RESEARCH NEEDS IN THERMAL SYSTEMS

Prepared by the
SELECT PANEL ON
RESEARCH GOALS AND
PRIORITIES

For the
National Science
Foundation

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS

United Engineering Center   345 East 47th Street   New York, N. Y. 10017

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under the auspices of the
Technology Opportunities and Planning Committee
of the
ASME Board on Research and Technology Development

for the

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Report Committee

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Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation or the American Society of Mechanical Engineers.

FOREWORD

The Board on Research and Technology Development of the American Society of Mechanical Engineers (ASME), has the responsibility to implement the Society's Goal No. 9:

> "To undertake, on a continuing basis, an assessment of the priorities for research and identification of new or unfilled needs."

Previous reports which have been published by the ASME address research needs in the following areas: design, materials and manufacturing; energy conversion; environment and conservation; energy conservation through tribology; fundamental research in mechanical engineering; and research needs in mechanical systems.

This report summarizes a comprehensive study of research needs in thermal systems carried out under National Science Foundation (NSF) Grant MEA 8400825 to the ASME. It is expected that this report will provide guidance to the NSF in the identification of research needs that should be met through the Thermal Systems Program.

We acknowledge the many contributions made by the remaining members of the Steering Committee, the "Select Panel on Research Goals and Priorities in Thermal Systems," the ASME leadership, and our numerous colleagues in the engineering community.

For further information on the NSF thermal systems and Engineering Program contact Dr. Win Aung, Program Director, National Science Foundation, 1800 G St. NW, Washington, DC, 10550, Phone (202) 357-9606. Copies of the complete report can be obtained from the ASME Order Department, ASME, United Engineering Center, 345 E. 47th St., New York, NY 10017.

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ASME Study on Research Goals and Priorities for Research in Thermal Systems

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EXECUTIVE SUMMARY

The National Science Foundation in FY83 established a new area entitled Thermal Systems within the Heat Transfer Program of the Mechanical Engineering and Applied Mechanics Division. This was a new initiative by the NSF to provide support for basic research in the area of thermal systems. In the reorganization of the NSF Directorate for Engineering in late 1984, the Thermal Systems and Engineering Program was established as part of the new Division for Engineering Science in Chemical, Biochemical, and Thermal Engineering. This report summarizes the results of a comprehensive study which defined the field of thermal systems and identified long-range goals and priorities for research in this field. The primary objective of the study was to prepare recommendations to the NSF on research needs that should be met through the Thermal Systems Program.

The ASME Board on Research, through the Committee on Research Needs, initially appointed a five-person task force under the chairmanship of Dr. H. H. Richardson and including Dr. W. O. Winer, Dr. M. J. Rabins, Dr. R. S. Fein, and Dr. C. J. Cremers. In July 1983, the ASME through the efforts of this task force submitted a proposal to the NSF to undertake the study that has resulted in this report. The five-person task force, in cooperation with the NSF, appointed an eleven-person Steering Committee under the chairmanship of Dr. W. O. Winer.

The study was conducted under the supervision of the Steering Committee and was carried out through the appointment and action of a forty-seven person panel. This panel included leaders from academia, industry and government, representatives of relevant ASME technical divisions, and authorities in various areas involved in thermal systems. The Panel met in a Workshop in April 1984 to identify and prioritize research needs in thermal systems, and to formulate preliminary recommendations. This final report integrates the results from the Workshop, input from a national mailing, and the feed-back from the technical leadership of ASME concerned with thermal systems. A summary of the recommendations of the Workshop was also presented during the period of August 1984 to February 1985 at seven professional society meetings and at a meeting of the National Science Foundation Advisory Committee for the Division of Mechanical Engineering and Applied Mechanics.

In addition to establishing a definition of the field of thermal systems, this study has identified high priority fundamental and generic research needs that have a high potential for medium and long-range technological and economic impact on the industrial sector.

DEFINITION OF THE FIELD AND ITS SUBDIVISIONS

Thermal Systems is an interdisciplinary field employing the traditional disciplines of thermodynamics, heat transfer, fluid mechanics, mass transfer, and chemical kinetics. It is concerned with basic and applied research relevant to the design, simulation, and optimization of mechanical systems and components utilizing thermal energy.

Four major areas have been identified within the field of thermal systems. These four areas are the following:

- Combustion Related Thermal Power (including internal and external combustion devices and propulsion)

- Noncombustion Related Thermal Power (including nuclear, solar, and geothermal power systems and fuel cells)

- Thermal Environmental Control (including heating, ventilating, and air conditioning systems, fire, thermal pollution, and electronic system thermal control)

- Thermal Processing (food and agricultural drying, process heat exchange equipment, and materials thermal processing)

There are also three areas which are common to all four of the major areas, and are generic to many fields of engineering. These are

- Modeling, simulation, and optimization of thermal systems
- Control of thermal systems
- Measurements and sensors in thermal systems

The area of combustion related thermal power systems involves all power systems wherein the energy is derived from the high-temperature exothermic reaction (typically an oxidation process) of materials referred to as fuels. The systems may be designed for electric power generation, automotive usage, propulsion, or mechanical power generation. Relevant devices include gas turbines, internal combustion engines, rockets, ramjets, and boilers. Fuels of interest are typically hydrocarbons in liquid, solid, or gaseous forms but do include other substances, e.g., hydrogen. The most significant technology limitations are related to the high-temperature combustion processes and to the combustion/materials interaction. Some of the fundamental combustion issues would also apply to systems for space heating or materials processing.

The noncombustion related power area involves systems producing power by the use of heat not derived from the combustion of a fuel. These systems include nuclear power, solar power, ocean thermal energy conversion, geothermal power, earth-coupled heat exchange, and fuel cells. (Fuel cells are included because no flame occurs during electrochemical oxidation.)

Thermal Environmental Control may be defined as an engineering field concerned with the characteristics, behavior, and control of thermal environmental systems, including analysis, synthesis, design, optimization, and control. It is an area that has evolved from the classical field of thermodynamics and, depending on the system under consideration, also has roots in heat transfer, fluid mechanics, mass transfer, dynamic systems and control, chemical kinetics, and economics. The definition includes environments that are benign or harmful, micro- or macro-, and human or non-human. The study of thermal environmental systems can have a large impact on the economy and well-being of our nation.

Thermal process systems accomplish one or more physical and/or chemical changes through heat addition and/or removal to a feed material to produce a product of desired composition, properties, and physical state. Typical systems would include chemical plants, refineries, basic metal plants, grain processing plants, and food processing plants. A thermal process system can be composed of many different components, including heat exchangers, furnaces dryers, pumps, distillation columns, filters, compressors, turbines, blowers, connecting piping, instrumentation, and controls.

Taken as a whole, the field of thermal systems provides a new integrating framework within engineering for the traditionally relevant engineering sciences (e.g., thermodynamics, fluid mechanics, heat transfer, and chemical kinetics) as well as those other disciplines that are increasingly required in the field of thermal systems (e.g., materials engineering, information and computer engineering, physics and chemistry). The field of thermal systems provides a framework for the continued engineering significance of these disciplines.

RELEVANCE AND IMPACT OF THE FIELD OF THERMAL SYSTEMS

The field of thermal systems is a very broad one involving many separate engineering disciplines. Accordingly developments in thermal systems have a major impact not simply on a large number of varied applications, but on a very large fraction of industrial activity as well as on our daily lives. Manufacturing of steel, plastics, cement and semi-conductors; transportation by air, by car and by ship; space heating and air-conditioning; processing of chemicals and food; and, of course, the production of electricity itself are all activities in which thermal systems play a major role. These activities account for as much as one-fifth of the nation's Gross National Product. Our standard of living and our ability to compete in the world markets depend critically on the continued developments and innovations that must come from research in the area of thermal systems.

The advent of microprocessor technology and related developments in information processing on the one hand, and the expanding need to optimize the performance of thermal systems subject to multiple conflicting objectives on the other hand, has created an unprecedented opportunity for improvement of thermal systems productivity through research. Research conducted in this field will have a broad impact on endeavors such as improving efficiency in energy conversion and utilization systems; enhancing the performance, quality, and reliability of consumer products; and obtaining improved performance from a wide variety of industrial and public-sector systems which have expensive infrastructures and equipment already in place. More specifically, research in thermal systems could have a major impact on newly emerging applications such as high density electronic systems.

Estimating the economic impact of the field of thermal systems is difficult. The field is related, in one way or another, to most economic activity. However, an indication of the importance of the field can be obtained from data for those industries obviously involved with thermal systems by looking at the **1984 Statistical Abstract of the U.S.** Based on private, nonagricultural industries, 19% of the employed persons in the U.S. are in industries obviously involved with thermal systems technology. The same industries generate income which is 19% of the Total National Income. In addition, those same industries account for 61% of the R&D outlay by industry (1980) and employ 57% of the R&D scientists and engineers (1981) as a percent of industry totals. Thermal systems technology is an important component in the technological and economic well-being of the U.S.

CATEGORIES OF RESEARCH IN THERMAL SYSTEMS

Three categories of research were identified in each of the four subareas and generic areas listed above. The first is high-risk "frontier" research which may lead to revolutionary advances in the field. This type of research cannot be defined at the outset in a topical manner, nor can the probability of useful or even successful outcomes be determined in advance. Yet this type of research is very important because of its potential payoff. The NSF has a special role to play in support of frontier research, since research of this type is not likely to be supported by industry or by most of the federal mission agencies.

The second category of research extends the knowledge base of an existing field. The Panel identified research needs of this type that are feasible to fill, are fundamental and generic, have high potential for medium and long-range impact on industrial productivity, and are appropriate to the NSF mission. These research needs are summarized below.

The third category of research involves codification of research results, placing them in a form useful in professional practice and transferring them to the professional user community. The neglect of this class of research in recent years has undoubtedly contributed to the more rapid utilization of U.S. research results in foreign, rather than in domestic, industries, and to the loss of U.S. leadership in an increasing number of industries.

Two important technological factors will contribute to future productivity and competitiveness of the U.S. in the thermal systems industries. First is the supply of technical expertise in the area of thermal systems, and second is the availability of user-oriented computer-aided design tools in the field of thermal systems. By placing greater emphasis on thermal systems research (and the education which results therefrom) and by broadening the scope of its research to include research codification and technology transfer, the NSF is in a position to make major contributions to the future technological strength of the nation.

MAJOR RECOMMENDATIONS

Recommendation #1: Composition of the Thermal Systems Program

The Select Panel recommended that the NSF Thermal Systems Program include the following five subprograms:

- Combustion Related Thermal Power Systems
- Noncombustion Related Thermal Power Systems
- Thermal Environmental Control Systems
- Thermal Processing
- Generic Techniques

Because of its broad scope, integrative nature and relevance to the critical industries of the nation, the size and extent of the Thermal Systems Program should be increased over the next several years to provide stimulus to the university community to develop both faculty and basic research, and to encourage university/industry coupling to strengthen the nation's resources in the thermal systems field for the future. Special attention should be given to encouraging and supporting both research to advance the thermal systems disciplines, and research to codify and transfer knowledge to industrial users.

The funding levels should be built gradually as excellent proposals are attracted. A goal should be set of supporting about 200 of an estimated 800 faculty concerned with the thermal systems disciplines in U.S. engineering departments. (The figure of 800 is an estimate from the survey of mechanical engineering departments discussed in Section 8.4.) The Program should allow for and encourage appropriate university/industry cooperative relationships involving technology transfer, sharing of facilities and people, and joint research and educational activities. It is important that the program grow in a stable manner in order to encourage the type of long-term faculty commitments to the field that are needed to insure excellence.

The Thermal Systems Program should encourage and support some frontier and emerging technology research. NSF should explicitly invite proposals of this type and may want to establish a special review process for such proposals. For example, a special review panel of individuals having broad perspective and experience, and positive attitudes toward high-risk, high potential payoff research might be established. Clearly a major factor in the proposal review will be the qualifications, quality and past record of the principal investigators. Bringing vision, judgment and insight to the review process for these proposals is crucial to selecting work which is likely to produce major advances in the future similar to those which have resulted from high-risk research in the past.

It is recommended that the thermal systems Program incorporate the following three modes of support:

Project Support to Individual Investigators

This is the traditional mode for NSF support of university research, and it should continue in the thermal systems area. Typically, a project will involve one or two faculty members working with graduate students and will provide for support services, computer time, equipment and other items such as travel and publications. Provisions should be made for the support of innovative relationships with industry. Special attention should continue to be given to the needs of young faculty who are making professional commitments to the area. These projects will typically require annual funding of the order of $50,000 to $200,000 each (1985 $).

Coherent Area Programs

Programs in this category are intended to provide coherent research activities having a degree of "critical mass" at a single university that cannot be achieved through the efforts of one or two faculty. These programs would support several investigators and a group of graduate students and may be the nucleus for larger centers of activity at universities in one of the thermal systems disciplines or generic areas. Normally such programs would be expected to form strong relationships with industry and to derive part of their support and personnel from industry. Funding for coherent area programs would range from about $100,000 to $400,000 per year (1985 $). This type of program is especially important in stimulating the type of interdisciplinary coupling which is necessary for major advances in thermal systems and may support groups which subsequently could apply for funds under the Engineering Research Center Program.

Distributed Programs

Programs of this type would be similar to coherent area programs but would involve collaboration among investigators from more than one university. The advantages of this type of program are the ability to combine the strengths of more than one institution, to obtain geographic distribution of expertise and educational opportunities, and to bring the best talents in the country to bear on research needs. Funding requirements for distributed programs are likely to be in the range of $300,000 to $500,000 per year (1985 $).

In each of these three models of research it is recommended that NSF provide mechanisms for nation-wide coordination of research in each of the thermal systems areas, and for industrial input into the review of research results. Special attention should also be given to technology transfer to practicing engineers and to industry.

Recommendation #2: Research Needs in the Basic and Generic Areas of Thermal Systems

High priority research needs identified in each of the five subprogram areas of thermal systems are described in detail in Sections 3.2 through 3.6 of this report. The selection of these major needs was based on four major criteria: contributing to fundamental knowledge, opening new fields of future importance, enhancing industrial productivity, and enhancing the technological level and sophistication of engineering manpower. A summary of the major needs by area follows:

Research Needs in Combustion Related Thermal Power Systems

1. **Combustion Processes:** Combustion of chemical fuels is the source of energy for many thermal systems. Many aspects of liquid and solid combustion processes require further understanding for the advancement of thermal power systems. These include the chemical kinetics of combustion, both unsteady and turbulence effects, the influence of fuel properties on combustion, and combustion/material interaction.

2. **Simulation and Modeling:** The ability to model the combustion process is a major factor in defining the frontier of the field. In the area of combustion the advancements of modeling should be pursued to further the optimization and control of thermal systems, and to understand near-limit combustion behavior, as well as to model the combustion process itself.

3. **Measurement Science in Combustion:** Innovation and development of diagnostic methods designed to provide new experimental data of prime importance to combustion science must be pursued. Two major categories of measurement technique development are emphasized: (1) Non-intrusive space- and time-resolved diagnostics (especially with lasers) for characterizing fundamental combustion processes, generic systems, and devices, and (2) sensors for determining and controlling operating characteristics of combustion systems.

Research Needs in Noncombustion Related Thermal Power Systems

1. **Thermal Storage and Transport Systems:** Many energy sources for noncombustion power systems are intermittent and the availability does not coincide with energy demands. Innovative means for storage and transport of the energy in some form is needed to minimize energy losses and to optimize overall power system efficiency and reliability.

2. **Modeling, Simulation, and Optimization:** Innovative methodologies are needed for applications to design, operation, and adaptive control of thermal systems, all of which can lead to improved forcasting of loads and resources. The methodology should include the second law explicitly in optimizing systems and subsystems. At the process level modeling laws are also needed for multiphase flow.

3. **Innovative Processes for Utilizing Thermal Energy:** A number of systems now available for recovering and utilizing energy must be studied if they are to be used advantageously. These include double diffusive convection systems such as solar ponds, crystal growing, and ocean swelling; and thermal processes for chemical fuel production such as the production of hydrogen from solar energy or high temperature gases from nuclear gas cooled reactors.

4. **Modular Decentralized Energy Conversion Systems:** Systems utilizing solarthermal, photovoltaic, fuel cells, and some conventional devices have the potential of being used in a modular or even decentralized manner. Potential research related to thermal coupling of modules, heat loss, and thermal control of small units is needed.

Research Needs in Thermal Environmental Control

1. **Modeling, Simulation and Control:** The modeling of human environments for thermal control, especially large buildings, is complex. On-line adaptive control strategies should be developed for energy-efficient system operation. At least four areas of research needs exist: (a) thermal interaction of the structure and the environment including the definition of the thermal micro-environment, (b) capacity modulation and interaction among building components, (c) on-line adaptive control and the application of artificial intelligence for optimal control, (d) research into the thermophysical properties of complex materials in the system.

2. **Cooling of High-Power Density Electronic Systems:** The thermal control of electronic equipment, especially integrated circuits, requires heat transfer and flow research on small length scales that were of little prior interest. Three areas of research needs are required: (a) flow and heat transfer, on a small scale and at low to transitional Reynolds numbers, in complex geometries with mixed boundary conditions, (b) thermal behavior of materials, including thermal stresses and contact conductance with low pressures, elastic contacts, and boiling of dielectric fluids, (c) the development of innovative cooling techniques for electronic systems.

3. **Burning of Solids:** Research is needed on the fundamentals and modeling of the physical and chemical degradation of solids subjected to combustion. This research should include the effects of homogeneous and composite structures, phase changes, charring, and the transport of phases within the structure. Study is also needed on life cycle burning of solids, including ignition, sustained combustion, and extinction. Research is recommended in three areas: (a) ignition, sustenance, propagation, and extinction of flames, (b) behavior of the solid during combustion and its interaction with the gas phase, (c) heat and mass transfer effects of combustion on the surroundings.

4. **Dissipation of Rejected Heat to the Environment:** Research needs in this area exist because the scale of the problem is not one of traditional interest. Study is needed on the numerical modeling of these systems, but their scale and complexity limit the usefulness of experiments. Three research areas are recommended: (a) fundamental research into large buoyant flows, (b) buoyant flows with mass transfer, especially in combination with turbulence or recirculation, and (c) particulate behavior in buoyant turbulent flows.

5. **Sensors for Thermal Systems:** Smart, self-calibrating, and inexpensive sensors for thermal environmental systems are needed, especially for non-invasive applications. Research on sensors and fault detection mechanisms is recommended across the spectrum of thermal environmental systems.

Research Needs in Thermal Processing Systems

1. **Thermodynamic Optimization and Design Methodology at Both the System and Component Level:** Second law analysis or synthesis is a method for achieving the thermodynamic optimization of thermal systems. Research should be done on second law application methodology. An analysis of all major systems and components to identify ideal targets for thermodynamic optimization should be undertaken. Design methodology for thermal systems needs to be developed with

an emphasis similar to that currently given to the design methodology of mechanical systems. This design process must involve an approach to systems in which thermal processes are of principal concern, and an examination of alternatives to produce an objective with certain constraints, such as economics and thermal performance regarding both first and second law considerations. This methodology is important both for the evaluation of existing systems and for the development of new thermal processes.

2. **Advanced Areas Associated with Heat Recovery Systems:** Many thermal systems rely on heat recovery devices. Several aspects of these devices limit the further development of heat recovery systems. These factors include extreme service conditions such as very high temperature, large power and process heat exchangers, combustion and transport processes in industrial furnaces, and earth-coupled heat exchangers.

3. **Fundamental Issues Associated with Heat Recovery Processes:** Many research needs exist in a variety of basic mechanisms occurring in heat recovery systems. These include transport phenomena in drying processes, flow and heat transfer in processing systems for complex fluids, and the characterization of biomass fuels.

<u>Research Needs in the Generic Areas of Thermal Systems</u>

1. **Modeling, Simulation and Optimization (MSO):** Three levels of thermal system structure are identified for modeling, simulation and optimization: phenomena, component, and system. MSO is applicable to all four broad areas of thermal systems at the systems and component levels but not universally applicable at the phenomena level. At the systems and component levels research needs exist in the areas of sensitivity analysis, mathematical methods for optimization, interactive synthesis/design evaluation, and selection of most efficient parameters. At the phenomena level there are research needs in the modeling of multiphase flow and turbulence which have general applicability to thermal systems. Needs also exist in the definition of thermodynamic targets for processes and models for capital-versus-energy balance.

2. **Control of Thermal Systems:** Several aspects of thermal systems complicate their control. These include complexity and non-linearity of the systems and the general lack of a range of sensors. Research needs in the control of thermal systems include such areas as the adaptive control of instabilities in thermal systems, the control of distributed field processes and the optimization of thermal systems.

3. **Measurement Systems:** The need for measurement devices is common to all areas of thermal systems. Instrumentation is needed for control systems, fault detection and basic research. Research needs exist for in situ non-intrusive time and space-resolved measurements which can be used in the control of thermal systems. The availability of state-of-the-art research instrumentation is a common need of several of the areas of research listed for thermal systems.

REPORT COMMITTEE

The persons listed below prepared this final report. They also served as members of the Steering Committee. The additional members of the Steering Committee were C. A. Amann (General Motors Research), J. P. Appleton (Thermo Electron Corp.), C. E. Johnson (Bell Laboratories), P. S. Myers (U. Wisconson/Madison), and N. Zuber (Nuclear Regulatory Commission).

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James W. Westwater is a Professor of Chemical Engineering at the University of Illinois. He has been Chairman of the Heat Transfer Division AIChE, General Chairman of the III International Heat Transfer Conference, and recipient of the Max Jacob Award. He is also a member of the National Academy of Engineering.

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