extend to all aluminium composite panels with a PE core of greater than 30 per cent, and it would restrict usage across all buildings in Queensland.

In March 2018, the Minister for Planning set a new requirement that expanded polystyrene, as well as aluminium composite panels with a core comprising greater than 30 per cent by mass of polyethylene, can only be used on multi-storey buildings in Victoria if the building permit includes a determination by the Building Appeals Board that use of such materials is in accordance with the Building Act and the Building Regulations 2018 (the Regulations). This requirement applies to buildings comprising more than two residences, health care buildings or schools.
APPENDIX B: ASSESSMENT OF RELEVANT TESTING PROTOCOLS THAT DO NOT FORM PART OF THE UK TESTING REGIMES

B0.1. As a part of this assessment of the adequacy of the testing protocols underpinning the UK regulation and guidance relevant to external wall systems, additional reviews have been undertaken of the information delivered by a limited range of corresponding international testing protocols to determine if any of these tests might provide any noteworthy information that could be useful to the discussion moving forward.

B0.2. The list of tests are assessed was not exhaustive and did not yield any particularly noteworthy findings however the information gathered is briefly summarised here for information.

B1. AMERICAN STANDARD NFPA 285: 2019

B1.1. In the United States, test method NFPA 285, Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Wall Assemblies Containing Combustible Components\(^{376}\), is a large-scale fire test for exterior wall assemblies which is notionally equivalent to BS 8414 in the UK.

B1.2. Regulation in the US is structured differently as a result of the State / Federal system. Regulation is managed at State level and varies from State to State, however the International Building Code (IBC)\(^{377}\) (formerly Uniform Building Code) forms the basis of the majority of the States’ regulation.

B1.3. The IBC classifies buildings into fire construction types, which each have limitations / requirements placed on them, for example the fire resistance rating of the structure or maximum permissible number of storeys. Typically, the stricter the requirements, the greater the permissible number of storeys.

B1.4. Construction Types I to IV require a non-combustible external wall. Combustible elements may still be used within these ensemble arrangements, however there will be certain restrictions placed on them. One such restriction which is typically used is that the wall assembly needs to be tested according to NFPA 285 and assessed in accordance with its

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\(^{376}\) NFPA 285 2019 (INQ00014961)
\(^{377}\) IBC 2018
acceptance criteria. Unlike in the UK, the performance criteria are specified within the NFPA 285 test document i.e. there is no equivalent to the UK’s BR 135 guidance document.

**B1.5. Example scenarios for which the IBC requires the use of NFPA 285 testing are as follows:**

I. The use of specific products in an exterior wall assembly such as:
   - MCM (Metal Composite Materials)\(^{378}\)
   - HPL (High-Pressure Decorative Exterior-Grade Compact Laminates)
   - Mechanical equipment screens constructed of combustible materials

II. If a designer wishes to exclude the use of cavity barriers (fire blocking), the wall assemblies must demonstrate that they meet the acceptance criteria of NFPA 285 regardless.

III. Where exterior wall assemblies contain a combustible water-resistive barrier (aside from very specific criteria) the exterior wall assembly must meet the criteria of NFPA 285.

**B1.6. As per other regulatory systems, the IBC makes numerous statements to the effect that the tested specimen must resemble that which is intended for use. Thus, as per BS 8414, NFPA 285 can be classified as a scenario test.**

**B1.7. Designers in the US (and often internationally) may also follow NFPA documents such as the NFPA 5000\(^ {379}\) Building Construction and Safety Code. This document also specifies the need for NFPA 285 testing. It states that a building of Type I to IV construction greater than 40ft (~12m) in height should have the external wall tested to NFPA 285.**

**B1.8. For all other buildings that require construction Types I to IV and therefore “non-combustible external walls”, NFPA 5000 allows for combustible elements to be used, so long as the assembly is demonstrated to meet the criteria of NFPA 285, much as per the IBC.**

**NFPA 285 TESTING PROTOCOL AND FAILURE CRITERIA**

**B1.9.** The NFPA 285 test facility comprises a two-storey concrete rig of fixed dimensions. The setup creates an upper and lower compartment with one face missing. A mock-up of an external wall assembly is constructed within a movable test frame that is then attached to the front of the rig to close the compartments. Unlike BS 8414 there is no wing wall, only a single flat exterior surface. A diagram of the setup is shown in Figure A2-1.

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\(^{378}\) It is understood that ACM panels would fall within this classification.

\(^{379}\) NFPA 5000 2018
B1.10. The test specimen must leave a window opening of fixed dimensions, centred at a fixed height above the ground floor slab. The finish around the “window” opening is also prescribed by the standard. It can either be aluminium sheet metal conforming to certain size constrictions, or else “representative” of the end use construction detailing.

B1.11. NFPA 285 is a scenario test and therefore, within the constraints posed by the fixed dimensions of the test rig and opening, the tested ensemble is expected to be as representative as possible of end-use condition.

“Details of the construction of the test specimen shall be representative of actual field installations in accordance with the manufacturer’s instructions.”

B1.12. NFPA Rather than a wooden crib, NFPA 285 uses a pair of gas burners to produce a flame that emerges from the opening and impinges on the external surface. The main burner is located in the lower compartment and second smaller burner is located towards the top of the opening, more or less on the same plane (see Figure 15). Both burners have prescribed dimensions and energy output to ensure continuity across test rigs.

B1.13. Publicly available literature\textsuperscript{380} reports that the heat-flux that is exerted on the external façade is of the order of 40\text{kw/m$^2$}, which is significantly lower than that in BS 8414 but within the range expected as a result of external flaming or a wall flame (albeit at the lower end of the range).

B1.14. A number of thermocouples are placed in and around the test specimen and within the upper compartment. As with BS 8414, these measurements form the basis against which pass / fail criteria are assessed. Locations of thermocouples adjacent to and within the test sample are shown in Figure A2-2. The upper row of external thermocouples (labelled X – Y in Figure A2-2) are approximately 3m above the window opening.

B1.15. There are also three heat flux meters measuring flux to the external surface. These verify that the burners are operating properly and producing the expected thermal boundary condition. They are located at 2ft, 3ft, and 4ft (0.61m, 0.91m and 1.22m) above the centreline of the opening.

B1.16. The main room burner is ignited and temperatures and heat fluxes are checked to ensure it is operating within the prescribed boundaries. Five minutes later, the window burner is activated. A further 25 minutes later, both burners are extinguished and all data and image acquisition is halted.

Figure A2-1: A schematic of the side view of the test rig and test specimen.  

B1.17. No justification for this mode of operation has been found but it appears that the intention is to roughly approximate a “typical real” fire where the fire develops inside the room, breaks out of the opening and additional burning occurs with the extra oxygen available. As per BS 8414, the duration is 30 minutes which is considered a typical upper bound compartment fire duration.

B1.18. Finally, ventilation conditions for the upper and lower compartment are also specified. The window opening to the lower compartment is the only allowable opening at the lower level.

An access opening (presumably door sized and facing the rear of the test rig, but not specified or shown in diagrams) is left open in the upper compartment.

B1.19. The performance criteria for NFPA 285 are a range of limits that, if surpassed within the 30-minute measurement period, result in the specimen failing. They are in the form of failure temperatures measured by thermocouples or visual observation of the location of flaming.

B1.20. The temperature failure criteria are 538°C (1000°F) in the gas phase (external or cavity) thermocouples and 417°C (750°F) in the solid phase thermocouples (mid depth within combustible cavity insulation). The locations of the thermocouples relevant to these criteria are shown by the red dotted line in Figure 16. No explanation for the choice of temperature thresholds is provided in the standard.

B1.21. Failure due to unacceptable levels of flame spread is determined by the presence of flame observed above the centreline of the upper compartment’s roof slab, or laterally beyond the internal surfaces of the compartment walls i.e. out with the red shaded area in Figure A2-2.

B1.22. Failure criteria are also defined for the upper compartment. A gas phase thermocouple measurement of 278°C (500°F), adjacent to the internal surface of the test specimen, is adjudged as a failure. It should be noted that there are no openings to this compartment on the fire face, therefore this level of heat would only reach this location via heat transfer through the test specimen.

B1.23. While not explicitly described in the document, it is assumed this temperature represents an ignition criterion for easily ignitable materials, similar in nature to the “cotton wool test” often utilised in fire resistance furnace testing. The rationale is that the wall system should provide sufficient insulation to prevent materials near to its unexposed side being ignited as a result of the heat being transferred through the wall.

B1.24. On the same basis, the presence of a flame within the upper compartment, as a result of flame penetration through the test specimen, also results in a failure. Again, this mimics the failure criteria of fire resistance furnace testing.

B1.25. Figure A2-3 shows an image of a test in progress.
Figure A2-2: Schematic of the test frame showing relative locations of the sample, opening, and thermocouple locations.\footnote{NFPA 285 2019 (INQ00014961)}
Figure A2-3: NFPA 285 test in process.
B1.26. While there are pass / fail criteria for the NFPA 285 test itself, unlike the UK approach, there are no higher-level performance criteria (equivalent to functional requirement B4) against which to assess the result of the test. The US code system is presented as a set of rules to be adhered to, rather than an engineering process. Therefore, if the test is passed, the performance of the external wall ensemble is adjudged to be adequate, providing the necessary level of performance consistent with the wider prescriptive requirements, and no further consideration is required by a competent professional.

B1.27. Broadly, the context in which an NFPA 285 test is required by IBC or NFPA 5000 is when the project wishes to include combustible components in a wall assembly that is otherwise required by code to be non-combustible. It can be inferred from this that a pass in the test is deemed to be equal to non-combustible behaviour. In actuality, a pass in NFPA 285 equates to a limited amount of fire spread over a period of 30 minutes and therefore this equivalency has the same weaknesses described above in relation to the failure criteria for BS 8414.

B1.28. Having distilled the project characteristics and placed the design in a classification system (Type I to Type V construction), the context of the end-use application of the external wall ensemble is lost and is entirely removed from the pass/fail classification system of the test. The aforementioned imprecise equivalency (limited fire spread = non-combustible) is made independently of the end-use scenario and does not consider the nuanced performance requirements of individual fire safety strategies through the building classification.

B1.29. It is therefore possible that an external wall system that meets the pass criteria of NFPA 285 may be appropriate for some end-use scenarios, but not others. While in the UK system, the onus is openly placed on the designer/engineer to interpret the test results and observations in the context of the end-use scenario, as stated previously, in the US system, no such assessment is mandated.

B1.30. Accordingly, a façade ensemble that meets the criteria of NFPA 285 may not be appropriate for a HRRB, yet still be utilised in this application within the US regulatory framework.

B1.31. To assess the adequacy of NFPA 285 when applied to HRRBs, independently of the regulatory system in which it is applied, the details of the pass / fail criteria of the test become the critical metric.

B1.32. In the context of a HRRB with a stay-put strategy, meeting the criteria of NFPA 285 in no way guarantees adequacy for this application. There is no extinction criterion, and fire can establish itself on the façade system to an extent that it will threaten the compartment immediately above the fire unit. As previously stated, this would likely result in a fire entering the unit above, thereby breaking the restrictions required by a 'stay-put' policy.
B1.33. In NFPA 285, the flame location is observed and the failure criteria define a maximum extent of propagation for the 30-minute duration of the test. So, this can be inferred as a crude measure of the flame spread rate at the initial stages of the fire. However, a direct rate of flame spread is not recorded in the test and neither is the propensity for the flame spread rate to accelerate as the external fire develops beyond the duration of the test. In addition, the test does not provide any direct means to establish $L_h$. As with BS 8414, the recorded temperature data will provide little useful information in respect of this assessment.

B1.34. Spread to the inside of the compartment above is to an extent accounted for, albeit in a similar manner to fire resistance testing (penetration of flame or excessive heat passage by conduction), however such a measure of resilience to fire spread is difficult to assess because a reduction of heat transfer to the interior can be achieved by thermal barriers with no requirements to resist fire penetration.

B1.35. NFPA 285 has exactly the same limitations as BS 8414 when it comes to the assessment of mechanical failure, including encapsulation.

B1.36. The failure criteria used in NFPA 285 therefore do not provide an adequate measure of the test specimen’s suitability for use in a HRRB such as Grenfell Tower and the data recorded will provide little useful additional information by which an engineer can transform the test output into a useful tool to this effect.

B1.37. In summary, the NFPA 285 testing protocol is conceived as a scenario test directly applicable to a fire exiting a window of a compartment. While there are significant differences between NFPA 285 and BS 8414, both tests are intended to represent the same scenario.

B1.38. NFPA 285 was conceived as an acceptance test and therefore does not require interpretation by a competent professional. This is compatible with the US regulatory framework but is inconsistent with the approach towards fire regulation adopted currently in the UK.

B1.39. Otherwise, NFPA has very similar limitations to those already described for BS 8414. It does not provide any additional information that cannot be obtained from BS 8414 and the testing protocols used cannot provide further data in support of building design.
B2. ISO 13785

B2.1. The ISO 13785 test standard is divided into two parts, an “intermediate-scale” test and a “large-scale” test as follows:

“The two parts of ISO 13785 provide two methods of test: an intermediate scale test specified in this part, which should only be used for screening or evaluation of sub-components or “families of products”, and a large-scale test specified in Part 2, which should be used to provide the end-use evaluation of all aspects of the façade system.”

B2.2. Diagrammatic representations of the intermediate- and large-scale tests respectively are shown in Figures A2-4 and A2-5.

B2.3. Whether considering the intermediate- or large-scale test, this standard is essentially identical in general concept to BS 8414 and NFPA 285 in that it is a scenario test intended to represent a fire spilling from a post-flashover compartment fire an impinging on an external wall system.

B2.4. The introductions to both parts 1 and 2 describe the scenario as a fully-developed compartment fire “venting through a window and impinging directly on to a façade”. The rationale behind the variation of scales is explained as follows:

B2.5. The intermediate-scale test, as described above, is intended only to be “be used for screening or evaluation of sub-components or “families of products” ”, and “... may be used for comparative purposes or to ensure the existence of a certain quality of performance considered to have a bearing on the fire performance of the façades generally. No other meaning is attached to performance in this test.”

B2.6. Whereas the large-scale test “... is intended to determine the contribution from the façade components to upward fire spread, beyond the floor immediately above the level of fire origin (i.e. the contribution from façade components for fire to spread from the level of fire origin to two levels above, also called leap-frogging).”

B2.7. The intermediate-scale test is therefore effectively intended to be a more cost effective means to provide information for the development of aspects of an external wall system whereas the large-scale test is intended to illustrate whole system performance.

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Figure A2-4: ISO 13785-1:2002 test apparatus diagram.

Key
1. Position of heat flux meter
2. Back wall
3. Draught screen
4. Test specimen back wall
5. Test specimen side wall
6. Ignition burner: height 150 mm, depth 100 mm, width 1200 mm
X. Surface thermocouple positions
Figure A2-5: ISO 13785-2:2002 testing apparatus diagram.
While this distinction is made, the test standard as a whole ultimately simply provides a set of data as a mechanism for the user / commissioner of the test to assess the fire spread performance of an external wall system. It is not aligned to any particular regulatory system and thus there are no pass/fail criteria specified or guidance on appropriate interpretation of the results.

The data provided is very similar to in essence to the BS 8414 and NFPA 285 tests, consisting of a range of temperature and heat flux measurements, coupled with visual observations of flame front locations etc. It is of note that the definition of what constitutes the flame front is not explicitly defined.

In this regard then, the output from these tests does not provide any additional information in regard to performance metrics relevant to external fire spread or other advantageous protocols that could be used in support of HRRB design.

The LPS standards are produced and utilised by the Loss Prevention Certification Board (LPCB), a part of BRE, which defines its roles as working “with industry and insurers since 1868 to set the standards needed to make sure that fire and security products perform effectively”\(^\text{384}\). LPS 1581\(^\text{385}\) and 1582\(^\text{386}\) are two of its standards that relate to assessment of external wall systems.

The LPCB standard LPS 1581 defines “Requirements and tests for LPCB approval of non-load bearing external cladding systems applied to the masonry face of a building”. It is the LPC equivalent to BS 8414-1 and indeed states:

“The BS 8414-1 Fire performance of external cladding systems, Part 1: Test method for nonloadbearing external cladding systems applied to the face of the building test method forms the basis of the full scale test in this standard.”

Likewise, LPS 1582, titled, “Requirements and tests for LPCB approval of Non-load bearing external cladding systems fixed to and supported by a structural steel frame”, makes an identical statement concerning BS 8414-2.

These tests are described in detail in section 12 of this report.
In addition, the foreword of both standards state:

“This standard builds on the guidance set out in section 12 of Volume 2 of Approved Document B – Fire safety, and BR 135 Fire performance of external thermal insulation for walls of multi-storey building to address some of the fire safety and property protection issues associated with external fire spread in multi-storey buildings.”

These standards are therefore intended to be an extension to the typical UK regulatory assessment process for the purpose of assessing and approving external wall system use by insurers.

In addition to the baseline BS 8414 standard tests on which these standards are based, the LPS standards require all component parts of a tested system to be classified by the European reaction-to-fire classification system i.e. EN 13501-1, and additionally any insulation material to undertake a “ramped basket test” to establish if it has any propensity to exhibit “glowing combustion”.

No means is however provided for interpretation of this additional information, therefore it is presumably provided only required as additional information for a subsequent assessment of the system.

Additional measurements are prescribed and include extra thermocouples, and observation of debris / molten material falling out with a designated area (the “crib collapse zone”) at the base of the test rig.

These measurements do not however provide any additional means for assessing the relevant performance metrics (potential for ignition, rate of fire spread, tendency to extinction) beyond that already (inadequately) provided by the baseline BS 8414 tests.

Unlike BS 8414-1 and -2, the LPS standards do define failure criteria for the tested systems. These include:

I. Early termination of the test for safety reasons within 30 minutes of the start of the test

II. Visible flaming for more than 60 seconds beyond the confines of the test rig within 30 minutes of the start of the test

III. A temperature in excess of 600°C recorded by any internal or external thermocouple located at Level 2 for period of at least 30s within 30 minutes of the start of the test

IV. Collapse of the system, or part thereof, onto the floor outside the designated “crib collapse zone” within 60 minutes of the start of the test

V. Development of burning debris or a pool fire outside of the designated “crib collapse zone” within 60 minutes of the start of the test
VI. Excessive smouldering propagation (specific limits defined) within the insulation products within 24 of the end of the test

B3.12. LPS 1582 has an additional failure criterion related to “system burn through” defined as “continuous flaming (flame with a duration in excess of 60 seconds) observed anywhere on the internal surface of the test specimen at or above a height of 2m below Level 1 within the duration of the full 60 minute test period”.

B3.13. Therefore, while these represent an extension of the failure criteria of BR 135, these failure criteria do not provide any additional meaningful way to assess if the tested system can be considered compliant with the Building Regulations.

B3.14. Both documents also state the range to which systems can be varied i.e. changes in insulation thickness, cavity depth etc. while still being covered by the same assessment. No justification is given for why the permitted changes would not be expected to significantly alter the observed performance.

B3.15. In summary therefore, again, the output from these tests does not provide any additional information in regard to performance metrics relevant to external fire spread or other advantageous protocols that could be used in support of HRRB design.


B4.1. The Building Code of Australia Volume 1\(^{387}\) requires external wall system to be classified according to AS 5113\(^{388}\). The scope of this document states:

“This Standard sets out the procedures and criteria for the classification of external walls of buildings according to their tendency to spread fire:

(a) Via the external wall;

(b) Between adjacent buildings;

And production of falling debris that could be hazardous to evacuating occupants and fire fighters.”


\(^{388}\) AS 2113:2016 Classification of external walls of buildings based on reaction-to-fire performance, Standards Australia.
B4.2. This standard does not specify its own testing protocol but allows the user to select either of the previously described test standards of ISO 13785 or BS 8414. In both options, the use of a timber crib as an ignition source is required. The AS 5113 standard then sets out its own range of performance criteria according to the test chosen.

B4.3. In both cases, the performance criteria are similar to those of other testing protocols described here, based around temperature limits at specific heights, limitations on the extent of flaming in regards the edges of the test samples, restriction on penetration to the unexposed side of the external wall system, and restrictions on falling debris.

B4.4. Unlike other testing protocols, the appendices to this standard do provide an indication of the objective behind each of the specified failure criteria. As an example, the table stating the intent behind the failure criteria applied to BS 8414 tests is reproduced in Figure A2 – 6 below.

<table>
<thead>
<tr>
<th>Risk Mitigation</th>
<th>Measurement/Observation</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prevention of fire spread to two floor levels above fire</td>
<td>Temperature 50 mm from façade, 5 m above opening</td>
<td>≤800°C</td>
</tr>
<tr>
<td>Prevention of incipient fire spread to two floor levels above fire</td>
<td>Internal temperatures of materials and cavities 5 m above opening</td>
<td>≤250°C</td>
</tr>
<tr>
<td>Prevent fire spread to two floor levels above fire and lateral spread</td>
<td>Flame spread beyond confines of specimen</td>
<td>Not permitted</td>
</tr>
<tr>
<td>Prevent fire spread to floors below</td>
<td>Continuous flaming on ground for more than 20 s from debris or molten material</td>
<td>Not permitted</td>
</tr>
<tr>
<td>Limit debris impact with fire fighters, occupants and passers-by</td>
<td>Total mass of debris</td>
<td>≤2 kg</td>
</tr>
<tr>
<td>Prevent fire spread to floor above if wall not fire resistant</td>
<td>Non-fire side temperature 900 mm above opening</td>
<td>≤180K rise</td>
</tr>
<tr>
<td>Prevent fire spread to floor above if wall not fire resistant</td>
<td>Flaming on non-fire side or the occurrence of openings in the unexposed face</td>
<td>Not permitted</td>
</tr>
</tbody>
</table>

Figure A2-6: Table from AS 5113 describing the intent of the classification criteria applied to tests conducted according to BS 8414.
B4.5. Given the nature of the measurement techniques deployed in the tests however, the limitations that apply to the underlying test protocols (i.e. their inability to provide a means to establish the key performance metrics of potential for ignition, rate of fire spread, tendency to extinction) in terms of assessing the adequacy of resistance to external fire spread, must also apply to this standard too.

B4.6. Thus again, the output from assessment by this standard does not provide information to enable an adequate assessment of resistance to external fire spread or other advantageous protocols that could be used in support of HRRB design.

B5. SWEDISH STANDARD SP FIRE 105

B5.1. Swedish testing protocol SP FIRE 105\(^{389}\) is described in the standard as a test procedure that "enables the determination of the reaction to fire of an external wall assembly or a facade wall cladding, when exposed to a simulated apartment fire with flames emerging out through a window. The flame spread can be studied directly on the outside and indirectly on the inside of the external wall assembly or facade cladding".

B5.2. SP FIRE 105 is another large-scale scenario test utilising a mock-up of an external wall system (6m x 4m) and subjecting it to a fire source resembling of a fully-developed compartment fire spilling through an opening through the façade.

B5.3. The basic test setup is reproduced from the test standard in Figure A2-7. As can be seen in the diagram, unlike any of the other similar scenario testing protocols, the setup requires two “fictitious windows” to be specified, rather than a continuous wall. The lower of the two window openings has a heat flux meter at its centre.

B5.4. The fire source is provided by a 2m x 0.5m heptane pool. It is expected to result in a rapid flashover within the “fire room” and flame spill that creates a measurable heat flux of 15kW/m\(^2\) for at minimum 7 minutes, 35kW/m\(^2\) for 1.5 minutes though never exceed 75kW/m\(^2\). The duration of thermal exposure is expected to be of the order of 15 minutes.

B5.5. Beyond the aforementioned heat flux meter, the only other diagnostic devices are two thermocouples located beneath the “eave” at the top of the test rig.

\(^{389}\) SP FIRE 105 Issue No: 5, Rev 1994-09-09, External Wall Assemblies and Façade Claddings, Reaction to Fire, SP Technical Research Institute of Sweden, (INQ00014964).
Figure A2-7: Diagrammatic representation of fire test standard SP FIRE 105.
B5.6. All other required recording for reporting is based on visual observation. During the test they include the spread of flame at different times, the length of the flame at different times, times of drop off of materials, damage, or deflections. In this respect, they are similar to other tests described in this report.

B5.7. After the test, further observations are required, including the ultimate extent of fire spread over the external surface, and within the system or through concealed spaces, fire damage around the windows, and the extent of functional success of internal fire stops if included. The notable difference in this test compared to other tests is the ability to assess, albeit crudely, the impact of fire on window openings.

B5.8. Overall, however, given the limited nature of the instrumentation, an adequate means to establish the relevant performance metrics to support HRRB design (potential for ignition, rate of fire spread, tendency to extinction) is not provided by this test.

B6. FACTORY MUTUAL STAND FANDARD FM 4880

B6.1. The details of FM 4880 are described by Agarwal et al in published literature.\textsuperscript{390} This test adopts a different approach to the definition of a representative ‘scenario.’ It is therefore also a ‘scenario test’.

B6.2. The test uses two parallel plates with the intention of reproducing a worst-case condition for vertical fire spread. In as such, and as reported by Agarwal et al\textsuperscript{391}, several assemblies that would have passed the NFPA 285 test will fail the FM 4880 test.

B6.3. Thus, while the ‘scenario’ which is being represented appears more serious/severe, it remains a scenario test with the same limitations and problems as BS 8414 and NFPA 285. In consequence, no more attention will be given to this ‘scenario test’ in this report.
