Scaling-Up Fire

José L. Torero[1]
BRE Centre for Fire Safety Engineering
The University of Edinburgh
United Kingdom

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

[1] Present Address: Department of Civil Engineering, The University of Queensland, Brisbane, Australia

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 ($k\rho C$), and ignition temperature (T_{ig}) and a flame spread parameter (ϕ) 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.

$$\dot{Q} = A.\dot{Q}" \qquad (1)$$

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 ($r=V_S t$) that when substituted into Equation (1) results in a simple expression for the heat release rate

$$\dot{Q} = A.\dot{Q}" = \pi V_S^2 t^2 \dot{Q}" = \alpha t^2 \qquad (2)$$

where the parameter $\alpha = \pi V_S^2 \dot{Q}"$ and the flame spread velocity (V_S) 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 (α) 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 from 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 where 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.

(a)

(b)

(c)

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.

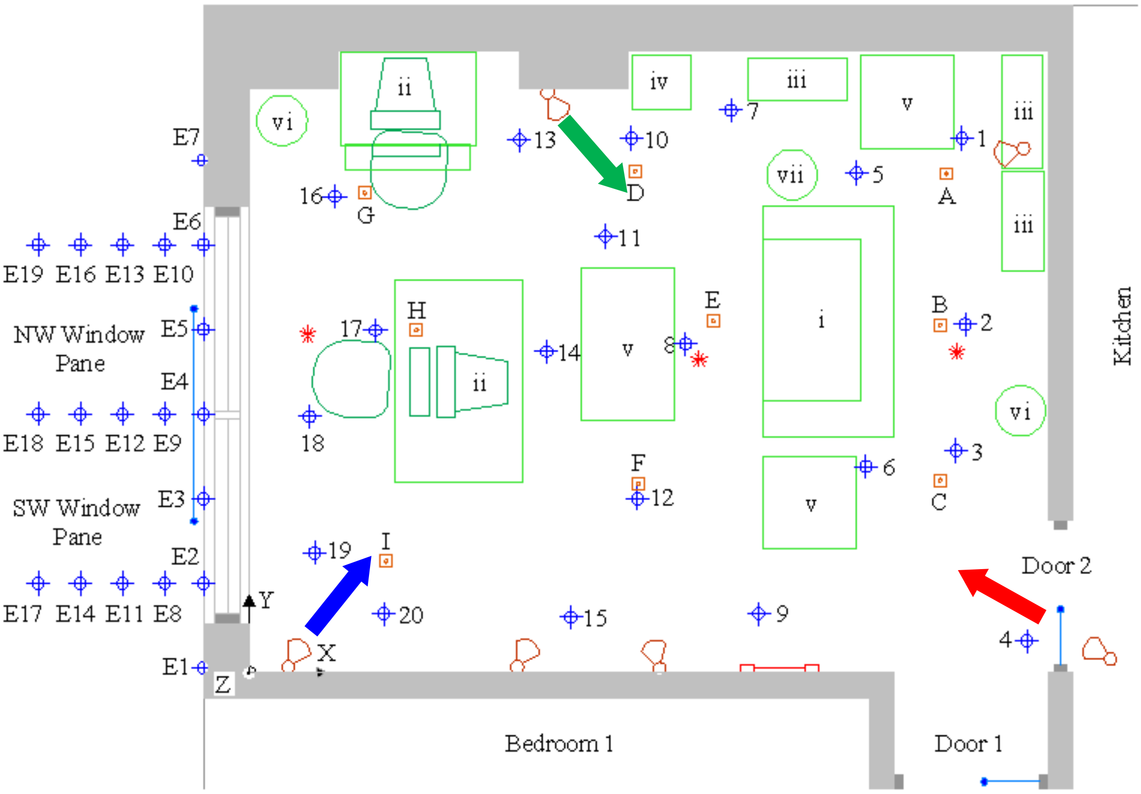
A typical set of thermocouple data for a plane perpendicular to the window wall (3.10 m from the Bedroom 1 wall) is presented in Figure 3 showing the spatial distribution of isotherms for an individual plane at a specific point in time. As shown in Figure 3 these isotherms provided a level of resolution 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.



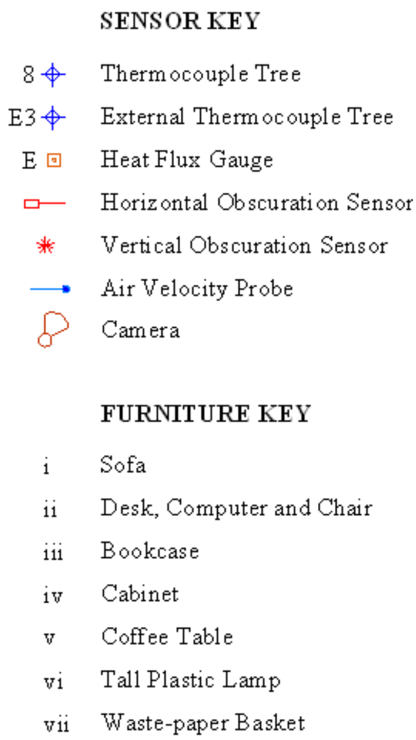


Figure 2 Sensors distributed within the main compartment. The red arrow indicates the view corresponding to the image of Figure 1(a), the blue arrow corresponds to the image of Figure 1(b) and the green arrow to the image of Figure 1(c). The sensor key indicates the type of sensor and the symbol next to it corresponds to the nomenclature used.

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.).

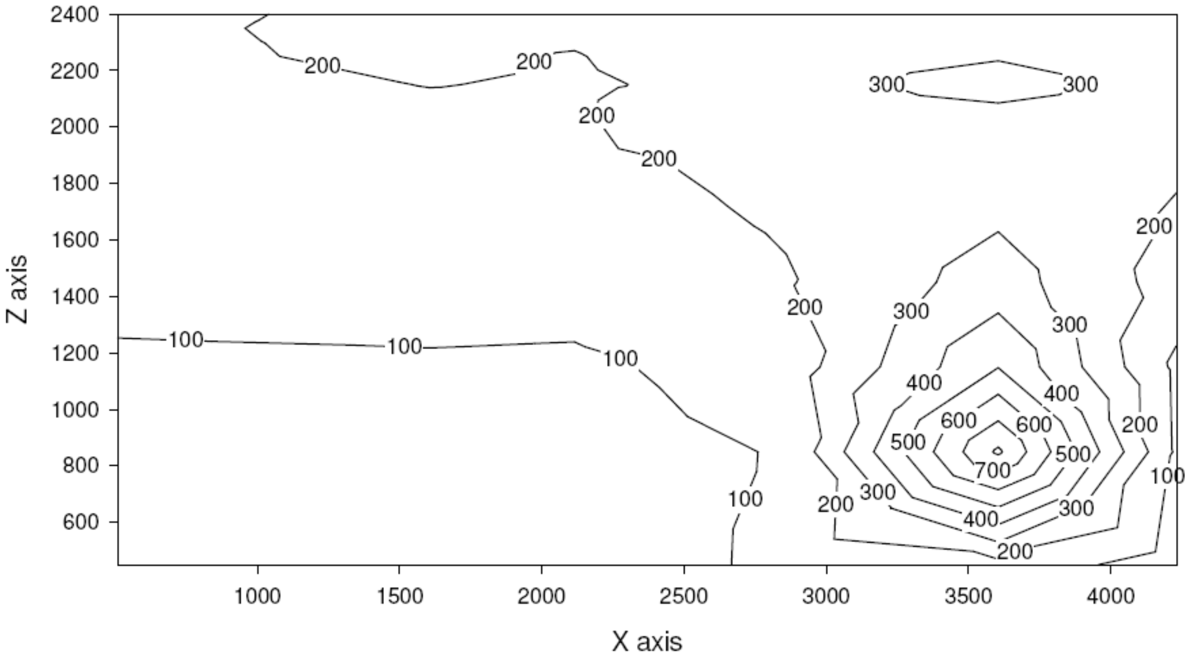


Figure 3 Temperature isotherm for a plane parallel to the side wall where x=0 is the plane of the window and x=4,750 mm the plane of the back wall. The plane is 400 mm away from the side wall and the data was taken 251 seconds after ignition. Data used for the plot was adapted from reference [103].

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 (<150ºC) 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.

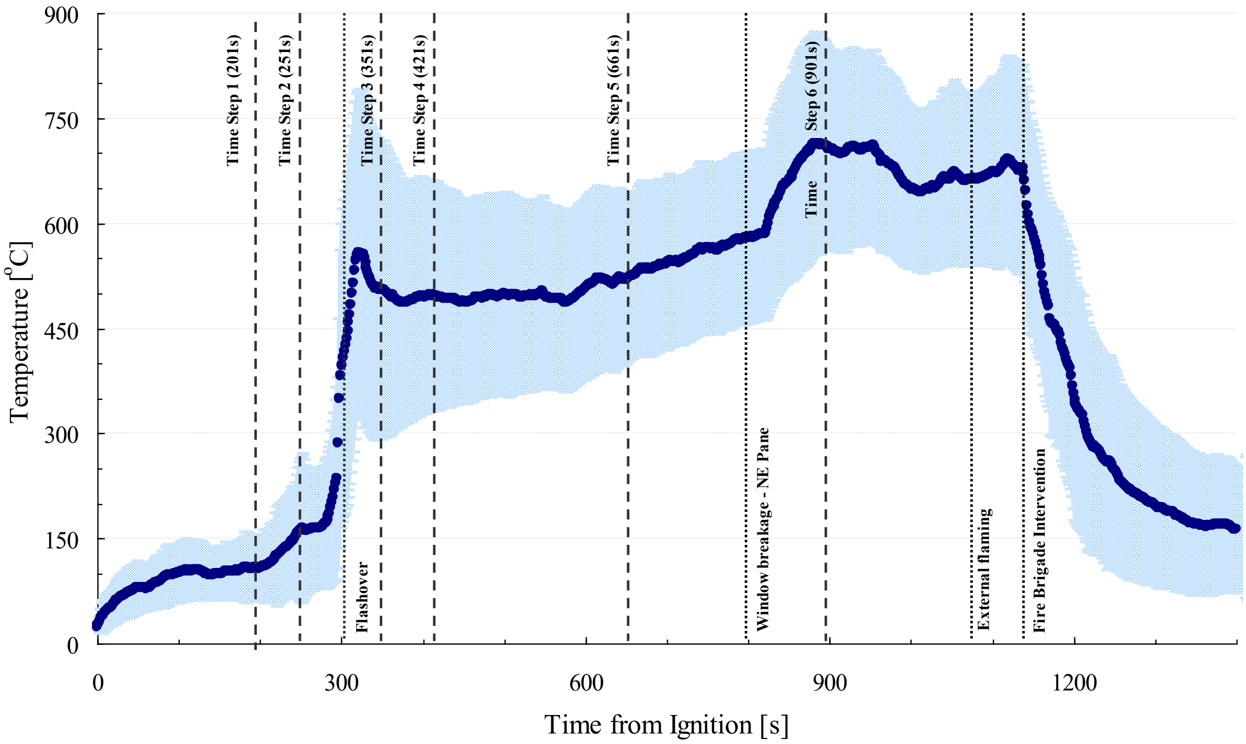


Figure 4 Gas-phase average compartment temperature-time variation (thick line) with the standard deviation of temperature throughout the compartment (shaded). Vertical lines indicate times at which significant events occurred and times at which the data was analyzed spatially. Data for the plot was adapted from reference [103].

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.

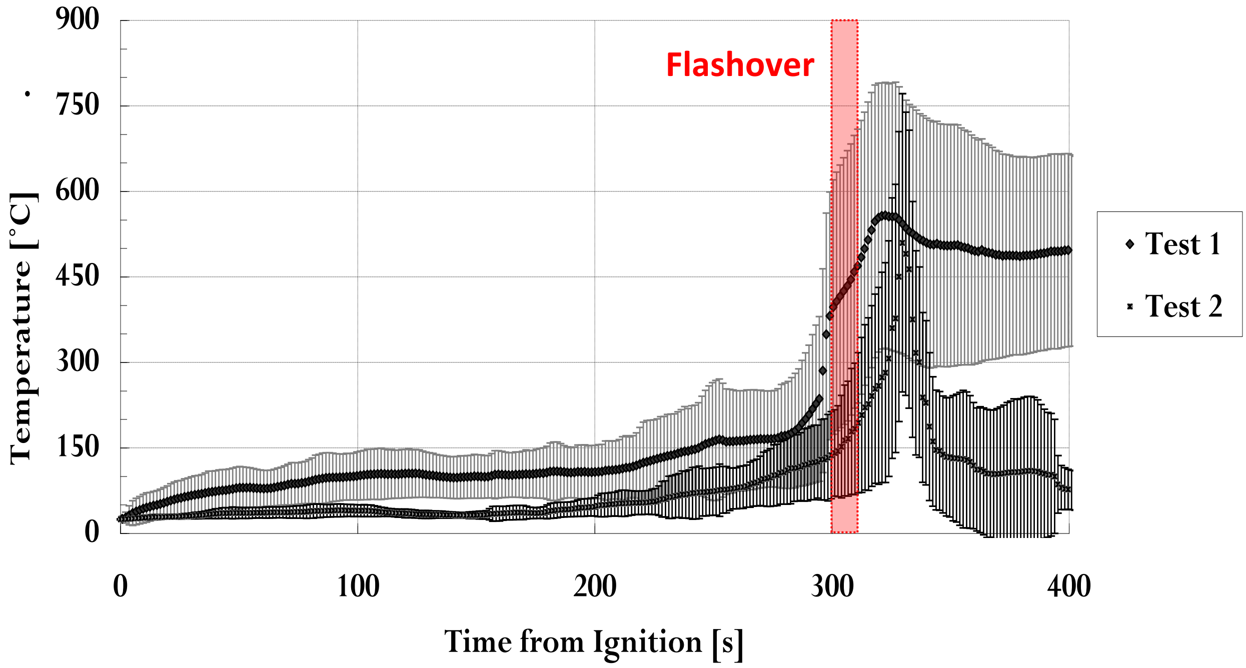


Figure 5 Comparison of the experimental average room temperature (˚C) variation in time (s) of Test One and Test Two. Data is only presented until extinction of Test Two (400 seconds). Data for the plot adapted from reference [103].

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 posterior* 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.

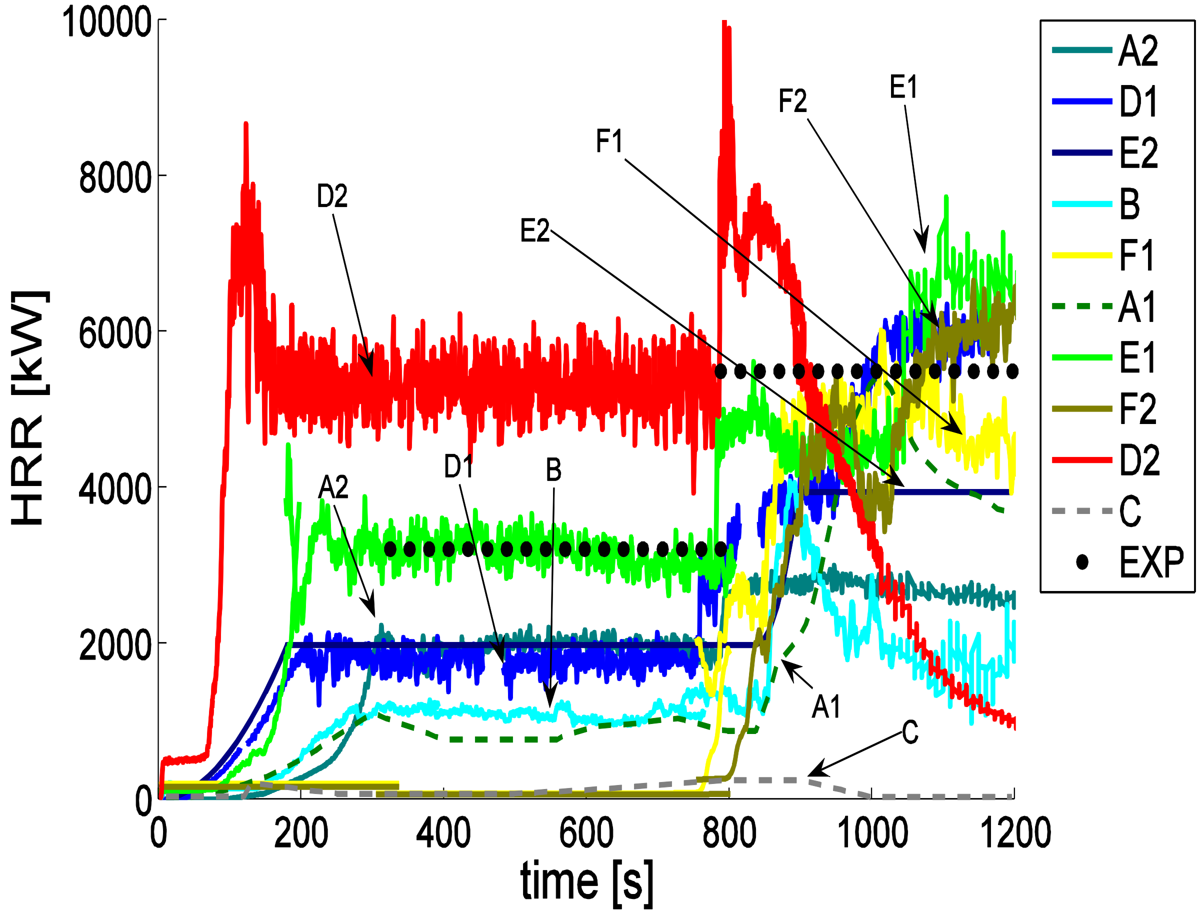


Figure 6 Heat release rate in the whole compartment. Legend for the different curves; continuous line for CFD models, dashed line for zone models, and dots is for experimental data. Data adapted from reference [104]. A1 and C correspond to zone models and all the other data was obtained using CFD models.

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 *a priori* Round Robin but the former needs to be explored by means of an *a posterior* modelling analysis that focuses on the secondary ignition process.

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 *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 posterior* 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 posterior* 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.

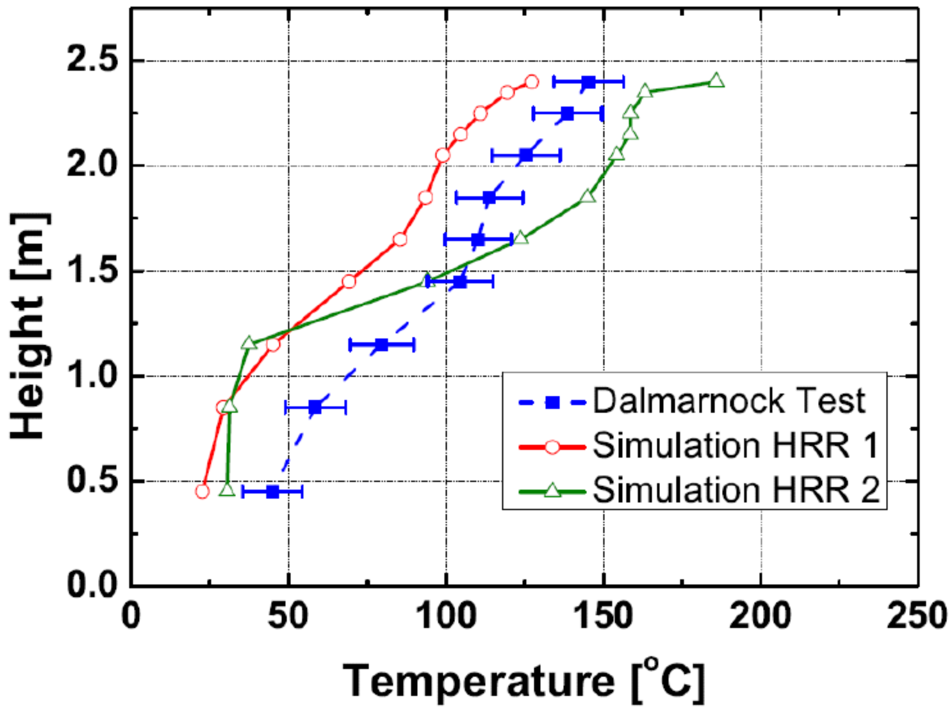


Figure 7 Vertical temperature distribution at a specific time as measured by one of the thermocouple racks of the Dalmarnock Test and as predicted by the model using two bounding heat release rates. Data adapted from reference [120].

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 straight forward. 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.

Acknowledgements

It is impossible to direct acknowledgements to individuals without forgetting someone, in my case the list of names is extremely long, thus I will refrain from mentioning any names in the acknowledgements. Nevertheless, I will like to express my most sincere gratitude to those "senior colleagues" who shared their wisdom with me throughout the years, those "contemporaries" who travelled the professional path with me enabling me to benefit from their ideas and knowledge and those "junior colleagues" who gave me their energy, enthusiasm and imagination. Finally, I want to thank all of those who needed me and patiently waited for me when my obsession for fire safety was taking me away from them.

My most sincere gratitude to all the funding agencies who supported my research through the years. This paper was written while the author was on sabbatical at Ecole Polytechnique Fédéral de Lausanne holding the Landolt & Cia Visiting Chair in Innovation for a Sustainable Future.

References

1. May, M.R., "Uses and Abuses of Mathematics in Biology," *Science*, 303, pp.790-793, 2004.
2. Neyman, J. "Statistics –Servant of all Science," *Science*, 122, pp. 401-406, 1955.
3. Thomas, P.H., "Fire Modelling: A Mature Technology," *Fire Safety Journal*, 19, pp. 125-140, 1992.
4. Emmons, H.W., "The Further History of Fire Science," *Combustion Science and Technology*, Volume 40, Issue 1-4, pp. 167-174, 1984.
5. Gann, D.M., "Building Innovations: Complex Constructs in a Changing World," Thomas Telford, London, 2000.
6. Van Ginkel, H., "Urban Future," *Nature*, 453, pp. 32-33, 2008.
7. Rasbash, D.J. "Fire Safety Objectives for Buildings," *Fire Technology*, 32, 4, pp. 348-350, 1996.
8. Bryan, J.L., "Human Behaviour in Fire: The Development and Maturity of a Scholarly Study Area," *Fire and Materials*, 23, pp. 249-253, 1999.
9. Buchanan, A. H., *Structural Design for Fire Safety,* John Wiley and Sons, New York, 2002.
10. Rasbash, D.J., Ramachandran, G., Kandola, B., Watts, J., Law, M. "Evaluation of Fire Safety," John Wiley and Sons Ltd. New York, 2004.
11. Drysdale, D., *An Introduction to Fire Dynamics*. Third Edition. John Wiley and Sons, New York, 2011.
12. The SFPE Handbook of Fire Protection Engineering, Fourth Edition, DiNenno, Drysdale, Beyler, Walton, Custer, Hall and Watts Editors, Society of Fire Protection Engineers, National Fire Protection Association, Quincy, Massachusetts, 2008.
13. Combustion Fundamentals of Fire, G. Cox Editor, Academic Press, New York, 1995.
14. Transport Phenomena in Fire, Faghri and Sundén Editors, WIT Press, Southampton, Boston, 2008.
15. Olenick, S.M., Carpenter, D.J., "An Updated International Survey of Computer Models for Fire and Smoke," *Journal of Fire Protection Engineering*, 13, pp.87-110, 2003.
16. Tanaka, T., "Integration of Fire Risk Concept into Performance-Based Evacuation Safety Design of Buildings," Proceedings of the Tenth (10th) International Symposium, International Association for Fire Safety Science (IAFSS), 19-24 June, Maryland, USA, Spearpoint Editor, pp. 3-21, 2011.
17. K. Hill, J. Dreisbach, F. Joglar, B. Najafi, K. McGrattan, R. Peacock, and A. Hamins. Verification and Validation of Selected Fire Models for Nuclear Power

Plant Applications. NUREG 1824, United States Nuclear Regulatory Commission, Washington, DC, 2007.

18. McGrattan, K. B., "Fire Modeling: Where Are We? Where Are We Going?" Fire Safety Science. Proceedings of the Eighth (8^{th}) International Symposium, International Association for Fire Safety Science (IAFSS). September 18-23, 2005, Beijing, China. Gottuk, D. T.; Lattimer, B. Y., Editors, pp. 53-68, 2005.

19. Trouvé, A., Wang, Yi, "Large Eddy simulation of compartment fires," *International Journal of Computational Fluid Dynamics*, 24, 10, pp.449-466, 2010.

20. Chen, J.H., "Petascale direct numerical simulation of turbulent combustion—fundamental insights towards predictive models," *Proceedings of the Combustion Institute*, 33, pp. 99–123, 2011.

21. Westbrook, C.K., Mizobuchi, Y., Poinsot, T.J., Smith, P.J., Warnatz, J., "Computational combustion," *Proceedings of the Combustion Institute*, 30, pp. 125–157, 2005.

22. Baum, H.R., McCaffrey, B.J., "Fire Induced Flow Field – Theory and Experiment," Fire Safety Science. Proceedings of the Second (2^{nd}) International Symposium, International Association for Fire Safety Science (IAFSS). June 13-17, 1988, Tokyo, Japan. Hemisphere Publishing Corp, New York, Wakamatsu, T., Hasemi, Y., Sekizawa, A., Seeger, P. G., Editors, pp.129-148, 1988.

23. Baum, H. R., Rehm, R. G. "Calculations of Three Dimensional Buoyant Plumes in Enclosures," *Combustion Science and Technology*, 40, 1-4, pp. 55-77, 1984.

24. McGrattan, K. B.; Rehm, R. G.; Baum, H. R. , "Fire-Driven Flows in Enclosures," *Journal of Computational Physics*, 110, 2, pp. 285-291, 1994.

25. Joglar, F., Mowrer, M., Modarres, M., "A Probabilistic Model for Fire detection with Applications," *Fire Technology*, 41, pp. 151–172, 2005.

26. McGrattan, K., Hostikka, S., Floyd, J., Baum, H., Rehm, R., Mell, W., McDermott, R. "Fire Dynamics Simulator (Version 5)- Technical Reference Guide," NIST Special Publication 1018-5, October 29, 2010.

27. FireFOAM, Available from: <http://code.google.-com/p/firefoam-dev/>.

28. OpenFOAM, Available from: <http://www.opencfd.co.uk/openfoam/>.

29. Van Maele, K. and Merci, B. "Application of RANS and LES Field Simulations to Predict the Critical Ventilation Velocity in Longitudinally Ventilated Horizontal Tunnels", *Fire Safety Journal*, Vol. 43 (8), pp. 598-609, 2008.

30. Morandini, F., Simeoni, A., Santoni, P.A., Balbi, J.H., "A model for the spread of fire across a fuel bed incorporating the effects of wind and slope," *Combustion Science and Technology,* 177, 7, pp. 1381-1418, 2005.

31. DesJardin, P.E., "Modeling of Conditional Dissipation Rates for Flamelet Models with Application to Large Eddy Simulation of Fire Plumes," *Combustion Science and Technology*, 177, pp.1883–1916, 2005.

32. Henderson, T. C., McMurtry, P.A., Smith, P.J., Voth, G.A., Wight, C.A., Pershing, D.W., "Simulating Accidental Fires and Explosions," *Computing in Science and Engineering*, March/April, pp.64-76, 2000.

33. Rehm, R.G, Mell, W.E. "A simple model for wind effects of burning structures and topography on WUI surface-fire propagation," *International Journal of Wildland Fire,* 18, pp. 290–301, 2009.

34. Dupuy, J.L., Morvan, D., "Numerical study of the a crown fire spreading toward a fuel break using a multiphase physical model," *International Journal of Wildland Fire*, 14, pp. 141–151, 2005.

35. Linn, R. Reisner, J., Colman, J.J., Winterkamp, J., "Studying wildfire behavior using FIRETEC," *Internbational Journal of Wildland Fire,* 11, pp. 233–246, 2002.

36. Porterie, B., Consalvi, J.L., Loraud, J-C., Giroud, F., Picard, C., "Dynamics of wildland fires and their impact on structures," *Combustion and Flame*, **149**, Issue 3, pp. 314-328, 2007.

37. Séro-Guillaume, O., Ramezani, S., Margerit, J., Calogine, D., "On large scale forest fires propagation models," *International Journal of Thermal Sciences*, 47, 6, pp.680-694, 2008.

38. Colella, F. Rein, G., Verda, V., Borchiellini, R., "Multiscale Modelling of the Transient Flows from Fire and Ventilation in Long Tunnels," *Computers and Fluids*, 51 (1), pp. 16-29, 2011.

39. Di Blasi C., "Modeling and Simulation of Combustion Processes of Charring and Non-Charring Solid Fuels," *Progress in Energy and Combustion Science*, 19, pp. 71–104, 1993.

40. Di Blasi, C., "Modeling Chemical and Physical Processes of Wood and Biomass Pyrolysis," *Progress in Energy and Combustion Science*, 34, pp. 47–90, 2008.

41. Lautenberger, C. and Fernandez-Pello, C., "Generalized Pyrolysis Model for Combustible Solids," *Fire Safety Journal*, 44, pp. 819–839, 2009.

42. Nyden, M.R., Stoliarov. S.I., Westmoreland, P.R. Guoc, Z.X., Jee, C., "Applications of Reactive Molecular Dynamics to the Study of the Thermal Decomposition of Polymers and Nanoscale Structures," *Materials Science and Engineering*, A365, pp. 114–121, 2004.

43. Stoliarov, S.I., Lyon, R.E., Nyden, M.R., "A Reactive Molecular Dynamics Model of Thermal Decomposition in Polymers. II. Polyisobutylene," *Polymer*, 45, pp. 8613–8621, 2004.

44. McGurn, M.T., DesJardin, P.E., Dodd, A.B., "Numerical Simulation of Expansion and Charring of Carbon-Epoxy Laminates in Fire Environments," *International Journal of Heat and Mass Transfer,* 55, pp.272–281, 2012.

45. Wasan, S., Rauwoens, P., Vierendeels, J., Merci, B., "An Enthalpy-Based Pyrolysis Model for Charring and Non-Charring Materials in Case of Fire", *Combustion and Flame*, 157, pp. 715-734, 2010.

46. Wang, H. "Formation of Nascent Soot and Other Condensed-phase Materials in Flames," *Proceedings of the Combustion Institute*, 33, pp. 41–67, 2011.

47. DeRis, J. "Fire radiation—A review," *Seventeenth Symposium (International) on Combustion*, pp. 1003–1016, 1979.

48. Hostikka, S., McGrattan, K.B. and Hamins, A., "Numerical Modeling of Pool Fires using LES and Finite Volume Method for Radiation," Proceedings of the Second (7^{th}) International Symposium, International Association for Fire Safety Science

(IAFSS). June 15-19, 2002, Worcester, MA, USA. Evans, D. Editor, pp.383-394, 2003.

49. Krishnamoorthy, G., Rawat, R., Smith, P.J., "Parallel Computations of Radiative Heat Transfer Using the Discrete-Ordinates Method," *Numerical Heat Transfer B*, 47, pp. 19-38, 2005.

50. Krishnamoorthy, G., Rawat, R., Smith, P.J., "Parallel Computations of Non-Grey Radiative Heat Transfer," *Numerical Heat Transfer B*, 48, pp. 191-211, 2005.

51. Grant, G., Brenton, J., Drysdale, D.D., "Fire Suppression by Water Sprays," *Progress in Energy and Combustion Science*, 26, 2, pp. 79–130, 2000.

52. Haynes , K., Handmer, J., McAneney, J., Tibbits, A., Coates, L., "Australian bushfire fatalities 1900–2008: exploring trends in relation to the 'Prepare, stay and defend or leave early' policy," *Environmental Science and Policy*, 13, pp.185-194, 2010.

53. Torero, J.L. "The Risk Imposed by Fire to Buildings and how to Address it," The Protection of Civil Infrastructure from Acts of Terrorism, NATO Advanced Science Institute series, Kluwer Academic Publishers, Frolov and Becker Eds. Pp. 37-56, 2006.

54. Quintiere, J.G.,"Principles of Fire Behavior," Delmar Publishers, 1998.

55. Zhang, W., Olenick, S.M., Klassen, M.S., Carpenter, D.J., Roby R.J. and Torero, J.L. "A Smoke Detector Activation Algorithm for Large Eddy Simulation Fire Modelling," *Fire Safety Journal*, 43, 2, 96-107, 2008.

56. Milarcik, E.L., Olenick, S.M., Roby, R.J., "A Relative Time Analysis of the Performance of Residential Smoke Detection Technologies," *Fire Technology*, 44, pp. 337-349, 2008.

57. Ren, N., Baum, H.R., Marshall, A.W., "A comprehensive methodology for characterizing sprinkler sprays," *Proceedings of the Combustion Institute*, 33, pp. 2547-2554, 2011.

58. Xia, J., Luo, K.H., "Direct numerical simulation study of evaporation effects in combustion suppression by inert droplets," *Proceedings of the Combustion Institute*, 33, pp. 2581-2590, 2011.

59. Arias, P.G., Im, H.G., Narayanan, P., Trouvé, A., "A computational study of non-premixed flame extinction by water spray," *Proceedings of the Combustion Institute*, 33, pp. 2591-2597, 2011.

60. Sunder, S.S. Gann, R.G., Grosshandler, W.L., Averill, J.D., Bukowski, R.W., Cauffman, S.A., Evans, D.D., Gayle, F.W., Gross, J.L., Lawson, J.R., Lew, H.S., McAllister, T.P., Nelson, H.E., Sadek, F., "Federal Building and Fire Safety Investigation of the World Trade Center Disaster Final Report of the National Construction Safety Team on the Collapses of the World Trade Center Towers," NIST, 2006.

61. Prasad, K. and Baum, H.R., Coupled fire dynamics and thermal response of complex building structures, *Proceedings of the Combustion Institute*, 30, pp. 2255-2262, 2005.

62. Hottel, H.C., “Stimulation of Fire Research in the United States After 1940 (A Historical Account),” *Combustion Science and Technology*, Volume 40, Issue 1-4, pp. 1-10, 1984.

63. Ingberg, S.H., “Tests of the Severity of Building Fires,” National Fire Protection Association, 22, pp. 43-61, 1928.

64. History of Fire Protection Engineering, J.K. Richardson, Editor, National Fire Protection Association, Quincey, USA, 2003.

65. Karlsson, B., Quintiere, J.G., “Enclosure Fire Dynamics,” CRC Press LLC, Boca raton, FL, USA, 2000.

66. Quintiere, J.G., “Fundamentals of Fire Phenomena,” John Wiley and Sons Ltd. New York, 2006.

67. Thomas, P.H., Heselden, A.J.M. “Behaviour of fully-developed fire in an enclosure,” *Combustion and Flame*, 6, 3, pp. 133-132, 1962.

68. Thomas, P.H., Nilsson, L. “*Fully-developed compartment fires: new correlations of burning rates*,” Fire Research Note 979, Fire Research Station, Borehamwood, England, UK, 1973.

69. Thomas P.H., “*Fully-developed compartment fires - 2 kinds of behaviour*,” Fire Research Technical Paper Nº 18, Ministry of Technology and Fire Offices Committee, Joint Fire Research Organization, Fire Research Station, London, England, UK, 1967.

70. Magnusson, S. E. and Thelandersson, S., “A Discussion of Compartment Fires,” *Fire Technology*, Vol. 10, Nº 3, pp. 228-246, August 1974.

71. Harmathy, T. Z. “*The Role of Thermal Feedback in Compartment Fires*,” *Fire Technology*, Vol. 11, Nº 1, pp. 48-54, February 1975.

72. Thomas, P.H. “Old and New Looks at Compartment Fires,” *Fire Technology*, Vol. 11, Nº 1, pp. 42-47, February 1975.

73. Yokoi, S., “Study of the Prevention of Fire Spread Caused by Hot Upward Currents,” Building Research Institute, Report No. 34, Tokyo, Japan, 1960.

74. Heskestad, G. “Engineering Relations for Fire Plumes,” Society of Fire Protection Engineering, Technology Report 82-8, 1982.

75. Heskestad, G., Delichatsios, M.A., “The Initial Convective Flow in a Fire,” Seventeenth Symposium (International) on Combustion, pp. 1113–1123, 1979.

76. Law. M. "Some Selected Papers by Margaret Law". London: Arup, 2002.

77. Williams, F.A., “Mechanisms of Fire Spread,” *Sixteenth Symposium (International) on Combustion*, pp. 1281-1294, 1977.

78. Pagni P. J. and T. M. Shih, T.M., “Excess Pyrolyzate,” *Sixteenth Symposium (International) on Combustion*, The Combustion Institute, pp.1329-1339, 1977.

79. ASTM 1321-97a, Standard Test Method for Determining Material Ignition and Flame Spread Properties,” American Society for Testing and Materials, Philadelphia, 1997.

80. Quintiere, J.G., “A Simplified Theory for Generalizing Results from a Radiant Panel Rate of Flame Spread Apparatus,” *Fire and Materials*, Vol.5, No.2, pp. 52-60, 1981.

81. Fernandez-Pello, A.C. and Hirano, T., “Controlling Mechanisms of Flame Spread,” *Combustion Science and Technology*, 32, pp. 1-31, 1983.

82. ASTM E-1354-03, Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter,” American Society for Testing and Materials, Philadelphia, 2003.

83. Babrauskas, V., Peacock, R. D. “Heat release rate. The single most important variable in fire hazard”, *Fire Safety Journal*,18, 3, pp. 255 – 272, 1992.

84. Thornton, W.M., “The Relation of Oxygen to the Heat of Combustion of Organic Compounds”, *Philos. Mag. Ser.*, 6, 33, 196 – 203, 1917.

85. Huggett, C., “Estimation of Rate of Heat Release by means of Oxygen Consumption Calorimetry”, *Fire and Materials*, 4, 2, pp.61 – 65, 1980.

86. Fire Retardancy of Polymeric Materials, Wilke and Morgan Editors, CCR Press, London, 2009.

87. Hopkins Jr, D., Quintiere, J.G., “Material fire properties and predictions for thermoplastics,” *Fire Safety Journal*, 26, 3, pp. 241-268, 1996.

88. Wickstrom, U., Goransson, U., “Prediction of heat release rates of surface materials in large-scale fire tests based on cone calorimeter results,” *ASTM Journal for Testing and Evaluation*, 15, pp. 6-16, 1987.

89. Pettersson O., Magnusson S.E. and Thor J. “Fire engineering design of steel structures,” Publication 50, Swedish Institute of Steel Construction, Stockholm, 1976.

90. ISO. *Fire Resistance Tests. Elements of Building Construction*. ISO 834. International Organization for Standardization. Geneva. 1975.

91. CEN Eurocodes 0-9, BS EN 1990-1999, British Standards Institution, London, 2005.

92. Stern-Gottfried, J. Rein, G., Bisby, L., Torero, J.L., “Experimental Review of the Homogeneous Temperature Assumption in Post-Flashover Compartment Fires,” *Fire Safety Journal*, 45, pp. 249–261, 2010.

93. Usmani, A.S., Rotter, J. M., Lamont, S., Sanad, A.M. and Gillie, M. Fundamental principles of structural behaviour under thermal effects”, *Fire Safety Journal*, 36, 721-744, 2001.

94. SFPE, Engineering Guide to Performance-Based Fire Protection, 2nd Edition, Society of Fire Protection Engineers, 2007.

95. Franssen, J-M., “Structures in Fire: yesterday, today and tomorrow,” Proceedings of the Eighth (8th) International Symposium, International Association for Fire Safety Science (IAFSS). September 18-23, 2005, Beijing, China. Gottuk, D. T.; Lattimer, B. Y., Editors, pp. 21-36, 2005.

96. Steckler, K.D., Quintiere, J.G., Rinkinen, W.J., “Flow Induced By a Fire in a Compartment,” *Nineteenth Symposium (International) on Combustion*, pp. 913-920, 1982.

97. Karpetis, A.N., Barlow, R.S., "Measurements of flame orientation and scalar dissipation in turbulent partially premixed methane flames," *Proceedings of the Combustion Institute*, 30, pp. 665–672, 2005.

98. Barlow, R.S. Frank, J.H., "Effect of turbulence on species mass fractions in methane/air jet flames," Proceedings of the Combustion Institute, 27, pp. 1087-1095, 1998.

99. Sheikhi, M.R.H., Drozda, T.G., P., F.A., S.B., "Large eddy simulation of a turbulent nonpremixed piloted methane jet flame (SandiaFlame D)," *Proceedings of the Combustion Institute*, 30, pp. 549–556, 2005.

100. Pitsch, H., Steiner, H., "Large-eddy simulation of a turbulent piloted methane/air diffusion flame (Sandia flame D),"*Physics of Fluids*, 12, 10, pp. 2541–2554, 2000.

101. Micro-Gravity Combustion: Fire in Free Fall, Ross, H.D. Editor, Academic Press, London, UK, 2001.

102. Abecassis Empis, C., Reszka, P., Steinhaus, T., Cowlard, A., Biteau, H., Welch, S., Rein G., and Torero, J.L., "Characterization of Dalmarnock Fire Test One," *Experimental Thermal and Fluid Science,* 32, Issue 7, pp. 1334-1343, 2008.

103. The Dalmarnock Fire Tests: Experiments and Modelling, Editors: G. Rein, C. Abecassis-Empis and R. Carvel, 221 pages, University of Edinburgh, 2007. ISBN 978-0955749704.

104. Rein, G., Torero, J.L., Jahn, W., Stern-Gottfried, J., Ryder, N.L., Desanghere, S., Lazaro, M., Mowrer, F., Coles, A., Joyeux, D., Alvear, D., Capote, J.A., Jowsey, A., Abecassis-Empis, C., Reszka, P., "Round-Robin Study of a priori Modelling Predictions of The Dalmarnock Fire Test One," *Fire Safety Journal*, 44, 4, pp. 590-602, 2009.

105. Norton, T.S., Smyth, K.C., Miller, J.H., Smooke. M.D., "Comparison of Experimental and Computed Species Concentration and Temperature Profiles in Laminar, Two-Dimensional Methane/Air Diffusion Flames," *Combustion Science and Technology*, 90, pp. 1–34, 1993.

106. Smyth. K.C., "NO Production and Destruction in a Methane/Air Diffusion Flame," *Combustion Science and Technology*, 115, pp.151–176, 1996.

107. Tieszen, S.R., O'Hern, T.J., Schefer, R.W., Weckman, E.J., Blanchat. T.K., "Experimental study of the flow field in and around a one meter diameter methane fire. Combustion and Flame, 129, pp.378–391, 2002.

108. Tieszen, S.R., O'Hern, T.J., Weckman, E.J., Schefer. R.W., "Experimental study of the effect of fuel mass flux on a 1-m-diameter methane fire and comparison with a hydrogen fire," *Combustion and Flame*, 139, pp.126–141, 2004.

109. Hsu, S-Y., T'ien, J.S., "Flame spread over solids in buoyant and forced concurrent flows: Model computations and comparison with experiments," *Proceedings of the Combustion Institute*, 33, pp. 2433-2440, 2011.

110. Bhattacharjee, S., Takahashi, S., Wakai, K., Paolini, C. P., "Correlating flame geometry in opposed-flow flame spread over thin fuels," *Proceedings of the Combustion Institute*, 33, pp. *2465-2472*, 2011.

111. Xie, W., DesJardin, P.E., "An embedded upward flame spread model using 2D direct numerical simulations," *Combustion and Flame*, 156, pp. 522–530. 2009.

112. Raghavan, V., Rangwala, A.S., Torero, J.L. "Laminar Flame Propagation on a Horizontal Fuel Surface - Analysis of Classical Emmons Solution," *Combustion Theory and Modelling*, 13, 1, pp.121-141, 2009.

113. Chaos, M. Khan, M.M., Krishnamoorthy, N., de Ris, J.L., Dorofeev, S.B., Evaluation of optimization schemes and determination of solid fuel properties for CFD fire models using bench-scale pyrolysis tests," *Proceedings of the Combustion Institute*, 33, pp. 2599-2606, 2011.

114. Lautenberger, C., Rein, G., Fernandez-Pello, A.C., "The application of a genetic algorithm to estimate material properties for fire modeling from bench-scale fire test data," *Fire Safety Journal*, 41, 3, pp. 204-214, 2006.

115. Zhang, J., Delichatsios, M.A., Bourbigot, S., "Experimental and numerical study of the effects of nanoparticles on pyrolysis of a polyamide 6 (PA6) nanocomposite in the cone calorimeter," *Combustion and Flame*, 156, 2056-2062, 2009.

116. Rogaume, T., Bustamante Valencia, L., Guillaume, E., Richard, F., Luche, J., Rein, G., "Development of the thermal decomposition mechanism of polyether polyurethane foam using both condensed and gas phase release data", *Combustion Science and Technology*, 183, pp. 627-644, 2011.

117. American Society for Testing and Materials, West Conshohocken, Pennsylvania. ASTM E 1355-04, Standard Guide for Evaluating the Predictive Capabilities of Deterministic Fire Models, 2004.

118. Lazaro, M., Boehmer, H., Alvear, D., Capote, J.A., Trouve, A. "Numerical simulation of fire growth, transition to flashover, and post-flashover dynamics in the Dalmarnock fire test," Proceedings of the Ninth (9^{th}) International Symposium, International Association for Fire Safety Science (IAFSS), 21-26 September, Karlsruhe, Germany, Gottuk and Lattimer Editors, pp. 1377-1388, 2008.

119. Jahn, W., Rein, G., Torero, J.L. "The Effect of Model Parameters on the Simulation of Fire Dynamics," Proceedings of the Ninth (9^{th}) International Symposium, International Association for Fire Safety Science (IAFSS), 21-26 September, Karlsruhe, Germany, Gottuk and Lattimer Editors, pp. 1341-1352, 2008.

120. Jahn, W., Rein, G., Torero, J.L. "A Posteriori Modelling of the Growth Phase of Dalmarnock Fire Test One," *Building and Environment*, 46, 5, pp.1065-1073, 2011.

121. Lorenz, E., "Deterministic Nonperiodic Flow," *Journal of the Atmospheric Sciences*, 20, 2, pp. 130–141, 1963.

122. Swillens, A., De Santis, G. , Degroote, J., Lovstakken, L., Vierendeels, J., Segers, P., "Accuracy of carotid strain estimates from ultrasound wall tracking : a study based on multiphysics simulations and in-vivo data, " *IEEE Transactions on Medical Imaging*, 31, 1, 131-139, 2012.

123. Lautenberger, C.W., de Ris, J.L., Dembsey, N.A., Barnett, J.R., Baum, H.R. "A simplified model for soot formation and oxidation in CFD simulation of non-premixed hydrocarbon flames," *Fire Safety Journal*, 40, pp. 141–176, 2005.

124. Barlow, R.S., "Laser diagnostics and their interplay with computations to understand turbulent combustion," *Proceedings of the Combustion Institute*, 31, pp. 49–75, 2007.

125. Westbrook, C.K., “Chemical Kinetics of Hidrocarbon Ignition in Practical Combustion Systems,” *Proceedings of the Combustion Institute*, 28, pp. 1563–1577, 2000.

126. Glarborg, P., “Hidden interactions—Trace species governing combustion and emissions,” Proceedings of the Combustion Institute, 31, 1, pp. 77–98, 2007.

127. Peters, N., “Multiscale combustion and turbulence,” *Proceedings of the Combustion Institute*, 32, pp. 1–25, 2009.

128. Williams, F.W., “The Role of Theory in Combustion Science,” *Twenty-Fourth Symposium (International) on Combustion*, The Combustion Institute, pp. 1-17, 1992.

129. Kalnay, E., “Atmospheric Modeling, Data Assimilation and Predictability,” Cambridge University Press , Cambridge, 1st Edition, 2003.

130. Richards, R., Munk, B., Plumb, O. A., “Fire Detection, Location and Heat Release Rate Trough Inverse Problem Solution, Part I: Theory,” *Fire Safety Journal* 28, 4, pp.323–350, 1997.

131. Richards, R., Ribail, R.T., Bakkom, A.W., Plumb, O.A., “Fire Detection, Location and Heat Release Rate Through Inverse Problem Solution. Part II: Experiment,” *Fire Safety Journal* 28, 4, pp.351–378, 1997.

132. Leblanc, M., Trouvé, A., “Inverse Modeling of Enclosure Fire Dynamics. Proceedings of the 6th U.S. National Combustion Meeting, 2009.

133. Koo, S., Fraser-Mitchel, J., Welch, S., “Sensor-steered fire simulation,” *Fire Safety Journal*, 45, 3, pp. 193–205, 2010.

134. Jahn, W., Rein, G., Torero, J.L., “Forecasting fire growth using an inverse zone modelling approach,” *Fire Safety Journal*, 46, 3, pp. 81–88, 2011.

135. Jahn, W., Rein, G., Torero, J.L., “Forecasting fire dynamics using inverse Computational Fluid Dynamics and Tangent Linearisation,” *Advances in Engineering Software* (in press), 2012.

136. Jahn, W., Rein, G., Torero, J.L., “Forecasting fire growth using an inverse CFD modelling approach in a real-scale fire test.” Proceedings of the Tenth (10th) International Symposium, International Association for Fire Safety Science (IAFSS), 19-24 June, Maryland, USA, Spearpoint Editor, pp. 1349-1358, 2011.

137. Cowlard, A., Auersperg, L., Richon, J., Rein, G., Welch, S., Usmani, A., Torero, J.L. “A Simple Methodology for Sensor Driven Prediction of Upward Flame Spread,” *Turkish Journal of Engineering and Environmental Sciences*, 31, 6, pp. 403–413, 2007.