Purdue Heat Transfer Celebration
April 3-5, 2002, West Lafayette, IN

FUNDING TRENDS FOR BASIC RESEARCH IN HEAT TRANSFER: A NATIONAL SCIENCE FOUNDATION PERSPECTIVE

Richard N. Smith
Program Director, Thermal Transport and Thermal Processing Program
Division of Chemical and Transport Systems
National Science Foundation
4201 Wilson Blvd.
Arlington VA 22230
(rnsmith@nsf.gov)

INTRODUCTION

It is particularly appropriate and with great pleasure that I am able to represent the National Science Foundation "Heat Transfer" program at this celebration of heat transfer research accomplishments—past, present, and future—at Purdue. It will be my goal in this short article to provide a description of current and future directions for heat transfer research, at least from my perspective at NSF. It should be emphasized that any opinions expressed here represent those of the author and not necessarily those of the Foundation. Furthermore, my perceptions are based primarily on my activities at NSF, and they may be somewhat different from those of program managers at the mission-oriented funding agencies such as DOE, NIH, ARO, ONR, AFOSR, DARPA, and so forth.

The presentation below will begin with a brief description of the mission and strategic goals of NSF, as the basis for the Congressional appropriations that provide the necessary funds. Some current Foundation Priority Areas will be presented, as will their representation within the Engineering Directorate. I will then describe the Thermal Transport and Thermal Processing Program along with some of the current projects that characterize important new areas. Especially prominent among these are important activities funded here at Purdue. I will conclude with some final observations for the present state of heat transfer research in the United States and how the thermal science community may best take advantage of this somewhat mature area in light of a number of emerging technologies.

NSF AND THE ENGINEERING DIRECTORATE

As part of the executive branch, NSF works for the President. We are asked for guidance on intellectual and financial priorities. However, we ultimately receive directions from the Office of Science and Technology Policy (OSTP) on intellectual priorities and the Office of Management and Budget (OMB) concerning financial priorities, in line with the President's Management Agenda and the resources provided by Congress. Major federal departments have Secretaries; independent agencies do not, and NSF is an independent agency.

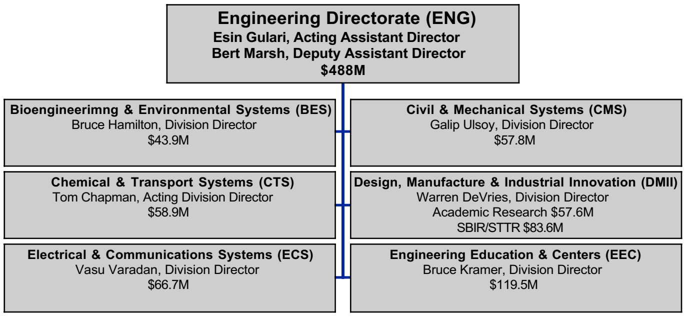
The NSF Mission is "Enabling the Nation's future through discovery, learning, and innovation". The Strategic Goals associated with fulfilling this mission are embodied in three words, and the order is important:

People - *A diverse, internationally competitive and globally-engaged workforce*
Ideas - *Discovery across frontiers and connections in service to society*
Tools - *Accessible, state-of-the-art information bases and shared tools*

When NSF prepares a budget request to the White House and then presents this request as part of the White House budget to the Congress, all initiatives and priorities that are the basis for funding increases (and in fact funding maintenance) are characterized in terms of these missions and strategic goals. It is important that each research program, including Thermal Transport and Thermal Processing, and the constituent communities bear this in mind when trying to leverage future funding and to develop new areas for research. For the FY03 Budget Request, the major Foundation priorities were

- Nanoscale Science and Engineering
- Information Technology Research
- Mathematical Sciences
- Social, Behavioral and Economic Sciences
- Biocomplexity in the Environment
- Learning for the 21st Century Workforce

The Engineering Directorate at NSF comprises one of seven that fund the bulk of the basic research. It is one of the youngest directorates, having been elevated from a division of the Mathematical and Physicals Sciences Directorate approximately 25 years ago. The organization and FY03 budget request is shown in the following chart:



It should be noted that the Congressional appropriation passed just in advance of this writing will probably increase these amounts slightly.

Engineering Directorate investment priorities for most recent and current fiscal year are summarized in the following chart:

FY02 Investments	New in FY03
Nanoscale Science and Engineering NSE in FY02 $199M (ENG share $86.3M)	Workforce for the 21st Century ENG and EHR Partnership
Information Technology Research ENG invested $11.2M	Human and Social Dynamics ENG and SBE Partnership
Biocomplexity in the Environment ENG share $3M	Mathematical Sciences ENG and Math Partnership

The principal technological themes for future Engineering research were characterized during a recent retreat that consisted of the Division Directors and selected senior Program Managers. At the heart of all the divisions are the common threads of *Materials*, *Design*, and *Processing*. Important supporting topics include overlapping areas of Energy, Environment, Hazard Reduction, Health, Infrastructure, Manufacturing, and Security (no significance in the order). As a result, the Acting Assistant Director has formed six Working Groups to identify gaps and opportunities related to these themes. Three of these have been charged and three more are being formulated for initiation within the next year:

- **Sensors** (Charged; new program solicitation developed for FY03 funding)
- **Transformation of Performance Driven Materials** (Charged)
- **Energy** (Charged)
- **Environment** (To be charged)
- **Infrastructure** (To be charged)
- **Health** (To be charged)

Significant cross cutting investment opportunities may be expected from some or all of these Working Groups in the next 2-3 years.

CURRENT EMPHASIS AND FUTURE OPPORTUNITIES IN HEAT TRANSFER RESEARCH

The Thermal Transport and Thermal Processing (T^3P) Program is one of eight programs in the Chemical and Transport Systems Division, whose focus is the science and technology of operations that involve transformations—physical, chemical, or biological—and transport of matter and energy. The investigator community comes primarily from chemical engineering and mechanical engineering, but also includes aeronautical engineers, physicists, chemists, mathematicians, civil engineers, and materials scientists. The primary emphasis of the T^3P program is to provide support for research leading to an improved understanding of the basic heat transfer modes and their application to manufacturing, materials processing, energy conversion, and temperature control. Traditionally, it has been a major sponsor of research in heat transfer and thermal processing, and it is affectionately known as the “Heat Transfer Program.” The current Program Director and author of this paper humbly follows in a long line of distinguished researchers who have devoted a portion of their careers to the nurturing of the area. These individuals include Stefan Thynell, Ashley Emery, Tim Tong, Debbie Kaminsky, Jack Howell, Mike Chen, Bud Peterson, Joan Gosink, Eph Sparrow, Richard Buckius, Bill Grosshandler and Win Aung to name only a few. It should be emphasized that a Program Director has little opportunity to influence the direction of a program over the short time period when he or she is in residence. Rather, the research community must respond to important new initiatives and recognize the thermal science research needs within the context of emerging areas and Foundation priorities. In addition, reviewers must respond by promoting new advances through the peer review process that is at the heart of the NSF funding process.

The T^3P program continues to enjoy high visibility and popularity among researchers. The vast majority of American industry, and in fact our everyday lives, involve processes that are either enabled or controlled by thermal energy transfer. Almost every energy conversion process includes a transfer of heat, either as a primary energy source or as a secondary process. In addition, thermal transport plays a dominant role in manufacturing and materials processing, and as such has received significant attention in many different application areas including, among others, crystal growth, optical fiber processing, fast-pulse laser interactions with surfaces for processing, cleaning or tempering, as well as electronic assemblies and chips. Continued advancement in electronic devices, from computers to telecommunications, requires careful control of temperature to permit long-life operation, and the reduction in scale of the basic dissipative mechanisms to only a few nanometers has opened entirely new physical domains for heat transfer research.

The following are some of the major topical themes that have emerged during the past few years. The subtopics represent actual projects currently being funded through the T^3P Program.

Phase change enabled or driven by thermal transport
- high speed annular flow
- unsteady condensation
- multicomponent solidification, including microporosity and inclusions

High heat flux applications, especially at small length scales
- microchannel flow in rough channels
- microchannel condensation
- thermal ink jet flows

Complex flow processes (in terms of driving forces, geometry, etc.)
- magnetic and electric fields
- turbulent combustion with radiation
- turbulence with real surface roughness
- turbulence with pin fin structures
- turbulence in building flow environments
- fuel cell transport processes

Manufacturing and materials processing
- ultrafast, precision laser processing
- optical fiber drawing and coatings
- MEMS processing
- control of industrial crystal growth processes

Nanoscale transport phenomena
- novel energy conversion devices
- semiconductor devices
- multiscale conduction modeling
- sub-nano second thermal transport
- fuorescence microscopy

Properties
- non-isotropic conductivity under shearing conditions
- radiative properties of ultra-thin films
- functionally graded shape memory alloys
- high temperature combustion gases

Design, control and optimization
- inverse design
- Second Law optimizaion of transport processes
- active control of non-linear convection

Exemplary among current directions for heat transfer research are recently funded projects at Purdue, with brief summaries provided here.

Tim Fisher, as part of his continuing CAREER award, is investigating thermal-electrical energy conversion phenomena in vacuum electron field emission microstructures with synthetic diamond and diamond-like cathodes. Guided by new theoretical and computational analyses, new experiments will be conducted to characterize thermodynamic performance for low-temperature refrigeration and high-temperature electrical power generation. The results could have significant impact on emerging needs in portable cooling technology and mobile electrical power generation. Further, the efficiency and simplicity promised by this concept could improve large-scale energy systems, such as renewable solar energy converters.

An Industry/University Cooperative Research Center (I/UCRC) for Compact High Performance Cooling Technologies, under the direction of Suresh Garimella, will address research and development needs of industries in the area of high-performance heat removal from compact spaces. The Center brings together faculty from the Schools of Mechanical Engineering, Electrical and Computer Engineering and Aeronautics and Astronautics at Purdue University, and contribute complimentary competencies in heart transfer, microfluidics, microfabrication, refrigeration, computational techniques, mechatronics, controls, acoustics, sensing and actuation and diagnostics and measurements.

A new Information Technology Research grant was recently awarded to Jayathi Murthy and Xianfan Xu for development of a comprehensive set of numerical models and techniques for the simulation of ultra-fast laser machining and to employ these techniques to obtain a detailed understanding of the fundamental physics of ultra-fast laser processing. Large-scale simulation offers the possibility of resolving a number of fundamental questions concerning mechanisms of the ablation process in ultra-fast laser machining. The large-scale parallel computing aspects of the research will broaden the capabilities of thermal science researchers in this important information technology area.

Purdue is playing a significant role in a new Nanoscale Interdisciplinary Research Team (NIRT) category. In a project funded at Vanderbilt under the leadership of Tim Fisher, a multi-university team of researchers will examine direct thermal-to-electrical power generation using electron emission from arrays of carbon-based nanostructured emitters, such as carbon nanofibers and diamond nanotips. With characteristic dimensions of one to ten nanometers, these materials enable highly efficient electron emission and the possibility of quantum confinement effects that enhance the energy conversion process.

Suresh Garimella and Tim Fisher have teamed together to study ion driven air flow at the microscale, integrated within micro-featured heat generating surfaces. The work could advance air cooling technology in a variety of electronic products for which air cooling is the only practical means of thermal management. It is the aim of this work to fill a technological gap in microscale convective cooling by developing a pump that is itself truly at the microscale. Preliminary calculations have suggested that cooling rates that compare favorably to those in many liquid-cooled applications are achievable, providing an air-cooling alternative to meet the needs of future semiconductor devices.

As difficult as it may be to believe, there are a number of high quality research activities underway at competing institutions that represent significant advancement of the thermal sciences. A few of those will be highlighted here to indicate by example some of the directions that the field is taking.

Stefan Thynell (Penn St.) is investigating the coupling between anisotropic thermal transport and water management in PEM fuel cell membrane systems. The results will have impact on fundamental understanding of anisotropic thermal transport, will address the critical water management issues for PEM fuel cells, and will serve to expose mechanical engineering students to a technology area often considered to be outside the discipline.

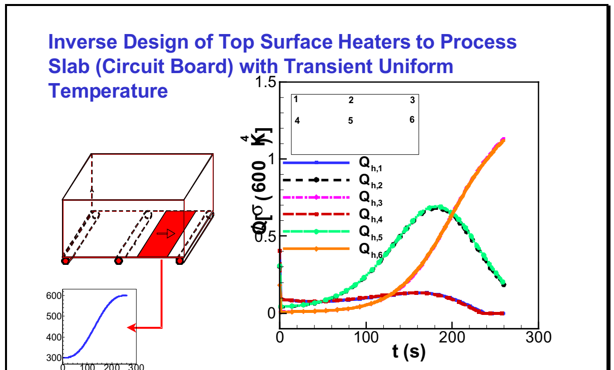
The use of arrays of sensors and actuators to control thermally induced convective flows is being studied experimentally and theoretically by Haim Bau (Penn) and his students. Because such flows are nonlinear with many degrees of freedom, effective control is quite difficult. This is a fundamental study that has the potential of enabling control strategies for modifying transport phenomena in significant industrial processes. The research should also facilitate the integration of active control strategies with thermal transport into new educational materials.

Studies of thermal and mass transport processes that lead to dross formation during the oxidation of molten aluminum are being carried out by Ishwar Puri and co-workers at Illinois-Chicago. Reduction of dross formation has potential for significant increases in energy efficiency and reduction of waste in the secondary aluminum processing industry, which produces 1/3 of the aluminum produced in the United States. The project has enabled the PI and his students to interact with their industrial partners at the Gas Technology Institute. Some secondary investigations have lead to a burner redesign for reverberatory furnaces, which may lead to savings for the aluminum industry of as much as $24M per year.

Adrian Bejan (Duke) is striving to develop a strategy (method) for optimizing the tree-shaped flow architectures in diverse flow systems such as the collection and distribution of water, the distribution of electric power, vascularized tissues, the cooling of electronics, etc. For vascularized tissues under the skin, Prof. Bejan and his students have explained why blood vessels are assembled into perfectly matched arterial and venous blood trees. The reason is that the objective of the vascularized structure is to be the best thermal insulation possible, to minimize the heat leakage from the body core to the ambient. They also derived analytically the proportionality between body heat loss and body mass raised to the power _, in warm-blooded animals of all sizes.

A common objective in the design of radiant enclosures is to identify an enclosure geometry that produces a desired heat flux distribution over the design surface. Jack Howell and Ofodike Ezekoye (Texas) have been applying non-linear programming to automatically identify the optimum enclosure geometry.

In the figure below the red shaded surface is heated following a specified temperature history while it is kept spatially isothermal as it moves through the heating chamber. The temperature distribution and the power input for the heaters on top are the unknowns, and the predicted values of the power input at various positions on the top surface are shown on the graph. These are predicted by inverse analysis using a conjugate gradient method limited to a few terms.



Project: CTS 0070545-- Inverse Design of Thermal Systems with Predominant Radiation, John R. Howell and O.A. Ezekoye,University of Texas-Austin

The University of Puerto Rico-Mayagüez and Hewlett-Packard of Puerto Rico are collaborating to investigate fundamental thermo fluids problems associated with thermal ink jets. Directed by Jorge Gonzalez-Cruz, the project includes modeling and experimentation of the fluid flow process in flexible porous media, development of non-contact thermal sensors using Laser Induced Fluorescence Thermometry (LIFT), and studies of the microboiling process that occurs in the atomization chamber.

Mike Olsen (Iowa State), as part of his CAREER award, will investigate the effects of controlling the surface microstructure on the single phase flow and heat transfer in microchannels, using whole field temperature measurement techniques. If successful, the research could lead to improved performance of MEMS devices and a variety of small scale, high heat flux devices, such as heat sinks for microprocessors, wearable air conditioners for harsh environments, and portable cooling units.

In another recent CAREER award, Li Shi (Texas) will study the thermal transport of nanotransistors that are influenced by ballistic charge transport, and to characterize thermoelectric properties of nanowires and superlattices with potentially superior thermoelectric figure of merit.

H.S. Udaykumar (Iowa) is using his CAREER award to study the interaction of microscale solidification fronts with embedded particles. The work impact on two important areas: the manufacture of metal matrix composites and the cryogenic preservation of biological tissues.

In a continuation of work that has been active for a number of years, Yogesh Jaluria and Costas Polymeropoulos at Rutgers are conducting research focused on high speed coating of optical fibers, a step in the draw process that is critical to the quality and low cost fabrication of optical fibers for telecommunications and other applications. The work includes comprehensive modeling and simulation of the transport processes within coating applicator/die systems, (b) experimentation with a laboratory off-line system developed previously, allowing measurements with different operating conditions, (c) experimentation on a full-scale draw tower, and (d) measurement of specific properties (thickness, concentricity, integrity, presence of bubbles, etc) of coatings produced under controlled conditions. This approach will therefore provide a quantitative, systematic, and validated means to predict and control fiber-coating characteristics.

The projects highlighted above represent only a brief cross section of the diversity of technological areas and potential industrial impact of the fundamental research activities in the T^3P program. A complete listing of active and even past grants can be obtained from the NSF web page (www.nsf.gov) by "clicking" on "Grants and Awards" and then on "Award Data."

FUTURE FUNDING DIRECTIONS

Over the last decade, the T^3P program has significantly increased its support of materials processing and micro/nanoscale heat transfer. From a strategic point of view, support for materials processing manufacturing research in the microelectronics area is clearly linked to Information Technology Research, and the micro/nanoscale heat transfer to the Nanoscale Science and Engineering Initiative.

The fundamental mechanisms of macroscale thermal transport and their underlying theories are in large part well understood. However, thermal transport and processing usually involves all of the traditional mechanisms to differing degrees, introducing complexity and challenge to both computational and experimental investigations. For most applications of interest to T^3P, the major difficulties with applying the fundamental concepts are: a) specification of properties, b) definition of the appropriate constitutive laws, c) development of accurate and efficient methods to solve the combined equations of multi-modal transport, and d) application of theory and algorithms to practical manufacturing or processing situations. For example, radiative properties of most infrared-active molecules at elevated temperatures are not accurately quantified, and modeling both macro- and microscopic behavior during the solidification of metals continues to be a computational challenge. Therefore, future research support is likely to address these difficulties and challenges.

It is expected that funding for research in emerging technologies will continue to increase. The area of particular interest is largely related to micro- and nano-scale heat transfer. Applications of practical interest can be found in electronics, flow and heat transfer in microchannels, laser-induced phase changes for microelectronic manufacturing, coating of optical fibers, optimization of thermal systems and improved gas turbine performance.

Besides investigations at small *spatial* length scales, it is clear that T^3P will continue to address both fundamental and phenomenological investigations in which the *temporal* length scales are in the subnano- or femto-second range. The impetus for these investigations is the availability of inexpensive, high-fluence lasers which have been considered for use in removing contaminants from surfaces in materials processing, altering the crystal structure of material near the surface in displays, or removing coatings from painted surfaces.

An area of some uncertainty with regard to T^3P is the area of biological and bioengineering thermal transport. There has been limited activity in this area in recent years at NSF, despite the overall growth in research devoted to biological advances and health, as evidenced by the extraordinary increases in funding levels to the National Institutes of Health, and the new National Institute for Bio-imaging and Bioengineering. Funding levels in the Division of Bioengineering and Environmental Engineering at NSF are among the lowest in the Engineering Directorate, with a great many research groups striving to compete for those funds. The programs in the CTS Division, in particular T^3P, have a limited capacity to absorb significant increases in proposals in these areas, despite the importance of thermal transport issues in bioengineering. There is hope that a marshaling of interest in "bioheat" may in the next few years help to mobilize an expansion of investment that may involve a productive partnership between NSF and other federal agencies.

ADDITIONAL FUNDING TRENDS

The heart of the core research programs at NSF, such T^3P, will continue to lie in the funding of unsolicited, or investigator initiated, proposals. Over half the total research budget of the Foundation is devoted to such activity. In this way a good, novel idea by an investigator that seeks to break new ground of scientific inquiry can prepare a proposal, obtain a fair peer review, and potentially receive financial support for the activity. However, it is clear that most funding *increases* in the next several years will be tied to multi-disciplinary and cross-cutting initiatives, such as Information Technology, Nanoscale Science and Engineering, Sensors, etc. In addition, there will be increasing opportunities and pressures for programs to participate in (that is, devote a portion of their core budgets to) special initiatives and interagency cooperative activities. Examples are the NSF/EPA Partnership for Environmental Research, the NSF/Sandia Program in Engineering Sciencs for Modeling, Simulation, Decision Making and Emerging Technologies, the NSF/HUD Partnership for Advanced Technology in Housing, and the NSF/DARPA High Capacity Optical Communications and Networking Solicitation. The T^3P Program will "participate" in each of these during FY03.

Another funding trend that merits discussion for both advantages and disadvantages is a perceived emphasis on multi-disciplinary proposals. On the one hand, issues in the thermal sciences area can seldom be understood in isolation. Related problems in computational science, electrical behavior, materials behavior, and mechanical behavior are integrally coupled to the advances of many new technology areas. This naturally calls for multiple investigators partnering to produce a more synergistic research activity. Therein lies dilemma, in that research proposals that are multidisciplinary tend to require greater financial resources to be successful. In addition, they may have to satisfy separate peer reviewer constituencies to receive ratings that are high enough to merit a favorable funding decision. The most difficult aspect of initiating such activity successfully is to develop the true synergistic interaction among different research groups working together. In other words, "one plus one" should come out to be equal to "three."