Capabilities of Shock Tube/Laser Absorption Experiments
By Prof. Ronald K. Hanson and Dr. David F. Davidson

There is a continuing, critical need for accurate chemical kinetics data to refine and validate detailed mechanisms used in combustion chemistry modeling. Shock tubes and laser absorption experiments have provided and continue to provide some of this needed data, primarily in the form of ignition delay times, species time-histories and reaction rate constant data. However, recent advances in shock tube strategies and new laser capabilities have revolutionized the quality and content of this shock tube-generated kinetic data, as highlighted below.

A shock tube in its simplest form is a long tube with closed ends separated into two sections by a diaphragm. The test gas mixture is placed in the driven (low-pressure) end of the tube and the driver (high-pressure) end of the tube is over-pressured with gas, typically helium, until the diaphragm bursts. A shock wave quickly forms and moves rapidly ahead of the helium expanding into the driven section. Conservation of mass, momentum and energy, along with the equation of state of the test gas and the measured speed of the shock wave, enable a very accurate calculation of the step change in temperature and pressure of the moving test gas behind the wave. Upon reflection of this incident shock wave from the closed end wall of the driven section, the test gas is further compressed and stagnated. Because of the near-one-dimensionality of the shock tube and the near-planar nature of the shock wave (excluding a very thin boundary layer), it is possible, with a precise measurement of the incident shock speed, to accurately determine (<±1%) the temperature and pressure behind the reflected shock. The reflected-shock regime can potentially be treated as a zero-dimensional reactor with very well-defined conditions that occur in a step-wise fashion. See Fig. 1 for an example x-t diagram that characterizes these processes. When the geometry and gas mixtures in the driver and driven sections are optimized, including the use of driver inserts to compensate for facility effects, it is possible to extend the uniform test times for these experiments to beyond 80 ms.

Fig. 1: An x-t diagram showing the wave structure during a typical shock wave experiment. Region 5 is the stagnated gas behind the reflected shock wave that behaves as a zero-dimensional constant V or constant P reactor.

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It has recently been recognized that it is also possible to use shock tubes to study the gas phase kinetics of low-vapor-pressure liquid fuels and to separately study their evaporation and chemical processes. In the aerosol shock tube configuration developed at Stanford, a spatially-uniform distribution of fuel aerosol droplets and oxidizer/buffer is drawn into the shock tube driven section near the end wall. When the incident shock wave passes through this fuel mixture, it rapidly evaporates the micron-sized droplets and the evaporated fuel quickly diffuses to create a uniform gas-phase mixture of the low-vapor-pressure fuel and oxidizer/buffer. The reflected shock wave further compresses and stagnates the evaporated test gas mixture enabling the same types of experiments that are performed in conventional shock tubes.

One difficulty in modeling energetic ignition events in shock tubes is that because of the open-endedness of the test gas volume behind the reflected shock, the gasdynamics constraint on the test gas is not truly constant volume throughout the entire ignition process. This problem can be addressed using a new constrained-reaction-volume (CRV) strategy, shown schematically in Fig. 2. With the CRV strategy, only a small part of the driven section nearest the end wall is filled with the reactive test gas mixture. The rest of the driven section is filled with a non-reactive or non-explosive mixture. Thus there is only a small region of reactive gas mixture that is capable of energy release and only a small tendency for the pressure to rise. When the reflected shock passes through the reactive gas mixture, any pressure rise due to combustion is mitigated by variations in the reflected shock speed. Using this method, non-local (remote) ignition events can be avoided and near-constant-pressure test conditions can be achieved, thereby facilitating modeling of the reactive gas dynamics process.

Laser absorption diagnostics provides a sensitive, quantitative, and non-intrusive method to measure species concentration and temperature time-histories in shock tube experiments. Earlier studies allowed the measurement of species using UV and visible and some IR light sources, but recent developments in solid state diode laser manufacturing have provided very stable CW laser light sources across the IR spectrum, from 1 micron to beyond 10 microns. These lasers have allowed the development of new absorption diagnostics to monitor many new species with high sensitivity. The recent extension of the laser absorption method to the simultaneous, multi-wavelength detection of multiple species is enabling the development of kinetics databases that

(Continued on page 3)

![Fig. 2: Conventional and Constrained Reaction Volume (CRV) shock tube strategies.](Fig2_C.png)
Capabilities of Shock Tube/Laser Absorption Experiments (cont’d)

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include species time-histories for fuel, transient radical species such as OH and CH₃ at ppm and sub-ppm levels, stable intermediates such as C₂H₄ and CH₄, and combustion products such as CO, CO₂ and H₂O; an example is shown in Fig. 3. These databases can be used to strongly constrain the hypothetical reaction pathways and rate constants used in detailed sub-mechanisms and full reaction mechanisms proposed for fuel pyrolysis and oxidation.

Recent advances in shock tube/laser absorption methodologies are revolutionizing the use of shock tubes for chemical kinetics studies. Shock tube/laser absorption experiments can now provide long test times with very well-characterized test conditions, even during energetic reaction events, and laser absorption diagnostics can provide quantitative high-bandwidth time-history measurements of a wide range of species. This work builds on the past 40 years of laser development and offers to provide direct and quantitative methods to characterize the chemistry of important combustion systems.

![Fig. 3: Oxygen balance during the decomposition of methyl formate. Greater than 98% of the O-bearing species have been measured in these experiments.](image-url)

Upcoming Events

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<th>MARCH 2014</th>
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| 2014 Central States Spring Technical Meeting  
Tulsa, OK  
March 16-18, 2014 | Tsinghua-Princeton Summer School on Combustion  
Tsinghua University  
Beijing, China  
July 19-25, 2014 |
| 2014 WSSCI Spring Meeting  
[www.wosci2014.caltech.edu](http://www.wosci2014.caltech.edu)  
Pasadena, CA  
March 23-25, 2014 |  |

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<th>JUNE 2014</th>
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| 2014 Princeton-CEFRC Summer School on Combustion  
[www.princeton.edu/cefrc/combustion-summer-school](http://www.princeton.edu/cefrc/combustion-summer-school)  
Princeton University  
Princeton, NJ  
June 22-27, 2014 | 35th International Symposium on Combustion  
San Francisco, CA  
August 3-8, 2014 |
Using Quantum Chemistry to Investigate New Oxidation Pathways
By Prof. William H. Green and Amrit Jalan

The chemistry of hydrocarbons reacting with $O_2$ changes dramatically with temperature and pressure, and each hydrocarbon (i.e. fuel) reacts differently, leading to many of the most important fuel effects on engine performance. The chemistry at high temperatures (>1000 K) has been worked out over the past few decades and is now well-understood. However, the chemistry at lower temperatures, leading to ignition, is not completely understood, and is a major research area for members of the CEFRC.

Until a few years ago, most of our understanding of the fundamental kinetics of low-temperature combustion was based on first-principles calculations. This understanding, centered on the peroxy radical ($ROO^•$), was developed by combining electronic structure methods with advanced theories for tunneling, chemical activation and calculation of partition functions. The outcome of these efforts was the popular “R+O$_2$” reaction sequence found in most low-temperature combustion kinetic models. This mechanism was tested mainly against macroscopic observables (e.g. ignition delays) since detailed product or radical profiles were scarce. However, recent advances in experimental capabilities have led to detailed measurements on oxidation of alkanes such as propane, n-butane, heptane, etc.

The earliest of these studies, performed by Battin-Leclerc and co-workers in a jet-stirred reactor setup, found carboxylic acids among the major byproducts of n-butane oxidation at temperatures below 600 K. This was among the first demonstrations of acid formation in a combustion-relevant environment and therefore important from an emissions viewpoint. As such, it was important to understand the pathways leading to acids, their dependence on the parent fuel structure and potential impact on the combustion characteristics of a fuel. These studies also reported the first direct detection of ketohydroperoxides (HOOQ=O) in the gas phase lending partial support to the R+O$_2$ reaction sequence. Both the QOOH and OOQOOH intermediates are yet to be observed directly.

These observations raised important questions about our mechanistic understanding of the low-temperature alkane + O$_2$ chemistry and ability to predict basic features a priori. In order to find clues to acid forming pathways, we turned to the liquid-phase alkane oxidation literature where carboxylic acids have been known for decades. While it is fair to expect gaseous and liquid systems to behave very differently, oxidation of organic non-polar substrates like alkanes involves fundamentally similar pathways in both phases. This was demonstrated through an intricate set of experiments performed by Korcek and co-workers from the Ford Motor Company in the late 1970s where HOOQ=O was found to be among the primary products in liquid hexadecane oxidation. In fact, the reaction sequence proposed by Korcek to explain his observations was essentially similar to the R+O$_2$ reaction sequence. In addition to HOOQ=O, Korcek also noted high yields of carboxylic acids in his experiments which could not be accounted for using conventional pathways like Baeyer-Villiger oxidation. Through further analysis, Korcek noted that the formation of acids (and methyl ketones) was directly correlated with the decomposition of HOOQ=O and this process alone accounted for over half the experimental acid yield. For over 30 years, this pathway connecting two
Using Quantum Chemistry to Investigate New Oxidation Pathways (cont’d)

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important combustion species remained an unresolved mystery.

We recently used state-of-art quantum chemistry calculations to elucidate the molecular details of the Korcek reaction. Our investigation revealed that the Korcek reaction involves two elementary steps: exothermic isomerization of HOOQ=O to a 5-membered cyclic peroxide (CP) intermediate followed by concerted fragmentation of CP to give acid + aldehyde/ketone (e.g. HCOOH + CH₃CHO in Figure 1). While qualitatively consistent with Korcek’s observations, a more meaningful test was to compare predicted and measured rate coefficients. Collaborating with CEFRC PI Don Truhlar we employed a hybrid approach using Density Functional Theory (DFT) to explore the potential energy surface and obtain stationary point geometries/frequencies followed by high-level RCCSD(T)-F12a calculations for electronic energies. These calculations were used as input to sophisticated codes like MSTor and POLYRATE, developed partially under CEFRC efforts, to calculate high-level MP-VTST/SCT rate coefficients including solvent corrections to account for the alkane medium. Our predicted rate coefficients were within a factor of 2 of Korcek’s measurements, in almost quantitative agreement given the low temperatures involved (400-450 K). Furthermore, these pathways provide clues to acid formation in the n-butane JSR studies.

We are now actively exploring applications of this new class of reactions in other low-temperature oxidation systems (including biofuel combustion, atmospheric oxidation and polymer degradation) and expect quantum chemistry tools to be indispensable going forward.

Figure 1: Snapshots of molecular configurations involved in the Korcek reaction sequence with relative energies at the RCCSD(T)-F12a/VTZ-F12//M06-2X/MG3S level
Inauguration of the CCRC at KAUST

On February 17, 2014, members of the combustion community celebrated the inauguration of the Clean Combustion Research Center (CCRC) at King Abdullah University of Science and Technology (KAUST). The CCRC seeks solutions to the global challenges that arise from the combustion of fuels, particularly those of clean and efficient combustion, climate change, and fuel diversification. Both fundamental and goal-oriented research in combustion is being carried out based on the multi-disciplinary nature of combustion science and technology. Experimental, computational, and chemical kinetics approaches are being employed to advance the state of the art and provide real solutions to some of society's most vexing problems.

The inauguration of the CCRC was commemorated with a 3-day technical workshop showcasing the latest developments in the area of clean combustion science and technology. Over 30 internationally renowned combustion experts presented technical seminars at the workshop. The CCRC is based on the interdisciplinary nature combustion research, with expertise in experiments, modeling, chemistry, and physics, and thus, the conference was structured in a similar manner. The workshop covered the latest developments in underlying physical and chemical phenomenon affecting flame structure, emissions formation, autoignition, and engine operation, as well as numerical simulations for modeling combustion chemistry and physics using high performance computing resources. Growing research areas of the CCRC were covered during the workshop, including advanced engine research, next generation gas turbines, advanced diagnostics techniques, and high-pressure turbulent combustion. Further details of the events and an archive of the technical presentations are available on the CCRC's website (ccrc.kaust.edu.sa).

At this workshop CEFRC Director C. K. Law delivered a congratulatory speech on behalf of the Combustion Institute, and together with CEFRC PIs R.K. Hanson, S.J. Klippenstein and C.J. Sung also individually delivered technical talks.
5th Annual Princeton-CEFRC Summer School on Combustion, June 22-27, 2014

Mission: To provide the next generation of combustion researchers with a comprehensive knowledge in the technical areas of combustion theory, chemistry, experiment, computation and applications.

Program: The 2014 session will be the fifth time that the Combustion Summer School is offered. Scheduled for June 22 to June 27, 2014, the Combustion Summer School will offer two five-day foundation courses on combustion theory and combustion chemistry, respectively entitled: “Combustion Theory and Applications in CFD”, to be taught by Professor Heinz Pitsch of the RWTH Aachen University, and “Combustion and Fuels Chemistry”, to be taught by Professor William H. Green of MIT. Additionally, three enrichment courses will be offered, namely: “Reciprocating Engines”, “Unsteady Combustor Processes”, and “New Developments in Combustion Technology”, which are five, three and two-day courses will be respectively taught by Professor Rolf D. Reitz of the University of Wisconsin at Madison, Professor Timothy C. Lieuwen of Georgia Tech, and Dr. Geo Richards of NETL, DOE. Lodging and meals for students of U.S. academic institutions are covered by the Center. The deadline for application is Friday, March 14th. Visit http://www.princeton.edu/cefrc/combustion-summer-school/ for additional information.

Course Descriptions:

Combustion Theory and Applications in CFD (15 hours)

Lecturer: Heinz Pitsch, RWTH Aachen University

Objective: The aim of this course is to provide students with an understanding of the basic principles of combustion processes, how they relate to experimental observations and how they can be used in theoretical and numerical modeling. The subject is presented in a systematic way emphasizing, in particular, the mathematical character of the various combustion problems and the advances that took place in recent years. The first four lectures cover the fundamentals of chemically reacting flows, general conservation equations and various classifications of combustion processes. One lecture is allocated to detonation waves and the remaining lectures focus on low-speed combustion, or flames. Four lectures are devoted to premixed combustion, and include the structure of planar premixed flame and the determination of the laminar flame speed, hydrodynamic effects, stretched flames, and ignition and extinction phenomena. Three lectures are devoted to non-premixed combustion and cover the structure of diffusion flame, the mixture fraction formulation, flame lift-off and edge flames, the burning of condensed fuels and spray combustion. The remaining three lectures are devoted to flame instability, hydrodynamic and thermo-diffusive, and to turbulence covering in particular the various regimes of turbulent combustion and the notion of the turbulent burning velocity.

Professor Heinz Pitsch received his Ph.D. in mechanical engineering from RWTH Aachen University in 1998. He held post-doctoral positions at UC San Diego and Stanford University and joined the faculty of Stanford University in 2003. In 2010 he returned to RWTH Aachen University to assume his present position as Head of the Institute for Combustion Technology. Professor Pitsch’s research interests are in combustion theory, modeling of turbulent reacting flows with large-eddy simulations, development and analysis of chemical kinetic reaction mechanisms, modeling of pollutant formation, development of numerical methods, investigation and modeling of combustion instabilities, and model applications to modern aircraft engine combustion, reciprocating engine combustion, and chemical processing.

Combustion and Fuels Chemistry (15 hours)

Lecturer: William H. Green, MIT

Objective: The aim of this course is to provide students with an understanding of how rate coefficients and products of elementary reactions of importance in combustion are determined experimentally, how they are used in conjunction with theoretical models and how they are incorporated in chemical mechanisms for use in combustion models. Determination of the thermodynamic properties for radical species will also be discussed. The course will be illustrated by a number of examples of relevance to high and low temperature hydrocarbon oxidation and NOx formation and control; with a discussion on the impact of combustion emissions on climate change and air quality.

Professor William H. Green received his Ph.D. in experimental physical chemistry from the University of California at Berkeley in 1988, and is presently the Hotell Professor of Chemical Engineering at MIT. He was the Editor of the International Journal of Chemical Kinetics from 2008-2013, and received the American Chemical Society’s Glenn Prize in Fuel Chemistry in 2013.

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Green’s research interests are in the areas of chemical kinetics, molecular simulation and free radical reactions. His research group focuses on the central problem of reactive chemical engineering: quantitatively predicting the time evolution of chemical mixtures. Professor Green is a Principal Investigator at the Combustion Energy Frontier Research Center.

Reciprocating Engines (15 hours)
Lecturer: Rolf D. Reitz, University of Wisconsin at Madison
Objective: Engine fundamentals and performance metrics, computer modeling supported by in-depth understanding of fundamental engine processes and detailed experiments in engine design optimization.

Professor Rolf D. Reitz received his Ph.D. in mechanical and aerospace engineering from Princeton University in 1978, and is presently the Wisconsin Distinguished Professor in Mechanical Engineering at the University of Wisconsin-Madison. Professor Reitz’s research interests include internal combustion engines and sprays. He is currently developing advanced computer models for fuel injected engines, including diesel and spark-ignited engines. Reitz also performs engine and high-pressure spray experiments to study the effect of fuel injection characteristics on diesel engine soot and NOx emissions, as well as to provide validation data for the computer models. Professor Reitz is a Principal Investigator at the Combustion Energy Frontier Research Center.

Unsteady Combustor Processes (9 hours)
Lecturer: Timothy C. Lieuwen, Georgia Institute of Technology
Objective: This course will address the unsteady combustor physics that define many of the most important considerations associated with modern combustor design. These unsteady processes include transient, time harmonic, and stochastic processes. For example, ignition, flame blowoff and flashback are transient combustor issues. Similarly, combustion instabilities are a time-harmonic unsteady combustor issue where the unsteady heat release excites natural acoustic modes of the combustion chamber.

Professor Timothy C. Lieuwen received his Ph.D. in mechanical engineering from the Georgia Institute of Technology in 1999 and is presently a Professor in the School of Aerospace at Georgia Tech. Professor Lieuwen’s research interests are in dynamical combustion phenomenon, hydrodynamic stability of reacting flows, and thermoacoustics, as applied to low emissions combustion systems for power and propulsion applications.

New Developments in Combustion Technology (6 hours)
Lecturer: George A. Richards, NETL, DOE
Objective: This course will introduce students to emerging combustion technologies including chemical looping combustion, pressure gain combustion, and oxy-combustion for magnetohydrodynamic power generation. For each of these technologies, the basic chemistry and physics will be described, along with a presentation of the problems that must be addressed to develop these interesting new ideas.

Dr. George (“Geo”) A. Richards received his Ph.D. in mechanical engineering from Purdue University in 1987, and is presently a Focus Area Leader in the Office of Research and Development of the National Energy Technology Laboratory. Dr. Richards’s research interests are in energy systems, which include all types of energy conversion devices particularly gas turbines and combustion. Since 2001, he has led the Energy System Dynamics Focus Area, providing technical direction for research groups investigating stationary turbines, coal/biomass gasification,
5th Annual CEFRC Summer School on Combustion (cont’d)

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carbon dioxide capture, combustion, heat transfer, high-temperature fuel cells, fuel processing, and sensors. He also serves as a research advisor for both graduate and post-graduate investigators visiting from academic institutions, and has been an adjunct faculty member at West Virginia University and the University of Pittsburgh. Dr. Richards currently serves as an associate editor for AIAA Journal of Propulsion and Power.

Residence and Meals:
Dormitory lodging is available in air-conditioned, single-person rooms on the beautiful campus of Princeton University. Meal plans are also available to participants.

Student Scholarships:
All non-Princeton University students who are enrolled at U.S. academic institutions will receive scholarships sufficient to cover the expenses for up to 7 days of dormitory lodging from 6/21-6/28, 2014.
All Princeton University students will receive scholarships sufficient to cover the expenses for 5 days of lunch, from 6/23-6/27, 2014.

Important Dates:
Application deadline: March 14, 2014
Acceptance announcement: March 28, 2014
Registration deadline: April 11, 2014

Contact:
Further inquiries on the academic program or logistics of participation may be made by contacting:
Lilian Tsang, CEFRC Program Administrator
Email: ltsang@princeton.edu
Telephone: 609.258.5041

2014 Tsinghua-Princeton Summer School on Combustion

The third annual Tsinghua-Princeton Summer School on Combustion will be held at Tsinghua University, Beijing, China from July 19-25, 2014. This year’s program will feature courses in Combustion Theory, Combustion Chemistry and Modeling, Computational Turbulent Combustion, and Quantitative Laser Diagnostics for Combustion Chemistry and Propulsion, to be delivered respectively by Prof. Moshe Matalon of the University of Illinois at Urbana-Champaign, Dr. Charles K. Westbrook of Lawrence Livermore National Laboratory, Dr. Thierry Poinot of the Institut de Mécanique des Fluides de Toulouse, and Prof. Ronald K. Hanson of Stanford University.
CEFRC People in the News


In September 2013, the Italian Chemistry Society awarded **Prof. Carter** with the Sigillo D’Oro (Golden Sigillum) at the Avogadro Colloquium in Pisa, Italy.

In October 2013, **Prof. Carter** gave the keynote lecture at the 224th Electrochemical Society Meeting in San Francisco, CA. The lecture was titled “Mechanisms of (Photo)Electrochemical Reduction of Carbon Dioxide From First Principles.”

Also in October 2013, **Prof. Carter** gave the Lord Public Lecture at Allegheny College in Meadville, PA with the lecture titled “How Quantum Mechanics Can Help Solve the World’s Energy Problems.”

In November 2013, **Prof. Carter** gave the invited Mathematics of Planet Earth (MPE) 2013 Simons Public Lecture at the Institute for Pure and Applied Mathematics in Los Angeles, CA. The lecture was titled “Quantum Mechanics and the Future of the Planet.”

Also in November 2013, **Prof. Carter** gave the Kenneth S. Pitzer Lecture at the University of California, Berkeley. The lecture was titled “Quantum Mechanics Without Wavefunctions.”

In December 2013, **Prof. Carter** gave the 2013 Hoyt C. Hottel Lecture in Chemical Engineering at MIT in Cambridge, MA. The lecture was titled “How Quantum Mechanics Can Help Solve the World’s Energy Problems.”


**Prof. Carter** was the 2014 Linnett Visiting Professor of Chemistry at the University of Cambridge during February. During that time, she presented three talks: “Running Combustion Backwards: Fuels from Sunlight, From First Principles”, “Quantum Mechanics Without Wavefunctions”, and “(Photo)electrocatalysis: Theory and Mechanisms of Charge Transfer at Metal Surfaces.”

In September 2013, **Prof. William H. Green** received the ACS Glenn Award for Best Paper Submitted to the Energy & Fuels Division for the technical paper “Sulfur Group Type Response to an Oxidative Desulfurization Treatment.”

**Prof. Yiguang Ju** gave a plenary lecture entitled “In Situ Plasma Activated Low Temperature Chemistry and Ignition in DME/Oxygen/Helium Mixture” at the 8th International Conference on Reactive Plasmas and 31st Symposium on Plasma Processing in February 2014 in Fukuoka, Japan.

**Prof. Chung K. Law** gave the Second Adel F. Sarofim Distinguished Lecture at the Department of Chemical Engineering, University of Utah in February 2014. The lecture was entitled “Some Fundamental Combustion Problems of Terrestrial and Extraterrestrial Interest.” Professor A.F. Sarofim, who was the first chair of the International Advisory Board of the CEFRC, passed away in November, 2011.

**Prof. Law** offered the congratulatory speech on behalf of the Combustion Institute at the inauguration ceremony of the Clean Combustion Research Center, King Abdullah University of Science and Technology (KAUST), Saudi Arabia, followed by a plenary lecture on: “In Pursuit of Conceptual Simplicity and Unification in Combustion,” in February 2014.

**Prof. Stephen B. Pope** gave the William C. Reynolds Memorial Lecture at Stanford University, Stanford CA in November 2013. The lecture was titled “Computational Modeling of Turbulent Combustion.”

In September 2013, at the 247th National American Chemical Society Meeting in Indianapolis, IN, **Prof. Donald G. Truhlar** gave two lectures entitled “Computational Chemistry of Aqueous Clusters and Aqueous Solutions,” at the Symposium on Theory and Experiment on Water and Hydration and “Electronic Structure of Excited States in the Gas Phase and Solution,” at the Symposium on Computational Photocatalysis.

**Dr. Colin Smith**, a Combustion Energy Research Fellow who has been conducting research with Prof. Ronald K. Hanson and Dr. Nils Hansen, has accepted a position with Jet Propulsion Laboratory as a Thermal Engineer. We wish Dr. Smith all the best on the next phase of his scientific career.
Message from the Director

I just returned from visiting the Clean Combustion Research Center (CCRC) at KAUST (King Abdullah University of Science and Technology) as part of a delegation invited to celebrate its inauguration. What I heard from colleagues who had already visited KAUST did not prepare me for witnessing first-hand the grandeur of the project - to build a university city from scratch, endow it with a comfortable living environment and the best scientific equipment, and use them to attract the best talents around the world. In many aspects they have already accomplished these goals, especially in setting up the physical infrastructure. As far as the CCRC is concerned, it seems that they have all the state-of-art equipment available for cutting-edge combustion research, and has attracted a strong group of faculty, post-doc fellows and students to perform the research. As one member of our delegation commented, the beauty of the concept of this enterprise is that the researchers are freed from many of the non-scientific distractions such as fund raising and adequate technical support, such that they can devote all their attention to doing science, which is what they are trained and supposed to do. The CCRC has our very best wishes in its quest to be a major center of excellence in combustion research.

Many members of the delegation were from the US, and it was inevitable that comparisons were made with the hardship in funding faced by researchers in this country. Through my recent visits to various academic institutions and discussions with colleagues, the contrast in funding adequacy couldn’t be starker. The expected level of funding for a faculty member in a major research university has been steadily increasing, while the amount of funding per grant has either remained flat or actually decreased in many instances. Furthermore, the odds of having a proposal funded are rather low, while the cost of doing academic research is also getting higher. Consequently faculty members are spending disproportionately more time in writing proposals than doing science, and are also expected to have the confidence of steel in being continuously disappointed with rejections.

While a comparison with KAUST may not be representative considering its immense resource, in recent years we have also witnessed the rapid increase of research resources and activities in countries in Europe and Asia. This is a welcome development, facilitating the tackling of problems that are of a global nature such as energy sustainability and climate change. On the other hand, the policymakers of this country should nevertheless take heed and assure our leadership position in scientific research and education, as science is the engine of progress and prosperity. History has shown that societies that are weak in science will eventually sink to the lower echelon of relevance.

For technical reporting, this issue contains articles by Professor Ron Hanson and Dr. David Davison of Stanford on the development and capabilities of shock tubes and the associated optical techniques in the study of chemical kinetics, and by Professor Bill Green of MIT on low temperature chemistry. As you read the Stanford article, you will appreciate the various ingenious ways the conventional shock tube has been cleverly modified to yield results of ever more utility and accuracy. The article by Green exemplifies a direction that the CEFRC is heading, namely low-temperature chemistry characterized by the NTC (negative temperature coefficient) and knock phenomena.

In the last issue I mentioned the intention of the CEFRC PIs to write review articles on various topics related to combustion chemistry, emphasizing the difficulties and challenges rather than just trumpeting the successes. So far four of these reviews (on techniques using shock tubes, rapid compression machines, flow reactors, and laminar flames) have been submitted and are in various stages of revision for journal publication. Four more are in preparation, covering jet stirred reactors, theories of combustion chemistry, uncertainty quantification and butanol mechanisms. When all of them are published, this suite of articles not only will provide the state-of-art evaluation of the various topics in combustion kinetics, but it will also constitute an accounting to our sponsor of our funded work.

Many of you have submitted papers to the upcoming Combustion Symposium and are probably anxiously waiting for the outcome. I have had the privilege of communicating with some of the colloquium co-chairs at a personal level, and have been very much impressed with their seriousness and dedication to the selection job at hand. Consequently, when all is settled and regardless of the outcome of your submission, I encourage you to send them a note of appreciation, which they richly deserve. This is the strength of our community: technical excellence communicated through collegiality and cordiality.

On behalf of all of us at the CEFRC, I wish you all the best in your scholarly pursuit!

Sincerely,

[Signature]

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Editors: C.K. Law, N. Hansen, L. Tsang
Contact: Lilian Tsang, itsang@princeton.edu

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