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Frontiers in transport phenomena research and education: Energy systems, biological systems, security, information technology and nanotechnology

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Abstract

A US National Science Foundation-sponsored workshop entitled "Frontiers in Transport Phenomena Research and Education: Energy Systems, Biological Systems, Security, Information Technology, and Nanotechnology" was held in May of 2007 at the University of Connecticut. The workshop provided a venue for researchers, educators and policy-makers to identify frontier challenges and associated opportunities in heat and mass transfer. Approximately 300 invited participants from academia, business and government from the US and abroad attended. Based upon the final recommendations on the topical matter of the workshop, several trends become apparent. A strong interest in sustainable energy is evident. A continued need to understand the coupling between broad length (and time) scales persists, but the emerging need to better understand transport phenomena at the macro/mega scale has evolved. The need to develop new metrology techniques to collect and archive reliable property data persists. Societal sustainability received major attention in two of the reports. Matters involving innovation, entrepreneurship, and globalization of the engineering profession have emerged, and the responsibility to improve the technical literacy of the public-at-large is discussed. Integration of research thrusts and education activities is highlighted throughout. Specific recommendations, made by the panelists with input from the international heat transfer community and directed to the National Science Foundation, are included in several reports.

Keywords: Heat transfer; Energy; Biological; Security; Information; Nanotechnology; Education

1. Introduction

Advances in the sciences and in engineering continually fuel new technologies and pose new challenges to the engineering profession including the heat transfer community. Continuous evolution of fundamental knowledge, along with new technologies that enable instantaneous global communication, will cause radical changes in the way new products and systems are developed and manufactured, as well as the way engineers work.

To assess the evolving role of the transport phenomena community, a US National Science Foundation (NSF)-sponsored workshop was held on May 17–18, 2007 at the University of Connecticut. Similar related workshops have been convened from time-to-time in order to identify transport phenomena challenges and opportunities. The most recent workshop to deal with broad-based transport phenomena issues was held April 19–21, 1991 [1]. The 1991 workshop was also funded by NSF, and was attended by 140 individuals, almost all from the United States. The 1991 workshop report focused on several "critical technical areas vital to the economic success of the US", as shown in Table 1 [1]. A cursory examination of the table reveals the need to re-assess where the transport phenomena community is today, and where we may be headed in the future. And, if one assumes the number of contributors to each area of the 1991 Chicago Workshop Report was a gage

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Table 1
"Critical technologies" and the number of contributing individuals to the 1991 Chicago Heat Transfer Workshop Report [1]

Critical technology area	Contributors to report (from Academia)1
Manufacturing	65 (38)
Heat exchanger technology	59 (18)
Materials processing	47 (28)
Energy	42 (25)
Aerospace technologies	30 (13)
Environmental issues	25 (17)
Digital data processing	16 (9)
Bioengineering and biotechnology	13 (6)
Nano- and microtechnology	6 (6)

of overall interest in a particular topic, it can be argued that the transport phenomena community has very successfully addressed challenges related to many of the topics of Table 1, but is now addressing other issues that received sparse attention just 15 years ago. No mention of "education" can be found in the 240-page Chicago Workshop Report.

When the 2007 workshop was proposed (in 2005), research in *sustainable energy systems* had been dormant for nearly two decades and was just beginning to recapture major attention. Clearly, the technological advances over the last two decades now provide multi-disciplinary opportunities in which thermal engineering will play an important and perhaps leading role in terms of bringing new sources of energy online, developing cleaner traditional sources with reduced net emissions of greenhouse gases or in harvesting thermal energy that is currently wasted, and otherwise improving energy conservation effectiveness (see, for example, [2–6]). The world's demand for energy is expected to grow by over 50% in the next 25 years. Satisfying that demand in an economical and environmentally acceptable manner is one of the most significant challenges facing society. In spite of this expectation, there appears to be no urgent discussion of how some common and interrelated societal needs will be met. For example, a growing global population, the demands of energy production (i.e., from biofuels), the depletion of aquifers, contamination and other issues are affecting the world's supply of drinking water and availability of water for agriculture.

Although transport phenomena in *biological systems* are of obvious relevance, thermal science research has traditionally dealt with biomedical applications and thermal-based treatments and therapies. Today, there are new biotechnology and bioengineering challenges that would benefit from the contributions of, or would be enabled by the thermal science community (e.g., [7–14]).

In the last several years, increased attention has been paid to *security*, with large investments being made both by governments and the private sector. What are the challenges, and what is the role of the thermal science community in addressing the challenges (e.g., [15–17])? Although it may be argued that *information technology* and *nanotechnology* are broad topics that are becoming somewhat mature areas of research, information- and nanotechnology continue to pose technological challenges for the thermal sciences community, while simultaneously providing huge economic opportunities that will affect the daily lives of citizens throughout the world (e.g., [18]).

Regardless of the technical or scientific topic of the 2007 Workshop, *integration* of current research into the classroom has yet to be achieved on a widespread basis. What are the consequences of instantaneous global communication that is now available to individuals worldwide? What are the roadblocks regarding dissemination of transport phenomena research? Are there lessons to be learned from the past, or from other scientific communities that have taken aim at educating a much broader constituency including the general public (e.g., [19,20])?

2. Workshop organization

An executive committee (Appendix A) was formed in February of 2006 in order to nominate keynote speakers, identify participants and panel leaders in each topic, and to strive for a balanced, yet in-depth coverage of the focus areas. Subsequently, a plenary speaker (Dr. William Wulf, President of the US National Academy of Engineering), six keynote speakers (Appendix B), panel chairs, co-chairs, and panelists (Appendix C) were identified and invited. Rather than presenting a traditional technical paper, panelists were urged to begin by stating the societal impact of their topic, and to subsequently provide a brief overview of the technical principles involved, a review of the state-of-the-art, a delineation of barriers hindering progress, and specific recommendations. Copies of their presentations are available elsewhere [21]. To engage as many individuals as possible, invitations to attend the workshop were delivered to several hundred people, concurrent with several informational e-mail messages that were broadcast to thousands of members of the international transport phenomena community. The broadcast e-mails included a mechanism to request a personal invitation to the workshop. To facilitate open discussion, working lunches were held during the workshop to ensure that all attendees were given the opportunity to express their opinions, with preliminary position statements drafted by topic leaders and presented to the entire assembly, again with the opportunity to debate key points. Subsequently, draft reports were generated and posted for approximately one month on the workshop web site, and e-mails to several thousand individuals in the international transport phenomena community were sent, soliciting comments on the draft reports. All comments that were received from the international community were forwarded to the authors of the draft reports (panel chairs and co-chairs and several others) and final position statements (Section 4) were developed by the authors.

3. Assessment of interest in topical areas

In addition to the deliberative process described above, several methodologies were employed in an effort to gage, to the extent possible, the transport phenomena communities' relative interest in the topical areas of the workshop.

3.1. Registrant survey

As part of the online workshop registration process, each workshop attendee was asked to complete a brief survey, indicating the topic(s) of their interest. The results are shown in Table 2. (Note that the sum of interested individuals exceeds the number of registrants because individuals often identified multiple topics of interest.) Determination of the size and number of panels (two each in Energy, Biological Systems, and Nanotechnology; one each in Education, Information Technology and Security) was made in large part based upon the registrants' interest, as indicated in Table 2.

3.2. Keyword count

Each final report (Section 4) was examined for use of keywords directly related to the other five topics of the workshop. Keywords related to the topic of the report in which they were used were not counted (for example, reference to "energy" in the energy report was not counted). Although this is a somewhat subjective method to gage the community's interest, judgment was exercised during the keyword count to put the word usage into a proper context (see Table 3).

Table 2
Self-identified topics of interest by workshop attendees

Topic	Interested individuals
Energy systems	167
Nanotechnology	129
Education	111
Biological systems	94
Information technology	44
Security	44

Table 3
Keyword usage in final reports

Keyword	Keyword count
Energy	15
Education	10
Biology (or "medicine")	9
Nanotechnology (or "molecular scale," or "very small scale")	7
Security	7
Information technology	3

3.3. Community feedback on preliminary reports

As described in Section 2, comments were solicited from the international transport phenomena community in response to preliminary reports that were posted on the workshop web site. This open solicitation of comments resulted in feedback that was heavily weighted toward the energy (approximately 55% of comments) and biological systems (approximately 30% of comments) reports, with the remaining comments distributed among the other topics of the workshop.

Although we will let the reader draw their own conclusion regarding the levels of interest expressed in the specific *technical* topics, the strong interest in education is deemed to be important and encouraging.

3.4. Over-arching themes

Based upon the final reports (Section 4), several over-arching themes evolve. First, a continued need to understand the coupling between broad length (and time) scales is mentioned in all the technical reports, repeating a point that is stressed in the 1991 Workshop report [1]. One report (Energy) points out the need to better understand transport phenomena at the macro/mega scale, as was also noted in the 1991 Workshop report. The need to develop new metrology techniques and collect as well as archive reliable property data is a recurring theme (Biotechnology, Information Technology, Nanotechnology, and Security) that was also discussed extensively in the 1991 Workshop. New to the discussion is the broad issue of *societal sustainability* that receives major attention in two of the reports (Energy and Education). Also new are matters relating innovation, entrepreneurship, and globalization of the engineering profession, as discussed in the Education report. Similarly, the responsibility to improve the technical literacy of the public-at-large is stressed and/or discussed in three reports (Education, Energy and Nanotechnology). Finally, specific recommendations directed to the National Science Foundation are included in the reports on Biological Systems, Energy, and Education.

4. Topical reports

4.1. Biotechnology

The following biotechnology report was generated by Dr. Edward M. Carapezza (Chair, DARPA), Prof. Don P. Giddens (Georgia Institute of Technology), Prof. John R. Howell (The University of Texas at Austin), and Prof. Michael J. Pikal (University of Connecticut).

4.1.1. Introduction (biotechnology)

Enormous investments have been made in basic research into molecular biology by Federal agencies, particularly the National Institutes of Health (NIH) which enjoyed a recent doubling of its budget, as well as the private sector. Results of these endeavors should be viewed by the engineering community as an opportunity to contribute to the solutions of problems of global significance that will impact all of humanity. Engineering has the responsibility to bring to bear our quantitative approaches and strengths in modeling upon biological discoveries so that biological systems can be described, modeled, predicted and manipulated. Applications range from understanding phenomena at the molecular, cellular, tissue, organ and systems levels, whether these be in health, energy or environmentally related domains. And we hypothesize that no other field can achieve these translations into societal impact like engineering.

Transport phenomena will be ubiquitous in all such domains. Each endothelial cell lining a blood vessel is a minute factory that is subject to external mechanical and electrical stimuli, can adapt to its environment and regulate vessel function of the vessel wall, contribute to the development of arterial disease – each lives and dies in synchrony with its neighbors. The transport processes that govern each cell's function are beginning to be understood and are subject to modeling from an engineering perspective. Similar analogies can be made for entire ecosystems of the environment – transport processes are the means through which these systems function, adapt or become pathologic. The science of Biology cannot, in its present state, do much more than describe these processes qualitatively. Engineering is required to describe processes and system interactions in quantitative ways, thus enabling greater understanding and introducing the ability to predict and control. However, barriers to progress exist.

4.1.2. Barriers (biotechnology)

These include:

1. Separation between disciplines – the language, perspectives, approaches, and even funding agencies are different; this is especially obvious in the biomedical arena.
2. Despite the great advances in biological knowledge, there remain gaps – biologists are still uncovering basic mechanisms through which elements of a system interact, and hence phenomenological models are needed to enable applications.
3. Tackling problems of societal impact often requires integration of scales in space and time that span several orders of magnitude, and new models and ways of thinking are needed to accomplish this integration.
4. Education, curricula and learning are typically organized through silos that are impediments to progress and innovation; while strength and rigor in disciplines are critical ("fundamentals" are fundamental), new approaches to interdisciplinary education and to engaging students collaboratively in multi-disciplinary teams must be developed.
5. Interdisciplinary funding is sorely needed; federal agencies each have core missions, and there is inadequate collaborative funding that will bridge engineering with the biomedical/biological sciences.

There is a unique opportunity to address the challenges of infusing an agenda for transport phenomena into impacting understanding of biological systems. There is a great base of knowledge in both engineering and biology upon which we can build a formidable research agenda.

4.1.3. Recommendations (biotechnology)

Our panel offers the following recommendations, with several examples of each:

1. Invest in research programs that integrate single and coupled transport processes with biological processes over multiple length and time scales:
   - Models for intracellular function.
   - A model of the circulation from the heart through capillaries.
   - A model of the central nervous system.
   - Multi-scale modeling cell to tissue to organ.
2. Characterize and manipulate physical and transport properties of biological materials:
   - Biopreservation of molecules, cells (e.g., proteins, vaccines, embryonic stem cells), tissues and organs.
   - Properties of pathological cells and tissues (e.g., cancer, ischemic tissue).
   - Transport properties of new biological materials, including materials that dynamically adapt to their environments.
   - Variation in physical properties of materials such as arterial walls (e.g., Young's modulus and Poisson's ratio).
3. Develop models for the analysis, correlation, and prediction of transport phenomena across individual entities (e.g., cells, animal models, humans):
   - Model cell–cell interactions, cell–matrix interactions.
   - Model transport processes that control cell and tissue injury.
   - Learn how to interpret variability among individuals within populations (cells, animals, people).
   - Multi-physics modeling (fluid–wall interaction in arteries and the effect on solute transport).
   - Employ non-invasive methods to model biological function, e.g., MRI coupled with CFD to model blood flow in an individual.
4. Develop engineered biosensors and actuation/transport methods:
   - Nano and micro-scale material transport – how to get enough fluids/particles to the targeted cells.
   - Implanted biosensors for monitoring health and departures from health.
   - Biosensors for field and laboratory work (flu detection, chemical weapons, detection and quantification of biological markers).
5. Develop system approaches to study complex biological processes:
   - Single cell regulation and transduction processes.

- How does the brain control behavior, e.g., physical tasks, sensing.
- Develop tools that advance measurement and understanding of biological processes.
- Improve spatial and temporal resolution at all scales.
- Develop simulation and visualization tools, including validation.
- Create data bases of biological systems, e.g., properties, variability.
- Develop a simulation based environment to enable representation of complex biological systems and the prediction of operation and performance characteristics across scales from molecular, cellular, tissue, and organ.
- Develop tools for inverse analysis of transport phenomena for individual or patient specific process design.

NSF can fund research that builds methodological foundations that can be employed in various applications. NSF can fund methodologies (motivated by ultimate applications) that may not be funded by other agencies. NSF-funded research might be looked at as developing methodologies that could be applied to NIH-funded domains e.g., cancer, neuron, cardio, etc. (The creation of the National Institute of Bioimaging and Bioengineering (NIBIB) and the NIH Roadmap have helped improve the status of engineers, but the major focus in funding remains with hypothesis-driven research. The NIBIB budget is only about $300M per year.)

Having said this, NSF can also support domain research that is so engineering-based that other agencies would pass up. An example might be characterizing the mechanical properties of a cell or tissue. Such a study might be viewed as too methodological for NIH to support, unless it is tied directly to a particular clinical need or hypothesis-driven project.

Transport processes are critical in understanding a host of biological/biomedical phenomena and to addressing issues of health and disease. Many applications will be of interest to NIH and both NSF and NIH should support research in transport processes. However, these agencies do have different missions and thus should coordinate funding to some degree in order to make a bigger impact.

On the educational front, NIH supports some engineering research/education efforts. NIH also focuses on post-doctoral training, with some activity on pre-doctoral training. There is a need for bioengineering-specific training and educational programs, and NSF is the best agency for supporting such efforts.

One interesting approach might be for NSF to coordinate with one or more of the NIH Institutes, such as NIBIB, in a call for proposals in certain areas. There might be a requirement that there be co-PI's, one of whom is an engineer and the other a life scientist. This might provide good leverage for both agencies and also insure good multi-disciplinary interaction.

4.2. Energy

The report below was generated by Prof. George P. Peterson (Chair, University of Colorado), Prof. Fazle Hussain (University of Houston), Prof. Laura A. Schaefer (University of Pittsburgh), Prof. William A. Sirignano (University of California, Irvine), and Prof. Ralph L. Webb (The Pennsylvania State University).

4.2.1. Introduction (energy)

This report is divided into two portions. The background of the formal presentations and the topics raised for discussion will be summarized in the first section. Then, the major recommendations are outlined in the second section.

4.2.1.1. Presentations and topics for discussion and evaluation. The assembly of energy scientists and engineers benefited from overview presentations by many leaders in the field. Widely varying, important issues were highlighted that allowed for an ultimate integration and evaluation of the needs. The panelists and their presentations are included in [21].

In the several rounds of discussion and evaluation, 27 suggestions or areas for emphasis received substantial support. These are divided below into the 10 best-supported suggestions/areas and then 17 well-supported suggestions/areas. The *best-supported suggestions/areas* are as follows:

1. Using a multi-agency approach, with NSF as the lead and input from academia, industry and government, create a "National Energy Agenda" (i.e., Apollo type program to provide a path forward).
2. Examine novel concepts directed at conservation and energy efficiency research.
3. Expand fundamental research in carbon neutral energy sources.
4. Conduct studies of advanced energy storage technologies.
5. Invest in research for near-term renewable energy technologies.
6. Examine energy harvesting (e.g., waste heat energy recovery and utilization).
7. Expand and better publicize the existing NSF structure to increase the focus on sustainability.
8. Fundamental research in greenhouse gas control and carbon sequestration.
9. Distributed energy systems, including cascading energy systems.
10. Require interdisciplinary as well as disciplinary research which incorporates all aspects of sustainability.

The *other 17 well-supported suggestions/areas* are listed below:

1. Develop international initiatives on sustainability that should include what is being done elsewhere.
2. Educate the public along with our Engineering students.
3. New generation of heat exchangers should be developed using recent technological advancements.
4. Engineers define lifestyle that will reduce energy consumption.
5. Thermal chemical conversion of syngas to liquid fuel.
6. Give high priority to high power and safe energy systems.
7. Expand current laws to drive the issue, along with interest and economics.
8. Expand educational topics.
9. Configurations at macro/mega scales.
10. Design of the human/environment interfaces.
11. Continue fundamental research in efficient water usage and management.
12. Incorporate "policy" ramifications in technical RFP's.
13. The US Department of Energy (DOE) must take leadership position with respect to sustainability.
14. Energy research for sustainable non-energy systems and processes.
15. Flexible energy systems.
16. Organize energy research into focus areas (i.e., sources, storage, transport, conversion and environmental impact).
17. Energy conversion devices.

4.2.1.2. Sustainable energy roadmap: summary and recommendations. The National Science Foundation is well placed to take on a prominent role in guiding the direction of science and engineering research into sustainable energy both in the near future and from a long-term perspective. The existing work being done by DOE is important, but there is currently an opportunity available to broaden that work to include many fundamental and groundbreaking issues that must be addressed in the creation and implementation of sustainable energy technology. NSF should work toward the creation of a National Energy Agenda to help in providing a path forward, and should both expand and better publicize the existing NSF sustainability programs.

In the creation of the National Energy Agenda, NSF should focus on the following areas:

- Novel concepts directed at conservation and energy efficiency research.
- Fundamental research into carbon neutral energy sources.
- Advanced energy storage technologies.
- Near-term renewable energy technologies.
- Energy harvesting (e.g., waste heat energy recovery and utilization).
- Distributed energy systems (including cascading and flexible energy systems).

All of these research areas have the potential to have a wide-ranging impact on energy sources, storage, transport, and conversion. Additionally, a focus on these areas furthers NSF's mission to keep the US at the leading edge of discovery while supporting high-risk ideas and novel collaborations. For example, by funding research into the development of near-term renewable energy technologies, NSF can develop the needed resources for practical and rapid adoption of renewable energy while still supporting the cutting-edge research innovations that are required to advance the state-of-the-art. In all of these areas, it is important to look across length and time scales – for instance, to consider not only the science of nanotube creation for energy storage, but also the integration of that storage within energy conversion systems, and the utilization of those systems in more efficient configurations and with alternative fuel sources. To reach these goals, in addition to funding the traditional disciplinary research, it is essential to require interdisciplinary efforts that incorporate a variety of perspectives and multiple aspects of sustainability.

Furthermore, beyond the intellectual merit of this research, NSF must continue to consider the broader impacts of sustainable energy. Some of these impacts are obvious, such as controlling greenhouse gas emissions through both reductions and sequestration. Others are more challenging, such as educating not only engineering (or even general university) students, but also the public about the need for and ways to achieve a sustainable energy future. Innovative techniques for describing both the problem and the solution (the aforementioned research) on a general, but not "dumbed-down," level must be developed. Mechanisms for incorporating policy ramifications into technical RFPs should also be explored, as well as a bi-directional approach to international education and collaboration.

We are at a unique point in history, balancing public awareness of the need for sustainable energy with the opportunity to have a substantial impact. NSF must take the lead in shaping this research in order to create truly sustainable and innovative energy solutions.

4.3. Information technology

The following report was generated by Prof. Bahgat Sammakia (Chair, SUNY Binghamton), Dr. Ravi Prasher (Intel Corporation), Dr. Roger R. Schmidt (IBM), and Dr. Mark S. Spector (US Office of Naval Research).

4.3.1. Introduction (information technology)

This panel dealt with a number of issues related to the thermal management of electronics. The panelists [21] addressed issues related to applications in the military, consumer electronics, telecommunications and computers. While the specific challenges, needs, gaps and recommendations varied depending on the application area, there were many areas of common interest. The panelists also identified the challenges in the area of information technology with respect to thermal management and transport issues. The challenges are based on the existing roadmaps for the IT industry as well as the known historical progression in the different application areas. This summary represents all of the application areas identified by the panel.

4.3.2. Challenges (information technology)

- Continuous power increase (application and technology driven).
- Ultra high heat flux.
- Low allowable temperature difference.
- Localized high heat flux (hot spots).
- Temperature uniformity requirements (LED, Space applications).
- Demand for low weight, small scale (military and other).
- Integration and small scale.
- Multi-scale problem ranging from nanometers at the transistor level to tens of meters at the data center level.
- Stacking (results in higher power density and thermal resistances).
- Demand for low cost thermal solutions.
- Demand for high reliability for very aggressive application conditions such as mobile systems and military applications.
- Increasing energy cost.
- Environmental impact of high energy consumption.

4.3.3. Barriers and gaps (information technology)

The panel identified the following four key barriers and gaps in the area of information technology with respect to thermal management and transport issues.

1. Modeling
   - Multi-scale and multi-physics and multi-disciplinary models are often needed but are too complex or cumbersome.
   - Methodology for establishing a multi-scale model hierarchy.
   - Simple yet accurate design tools are needed for industry.
   - Two phase systems.
   - Turbulence modeling.
2. Experimental validation
   - Measurements at the very small scale.
   - Material properties *in situ*.
   - Interfacial measurements.
3. Characterization techniques
   - Interfacial properties particularly for thermal interface materials.
4. Material limitations in areas such as thermal interface materials, materials for two phase systems, adhesives, barrier layers, coatings and dielectrics.
5. The lack of disseminated effective energy efficient design systems, and the lack of disseminated energy harvesting and recovery systems.

4.3.4. Recommendations (information technology)

The panel identified five general areas of research that are of interest to the IT community with respect to thermal management and transport.

1. Energy efficient electronics
   - Architecture (performance-power compromise)
   - Functional–thermal–mechanical co-design approach.
   - Energy recovery/harvesting.
   - Dynamic re-configurability.
   - Revolutionary cooling approaches.
2. Multi-scale system level thermal management
   - Data center level.
   - Rack-box-board-module levels.
   - Alternative electronic system (macro-electronics, implantable, pervasive electronics, portable, embedded).
   - Micro-scale level.
   - Acoustic issues from flow and system.
3. Materials tools and processes research
   - Fundamental transport physics at interfaces (solid–solid and solid–liquid–vapor).
   - TIM (new materials, characterization techniques, models (interfaces)).
   - Transport physics of new device concepts.
   - Ultra high thermal conductivity electrical insulators and conductors (with matched CTE).
4. Modeling and design tools
   - Multi-scale models.
   - Reduced order models.
   - Combined electrical–thermal design tools and design automation.
   - Two phase flow models.
   - Two phase phenomena on extended surfaces such as nanostructures.
5. Experimental techniques and diagnostics
   - Interfacial measurements.
   - Measurements at the very small scale.
   - Precise *in situ* material property measurements.
   - Data center level measurements of flow and temperature.

4.4. Nanotechnology

The nanotechnology report was generated by Prof. Roop Mahajan (Chair, Virginia Tech), Prof. Ranga Pitchumani (University of Connecticut), Prof. Dimos Poulikakos (Swiss Federal Institute of Technology), and Prof. Raymond Viskanta (Purdue University).

4.4.1. Introduction (nanotechnology)

Hailed as the next industrial revolution, nanotechnology (NT) is poised to usher in a new age of developments that may impact countless aspects of our lives, including healthcare, communication, national security, consumer products, and transportation, to name just a few. At the nanoscale, materials exhibit properties that are not possible at the bulk scale, and for the first time in the history of humankind, we have engineering systems that are at the same scale as the basic units of life. Therefore, new opportunities have arisen to understand life at its basic cellular level and to optimize engineering systems based on the remarkable capabilities of cells to organize and self-assemble in response to external stimuli. Not unexpectedly, transport phenomena at the nanoscale play an important role in implementation of nanotechnology. However, there are a number of scientific and engineering challenges at the nanoscale energy transport that must be addressed by the heat transfer community. The major among them in realization of the following vision and goals are addressed in Section 4.4.2.

Vision: Widespread use of nanotechnology in key areas such as energy, health care, security, and environment.
Goals: To develop the fundamental transport phenomena knowledge base that will enable innovation and implementation of nanotechnology for the benefit of society.

4.4.2. Scientific and engineering challenges (nanotechnology)

1. *Science issues*: Interfacial phenomena, Size and dimension effects, Multi-physics and computational models, and Model validation topped the list.
   - It is recognized that the nanoscale energy and mass transport at different interfaces (metal–metal, hard–soft matter, solid–fluid, and metal–non-metal) is rich in scientific and engineering content but has not been fully explored. Our understanding of electron–phonon coupling in metal–non-metal interfaces is also inadequate.
   - Electron energies are quantized in a nanoscale structure, leading to novel effects. These effects, known as quantum size effect, depend on the size, the shape and/or the boundary conditions, and lead to unusual mass transport behaviors.
   - There is a need for the development of multi-physics and computational models that can address the molecular and electronic structure and physical and chemical dynamics of nanoscale structures. For these models to gain legitimacy and acceptance, they must be validated.
2. *Metrology/measurement techniques*: To exploit the promise of nanotechnology and to gain full understanding of the transport phenomena involved at the nanoscale, there is a need for state-of-the-art tools to measure dimensions, characterize materials, and examine structures of novel materials at the nanoscale. Developing standards and testing platforms for verification of techniques is an equally important part of developing capacity in metrology at the nanoscale.
3. *Nano-to-macro integration*: There is a genuine need in understanding coupling across spatial and temporal scales. To this end, numerical, theoretical and experimental approaches across scales and disciplines, including design and manufacturing of systems and devices should be developed.
4. *Scalable manufacturing of products*: An engineering priority is to provide a basic understanding of transport phenomena needed for developing tools and processes that will enable high-volume, low cost manufacture of nanoelements and structures, with due consideration to environmental, health, and ethical issues.

Meeting these challenges and developing solutions will impact many applications including Nano-enabled Energy Storage, Conversion and Conservation; Materials Processing and Manufacturing; Sensors; Biological and Health Care; and Water Treatment.

Finally, it is noted that to enable widespread use of the developed knowledge base and technologies, the community must engage with other technical, business, and policy-making communities. Apart from creating human capital, the public-at-large in understanding the benefits and risks of nanotechnology must be engaged.

4.5. Security

The security report was generated by Prof. Peter G. Simpkins, (Chair, Syracuse University), Prof. C. Thomas Avedisian (co-Chair, Cornell University), Dr. Mehmet Arik (GE Global Research Center) and Mr. John G. Voeller (Black & Veatch).

4.5.1. Introduction (security)

Transport phenomena are intimately coupled to national security issues through dispersion and detection of toxic gases or particulates, development of rapid response biological and chemical sensors, and infrastructure protection. The challenges are not only in research and development but also in commercialization. Outlined below is a draft of the material presented by the Panel on Security at the Workshop [21].

4.5.2. Summary (security)

The field of "security" as it relates to transport processes largely concerns sensing, detection, data analysis, prevention and response protocols associated with creation of hazardous conditions. It includes a broad array of technology areas and engineering disciplines such as micro-fluidics for sensor detection (e.g., lab-on-chip sensors), real-time monitoring of air quality in the atmosphere and building enclosures, fire dynamics, and development and validation of predictive tools. The education of a new generation of engineers and scientists is also an essential ingredient to meet the challenges that loom in the international security picture. Here the lack of programs that specifically target security issues involving transport phenomena must be addressed.

4.5.3. Background (security)

Since 9/11 we have become more aware of dangers associated with chemical and biological agents in the atmosphere as well as the hazards associated with fires as an outcome of deliberate intent. These dangers have emphasized the importance of developing new capabilities for improved situational awareness through sensing and detection with a view to prevention and corrective action. Heat and mass transport plays a critical role in this new world security dynamic through the importance it occupies in development of new sensor technologies that rely on micro-fluidic and MEMS-based systems, models for fire dynamics, coupling between transport and chemical kinetics, scaling laws to bridge bench-scale to realistic conditions, development of new diagnostics for detection, creation of "smart" building structures with adaptability, and data processing algorithms to coordinate information from integrated sensor networks.

4.5.4. Barriers (security)

There are significant barriers in our understanding of the enabling technologies for developing detection and prevention networks which motivate investments in this area. These include the following: algorithms to track and coordinate in real-time transport of chemical agents in networks of building interiors and over diverse geographical terrain; prediction of flashover associated with fires; material property databases for input to simulations; bridging length scales; and sensor technologies which are often deficient in their ability to discriminate among different chemical species. For example, the diverse nature of biological and chemical agents make it difficult to develop general-purpose detectors (i.e., "one size fits all"). In development of micro-scale sensing systems, the requirement to move fluids in lab-on-chip designs also poses requirements on pumping, valving and filtering that affect reliability.

4.5.5. Recommendations (security)

The recommendations for future work include, but are not limited to, the following:

- Fire suppression remains an important concern and approaches that either build on existing concepts (e.g., sprinkler technology) or develop improved chemical agents for suppression are needed.
- Bridging of small and large length scales in security system analysis poses significant computational challenges and efficient algorithms are needed to improve computational time.
- Algorithms are required for networking among sensors at different physical locations (e.g., through a central command installation) to provide improved situational awareness and real-time monitoring, and better submodels should be developed for predicting large-scale burning of solids and assemblies.
- The physics incorporated into predictive capabilities require benchmark data for validation (e.g., development of standards for validation) and high fidelity diagnostics.
- Creation of "smart" systems that can react and adapt rapidly (e.g., adaptable material or building structures that would allow them to respond to change), and new materials that offer improved fire protection, adhesion to building structures, and suppression capabilities should be developed.
- Micro sensors will require development of both analytical methods and components for operation (micropumps, valves etc), plus improved small-scale (on-chip) and large-scale (networked) integration; new concepts for MEMS-based sensing (e.g., proteomic circuitry for sensing in biosystems) which are robust and can survive many cycles of detection are needed.
- Novel concepts to influence the transport and distribution of hazardous agents are necessary to mitigate associated threats (e.g., electromagnetic flow control; transport and chemistry of contaminants in water and food; distribution of reactive plumes in the environment (e.g., ranging from chlorine to organic acids and biocatalysts)).

In addition to the technological issues listed above, the panel also articulated needs in the education of a new generation of engineers with and expertise and/or improved understanding of security issues. This goal could be achieved by incorporating relevant concepts in existing courses (e.g., which discuss fluid flow, combustion, heat transfer) that bring in application areas relevant to security, class demonstrations, or field trips.

4.6. Education

This report was generated by Prof. Richard S. Figliola (Chair, Clemson University), Prof. Theodore L. Bergman (University of Connecticut), Prof. John H. Lienhard V (Massachusetts Institute of Technology) and Prof. John R. Lloyd (Michigan State University).

4.6.1. Summary (education)

Sustainability of our planet is the single most important issue currently facing humanity. Problems dealing with energy availability, environmental and global warming, medical technologies to improve health and high quality longevity, security and information technology are the critical issues of our day. Yet the typical US citizen is technically illiterate on the fundamental concepts related to these issues. Transport processes, in particular, are central to the current critical technology challenges we face, but most citizens have no knowledge of even the most elementary principles of the subject. Citizens are therefore unable to make logically sound personal or public policy decisions that will shape the future direction for themselves, their families, this nation and our planet. Further perpetuating this ignorance, our K-12 education system currently lacks formal introductions to the most basic concepts of engineering technology or to concepts related to sustainability in everyday life practice, concepts that would establish the basis for life-long learning for informed decisions.

The Panel on Education believes that it is the responsibility of engineering educators, in partnership with government and industry, to make all of our public more technically knowledgeable. This would be accomplished through, for example, the development and introduction of pertinent modules of educational material targeted at various appropriate education levels and appropriate community groups from K-16 education to community-wide education for those beyond formal education years. These peer-reviewed technical modules must make use of the latest state-of-the-art visualization and entertainment methods, including interactive approaches, to introduce in simple, common-sense terms and visually stimulating examples, the concepts and alternatives for everyday life practice. These would range from simple to advanced concepts in scope. The modules should be highly produced drawing from the best talents and resources available. The requirement of peer-review by the engineering community will prevent the uninformed, concerned citizen from offering technically unsound or incorrect statements. The goal is a better educated public with which to shape informed public policy.

Concurrently, engineering education is squeezed by two competing policy pressures: (1) the pressure to reduce the formal four-year engineering curriculum; and (2) the pressure to educate our graduates in an expanding range of interdisciplinary technology topics, including innovation and globalization. We are presently in the midst of a merge of the boundaries of traditional engineering education as it absorbs rapidly-evolving areas of science, so that the historical engineering disciplines no longer provide clear delineations of content. Transport processes of current technical importance now include biological and chemical processes from the macro-scales down to the nano- and molecular-scales and the physical transport differences these scales may introduce. The four-year degree can hardly hold so much information, and some decision must be made to which topics to place at the Bachelor's degree level, which topics to place at the Master's degree level, and which topics must remain the province of advanced research. In essence, our engineering education community must decide what curriculum is truly important so that new and critical topics can be included in a newly defined core curriculum, and simultaneously determine which traditional core topics can be de-emphasized. At the same time, we must clearly define "what we are good at" and we must continue to invest our time and efforts effectively and efficiently at that.

This NSF Panel on Education believes that undergraduate engineering education must: (1) maintain strength in the core fundamentals of transport processes; (2) provide employable engineers to industry; and (3) prepare graduates to value the benefits of life-long learning. Now, however, the engineering community must also take a lead role in the sustainability problem facing our planet and in decisions that relate to new technologies, such as energy, medicine, security and the environment. For this we need to modify the way that engineers are educated and also the way we educate non-engineers and the public.

This Panel stresses the need for a change in the definition of engineering research, such that peer-reviewed innovations in engineering education, both within and outside of formal degree programs, will be considered a strong *research* area. NSF and other funding agencies, both in partnership with industry and in cooperation with academia, must support further advances in engineering education with materials that will: (1) have a profound impact on the ability of our citizenry to engage in informed debate regarding the huge technological issues challenging all of humanity; (2) inspire a broader range of our young population towards technical professions; and (3) improve teaching and learning in undergraduate engineering curricula.

The Grand Challenge: Ensure Technical Literacy and Global Leadership in Subjects of Sustainability, Energy, Medicine, Security and Other Relevant Areas among Engineers and Society-at-Large.

4.6.2. Recommendations (education)

1. Supply meaningful funding in transport processes to educate all citizens (K – Life) in innovative and exciting ways:
   - Peer-reviewed modules (e.g., Energy, Biological Systems, Security, Information Technology, and Nanotechnology) for flexible learning and at audience appropriate (K-12; advanced; technical; community) levels.
   - Peer-reviewed videos with animations.
   - Interactive software.
   - Modularized Curriculum for easy and dynamic structuring towards an audience.
   - Modern version of public "newsreel" and Reality formats for dissemination of engineering challenges and accomplishments through local media, cable-TV and web-based sites.
2. Identify core graduate and undergraduate engineering curricula that are truly core:
   - Increased biology, chemistry, and solid-state physics content.
   - Awareness of Globalization Challenges among students.
   - Introduction to the Concepts of Innovation and Entrepreneurship.
   - Eliminate overstuffing in curriculum.
   - Emphasize master's level education as the appropriate step for careers in advanced energy technologies.
   - Need to understand how to measure learning and assess effectiveness of various different methods of teaching.

3. Improve public and non-engineering student perception of engineering:
   - Develop well produced education modules and information for K-12 levels.
   - Promotion of engineering and technical accomplishments and challenges through videos targeted to local and cable media outlets and internet sites.
   - Promotion of engineering and science at the highest levels of government.
4. Build a roadmap:
   - Develop Short- and Long-Term Objectives with Priority on Sustainability of the Planet.
5. Re-Prioritize Faculty and Student Time:
   - Increased responsibility and expanded content must be offset by elimination of current inefficient and outdated practices.
   - Shift some emphasis to educational service to the community on sustainability and energy issues.
   - Expand research on pedagogical delivery and content with assessment.
   - Partnerships with industry, government, and other academic systems around the globe to enable the curriculum
     - To expand opportunities for student creative inquiry as an integral part of technical learning.
     - To increase global competitiveness of US engineers in the world market as the professionals best capable to make technically challenging decisions.
   - Encourage alternatives to lecture/problem-set format of engineering education.

4.7. Summary and conclusions

Based upon the involvement of, and input from a significant portion of the international heat and mass transfer community, important challenges and opportunities have been identified in the areas of sustainable energy systems, biological systems, security, information technology, nanotechnology and education. It is hoped that this document, along with the detailed information in the workshop proceedings [21] will trigger action within our technical community, and prove to be useful among the sponsors of our research and supporters of various education activities. In short, we hope that this workshop will assist the National Science Foundation in setting future funding priorities. Several broad-based suggestions follow.

1. Workshops of this type need to occur on a more frequent basis in recognition of the rapidly-evolving changes in research thrusts, education initiatives, and national policies. A frequency of once every three or four years would be appropriate.
2. Subsequent workshops should direct more attention to the impact of globalization made possible by today's capability for instantaneous communication ability among researchers, educators, and policy-makers worldwide.
3. Subsequent workshops might include a focus on university–industry–government interaction, including aspects of technology transfer and commercialization.
4. The heat transfer community must not only respond to technical needs of the society but also take a proactive stance in setting the national research agenda regarding large efforts (*grand challenges*) in technical areas where our community has demonstrated leadership and has great credibility, such as in sustainable energy.
5. The heat transfer community must take a proactive stance in leading a national discussion including the involvement of the non-engineering community, in understanding the societal implications associated with the technical areas of the workshop.
6. Important common interests of researchers working on sustainable energy and clean water developments intersect and provide a pressing motivation for interdisciplinary workshops in the future as *energy* and *water* head the list of humanity's top 10 problems [22] and 21st Century innovations topics [23].

Additional specific suggestions regarding the role the US National Science Foundation should play have been offered in the detailed reports included here.

Acknowledgement

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Appendix A. Executive committee members

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Adrian Bejan
  J.A. Jones Professor of Mechanical Engineering, Duke University
Arthur E. Bergles
  Emeritus Dean, Rensselaer Polytechnic Institute
Theodore Bergman
  Professor of Mechanical Engineering, The University of Connecticut
Dennis Bushnell
  Chief Scientist, NASA Langley
Jean Colpin
  Director, United Technologies Research Center
Thomas Cruse
  Chief Technologist, Air Force Research Laboratory
Ashley Emery
  Professor of Mechanical Engineering, University of Washington
Amir Faghri
  UTC Chair Professor of Thermal-Fluids Engineering, The University of Connecticut

Richard Goldstein
Regents' Professor of Mechanical Engineering, The University of Minnesota
Michael Hartnett
Chairman and CEO, RBC
Steve Heath
Emeritus President, Pratt & Whitney Commercial Engines
John R. Howell
Ernest Cockrell Jr. Memorial Chair and Baker Hughes Incorporated Centennial Professor, The University of Texas at Austin
John Krenicki
President and CEO, GE Energy
Chung K. Law
Robert H. Goddard Professor of Mechanical and Aerospace Engineering, Princeton University
Robert Leheny
Deputy Director, DARPA
Alfonso Ortega
James R. Birle Professor of Energy Technology, Villanova University
George P. (Bud) Peterson
Chancellor, The University of Colorado at Boulder
Patrick E. Phelan
Program Director Thermal Transport, The National Science Foundation
Ranga Pitchumani
Professor of Mechanical Engineering, The University of Connecticut
Dimos Poulikakos
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Mark Spector
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Head of Energy Sciences, Lund Universitet
Raymond Viskanta
W.F.M. Goss Distinguished Professor of Engineering, Purdue University
William Wulf
President, National Academy of Engineering
M. Michael Yovanovich
Emeritus Professor, University of Waterloo

Appendix B. Keynote speakers

Energy: Dennis Bushnell, Chief Scientist, NASA Langley
Biotechnology: Kenneth R. Diller, Robert M. and Prudie Leibrock Endowed Professor, The University of Texas at Austin
Information Technology: Roger Schmidt, Distinguished Engineer, IBM
Security: John Voeller, Senior Vice President, Chief Knowledge Officer, Chief Technology Officer, Black & Veatch
Nanotechnology: Alain Kaloyeros, Vice President and Chief Administrative Officer, College of Nanoscale Science & Engineering, University of Albany, State University of New York
Education: G.P. "Bud" Peterson, Chancellor, The University of Colorado at Boulder

Appendix C. Panel chairs, co-chairs, and panelists

Biotechnology I:

Chair: Don P. Giddens, Georgia Institute of Technology
Co-Chair: Ed Carapezza, DARPA
Panelists:
John C. Bischof, The University of Minnesota
"Multi-Scale Challenges in Biological Transport Application"
Sung Kwon Cho, University of Pittsburgh
"Issues in Micro Droplets and Bubbles for Bio-Applications"
Eric R. Dufresne, Yale University
"Transport Phenomena in Cell Biology"
Anubhav Tripathi, Brown University
"Biological Systems and Biotechnology: Its Role in Translational Science and Education"
John G. Georgiadis, University of Illinois at Urbana-Champaign
"Transport Phenomena in the Human Central Nervous & Musculatory Systems"

Biotechnology II:

Chair: John R. Howell, The University of Texas at Austin
Co-Chair: Michael J. Pikal, The University of Connecticut
Panelists:
Sangtae Kim, Purdue University
"Pharmaceutical Informatics and the Pathway to Personalized Medicines"
Michael Ladisch, Purdue University
"Process Engineering of Renewable Resources: Transport Phenomena in Cellulose Conversion"
Samir Mitragotri, University of California, Santa Barbara
"Multi-Scale Transport in Biological Systems: Role in Drug Delivery and Biomedicine"
Michael H. Peters, Virginia Commonwealth University
"Multiscale Analysis in Cellular Systems"
Petr Stehlik, Brno University of Technology
"Waste and Biomass Processing as a Contribution to Sustainable Development"

Kambiz Vafai, University of California, Riverside
"The Role of Porous Media in Addressing Some Challenging Issues in Biomedical Engineering"

Education:

Chair: Richard Figliola, Clemson University
Co-Chair: Theodore L. Bergman, The University of Connecticut
Panelists:
Yunus A. Cengel, University of Nevada, Reno
"Incorporating Green Practices into Engineering and Non-Engineering Education to Combat Climate Change"
Frank A. Kulacki, University of Minnesota
"Multiple Futures for Heat Transfer Education – Undergraduate to Graduate"
John H. Lienhard V, Massachusetts Institute of Technology
"What Do Students Need to Learn about Transport Phenomena?"
Pamela Norris, University of Virginia
"Teaching Nanoscale Transport Phenomena"
Patrick H. Oosthuizen, Queen's University
"Some Factors to Consider in Teaching Renewable Energy in an Undergraduate Engineering Program"
Robert J. Ribando, University of Virginia
"Use of Modeling, Simulation and Visualization to Teach Heat Transfer Concepts and Design"

Information Technology:

Chair: Bahgat Sammakia, State University of New York, Binghamton
Co-Chair: Ravi Prasher, Intel Corporation
Panelists:
Mark S. Spector, US Office of Naval Research
"Thermal Management Challenges of Military Electronics"
Darvin Edwards, Texas Instruments
"Thermal Management in Today's Electronic Systems"
Suresh V. Garimella, Purdue University
"Electro-Thermal Co-Design of Emerging Electronics"
Yogendra Joshi, Georgia Institute of Technology
"Energy Efficient Thermal Management for Information Technology Infrastructure Facilities – The Data Center Challenges"
William P. King, University of Illinois Urbana-Champaign
"Nanoscale Surface Modification and Nanometrology using Scanning Probes"
Sridhar Machiroutu, Intel Corporation
"Challenges in Heat Pipe Technology and Future Research Opportunities"

Nanotechnology I:

Chair: Dimos Poulikakos, Swiss Federal Institute of Technology, Zurich
Co-Chair: Raymond Viskanta, Purdue University
Panelists:
C. Thomas Avedisian, Cornell University
"Thermal Therapeutics with Nanoparticles for Treating Cancer: Challenges and Opportunities"
Debjyoti Banerjee, Texas A&M University
"Boiling Phenomena on Nanostructures"
Rashid Bashir, Purdue University
"Top-Down Micro/Nanosensors for Biology and Medicine: Opportunities and Prospects"
Ishwar K. Puri, Virginia Polytechnic Institute and State University
"First Principle Simulations to Enable Nanomaterials for Energy, Environment, and Biological Applications"
George L. Gould, Aspen Aerogels Incorporated
"Fundamental Challenges in the Industrial Production and Application of Nanostructured Aerogel Materials"
Costas P. Grigoropoulis, University of California, Berkeley
"Nanoscale Transport and Thermal Processing"

Nanotechnology II:

Chair: Roop Mahajan, Virginia Polytechnic Institute and State University
Co-Chair: Ranga Pitchumani, University of Connecticut
Panelists:
David G. Cahill, University of Illinois at Urbana-Champaign
"Nanoscale Thermal Conduction"
Arun Majumdar, University of California, Berkeley
"Transport Phenomena at Nanoscales"
Constantine M. Megaridis, University of Illinois at Chicago
"Fluids Confined in Carbon Nanotubes"
Gang Chen, Massachusetts Institute of Technology
"Energy Technology Enabled by Nanoscale Thermal Effects"
William M. Worek, University of Illinois at Chicago
"Nanofluids and Critical Heat Flux: An Experimental and Analytical Study"
Zhoumin Zhang, Georgia Institute of Technology
"Applications of Near-Field Thermal Radiation in Energy Conversion and Manufacturing"

Security:

Chair: Peter Simpkins, Syracuse University

Co-Chairs: C. Thomas Avedisian, Cornell University, Mehmet Arik, GE Research
Panelists:
Malcolm J. Andrews, Los Alamos National Laboratory
"Coupling of Diagnostics with Predictive Science"
Arvind Atreya, University of Michigan
"Transport Phenomena in Fire Security of the Built Infrastructure"
Jane P. Chang, University of California, Los Angeles
"Challenges of Transport Phenomena in Research and Education: Miniaturized and Integrated Sensors and Microsystems"
Darrell W. Pepper, University of Nevada Las Vegas
"Creating a Real Time Emergency Response Capability"
Kendra V. Sharp, The Pennsylvania State University
"Microfluidic Opportunities and Challenges in Security R&D"

Sustainable Energy I:

Chair: George P. "Bud" Peterson, University of Colorado, Boulder
Co-Chair: Ralph Webb, The Pennsylvania State University
Panelists:
Adrian Bejan, Duke University
"Energy and the Environment: Basis in Thermal Sciences"
Majid Charmchi, University of Massachusetts – Lowell
"Gasification of Biomass and Sulfur-Containing Carbonaceous Fuels"
Jane H. Davidson, University of Minnesota
"Advancement of Solar Thermal Technologies"
Wayne A. Eckerle, Cummins Inc.
"Efficient Power Systems – The Next Generation and the Impact of Renewable Fuels"
Amir Faghri, University of Connecticut
"Challenges and Opportunities in Transport Phenomena in Passive Fuel Cell Systems"
Trung Van Nguyen, University of Kansas
"Transport and Interfacial Phenomena in a PEM Fuel Cell"

Sustainable Energy II:

Chair: Fazle Hussain, University of Houston
Co-Chair: William A. Sirignano, University of California, Irvine
Panelists:
Michael E. Webber, The University of Texas at Austin
"Water, Power and Transportation: Our Next Great Heat Transfer Challenge"
Noam Lior, University of Pennsylvania
"About Sustainability Metrics"
Ken Okazaki, Tokyo Institute of Technology
"CO_2-Free Clean Coal Technology Integrated with CCS (Carbon Capture & Storage) and Hydrogen Energy Systems"
Laura Schaefer, University of Pittsburgh
"Greener Energy Systems for Buildings and Small Communities"
John R. Thome, Ecole Polytechnique Fédérale de Lausanne
"Microscale Two-Phase Flow and Heat Transfer Phenomena: Issues and Challenges"
Chao-Yang Wang, The Pennsylvania State University
"Transport Phenomena in Fuel Cells"

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