Final Report

of the

Joint NSF-NSFC Workshop on Combustion Related to Sustainable Energy

March 10 - 12, 2014

Jinxi Hotel

Hangzhou, China

Sponsored by:

U.S. National Science Foundation
National Science Foundation of China
Executive Summary of Workshop Findings

Global climate considerations have sparked considerable debate about the role of combustion in the future, particularly with regard to the combustion of fossil or non-renewable fuel resources. While renewable fuels are on a trajectory to provide an increasing fraction of the world’s energy needs, U.S. and global energy forecasts for the coming decades indicate that renewable fuel resources will only provide a portion of our overall energy consumption. Also, many of these renewable resources will still require the use of thermal processing, such as combustion or gasification, to release their available energy. Even with increased utilization of other renewable resources such as wind and solar, and continued or increased reliance upon hydroelectric and nuclear power for a portion of our energy portfolio, combustion, of either fossil or renewable fuels, will continue to play a key role in the global energy picture for many decades to come.

China and the U.S. are the top two generators of CO\(_2\) emissions from fossil-fuel combustion. Consequently, U.S.-China collaboration on combustion and sustainable energy is essential for addressing a variety of global energy-related challenges, ranging from sustainable fuel supply to air quality, solid waste management and global warming. If the U.S. and China do not address CO\(_2\) emissions, it is unlikely that other countries would or that they could make a difference even if they did take action. The U.S. National Science Foundation and the National Science Foundation China recently sponsored a workshop to explore the role of combustion in sustainable energy, which brought together 20 leading combustion scientists and engineers from the U.S. and China. The workshop was held in Hangzhou, China on March 10-12, 2014. The workshop featured brief presentations from each of the participants, followed by facilitated discussion sessions. Appendix A contains a detailed outline of all of the potential priority research topics identified in this workshop, but this summary highlights the promising priority areas for fundamental study, suitable for sponsorship by these two agencies, where U.S.-China collaborative research would be particularly beneficial:

Global Climate Change Considerations. Although carbon capture and storage (CCS) is currently practiced at the demonstration scale, it is currently too expensive to deploy at the scale necessary to affect worldwide CO\(_2\) emissions. In addition to CO\(_2\) emissions, combustion is the main source of black carbon, which contributes to climate forcing. In the near term, improvements are needed in oxyfuel combustion and gasification technologies that will 1) improve efficiency and 2) reduce carbon-capture costs. Over the medium to longer term, more efficient carbon capture strategies are needed, such as chemical looping combustion, which uses reactions with a metal oxide to react with fuel instead of air. Fundamental research can drive these near-term improvements as well as lay the groundwork for next-generation carbon-capture strategies, which may differ substantially from current air-type operating conditions. Examples of potential research areas include radiative properties under oxyfuel conditions, soot formation under oxyfuel and gasification conditions, and oxygen carrier development for chemical looping.

Sustainable/Renewable Fuel Supply. As the U.S. and China transition to less carbon-intensive fuels (i.e., natural gas, biomass, and hydrogen), fundamental research is needed to
ensure a smooth transition while avoiding unintended consequences, such as competition with food sources. These new fuels will change combustion characteristics, efficiency, and emissions. Fundamental challenges associated with biomass utilization include the alkali content of fuels, kinetics, emissions, performance, and heat-transfer characteristics of multicomponent fuels.

**Improved Efficiency of Combustion Systems.** Improving combustion system efficiency will reduce fuel use, the adverse impacts of fuel recovery, and greenhouse gas emissions, making it a key strategy for sustainability. Fundamental combustion research areas aimed at improving efficiency include low-temperature combustion, high-pressure combustion, flameless combustion systems, novel engine designs, and new fluids to improve the efficiency of the power cycle. Challenges will accompany these more efficient combustion technologies, such as understanding and addressing the transition from subcritical to supercritical in fuel feeding associated with high-pressure combustion.

**Environmental Impacts.** Combustion sources are ubiquitous and include power plants, vehicles, solid fuels used for heating and cooking, wildfires, and fires used for agricultural purposes. Consequently, its impacts, in addition to climate change, are wide ranging and include solid and liquid wastes, and air pollution in the form of particulate matter, NOx, SOx and air toxics. Combustion processes generate the majority of fine particulate matter, NOx, and SOx in both the U.S. and China. As population and the economies of the US and China continue to grow, the impacts of combustion must continue to be mitigated, and research will be key to addressing these challenges. Examples of fundamental research areas include soot formation and oxidation, trace element chemistry, design and fuel blending to mitigate emissions and emerging issues associated with new fuels, which need to be considered over the entire life cycle.

**Enabling Technologies and Novel Combustion Concepts.** Developments in sensors and diagnostics will lead improved understanding of combustion processes, such as soot formation and radiation, that can lead to transformational energy solutions. One example is improved understanding of radiation that could be used to develop a high-radiation engine or boiler. Radiation is also important because it affects flame temperature as well as chemistry, and is critical for designing oxycombustion systems. Improved materials can enable new engine and boiler designs, while gas-separation methods can translate into several other target areas, particularly carbon capture and separation, improved combustion efficiency, and the development of novel combustion concepts. Understanding the fundamentals of combustion processes, like radiation and soot formation, will foster the development of novel combustion processes. These could include the hybrid solar combustion/gasification systems, porous media combustion, and high-radiation systems. In addition, continued improvements in multi-scale modeling allow the coupling of radiation, chemistry, and turbulent flows and can lead to new understanding of important combustion mechanisms, such as predicting how new fuels will behave in terms of performance, radiation, ash chemistry, and emissions.
Introduction

A workshop on Combustion Related to Sustainable Energy was held in Hangzhou, China on March 10-12, 2014. The workshop was jointly sponsored by the U.S. National Science Foundation (NSF) and by the National Science Foundation in China (NSFC). The purpose of the workshop was to bring together a limited number of researchers from the U.S. and China (10 from each country) to identify priority research objectives for potential joint research projects involving collaborating investigators from the U.S. and China.

This workshop was a forum where lead researchers from the U.S. and China gathered to address critical needs in the general area of combustion (which includes combustion, gasification, pyrolysis and related thermal processes). It included several themes:

1) Global Climate Change Considerations, such as reducing the emissions of greenhouse gas emissions through carbon capture and sequestration (CCS), and switching to lower carbon or even more carbon-neutral fuels;
2) Sustainable/Renewable Fuel Supply, which includes a transition to more renewable resources, but also new fossil-based resources (e.g. shale gas) and new approaches for using fossil resources in a more climate-friendly manner;
3) Improved Efficiency of Combustion Systems, which would impact each of the 3 previous items.
4) Environmental Impacts beyond climate change (Hg, NOx, SOx, PM2.5, air toxics emission, solid/liquid waste streams); and
5) Enabling Technologies and Novel Combustion Concepts, which includes new developments in combustion and other related technologies.

Workshop Description

Need for this Workshop

Combustion has historically been the primary mode for energy utilization for electricity generation, transportation, and heating of homes and buildings. Combustion has also been a key factor in a wide variety of industrial processes. While many recent advances have facilitated an increasing use of alternative technologies such as solar cells, wind turbines, fuel cells for many of these applications, combustion continues to play an important role.

Global climate considerations have sparked considerable debate about the role of combustion in the future, particularly with regard to the combustion of fossil or non-renewable fuel resources. While renewable fuels are on a trajectory to provide an increasing fraction of the world’s energy needs, U.S. and global energy forecasts for the coming decades indicate that renewable fuel resources will only provide a portion of our overall energy consumption. Also, many of these renewable resources will still require the use of thermal processing, such as combustion or gasification, to release their available energy. Even with increased utilization of other renewable resources such as wind and solar, and continued or increased reliance upon hydroelectric and nuclear power for a
portion of our energy portfolio, it is apparent that combustion, of either fossil or renewable fuels, will continue to play a key role in the global energy picture for many decades to come.

Given that our global economy will continue to rely upon combustion-based technologies for the foreseeable future, it is critical that we address research needs that will assist in the utilization of combustion in a sustainable manner; in particular, that we address the global impacts of our reliance upon combustion technologies (which include combustion, gasification, pyrolysis and related thermal processes).

It is imperative that we evaluate existing combustion technologies for possible areas of improvement. Specifically we need to address: global climate change considerations; sustainable fuel supply, which includes not only a transition to more renewable resources, but also new fossil-based resources (e.g. shale gas) and new approaches for using fossil resources in a more climate-friendly manner; other environmental impacts beyond climate change; and energy efficiency considerations. In addition, there is a need to continue the development of alternative combustion technologies that can provide greater efficiency, reduced pollutant emissions and reduced climate impact.

Combustion is a critical component of developed and developing economies, and the U.S. and China represent two of the largest global economies with the greatest reliance upon combustion-based technologies for home and industrial power generation, heating and transportation. As such, it is critical that leaders in the field of combustion research gather together to identify critical needs to help shape the research agendas of the government funding agencies.

**Information on the Organizing Committee**

This meeting was jointly organized with support from the National Science Foundation of China (NSFC) and the U.S. National Science Foundation (NSF). A principal co-organizer was selected by each of the two sponsoring agencies to facilitate the workshop organization and execution. The co-organizer from China was Prof. Zhongyang Luo of Zhejiang University, who is a Professor of Energy Engineering, Dean of the Department of Energy Engineering, and is Director of the State Key Laboratory of Clean Energy Utilization. The co-organizer from the U.S. was Prof. Eric G. Eddings of the University of Utah, who is a Professor of Chemical Engineering, Associate Dean for Research in the College of Engineering, and Associate Director of the Institute for Clean and Secure Energy.

**Workshop Format**

The workshop included brief presentations from workshop participants to introduce novel research ideas to address the primary workshop topic, followed by facilitated discussion at the end of each of 3 half-day sessions. The last session of the workshop was a focused discussion by the group to coordinate overall recommendations to the NSF and NSFC. The recommendations that resulted from this final discussion are summarized in outline form in Appendix A. The individual presentations made by conference participants are listed in the detailed workshop agenda, which is attached as Appendix B. Detailed meeting notes of the discussions following each of the 3 sessions can be found in Appendix C. PDF copies of the individual workshop participant presentations will be made available on the website of...
the Institute for Clean and Secure Energy at the University of Utah (www.icse.utah.edu), along with an electronic copy of this report. The PDF files will be linked to the titles of the presentations in Appendix B in the web version of this report.

**Workshop Participants**

This workshop was an invitation-only event, and included 10 invited participants from the U.S. and 10 from China. With regard to recruiting participants, the focus was to identify individuals who had a strong background in combustion research, particularly with regard to the topics of interest for this workshop, and who were also available to travel to China for the meeting on the specified dates March 10-12, 2014. Efforts were expended to include women and underrepresented minorities among this group of participants. The participants from each country are shown in the photograph and are also listed below:

**U.S. workshop participants**

**Arvind Atreya**  
Professor, Dept. of Mechanical Engineering  
University of Michigan

**Richard Axelbaum**  
Jens Professor of Environmental Engineering Science  
Dept. of Energy, Environmental and Chemical Engineering  
Director of the Consortium for Clean Coal Utilization  
Washington University in St. Louis

**Eric G. Eddings**  
Professor, Dept. of Chemical Engineering  
Associate Dean for Research, College of Engineering  
Associate Director, Institute for Clean and Secure Energy  
University of Utah

**Ahmed Ghoniem**  
Ronald C. Crane Professor  
Dept. of Mechanical Engineering  
Massachusetts Institute of Technology  
(*Unable to participate at the last minute, due to illness*)

**Chung K. (Ed) Law**  
Robert H. Goddard Professor  
Dept. of Mechanical and Aerospace Engineering  
Director, Combustion Energy Frontier Research Center  
Princeton University

**Wayne Seames**  
Chester Fritz Distinguished Professor  
Dept. of Chemical Engineering  
Director, SUstainable eNergy Research, Infrastructure and Supporting Education program (SUNRISE)  
University of North Dakota
Christopher Shaddix  
Distinguished Technical Staff  
Sandia National Laboratories

Chih-Jen (Jackie) Sung  
Connecticut Clean Energy Fund Professor in Sustainable Energy  
Dept. of Mechanical Engineering  
University of Connecticut

Phillip Westmoreland  
Professor, Dept. of Chemical and Biomolecular Engineering  
2014 Past President, American Institute of Chemical Engineers  
Executive Director, NCSU Institute for Computational Science and Engineering  
North Carolina State University

Kevin Whitty  
Associate Professor, Dept. of Chemical Engineering  
Leader of International Energy Agency (IEA) Bioenergy Task 33: Thermal Gasification of Biomass  
University of Utah

In addition, travel funds were allocated to accommodate a graduate student to participate in the workshop and to assist in compiling detailed notes of the meeting. The student was:

Ms. Kerry Kelly  
Ph.D candidate, University of Utah  
B.S. Chemical Engineering, Purdue University  
M.S. Environmental Engineering, University of North Carolina, Chapel Hill

China workshop participants

Zhongyang Luo  
Professor of Energy Engineering  
Dean of the Department of Energy Engineering  
Director of the State Key Laboratory of Clean Energy Utilization  
Zhejiang University

Hao Zhou  
Zhejiang University

Changsui Zhao  
Southeast University

Mingfa Yao  
Tianjin University
Mingchuan Zhang  
Shanghai Jiaotong University

Shijin Shuai  
Tsinghua University

Liguang Li  
Tongji University

Zuohua Huang  
Xi’an Jiaotong University

Zhen Huang  
Shanghai Jiaotong University

Minghou Xu  
Huazhong University of Science and Technology

Participants from the sponsoring agencies

Bill Chang  
Acting Office Director  
Beijing Office  
U.S. National Science Foundation

JoAnn Lighty  
Division Director  
Chemical, Bioengineering, Environmental, and Transport Systems  
U.S. National Science Foundation

Ruey-Hung Chen  
Program Director  
Combustion, Fire and Plasma Systems  
U.S. National Science Foundation

Bruce Hamilton  
Program Director  
Environmental Sustainability  
U.S. National Science Foundation

Liyao Zou  
National Science Foundation of China
Workshop Findings and Recommendations

The workshop involved brief (15 minute) presentations from the invited participants, in which they provided an overview of some of their thoughts related to the topic of the workshop, as well as a brief summary of any related research from their own laboratories. The purpose of these presentations was to stimulate discussion and seed ideas among the participants gathered for the workshop. The brief presentations were divided into 3 sessions as follows: 1) a more general session on Combustion Related to Sustainability; 2) Advanced Combustion Topics, and 3) Fuels and Engines. After each session of approximately 5-8 presentations, an extended period of discussion was held where views were expressed by the workshop participants concerning the topics raised in the presentations, and in related areas. Notes were taken during each of these 3 discussion sessions, and these notes are included as Appendix C of this report.

On the afternoon of the second and final day of the workshop, an extended discussion was held in which earlier discussion points were revisited and examined with regard to their importance to both countries, and the likelihood of providing an opportunity for a joint research project between principal investigators from both the U.S. and China. The high priority research issues, as determined by the collective group of combustion researchers from the two countries, were identified and categorized into 5 different themes. The list was generated "live" during the discussion, by projecting it onto the main screen in the workshop meeting room, so that content, wording and categorization could be edited by the entire group during the final afternoon discussion.

The finalized list that resulted from this discussion is included in this report as Appendix A. A brief narrative summary of the key items in each of the categories is presented below. These items represent the critical research priorities, as identified by the workshop participants, for funding of joint NSF/NSFC research programs between the U.S. and China.

Global Climate Change Considerations. Although carbon capture and storage (CCS) is currently practiced at the demonstration scale, it is currently too expensive to deploy at the scale necessary to affect worldwide CO₂ emissions. In addition to CO₂ emissions, combustion is the main source of black carbon, which contributes to climate forcing. In the near term, improvements are needed in oxyfuel combustion and gasification technologies that will 1) improve efficiency and 2) reduce carbon-capture costs. Over the medium to
longer term, more efficient carbon capture strategies are needed, such as chemical looping combustion, which uses reactions with a metal oxide to react with fuel instead of air. Fundamental research can drive these near-term improvements as well as lay the groundwork for next-generation carbon-capture strategies, which may differ substantially from current air-type operating conditions. Examples of potential research areas include radiative properties under oxyfuel conditions, soot formation under oxyfuel and gasification conditions, and oxygen carrier development for chemical looping.

Sustainable/Renewable Fuel Supply. As the U.S. and China transition to less carbon-intensive fuels (i.e., natural gas, biomass, and hydrogen), fundamental research is needed to ensure a smooth transition while avoiding unintended consequences, such as competition with food sources. These new fuels will change combustion characteristics, efficiency, and emissions. Fundamental challenges associated with biomass utilization include the alkali content of fuels, kinetics, emissions, performance, and heat-transfer characteristics of multicomponent fuels.

Improved Efficiency of Combustion Systems. Improving combustion system efficiency will reduce fuel use, the adverse impacts of fuel recovery, and greenhouse gas emissions, making it a key strategy for sustainability. Fundamental combustion research areas aimed at improving efficiency include low-temperature combustion, high-pressure combustion, flameless combustion systems, novel engine designs, and new fluids to improve the efficiency of the power cycle. Challenges will accompany these more efficient combustion technologies, such as understanding and addressing the transition from subcritical to supercritical in fuel feeding associated with high-pressure combustion.

Environmental Impacts. Combustion sources are ubiquitous and include power plants, vehicles, solid fuels used for heating and cooking, wildfires, and fires used for agricultural purposes. Consequently, its impacts, in addition to climate change, are wide ranging and include solid and liquid wastes, and air pollution in the form of particulate matter, NOx, SOx and air toxics. Combustion processes generate the majority of fine particulate matter, SOx, and NOx in both the U.S. and China. As population and the economies of the US and China continue to grow, the impacts of combustion must continue to be mitigated, and research will be key to addressing these challenges. Examples of fundamental research areas include soot formation and oxidation, trace element chemistry, design and fuel blending to mitigate emissions and emerging issues associated with new fuels, which need to be considered over the entire life cycle.

Enabling Technologies and Novel Combustion Concepts. Developments in sensors and diagnostics will lead improved understanding of combustion processes, such as soot formation and radiation, that can lead to transformational energy solutions. One example is improved understanding of radiation that could be used to develop a high-radiation engine or boiler. Radiation is also important because it affects flame temperature as well as chemistry, and is critical for designing oxycombustion systems. Improved materials can enable new engine and boiler designs, while gas-separation methods can translate into several other target areas, particularly carbon capture and separation, improved combustion efficiency, and the development of novel combustion concepts. Understanding
the fundamentals of combustion processes, like radiation and soot formation, will foster the development of novel combustion processes. These could include the hybrid solar combustion/gasification systems, porous media combustion, and high-radiation systems. In addition, continued improvements in multi-scale modeling allow the coupling of radiation, chemistry, and turbulent flows and can lead to new understanding of important combustion mechanisms, such as predicting how new fuels will behave in terms of performance, radiation, ash chemistry, and emissions.
APPENDIX A
DETAILDED OUTLINE OF POTENTIAL RESEARCH TOPICS

Carbon Capture Strategies

Oxyfuel combustion
  – High-pressure, staged-fuel addition
  – Radiative properties under high CO₂ conditions
  – High-radiative homogenous combustion
  – Ash transformations
  – Fuel stoichiometry – who to reduce excess CO₂ without producing CO
  – Near-surface phenomena around the coal particle
  – Flame structure
  – Gas-phase chemistry for 3rd-body reactions
  – Soot formation and oxidation
  – Coupling radiation with chemistry
  – Variable CO₂ recirculation
  – Extreme combustion conditions (moisture, temperature, pressure, O₂, CO₂)

Gasification
  – Slag rheology versus temperature, and slag crystallization
  – Slag-refractory interactions
  – Partial gasification systems (combined with combustion)
  – Char kinetics
  – Soot and fume formation
  – Char formation and pore structure
  – Materials and sensors that are suitable for gasification conditions
  – Use of biomass fuels

Chemical Looping Combustion/Gasification
  – Oxygen carriers
    • Reaction kinetics
    • Survivability
  – Meso-scale structure and scale up of fast fluidization
  – Heat and mass transfer considerations
  – Combustion of volatiles versus char for solid fuels
    • Different oxygen carriers
    • Different reactor configurations

Sustainable/Renewable Fuel Supply
  – Low-carbon fuels
    – Natural gas with or without CO₂ capture
    – Shale gas
    – Ethanol
    – Synthetic fuels (H₂)
    – Coal-derived natural gas and liquids
• Underground coal thermal treatment
• Methanol and dimethyl ether
  – Impact on performance and emissions
– Fuel designs
  – Blended fuels
    • Active (online)
    • Passive (offline)
    • Chemical kinetics
    • Multicomponent fuels - heat and mass transfer characteristics
    • Ignition and combustion behavior
  – Impact on performance and emissions
  – Fuel characterization (chemical and physical)
  – Life-cycle assessment (LCA)

**Improved Efficiency of the Combustion System**
• Improved engine designs
  – The Argon Engine. Research areas include gas mixing challenges associated with the density differential and high-temperature heat transfer issues
  – Low-temperature combustion (IC engines) to improve efficiency and reduce soot
  – Compression ignition/flameless combustion engines
• Combustion strategies
  – Dilute combustion
  – Flameless combustion
  – Improved harnessing of radiation
  – High pressure/low temperature (extreme) combustion
  – High-pressure combustion
• Addressing challenges associated with the new engine designs and combustion strategies
  – Knock
  – Autoignition
  – Flashback/blowoff
  – Instabilities associated with syngas combustion, gas turbine combustion, and thermoacoustic vibrations
  – Combustion safety
• Improved fluids for the power cycle
• LCA/economic analysis

**Environmental Impacts**
• NOx
• SOx
• Fine particulates
  – Primary particulates
    • Soot/ black carbon
    • Coal flyash
  – Secondary particulates
• Nitrates
• Sulfates
• VOCs
• Surface chemistry issues
• Trace elements (heavy metals, mercury, minerals)
  – Surface chemistry issues
• Unregulated emissions (aldehydes, phenols, etc.)
• Organics
• Emerging pollutant issues with new fuels
  – New impacts from novel fuels, spills, etc.
• Distributed combustion issues, i.e., wood heating, cook stoves, wildfires, fires for land clearing, agricultural burning
• Aerosol dynamics
## Appendix B

**Detailed Workshop Agenda**

**Joint NSF-NSFC Workshop on Combustion Related to Sustainable Energy**

*March 10 - 12, 2014*

*Jinxi Hotel, Hangzhou, China*

<table>
<thead>
<tr>
<th>Time</th>
<th>Content</th>
<th>Chair</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>March 10</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14:00-22:00</td>
<td>Registration</td>
<td></td>
</tr>
<tr>
<td>18:00-21:00</td>
<td>Reception</td>
<td></td>
</tr>
<tr>
<td>**09:00-09:30</td>
<td>Opening Ceremony</td>
<td>Prof. Zhongyang Luo</td>
</tr>
<tr>
<td>09:00-09:30</td>
<td>Welcoming Remarks: Chairs of the workshop:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dr. Zhongyang Luo, Zhejiang University</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dr. Eric G. Eddings, University of Utah</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Welcoming Remarks: Dr. Bill Chang, NSF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Welcoming Remarks: Dr. Liyao Zou, NSFC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Welcoming Remarks: Dr. JoAnn Lighty, NSF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Welcoming Remarks: Dr. Tao Liu, NSFC</td>
<td></td>
</tr>
<tr>
<td>**09:30-12:00</td>
<td>Session 1: Combustion Related to Sustainability</td>
<td>Prof. Eric Eddings &amp; Prof. Minghou Xu</td>
</tr>
<tr>
<td>09:30-09:45</td>
<td>Professor Chih-Jen (Jackie) Sung: The Role of Green Combustion in Energy Sustainability</td>
<td></td>
</tr>
<tr>
<td>09:45-10:00</td>
<td>Professor Zhongyang Luo: Biomass &amp; other clean combustion</td>
<td></td>
</tr>
<tr>
<td>10:00-10:15</td>
<td>Professor Wayne Seames: A process engineering perspective on research towards the long-term sustainable use of coal for power generation</td>
<td></td>
</tr>
<tr>
<td>10:15-10:30</td>
<td>Professor Shijin Shuai: Low Carbon Fuels for High-efficient and Clean Combustion</td>
<td></td>
</tr>
<tr>
<td>10:30-10:45</td>
<td>Professor Chung K.(Ed)Law: Extreme Combustion: Chemistry and Dynamics of Low-Temperature/High-Pressure Flames</td>
<td></td>
</tr>
<tr>
<td>10:45-11:15</td>
<td>Photo &amp; Coffee break</td>
<td></td>
</tr>
<tr>
<td>11:15-12:00</td>
<td>Discussion (Facilitated by Prof. Eddings &amp; Prof. Xu) New directions for combustion related to sustainable energy</td>
<td></td>
</tr>
<tr>
<td>**12:00-13:00</td>
<td>Lunch</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>Session 2: Advanced Combustion Topics</td>
<td>March 11 Afternoon</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>13:00-17:30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13:00-13:15</td>
<td>Professor Arvind Atreya: High Radiation Homogeneous Oxy-Fuel Combustion to increase Efficiency, lower Emissions, and Sequester CO₂</td>
<td></td>
</tr>
<tr>
<td>13:15-13:30</td>
<td>Professor Minghou Xu: Formation and Control of Ash Particles and Deposits during Oxy-Coal Combustion</td>
<td></td>
</tr>
<tr>
<td>13:30-13:45</td>
<td>Professor Richard Axelbaum: Oxy-combustion of coal and wet fuels</td>
<td></td>
</tr>
<tr>
<td>13:45-14:00</td>
<td>Professor Changsui Zhao: Fundamental research on oxy combustion in circulating fluidized bed</td>
<td></td>
</tr>
<tr>
<td>14:00-14:15</td>
<td><strong>Coffee Break</strong></td>
<td>Prof. Zhen Huang &amp; Prof. Ruey-Hung Chen</td>
</tr>
<tr>
<td>14:15-14:30</td>
<td>Dr. Christopher Shaddix: Scientific Research Challenges in Oxyfuel Combustion of Natural Gas, Syngas, and Coal</td>
<td></td>
</tr>
<tr>
<td>14:30-14:45</td>
<td>Professor Mingchuan Zhang: Modeling for some meso-scale phenomena in PC combustion and fast fluidization</td>
<td></td>
</tr>
<tr>
<td>14:45-15:00</td>
<td>Professor Kevin Whitty: Gasification and Chemical Looping Combustion of Coal and Biomass: Reactor Design, Sampling and Sensors</td>
<td></td>
</tr>
<tr>
<td>15:00-15:15</td>
<td>Professor Hao Zhou: Investigation on the thermoacoustic vibration in large capacity oil/gas fired furnace</td>
<td></td>
</tr>
<tr>
<td>15:15-15:30</td>
<td><strong>Coffee break</strong></td>
<td></td>
</tr>
<tr>
<td>15:30-17:30</td>
<td>Discussion (Facilitated by Prof. Huang &amp; Chen)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. Research Objectives for solid fuels</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Complementary capabilities for solid fuels</td>
<td></td>
</tr>
<tr>
<td>17:30-20:00</td>
<td><strong>Dinner</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Session 3</strong></td>
<td></td>
</tr>
<tr>
<td>09:00-12:00</td>
<td><strong>Fuels and Engines</strong></td>
<td></td>
</tr>
<tr>
<td>09:00-09:15</td>
<td>Professor Zhen Huang: Fuel Design Concept: A Way to Manage the Right Fuel for Clean Engine Combustion</td>
<td>Professor Phillip Westmoreland, Prof. Shuai</td>
</tr>
<tr>
<td>09:15-09:30</td>
<td>Professor Eric G. Eddings: Production of Bio-derived and Low-Carbon Fossil Fuels</td>
<td></td>
</tr>
<tr>
<td>09:30-09:45</td>
<td>Professor Zuohua Huang: Combustion and Chemistry of alternative clean automotive fuels for the next generation</td>
<td></td>
</tr>
<tr>
<td>09:45-10:00</td>
<td>Professor Mingfa Yao: Investigation on the Sustainable Fuels Utilizing in Internal Combustion Engines with High Efficiency and Low Emissions</td>
<td></td>
</tr>
<tr>
<td>10:00</td>
<td>Professor Phillip Westmoreland: Elementary-Reaction</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>Session</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>-------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>10:15</td>
<td>Kinetics for Engineering the Pyrolysis and Combustion of Gas, Biomass, Synthetic Polymers, and Coal</td>
<td></td>
</tr>
<tr>
<td>10:15-10:30</td>
<td>Professor Liguang Li: Research on Key Science Fundamentals of High Efficiency Zero Emissions Argon Engine: Research on Key Science Fundamentals of High Efficiency Zero Emissions</td>
<td></td>
</tr>
<tr>
<td>10:30-10:50</td>
<td>Coffee break</td>
<td></td>
</tr>
<tr>
<td>10:50-12:00</td>
<td>Discussion (Facilitated by Professor Phillip Westmoreland, Prof. Shuai)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. Research objectives for transportation fuels</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Complementary capabilities for transportation fuels</td>
<td></td>
</tr>
<tr>
<td>12:00-13:30</td>
<td>Lunch</td>
<td></td>
</tr>
<tr>
<td>13:30-15:30</td>
<td>Discussion (Facilitated by Prof. Eddings and Prof. Luo)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Revisiting research objectives &amp; complementary capabilities</td>
<td></td>
</tr>
<tr>
<td>15:30-15:50</td>
<td>Coffee break</td>
<td></td>
</tr>
<tr>
<td>15:50-17:00</td>
<td>Additional Discussion (Facilitated by Prof. Eddings and Prof. Luo)</td>
<td></td>
</tr>
<tr>
<td>17:00-17:30</td>
<td>Closing Ceremony</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Closing Remarks: Representative of NSFC and NSF</td>
<td></td>
</tr>
<tr>
<td>17:30-20:00</td>
<td>Dinner</td>
<td></td>
</tr>
</tbody>
</table>
SESSION 1: COMBUSTION RELATED TO SUSTAINABILITY

High-pressure processes
- Supercritical combustion faces capital cost issues as well as operational and safety challenges.
- Changing the fluid may be a good option.
- There is ongoing work with supercritical feeding for gas turbine injection as well as modern diesel engines. The critical issue for IC engines is how do you mix the liquids because you lose the interface of surface tension, which weakens the mixing conditions (more like turbulent gaseous mixing). A worthy research topic is the transition from subcritical to supercritical in fuel feeding.

Coal properties
- In China – high sodium coal leads to operational issues. Could we use coal blending as a solution?
- Pilot testing must be done for coal blending. The fundamental issue is whether better modeling capabilities can be developed to predict the emission/behavior properties.

Where does haze come from?
- What is the contribution of coal combustion and other sources to PM$_{2.5}$ in China? Does the experience from the last century in the U.S. help us overcome haze in China?
- Source apportionment/attribution may be a good way to estimate where particles come from. This may be an opportunity for collaboration.
- U.S. scientists should not collect air quality measurements in China.
- Coal combustion in cement manufacturing could be important.
- Lots of concern about particulate. It is clear that there are many different sources, in addition to coal plants. A lot of concern about agricultural burning in remote areas. If we introduce biomass pyrolysis units at these remote locations to process the residue and produce bio-char to put back on the land, we can help address this?

General
NSF Programs offer the opportunity for U.S. graduate students and postdocs to perform research in China. Annually NSF funds 40 students. This includes $5000 for student support and their international travel, local accommodations and some funding to the Chinese laboratory to support the student. Existing NSF grants can apply for supplements.

SESSION 2: ADVANCED COMBUSTION TOPICS

Fundamental research areas that can have a high impact:
- Oxyfuel combustion flame properties in CO₂ diluted fuel
- Radiation. This is relevant for more than oxycombustion (coal, IC engines, gas turbine engines). This is important because it affects the flame temperature as well as the chemistry. Increasing radiation can improve efficiency and reduce pollution, so this covers two key issues. In addition, coupling radiation, chemistry, and turbulent flows is important.
- Soot emissions/formation.
- Flameless combustion flame structure
- Improved understanding of competing processes over various length and time scales. Tradeoffs, e.g., soot and NOx emissions. What are the underlying mechanisms for various behaviors (composition, fluids, kinetics) and when are they most important?
- Improved diagnostics and sensors for combustion and gasification systems
- Improved materials for O₂ separation.

**Important research areas for solid fuels**
- Increasing efficiency
- Radiation
- Investigation of extreme combustion; e.g., high pressure, low temperature to get to better efficiency (this is slightly more applicable to liquid fuels). There are a lot of unknowns in chemistry. *Note this may be more relevant for liquid fuels.*
- Use-inspired combustion research; e.g., boilers, in addition to IC engine.
- Particle formation. Ash is relevant to radiation as well as CO₂, and it is critical to operability. It lends itself to fundamental studies. We haven’t hit the fundamentals of fine particle formation, but we must understand fundamentals to do things in a different way. Difficult to perform these studies at the fundamental level, particularly with realistic recycle conditions. Consequently, we need to perform research on this topic at a slightly larger scale.

**Most important biomass issues**
- Alkali content in biomass and impact on the boiler
- Conversion of biomass to liquid fuels

**Oxycombustion needs**
- Near-term demonstration that CCS really works (DOE-type funding?)
- Long term. Existing approaches are too expensive, so how do we improve efficiency and reduce costs. NSF should focus on longer term oxycombustion not coupled to air-type operating conditions.

**Broader issues**
- How should we prepare for the transition from coal to natural gas? In China, power is generated 75% from coal, but this will decrease to 45%.
- Thermal and combustion efficiency. Where would we get the biggest benefit - focusing on combustion efficiency or thermal efficiency? What is the limit of combustion efficiency to raise thermal efficiency?
- Carbon capture is important for coal and liquid combustion.
- Greenhouse gas control through oxycombustion, IGCC, Chemical Looping Combustion (CLC)
- Sustainable energy systems - use different kind of coal (like lignite in China - huge resource, but has many problems like high alkali and high moisture, and brown coal, or “young coal”/biomass).
- Energy insecurity – enhance energy efficiency
- Air pollution from all sources.
- Fuels of the future - coal will decrease - what will backfill?
- Natural gas will be important for 10-30 years.
- Low-carbon fuels and carbon neutral fuels, like algae.
- CO₂ to generate DME and other beneficial products and the study of carbon cycles.
- US and China are No. 1 and 2 in CO₂ emissions, we need to face this issue. How to increase energy efficiency is first issue. Second issue is air pollution levels. Third is CO₂.
- China has more restrictive emission limits now than the U.S., but they still have emission problems (because coal plants are not the only source, of course).
- Important items also include biofuels, ethanol, etc.
- Also, how to use CO₂ plus hydrogen to produce even more fuels. Capture followed by CO₂ use for fuel generation.
- Also how to reduce CO₂ from vehicles.
- Soot formation/oxidation for different kinds of fuels

What is fundamental research from NSF’s viewpoint? (See examples listed under the first point - Fundamental Research Areas that have High Impact - above).
- Has NSF has been less interested in coal combustion historically because it has been too complicated to perform fundamental studies?
- In some cases you need scale to get realistic results; e.g., ash particle formation. Will you run into bias because you need to burn 2 kg/hr. Maybe we need to educate our NSF program officers. Funding for these larger-scale experiments is also a problem.
- NSF – CO₂ sequestration not typically a focus for NSF.

What is fundamental research from NSF-C’s viewpoint?
- There is a lot of debate, but they have a bit more flexibility than NSF. They support fundamental research to explore new theories as well as technologies.
- They have three funding mechanisms.
  - General program – no restriction – PI driven.
  - Key program – these are targeted. This type of research program will come out in their annual research program guide. Funding would be approximately $3 million RMB over 5 years, more or less.
  - Identify common interests from both sides (U.S. & China), which would lead to a specific request for proposals.

Funding questions
- More funding should be allocated to combustion by both NSF and NSF-C, especially towards these international collaborations.
- Where would radiation studies fit within NSF? Radiation from flames or interaction with combustion would be under combustion, fire and plasma systems. Radiation is a small fraction NSF funding, not sure how much.
- Collaboration could involve project(s) that are more expensive than a typical core project, and the total project cost could be shared by NSF and NSF-C for a total of about $1 million (US).

**Miscellaneous research ideas**
- Heterogeneous combustion – identifying reaction kinetics.
- Petrographic analysis applied to coal combustion that would affect coal technologies.

**SESSION 3: - FUELS AND ENGINES**

**General areas of focus**
- Global warming
  - CCS
  - Improve efficiency
- Other pollutants – PM2.5, NOx, SOx, etc. PM2.5 should serve as a platform for research.
  - Fuel design to reduce PM2.5 - right fuel formulation, can reduce soot/NOx/SOx - will that make a huge difference in terms of emissions overall?
  - Combustion processes – kinetics, flame speed, etc. (see below)
  - Atmospheric chemistry – further transformation of PM2.5 and precursors, fluid transport
- Transition from coal to natural gas/biofuels, then to hydrogen and renewables.
  - Solve issues today where we can through efficiency (coal, liquid, and solid fuels) and CCS (less needed if improve first one).
  - Innovative solutions for the next-generation fuels
  - Electricity use is decreasing in the U.S. through improved efficiency.
- General
  - We need fundamental information to develop transformational technologies. Should we have an eye on developing out-of-the-box concepts, like ARPA-E focuses on (e.g., the Argon Engine)?
  - We are developing vast modeling capabilities, but we can’t wait until we conceptually solve the problem before moving ahead.
  - We should not focus on incremental improvements because auto manufacturers and power plants are working on this. However, if the incremental improvement is a key that fits in the lock that makes the change, then it is OK.
  - Other. Simplification of reaction mechanisms and unification. One key piece was equation to unlock CFB.
  - What happens after it leaves the exhaust - secondary reactions, transport - atmospheric chemistry.
NSF and Fundamental Research Objectives

NSF is not worried if there is some overlap with DOE. Areas of interest may include:

- Formation of inhalable particles – both primary production and secondary formation.
- Biofuels – how this affects efficiency and pollutant formation
- For engines, research topics may include: laminar flame speed and turbulent flame speed, studies at higher temperatures, controlled diffusion phenomena. Kinetics control ignition. In engine, real conditions, such as intermediate temperature and high pressure, necessary for engine atomization.
- There is a big difference between liquid and coal combustion in the role of turbulence.
- We need improved laser diagnostics to better understand chemical kinetics.

How does combustion relate to sustainability?

- Environmental sustainability should be key point of China’s efforts.
- Measurements suggest that transportation is one of the most important sources of PM (primary and secondary).
- We are moving away from fuels where we typically have experience. As China’s fuels changes, e.g., shift from coal to natural gas to biofuels, how does this change the situation?
- NSF Combustion, fire and plasma systems program doesn’t fund atmospheric chemistry. However, if it takes cooperation between two program areas to solve a problem this is OK. This would be a special call for proposals.
- Best thing to do is to not let it out of the tailpipe.
- In the U.S., eliminating PM emissions (or conventional pollution) isn’t considered sustainable, but addressing CO₂ is considered sustainable. From government agency – bridge to sustainability – would particulate problem be part of sustainability – yes it is time-scale pragmatic. Is coal as equally sustainable? In U.S. sustainability is a permanent thing. Move sustainability to broader understanding.
- Combustion and sustainability – all carbon-based fuel (except hydrogen, although in most cases originally comes from carbon sources). How are we mitigating carbon? We wouldn’t consider it sustainable if we don’t mitigate carbon.
- We need to address both carbon capture and other pollutants. If these two countries don’t address it, it won’t get addressed.
- Themes – novel fuels, need to use biofuels, still related to same thing. We haven’t talked about CO₂ as the pollutant as well. CO₂ emission is the elephant in the room.
- Two different types of support:
  - DOE – technology
  - NSF - fundamental

What are the things that we need to know (fundamental science) to make a big difference - leading to translational technologies - that will provide new opportunities?