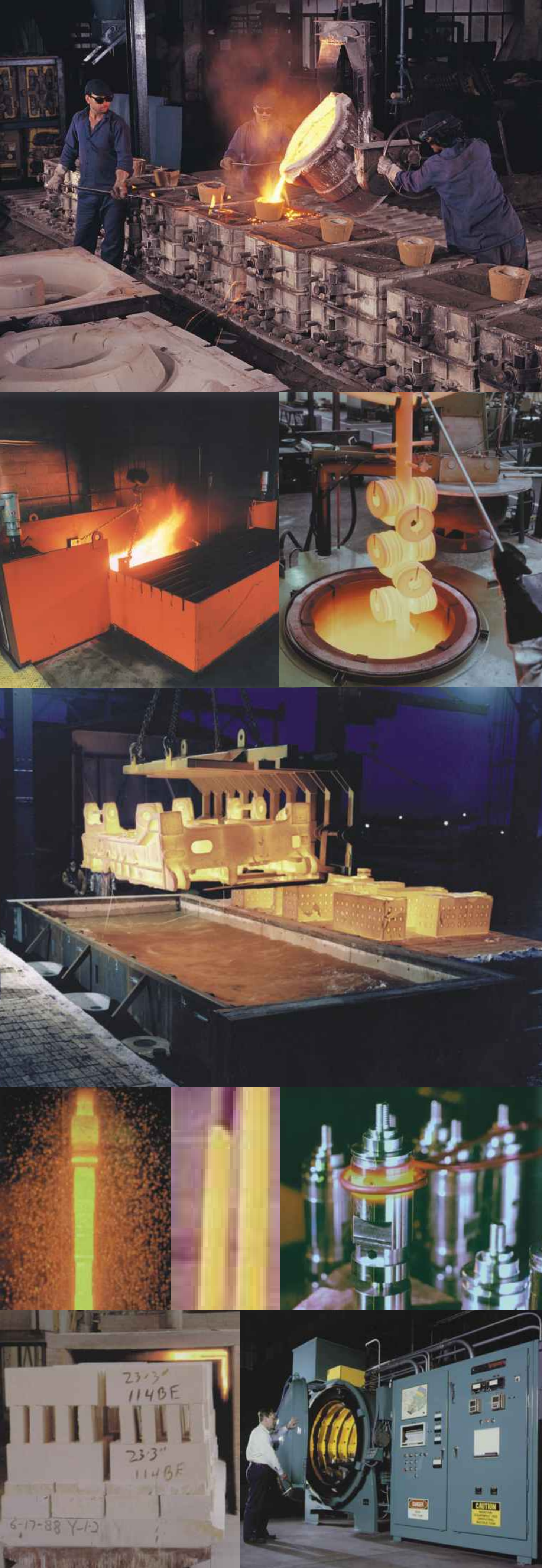

Roadmap for Process Heating Technology

Priority Research & Development Goals and Near-Term Non-Research Goals To Improve Industrial Process Heating

March 16, 2001

Sponsored by
Industrial Heating Equipment Association
and
U.S. Department of Energy
Office of Industrial Technologies

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Organized and Prepared by
Capital Surini Group International, Inc.
and
Energetics, Incorporated

About This Roadmap

The Industrial Heating Equipment Association and the U.S. Department of Energy co-sponsored a workshop that brought together a broad range of process heating manufacturers and end-user companies. This roadmap, which summarizes the insights of 35 workshop participants, sets forth the goals for improving industrial process heating performance. Achievement of these goals will significantly improve energy efficiency and productivity in many industries and help them reach their performance targets for 2020. Recognition and appreciation is extended to these volunteers for committing their valuable expertise, time, and resources.

The workshop was organized by Arvind Thekdi of Capital Surini Group International (CSGI), Incorporated, and was facilitated by Jack Eisenhauer, Nancy Margolis, and Melissa Eichner of Energetics, Incorporated. This roadmap was prepared by Melissa Eichner of Energetics, Incorporated and Arvind Thekdi of CSGI. *Industrial Heating, 2000* provided the cover photographs.

Roadmap for Process Heating Technology

Priority Research and Development Goals and Near-Term, Non-Research Goals to Improve Process Heating Technology

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1 Executive Summary and Introduction

Process heating technologies supply heat to nearly all manufacturing processes. Whether in the production of materials such as steel, cement, and composites or in the manufacture of value-added products such as electronics, computer chips, cosmetics, and textiles, process heating is a critical manufacturing step throughout industry. Because they consume 17 percent of U.S. industrial energy, process heating technologies also represent a significant opportunity to improve industrial productivity, energy efficiency, and global competitiveness. Despite some major improvements in the past two decades, efficiency levels for process heating equipment are still low. Faced with regulatory and competitive pressure, today's industries are now demanding process heating technology with improved performance, lower environmental impacts, and greater flexibility, all at a lower cost. However, few process heating equipment manufacturers have the resources to conduct the necessary research and development on their own.

In response, the process heating community, led by the Industrial Heating Equipment Association (IHEA) and the United States Department of Energy's Office of Industrial Technology (OIT), embarked on a proactive, collaborative effort to develop a comprehensive plan for meeting industrial process heating needs now and in the future. This document is the result of that collaboration.

Advanced technologies and operating processes could reduce process heating energy consumption by an additional 5 to 25 percent over the next decade.

In November 1999, 35 experts representing equipment manufacturers, end users, energy suppliers, and researchers met to address the issues facing industrial process heating. First, the participants defined key performance targets necessary to maintaining their competitive position. Second, a list of barriers was identified, and third, specific goals were developed to address the barriers and achieve the targets. The highly diverse nature of industrial heating applications, with temperatures ranging from 300 to 3000°F, presented significant challenges to participants. In the end, the group agreed on the goals needed to ensure the competitiveness of U.S. industries in process heating over the next two decades. An overview of the roadmapping workshop and a list of participants are included in the Appendix.

The top priority R&D goals were:

- Advanced sensors that measure multiple emissions
- Improved performance of high temperature materials, including alloy composites
- Predictive models of the process heating system
- Improved methods for stabilizing low emission flames
- Heating technologies that simultaneously reduce emissions, increase efficiency, and increase heat transfer
- Low-cost heat recovery for low and high temperature processes

The priority near-term non-R&D goals were:

- R&D and non-research priorities based on end-user input
- Rational and consistent policies
- Voluntary conventions/practices for equipment manufacturers
- Incentives for purchasing capital equipment that utilize new technologies
- Expanded number of process heating applications using advanced technology
- Use of advanced enabling technologies in new process equipment
- Developed workforce
- Efforts to educate end-users
- Efforts to educate the public

This roadmap sets forth the priority goals and direction that will enable the process heating community to meet end-users' process and equipment needs over the next 20 years. In the months ahead, the specific steps needed to implement the priority R&D and non-R&D activities will be pursued by process heating stakeholders, including:

- End-users who purchase, operate, repair, and maintain process heating systems
- Equipment and component designers and suppliers
- Process and system engineering designers and consultants
- Energy suppliers

Achievement of the priority R&D and non-R&D goals would offer significant industry-wide cost savings and performance efficiencies. With the use of advanced technology and operating practices, process heating energy consumption could be reduced by an additional 5 to 25 percent within the next decade.

This Roadmap Presents:

- **Industry-wide process heating performance targets to be achieved by 2020**.

- **Key barriers to achieving the performance targets today, including technological, institutional, regulatory, and market barriers**

- **Priority R&D goals and expected timeframes for completion linked to the performance targets.** Activities to achieve these goals are *not* listed. They will be identified and pursued in the implementation phase of this roadmap. The R&D goals address the technological barriers.

- **Priority near-term non-research goals with specific activities to achieve each goal within the next five years.** These goals focus on improving near-term process heating performance with existing technology and management practices, and present opportunities for industry collaborations. They also address institutional, regulatory, and market barriers.

- **Next steps for implementing roadmap goals.**

2 Process Heating Overview

Process heating is used to supply heat during manufacturing of basic materials and commodities. Its use is extensive throughout industry – from the smallest manufacturers to Fortune 500 companies – to transform basic materials into the goods we use every day: decorative fixtures in our homes, the flatware we use for eating, and high-performance engine components in our cars, to name only a few. Whether in the production of materials such as steel, cement, and composites or the manufacture of value-added products such as electronics, computer chips, cosmetics, and textiles, process heating plays a important part. Exhibit 2.1 illustrates the diverse range of businesses and industries that use process heating.

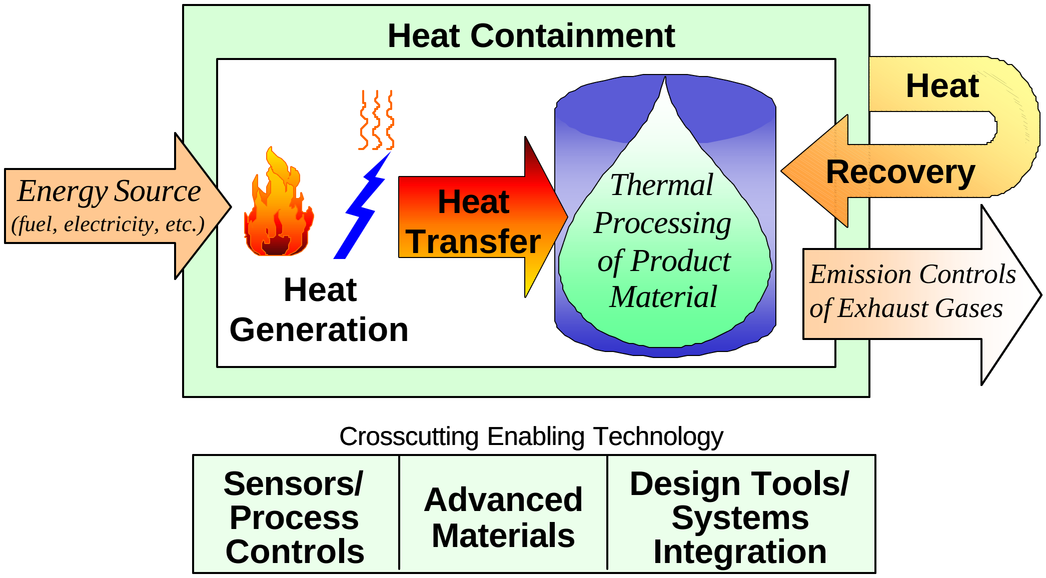
With its wide and varied industrial use, process heating directly and indirectly affects the employment of an estimated 16 million people in the United States at more than 300,000 establishments with total annual sales and shipments of $3.8 trillion.

Process heating systems, as shown in Exhibit 2.2, usually include a heating device that generates and supplies heat; heat transfer devices for transferring heat from the source to the product being heated; heat containment in the form of a furnace, heater, oven, kiln, etc.; and a heat recovery device.

Exhibit 2.1 Businesses and Industries Served by Process Heating Equipment

Materials	Value-added Product Areas	
• Steel • Glass • Basic Chemicals • Ores and Minerals • Copper & Brass • Ceramic • Petroleum • Paper • Aluminum • Composite Materials • Cement • Precious Metal	• Automotive Parts • Appliances • Specialty Steels • Food • Ship Building • Textile • Pipe & Tube • Fasteners • Machinery • Plastics • Tools • Powdered Metals • Weapons & Armaments • Farm & Heavy Equipment • Paper Products	• Gypsum • Foundry • Paint • Computer Chip • Jewelry • Defense Equipment • Beverage • Carbon & Graphite • Asphalt Paving • Forging • Cosmetic • Electronics • Construction Materials • Aerospace Components • Can and Container • Wire • Medical Products • Rubber

Exhibit 2.2 Process Heating Systems



The system can also include a number of other support systems such as sensors and control systems, material handling, process atmosphere supply and control, safety systems, and other auxiliary systems.

In most applications, heat is supplied by one or more of four heating methods: fuel-fired heating, steam heating, hot oil/air/water heating, and electric heating (see Exhibit 2.3). The heat is transmitted directly from the heat source, indirectly through the furnace walls, or through other means such as jets and recirculating fans.

These operations are performed in an enclosure with refractory material and insulation lining the walls and sealed doors and other openings for heat containment. Depending on design and operations, 10 to 25 percent of the total heat supplied may be lost through the enclosure. The flue gases from fuel-fired heating equipment may contain a large amount of the total heat input, ranging from 20 to 70 percent. Many furnaces, particularly those used for high-temperature operations, include some type of heat-recovery device to recycle part of this heat. Additionally, water cooling of furnace parts or load support systems can result in the loss of 5 to 20 percent of the heat input. Properly designed and applied sensors and control systems, material handling systems, and process atmosphere and other auxiliary systems can lead to substantial energy savings, ranging from 5 to 30 percent.

Process heating equipment is operated over a broad temperature range, from 300^{o} F to as high as 3000^{o} F. Consequently, the process consumes a large amount of energy. In fact, energy costs for process heating represent 2 to 15 percent of the total product cost. U.S. industries represent approximately 38 percent of total U.S. energy consumption supplied from four energy sources, as illustrated in Exhibit 2.4.

Exhibit 2.3 Industrial Process Heating Methods

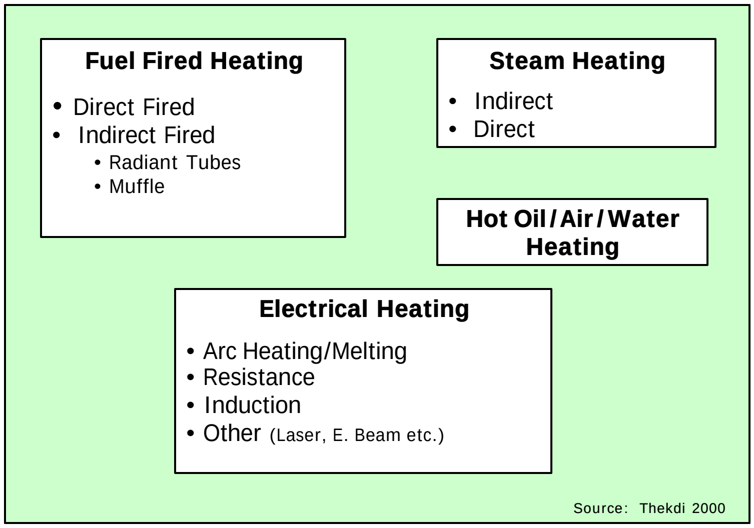
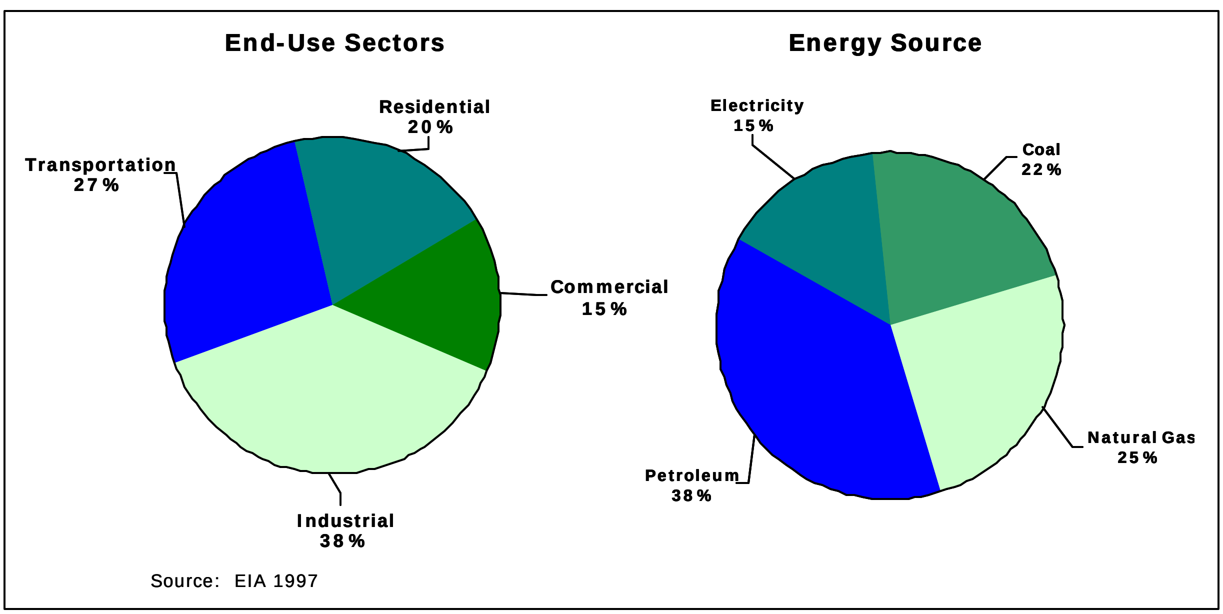


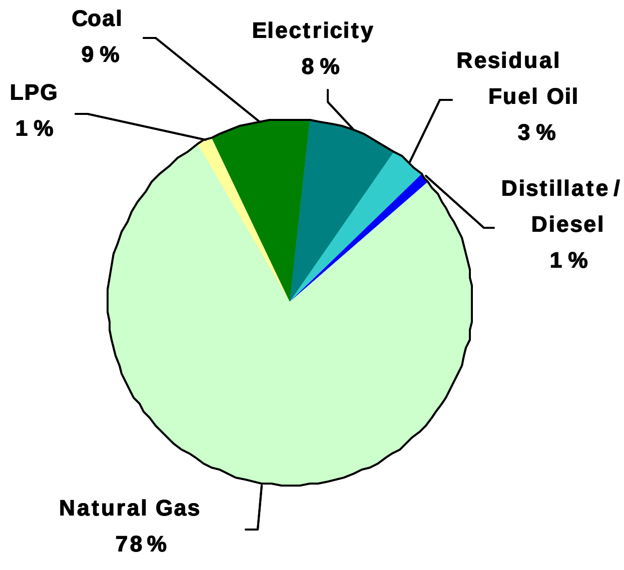
Exhibit 2.4 U.S. Energy Consumption, 1995



Industry-wide, process heating consumes about 5.2 quads (quadrillion Btu), which is about 17 percent of industrial energy consumption. The types of energy consumed in process heating are shown in Exhibit 2.5; heat derived from combustion of fossil fuels accounts for 92 percent of this energy, with electricity comprising the remaining 8 percent.

Throughout U.S. industry, process heating accounts for more direct energy use than any other processes that consume energy during manufacturing as illustrated in Exhibit 2.6. Steam generation and cogeneration, which involve combustion of fossil fuels as a primary source of heat, employ technologies commonly used for process heating. Although efficiency gains in process heating equipment are expected to make a significant impact on industrial energy use, the total energy demand for process heating is still expected to increase. Exhibit 2.7 shows the projected increases in energy use for important industry segments.

Exhibit 2.5 Types of Energy Used for Process Heating, 1994



Source: EIA, 1997

Exhibit 2.6 Industrial Energy Use by Function

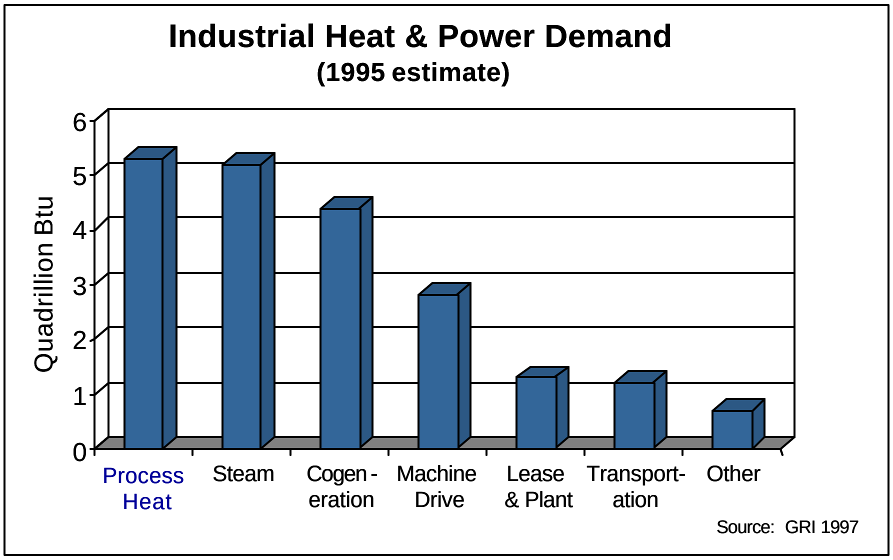
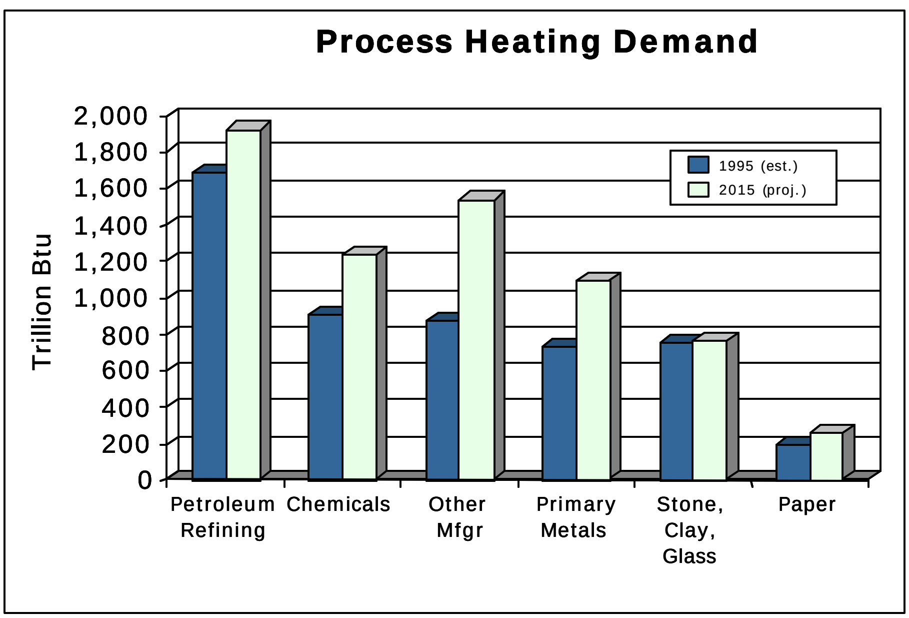


Exhibit 2.7 Process Heating Demand by Industry



Nine generic industrial operations use process heating: fluid heating, calcining, drying, heat treating, metal heating, metal and non-metal melting, smelting/agglomeration, curing and forming, and other heating. Different energy sources are preferred depending on cost, availability, and process and emission requirements. Energy sources for these operations are shown in Exhibit 2.8. Specific processes for each of these operations are listed in Exhibit 2.9. Most of these processes are used by more than one industry.

During the past 20 years, process-heating improvements have made significant contributions to reducing environmental impacts from combustion-related emissions. Compared to conventional systems, new ultra-clean technology has led to significant emissions reductions. Nevertheless, efficiency levels are still below practical limits and can be improved. Currently, overall thermal efficiency of process equipment varies from 15 to 80 percent, compared to the thermal efficiency of steam generation, which varies from 65 to 85 percent. Due to lower efficiency levels, process heating offers significant energy-saving opportunities. The greatest potential for improvements and savings lies in the higher temperature ranges, as the margin for improvement is large and the returns greater. With the use of advanced technologies and operating practices, reductions in process heating energy consumption by an additional 5 to 25 percent will be possible within the next decade.

Exhibit 2.8 Energy Sources for Commonly Used Operations

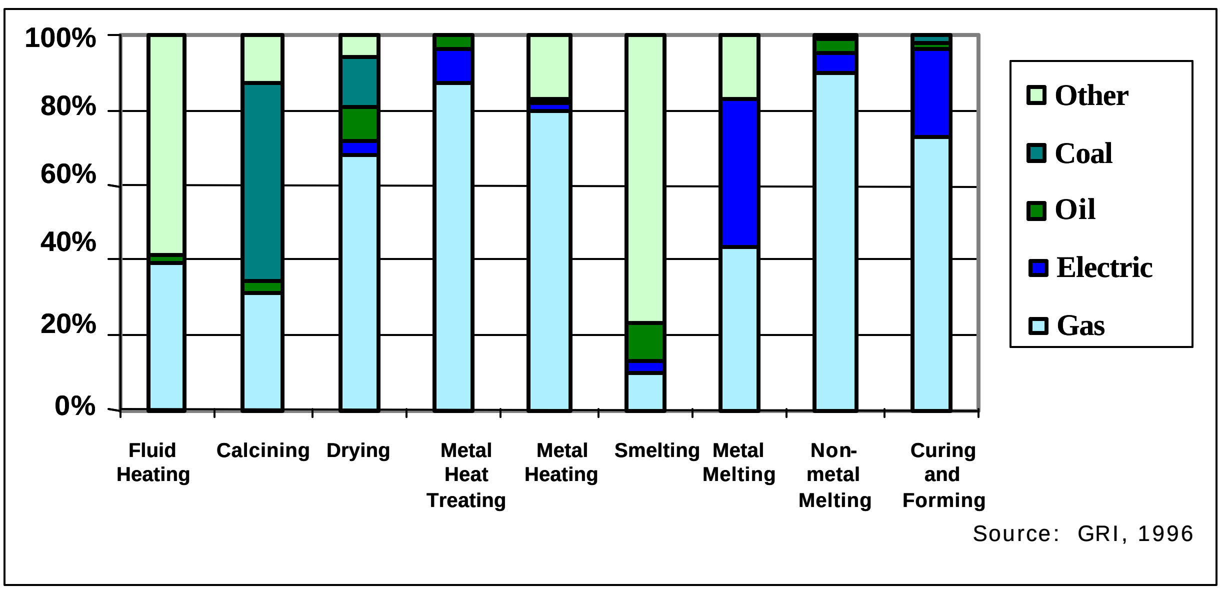


Exhibit 2.9 Typical Processes for Process Heating Operations

Fluid Heating	Calcining	Drying	Heat Treating	Metal and Non-Metal Heating	Smelting, Agglomeration, etc.	Curing and Forming	Other Heating
· Air Heating · Cat Reforming · Distillation · Fluid cracking · Hydrotreating · Liquid heating · Quenching systems · Reforming · Visc breaking	· Cement · Coke calcining · Minerals Calcining · Ore Calcining	· Crude oil · Food and Kindred Products · Ladle and vessel · Molds and cores · Natural gas · Powder (metal and non-metal) · Pulp and paper · Resin · Sludge and waste materials · Stone and clay	· Aging · Aluminizing · Annealing · Austempering · Blueing · Brazing · Carbon restoration · Carbonitriding · Carburizing/ decarburizing · Coatings (CVD, PVD) · Draw ing · Enamelilng · Glass tempering/ annealing · Hardening · Homogenizing · Malleableizing · Marquenching · Nitriding · Normalizing · Solution heat treating · Stress relieving · Tempering	· Baking · Castings · Clay, bricks, ceramics, etc. · Cleaning · Forging · Galvan-izing · Glass · Heat cleaning · Ladle preheating · Porcelain enameling · Preheating · Reheating · Sintering · Aluminum · Copper, Zinc, Lead, etc. · Glass · Iron and steel	· Aluminum ore · Blast Furnaces · Coke ovens · Coke ovens · Copper, Zinc, and Lead · DRI	· Ceramics · Clay · Glass · Metal (ferrous and non-ferrous · Resin and plastic · Heat forming · Thermal forming · Paint and organic coatings	· Atmosphere Systems · Gas cleaning · Gasification · Pyrolysis · Waste treatment · Incineration · Regenerative chambers

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Thekdi, Arvind, Analysis of DOE-MECS Survey 1994 and GRI-1996 data, personal communications, February 2000.

3 Performance Targets to Achieve by 2020

Process heating represents one of the larger industrial areas requiring energy, particularly for large energy - and emissions-intensive industries. Consequently, the development and application of cost-effective, advanced process heating technologies and processes will make a significant contribution to improving national energy efficiency and reducing emissions of air pollutants, as well as controlling costs and maintaining global competitiveness for U.S. industry.

The process heating industry is exceptionally diverse, as are the industries it serves. To guide the development of this roadmap and ensure a focus on priority needs in the market across the range of process heating applications, the process heating community established industry-wide performance targets (see Exhibit 3.1). These targets are the primary criteria used during equipment selection throughout the industrial sector and are intended to facilitate the achievement of industry-specific targets. In the vision and roadmap documents of each *Industries of the Future* vision industry, performance targets have been established that implicitly or explicitly reflect benefits expected from process heating advancements. By 2020, it is envisioned that advancements in process heating will make significant contributions to achieving the energy and environmental performance targets of the vision industries.

Exhibit 3.1
Industry-wide Process Heating Performance Targets for 2020

Overarching Targets:

- Maximize return on capital
- Increase productivity of processes requiring heat

Specific Targets:

- Decrease total costs (capital and operating)
- Decrease product loss
- Improve energy efficiency
- Improve heat transfer and heat recovery
- Decrease process emissions and environmental impact
- Increase equipment robustness and flexibility
- Create an accident-free workplace

Increasing the cost-effectiveness of process heating is an objective that is inherent in each performance target. *Maximizing return on capital* is an overarching target that includes reducing initial and operating costs, as well as the costs associated with reducing environmental impacts, improving energy efficiency, recovering and/or reusing waste energy and materials, improving safety, reducing the physical size of equipment, and optimizing human resource requirements. *Increasing productivity,* also an overarching target, includes factors such as process speed, equipment reliability (i.e., simplicity, ease-of-maintenance), product-quality repeatability, lowering yield loss, increasing heat-transfer rates, and training/education. Seven additional specific targets—*total cost, product loss, energy efficiency, heat transfer and heat recovery, emissions reduction, equipment robustness and flexibility, and safety*—are called out individually because of the significant contribution process heating advancements can make in these areas. In this roadmap, both priority R&D and non-research goals are identified. These goals will help achieve the 2020 performance targets.

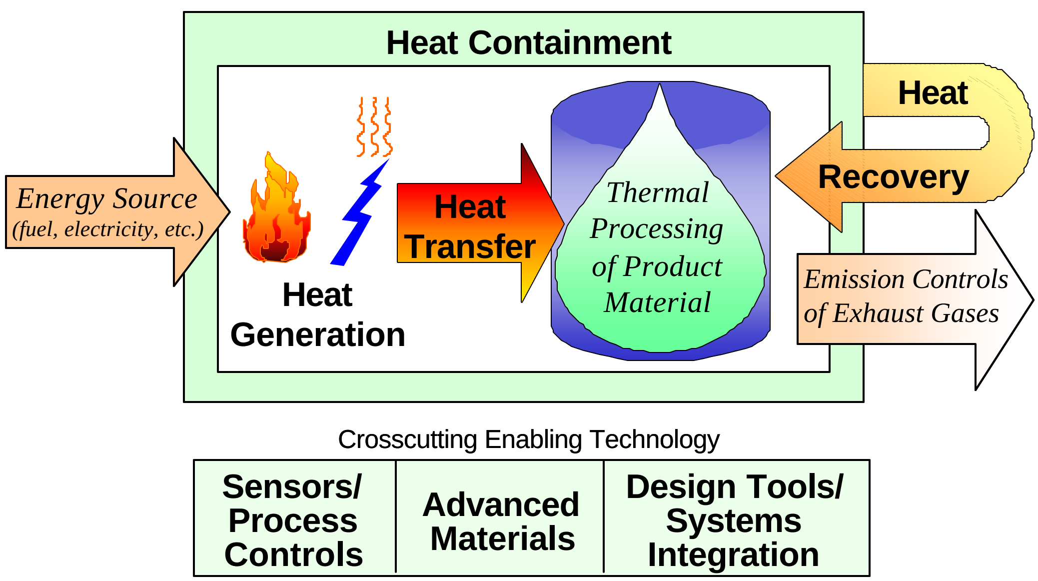
4 Barriers to Improvement

Many technological, regulatory, institutional, and market barriers prevent industrial process heating from achieving the envisioned 2020 performance targets today. In this section, key barriers to research, development, and implementation of advanced process heating technologies and processes are presented. Technological barriers are discussed separately from regulatory, institutional, and market barriers because they present different challenges and require different responses.

Technological Barriers

Industrial process heating is used for the thermal processing of a variety of materials and involves a number of steps. As illustrated in Exhibit 4.1, technological challenges exist in each process-heating step. Some of these steps result in emissions of regulated gases or other substances. Performance of these steps is greatly affected by enabling technologies such as sensors and process controls, advanced materials, and design tools/systems integration. Barriers are presented below for each technological challenge area, with enabling technologies discussed first because of their crosscutting nature. The R&D responses to these barriers are presented in Section 5.

Exhibit 4.1. Technological Challenge Areas in Process Heating



Sensors and Process Controls

Reproducible product quality during thermal processing depends on the ability to effectively measure, monitor, and control process heating operations, thus minimizing product variability. This level of control requires reliable and affordable sensors and control systems that can withstand harsh environments without recalibration for a certain minimum time (on the order of one year). Better, low-cost sensors are needed to monitor important process parameters such as material property uniformity, temperature, heat flux, air/fuel ratio, process atmospheres (oxidizing and reducing), emissions, and shop-floor infiltration, as well as to control burning and detect flames and flame stability. Improved controls and instrumentation are needed to implement appropriate actions based on the information provided by the sensors. Some of the actions include optimizing process air-fuel ratios to reduce emissions, providing intelligent responses to process variability, and providing control actions to meet desired or predicted outcomes.

Key Barriers

- Few direct process measurement sensors
- Few low-cost sensors that are rugged, accurate, non-intrusive, and easy-to-use and maintain
- Excessive failures and inaccuracies of thermocouples and other sensors
- Inability to reliably monitor and control critical product parameters (temperature, chemistry, pressure)
- Inability to reliably control processes
- Lack of smart controls
- Lack of cost-effective flow control devices (e.g., air/fuel ratio control)

Advanced High-Temperature Materials

The ability to increase the efficiency of thermal processing is severely restricted by the availability and cost of high-performance, high-temperature materials. Use of high-performance materials can aid design of compact equipment, reduce energy and emissions, offer lower operating and maintenance costs, and increase productivity. Material property requirements such as high-temperature creep strength, thermal shock, corrosion resistance, pressure resistance, formability, and machineability vary by application area. However, there are a number of requirements common to many industries, including long-lasting coatings, sensors, insulation, and structural materials for handling high-temperature gases and corrosive fluids. Availability of high-performance materials would accelerate the development of innovative process heating equipment.

Key Barriers

- Lack of high-temperature materials that are machineable and formable at reasonable cost
- Lack of high-temperature materials that are creep- and crack-resistant
- Lack of cost-effective, high-performance materials, especially for heating corrosive fluids

- Strength and corrosion of metallic components for structural and sensor protection
- Lack of coatings to operate at higher temperatures

Design Tools and System Integration

System performance is determined by equipment/component designs and system integration both within and across complex process heating operations. Models and other design tools can help achieve process specifications and optimize performance, while integration of the operations within a system can contribute to significant productivity gains. They can also help to reduce yield losses and maintain desired product quality. Process heating equipment manufacturers are continually presented with new challenges from industry, such as making equipment physically smaller while doing the same amount of work, enabling flexibility in processing of materials, increasing production rates, and maintaining greater control over product characteristics. Advances in high-speed computing and communications through the Internet can be applied to develop and provide access to a variety of tools and models for design and integration of process heating systems.

Key Barriers

- No easy-to-use design tools for complex heating applications
- Limited integration of design elements in models and simulation
- Lack of system integration in the areas of process control and heat recovery
- Lack of design tools and integration for optimal performance for ovens, furnaces, and burners
- Lack of techniques for repair and maintenance without shutting down equipment
- Difficulty optimizing process speed and other parameters while maintaining safety
- Increased probability of failure in complex systems
- Insufficient property data and validations for models
- Lack of precise, integrated process-flow control models
- Increasing sophistication of new computer technologies

Heat Generation Systems

In process heating equipment, fuel-fired combustion systems that involve flames or electric heating (i.e., induction and resistance) are used to produce heat. The heat is supplied to the materials being processed. For fuel-fired systems, the challenge is to optimize thermal efficiency, operating costs, and compliance with emission regulations. This optimization depends on factors such as control of fuel-oxidant during all stages of heating, fuel-mix variability, completeness of combustion, and performance of the burner over the range of its operation. With current technology, it is difficult to cost-effectively and simultaneously reduce emissions and increase efficiency. For electrical systems, system performance and cost depend on power losses associated with transmission and distribution, system cooling losses (particularly in induction heating), and reliability of the power supply. More effective heat generation could result in significant cost savings through improved energy efficiency, productivity enhancement, reduced emissions, and a safer workplace.

Key Barriers

- Inability to cost effectively accomplish high-temperature indirect heating
- Inability to prevent fouling which results in higher energy use
- Lack of alternate heating methods for specific processes
- Inability to extend equipment run life while maintaining integrity
- Lack of fundamental understanding of combustion processes (turbulent mixing, soot properties/formation/loading)
- Lack of combustion equipment for low heat-value fuels (e.g., waste fuels)
- Lack of fuel flexibility
- Inadequate air handling technology

Heat Transfer Systems

The heat generated in a furnace or from other process heaters needs to be transferred to the product material at a controlled rate to meet the heating requirements. Heat transfer from such heating systems is often the main cause of non-uniform product temperature. The equipment must deliver the correct heat flux and the process must be capable of accepting the heat without adversely affecting product quality, all while maintaining high production rates. Heat transfer from the heat source (e.g., radiation, convection, conduction, and/or a combination thereof) requires predictable and controllable heat transfer coefficients. Process performance is limited by many factors, including the inability to continuously predict temperature uniformity and thereby control heat transfer within the heating equipment and the load. This is especially relevant for processes that dictate different shapes or complex parts or loads. Advancements in heat-transfer techniques and the designer's ability to reliably predict them under varied operating production requirements would have an enormous impact on process productivity, product loss rates, energy efficiency, and operating costs.

Key Barriers

- Difficulty in achieving uniform heat transfer
- Difficulty in applying high-temperature direct and indirect convection systems
- Difficulty in formulating the heat transfer contribution of combined radiation and convection heating systems
- Difficulty in minimizing volume of heat transfer "box" or footprint relative to maximizing thermal efficiency, minimizing emissions, and optimizing uniform heat transfer

Heat Containment Systems

Controlled heat generation and heat transfer for industrial processes require the use of a "box" that can contain heat, maintain the desired atmosphere, assist in heat transfer, reduce energy losses, and facilitate material handling. Design and maintenance of the box has significant impacts on energy costs, emissions, productivity, product quality, and personnel safety. Proper design, construction, operation, and maintenance are important to industrial process heating efficiency.

Key Barriers

- Lack of resilient high-temperature seals
- Lack of low-density and low-permeability primary insulation products

Heat Recovery Systems

A large percentage of the total energy input to heating systems can be recovered in the form of waste heat. Waste heat is produced in many forms, such as exhaust gases from combustion equipment, cooling water, trays, belts, and fixtures and, in some cases, the heated product itself. Today's methods to collect, recover, and use waste heat often are not economically justifiable. This is especially true for low-temperature or low-grade heat (e.g., hot water or low-temperature flue products). Significant energy cost savings could be realized through advanced heat recovery systems.

Key Barriers

- Inability to economically capture/recover low-temperature heat with existing heat exchanger or heat-storage technology
- Inability to cost-effectively capture very high temperature exhaust heat
- Readily available and comparatively inexpensive supply of natural gas in North America reduces return on investment of recovery systems

Emissions Control Systems

During the last 25 years, combustion generated emissions (i.e., NO_x, CO, particulates) have been a major concern in design and operation of heat processing equipment. Costs related to low-emission equipment or components (burners) and controls for their operation to meet environmental regulations have been a major driver for advancements in combustion systems. However, performance of many systems still needs to be improved significantly. Emissions levels and compliance costs could both be considerably reduced if innovative emissions control technologies were developed for process heating.

Key Barriers

- Difficulty to cost effectively generate ultra-low emissions
- Difficulty to cost effectively reduce emissions and at the same time increase efficiency
- Inability to minimize all pollutants/emissions simultaneously
- Inability to cost effectively and simply filter nitrogen from ambient air for combustion systems
- Lack of low-cost, reliable multi-element sensors and analyzers for combustion and process emissions

Auxiliary Inputs

Optimal product quality and heating system performance may be determined by the process atmosphere (i.e., mix of gases) used during thermal processing in several critical operations. These protective or process-enhancing atmospheres are either generated on-site or are obtained by using a mixture of stored gases (e.g., N_2, H_2, CO_2, NH_3). Equipment and methods for using atmospheres have a significant effect on productivity and operating cost. Use of relatively pure oxygen for combustion is also becoming more common. Cost reductions in the production, storage, mixing, and control of these gases will increase efficiency, reduce emissions, and, in some cases, improve productivity and product quality.

Key Barriers

- Lack of low-cost oxygen to improve thermal efficiency of combustion equipment
- Lack of inexpensive separation of hydrogen from water
- Inconsistent and insufficient supplies of utilities and consumables

Institutional, Regulatory, and Market Barriers

Institutional, regulatory and market barriers significantly impact process heating economics and performance. These barriers address a diverse range of issues, including encouragement of R&D investment, optimization of operations and maintenance, safety, workforce availability, access to information for optimal decision-making, costs and approaches to regulatory compliance, and equipment test methods.

Priority institutional, regulatory, and market barriers are presented below. These types of barriers are addressed by both technical and non-technical activities that are not considered research. Priority non-research goals (and activities) needed to respond to these barriers are presented in Section 6. Successful activities to overcome these barriers will impact the ability of the process heating community to meet its technical challenges and promote the purchase and effective use of advanced technology.

Industry's Priorities for Process Heating

The development of this roadmap is the initial step in identifying industry's needs and how advancements in process heating can meet these needs. The priorities of this roadmap will need to be assessed by the end-users, yet these end-user industries have a diverse range of process heating needs. The process heating community will need to formulate an implementation strategy based on end-user input and the priorities identified in this roadmap. How the process heating community will be organized to achieve the goals will need to be determined. Activities to achieve the goals will involve the organization and participation of process heating equipment manufacturers, end-user industries, National Laboratories, trade associations, policy-makers, and other groups.

Key Barriers

- Diverse range of applications using process heat throughout industry
- Lack of view of the industry as a whole (combustion and electric)
- Lack of well recognized organizing body to oversee the implementation of the roadmap goals
- Lack of a process heating perspective in federal policies

Consistent and Rational Policies

Complying with emissions and other regulations poses significant costs and operational challenges to end users. Today, policies are set at the state and national level without coordination or sufficient consideration of how companies will be impacted. As a result, process heating equipment manufacturers must produce products for a segmented market. End users must consider divergent compliance requirements, which impact operational efficiency and project costs. More rational and consistent policies will reduce costs and in turn, reduce energy consumption and emissions.

Key Barriers

- Uncertainty and inconsistency of environmental regulations (state and Federal) and lack of systems approach to environmental policies
- Compliance, measurement, and reporting requirements for NO_x emissions are diverse and not well-understood by those end users that do not have the benefit of an in-house environmental department.
- Government regulations create disincentives that discourage use of new equipment or the most beneficial process heating system
- Lack of communication and coordination among government agencies
- Lack of end-user input to the regulatory process

Voluntary Conventions/Practices for Equipment Manufacturers

Many process heating systems are complex and custom engineered to end-user specifications. Individual equipment manufacturers employ practices, conventions, and technology to help differentiate their products. In select areas of the process heating trade, establishing industry-wide conventions could be beneficial but only if they do not create another layer of compliance costs. For example, conventions for safety controls could reduce the costs of meeting safety requirements and raise the knowledge level of the workforce that operates equipment safely. Other conventions/practices that could be beneficial include measurement standards, design norms, modeling or testing methods, and impact assessment methods. If these conventions could be developed without being intrusive and posing additional costs, they would assist end-users in expanding and/or replacing heat-processing facilities, thereby improving safety and encouraging cleaner and more efficient operations.

Key Barriers

- Lack of uniform standards and safety codes
- Lack of availability of unbiased evaluation of heat processes
- Numerous design, measurement, and quality standards (e.g., individual country standards such as UL, CE, and CSA, English versus metric)

Use of Existing Advanced Process Heating Technology

Advanced process heating technology exists today that could significantly improve industrial process heat applications. However, the successful introduction of new technology is impeded by high capital costs, competing corporate priorities, lack of knowledge, and other factors which need to be addressed to realize the benefits of advanced process heating technology.

Key Barriers

- Lack of focus on process heating as a priority until it is a problem
- Lack of end-user awareness on how to implement new technologies
- Lack of end-user knowledge of available technology applications
- Lack of sufficient new technology demonstration and case studies
- Lack of long-term end-user strategies to streamline processes
- Lack of adequate or effective implementation of process controls (due to costs or not understanding value)
- Lack of periodic preventive maintenance scheduling
- Customer resistance to accept new, unproven technology that could benefit or jeopardize processes
- Fear, uncertainty, and economic risk to project budgets
- Corporate culture tradition of commitment to older, proven technology
- High cost and/or long life of some technology, which limits the introduction of new, replacement technology
- Lack of market demand for efficient, low-emission equipment due to higher capital and operating costs
- Readily available and comparatively inexpensive supply of natural gas in North America decreases the return on investment of advanced combustion systems
- Lack of incentives for by-product and by-process recovery and reuse
- Relative magnitude of energy expenditures compared to operating costs

Technology R&D

To meet industry's process heating needs, the cost-effectiveness and technical performance of the technology must improve. Overcoming the technical challenges will require significant R&D achievements. However, R&D investment is limited by many economic, financial and institutional factors. The non-technical barriers need to be addressed to bolster technology advancement.

Key Barriers

- Relatively high return on investment and short payback expectations
- Slim margins in commodity markets inhibit investment in technology development
- Small companies lack resources and information
- Competition due to foreign government subsidies
- Lack of R&D tax credits for equipment manufacturers and end users
- Lack of incentives for collaborative efforts
- Lack of research funding
- Difficulty meeting 50 percent cost share requirement for R&D, especially for small companies
- High costs of prosecuting and defending new technology patents for small companies

Workforce Development

The supply of adequately trained engineering and plant operations staff is currently insufficient to meet the demand, and is projected to worsen. This impacts the cost of labor, both in process heating equipment manufacturing and in end-use operations. In addition, effective use of technology in industrial applications depends upon the skills of plant staff. A workforce with appropriate skills and in adequate supply is needed to ensure process heat performance and cost-effectiveness.

Key Barriers

- Inadequate hands-on training and facilities for operating and maintenance staff
- High training costs or insufficient training resulting from unique company needs
- Insufficient process heating curriculum at universities
- Lack of funds for fellowships and internships for graduate students
- Lack of sufficient technical talent at many levels within the industry to meet challenges

Public Education

The general public needs to have an accurate understanding of impacts of process heating, especially on the environment. The establishment of rational public policies is more likely if the general public understands the operation and importance of process heat. Policy makers must understand the technical feasibility and the costs of compliance. In addition, the public needs to understand that advanced process heating technology can significantly improve the efficiency of industrial operations and minimize environmental impacts.

Key Barriers

- Perception that anything "industrial" is harmful/dirty
- Media ignorance regarding emissions and waste
- Lack of respect for the complexity and maintenance of technically advanced equipment
- Lack of understanding of efficiency limitations due to the second law of thermodynamics

5 Priority Research and Development Goals

The priority research and development areas and goals to overcome major barriers to improving process heating performance are shown in Exhibit 5.1. R&D needs exist in each step of process heating (i.e., heat generation, heat transfer, heat containment, heat recovery), emissions controls, and auxiliary inputs, as well as in three enabling technologies used in all process heating applications: sensors and process controls, advanced materials, and design tools/systems integration (see Exhibit 4.1). The R&D goals are categorized as top-, high-, and medium-priority. The goals are aligned by time frame when useful results can be expected. It is assumed that the R&D will begin within the next year, and arrows show the main relationships between priorities. The process heating performance targets (addressed in Section 3) that will be significantly impacted by the R&D are listed in each area.

The R&D goals represent a comprehensive portfolio of innovations that can help meet the needs of end users and equipment/component suppliers. Although the R&D areas are not presented in any specific order of importance, the R&D areas for the enabling technologies are presented first because of the anticipated impact on industry-wide applications. The high-priority goals, considered the most critical to achieving the targets for 2020, are discussed below.

> ***Advanced sensors that measure multiple emissions.*** Systems are needed that can measure, control and monitor emissions of a number of species (i.e., gaseous and solid) to facilitate ease of installation, operation, and maintenance. The emissions originate from several sources: the combustion system, the process operation, and the product being heated. As a result, more than one sensor is often required. The system and sensors must meet the requirements for accuracy and sustainability for an acceptable time period (e.g., between the maintenance and replacement of the sensors and associated components).
>
> ***Improve performance of high-temperature materials including alloy composites.*** High-temperature materials are used in numerous critical areas within process heating, as well as in the support and transportation of the products being processed. Affordable, advanced materials (metallic, ceramic, or composites) with improved high-temperature properties are needed by process heating equipment suppliers and users. Although some material performance has modestly improved, the lack of economical application has prevented widespread use. Development and availability of cost-effective materials will improve productivity, reduce equipment size, lower energy use per unit of production, improve product quality, increase safety, and reduce costs associated with repairs and maintenance.

Exhibit 5.1 Priority R&D Goals

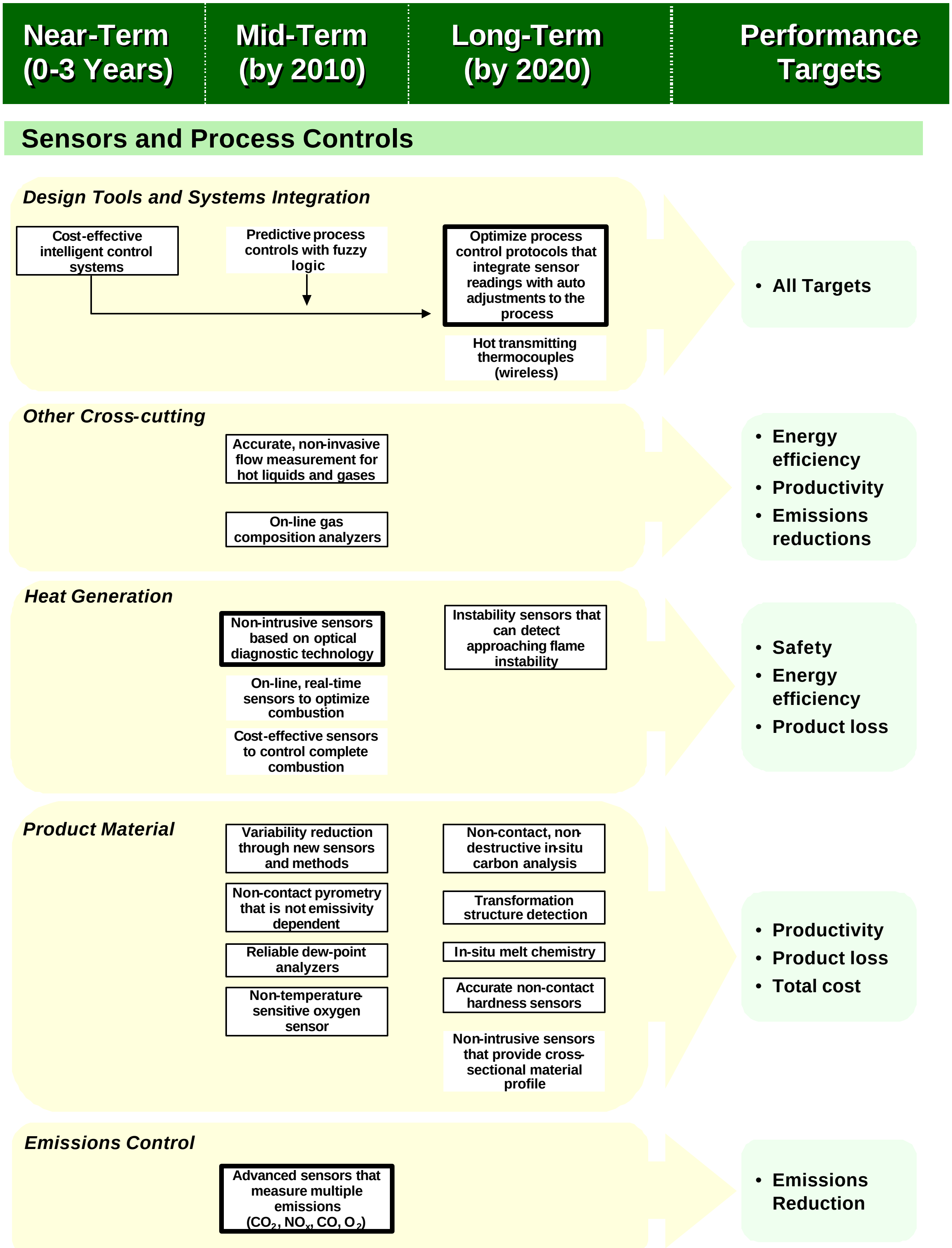


Exhibit 5.1 Priority R&D Goals *(continued)*

Near-Term (0-3 Years)	Mid-Term (by 2010)	Long-Term (by 2020)	Performance Targets

Improved High-Temperature Materials

- "Real world" testing of available materials (Medium) → Universal materials properties database (Medium)
- → Improve performance of high-temperature materials including alloy composites (Top)
- → Improved, cost-effective materials for heat recovery (High)
- → Materials with better aging properties and lower maintenance (Medium)
- → Improve refractory corrosion resistance (Medium)
- Composite materials with enhanced properties compared to existing material (for burners, tubes, sensors, etc.) (High)

Performance Targets:

- Energy efficiency
- Return on capital
- Robustness
- Productivity

Design Tools and Systems Integration

- Predictive models of heat process system (Top)
- Better material property data for design (High)
- Models for heat recovery equipment/ systems (High)
- Computational fluid dynamics models with experimental data to optimize combustion system integration (Medium)
- → Improve system integration from total process perspective (Medium) → Improve processing time with new technology and process improvements (Medium)
- → Understand variables and interactions and develop intelligent process (Medium)
- → Optimize furnace design, size, and shape for work piece (Medium)

Performance Targets:

- All targets

Priority:
Top | High | Medium

Exhibit 5.1 Priority R&D Goals *(continued)*

Near-Term (0-3 Years)	Mid-Term (by 2010)	Long-Term (by 2020)	Performance Targets

Heat Generation Systems

Near-Term (0-3 Years):
- Improved understanding of combustion process
- Apply oxy-firing technology to other industries
- Better ultra-low NO_x burners
- Temperature-flexible burner

Mid-Term (by 2010):
- Smart burners that adjust heat release profile
- Improve methods for stabilizing low-emission flames
- Combustion technologies that simultaneously reduce emission, increase efficiency, and increase heat transfer
- More efficient radiant heater with uniform surface temperature
- Improve submerged combustion in molten bath

Long-Term (by 2020):
- Heavy oil burner with gas emissions profile
- Develop the next generation of heating methods
- Hybrid gas/electric heating systems

Performance Targets:
- Energy efficiency
- Emissions reduction
- Productivity

Heat Transfer Systems

Near-Term (0-3 Years):
- Efficient air handling systems
- Minimize air volume of convection ovens
- Low-cost additives or devices to eliminate fouling

Mid-Term (by 2010):
- Enhance heat transfer (e.g., coefficients)
- Fluid heater that achieves uniform heat flux
- Rapid heating technology

Long-Term (by 2020):
- Rapid melting technology

Performance Targets:
- Energy efficiency
- Productivity
- Product loss
- Total cost

Heat Containment

Mid-Term (by 2010):
- Improve seal materials and seal designs
- Low-density, low-permeability insulation

Long-Term (by 2020):
- Improve cooling technology to avoid water use/cooling

Performance Targets:
- Energy efficiency
- Total cost

Exhibit 5.1 Priority R&D Goals *(continued)*

Near-Term (0-3 Years)	Mid-Term (by 2010)	Long-Term (by 2020)	Performance Targets

Heat Recovery Systems

- Low-cost, low-temperature heat recovery (Top priority)
- Low-cost designs and manufacturing methods for combustion air preheaters (Medium priority)
- Low-cost, compact heat exchangers (Medium priority)
- High-temperature cascading heat pump to recover all energy (Medium priority)

Performance Targets:
- Energy efficiency
- Return on capital

Emissions Control

- Reduce the capital and operating cost of environmental equipment (High priority)
- Cost-effective and compact emission scrubbers and catalytic converters for industry (High priority)
- Advanced incineration, pyrolysis, and/or gasification technologies for byproduct reuse (e.g., solid waste) (High priority)
- Cost-effective N_2 filter for combustion air and fuel (High priority)

Performance Targets:
- Emissions reduction
- Total cost

Auxiliary Inputs

- Generate low-cost process atmospheres (N_2 and H_2) and oxidants (O_2) especially near point-of-use (High priority)

Performance Targets:
- Total cost
- Energy efficiency
- Product loss

Priority:
Top High Medium

Predictive model of the process heating system. Integrated and comprehensive predictive models are needed that allow end users to produce quality products with near-zero defects and with minimum energy consumption and emissions. These advanced models must include the effects of all relevant factors associated with the necessary products and processes to allow equipment suppliers and end users to optimize process performance. Such models should consider characteristics of the incoming material, the end user's requirements (i.e., production, physical, or other properties), surface characteristics for the final product, energy and emission optimization, and allow automatic adjustments of the equipment operating parameters. The models should be simple to use and adaptable for different processes with appropriate corrections for meeting specific requirements.

Heavy oil burner with gas emissions profile. Use of oil as a fuel has decreased during the last two decades. However, fuel oil, particularly heavy fuel oil, could offer an economic alternative energy source for some applications and provide a fuel flexibility advantage. Major impediments to heavy oil use in process heating include difficulty in handling, emissions of regulated gases and particulates, and possible contamination of the product being processed. The technical challenges include developing an easy-to-use fuel oil handling system, cleaning the fuel prior to or during combustion to reduce or eliminate contaminants and associated emissions, and developing burner equipment that meets the energy demand profile of the processes at acceptable efficiency.

Improve methods for stabilizing low-emission flames. A new generation of combustion equipment has been developed that can help process heating users meet regulatory requirements for NO_x, VOCs, and particulate emissions. However, many developers and users have experienced limitations in the operating ranges of the burner equipment, including flame stability, sooting and cogeneration, and combustion-generated noise. Innovative approaches to develop process heating equipment (including burners) are needed that address operating performance requirements while maintaining high efficiency and meeting emissions regulations.

Combustion technologies that simultaneously reduce emissions, increase efficiency, and increase heat transfer. Industry needs compact and efficient process heating equipment that offers high thermal efficiency, lower emissions, and reduced heating time. In most equipment designs, heat transfer from the energy source (e.g., flame, heating elements) is a rate-controlling step, which has a major effect on the size of the equipment. Innovations are needed to integrate efficient heat generation, high heat-transfer rates, and efficient use of energy while meeting emissions requirements. Recent trends toward the use of flame and its manipulation as a means of enhancing heat transfer, the use of pure oxygen as an oxidant, and the use of cogeneration are a few examples of related advancements. Efforts are needed to investigate, develop, and implement these and additional designs and hardware to achieve the required results.

Low-cost, low-temperature heat recovery. A large amount of energy, mostly in the form of medium- to low-temperature gases or low-temperature liquids, is released from process heating equipment. Much of the time, this energy is wasted. In some cases, it is even necessary to use additional energy to process the waste gases or liquids prior to their discharge into the atmosphere. Process schemes, system designs, and equipment are needed that will reduce the discharge of such waste streams or allow economic recovery/re-use of the energy.

Successful activities to address the priority R&D goals are expected to have significant impact throughout industry over the next 20 years. Exhibit 5.2. highlights some of the industries that will be impacted by investments in top- and high-priority R&D. The anticipated improvements and innovations will increase industrial productivity and energy efficiency.

Exhibit 5.2 Top and High Priority R&D Goals and the Industries Impacted

Top and High Priority R&D Goals	Industries Impacted									
	Primary Steel	Heat Treating	Forging	Metal Casting	Aluminum	Pulp and Paper	Glass	Petroleum	Chemical	Food Products
SENSORS AND PROCESS CONTROLS										
Optimize process control protocols that integrate sensor readings with auto adjustments to the process	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cost-effective intelligent control systems	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Accurate, non-invasive flow measurement for hot liquids and gases	✓	✓		✓	✓		✓	✓		
On-line gas composition analyzers	✓	✓	✓	✓	✓		✓	✓	✓	
Non-intrusive sensors based on optical diagnostic technology	✓	✓	✓	✓	✓		✓	✓	✓	✓
Instability sensors that can detect approaching flame instability	✓	✓	✓	✓	✓		✓	✓	✓	✓
Variability reduction through new sensors and methods	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Non-contact pyrometry that is not emissivity dependent	✓	✓	✓	✓	✓			✓	✓	
Reliable dew point analyzers		✓			✓		✓			
Non-temperature-sensitive oxygen sensor	✓	✓		✓	✓			✓		
Non-contract, non-destructive in-situ carbon analysis	✓	✓								
Transformation structure detection	✓	✓	✓							
In-situ melt chemistry	✓		✓	✓						
Advanced sensors that measure multiple emissions	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Accurate non-contact hardness sensors	✓	✓	✓	✓	✓					
IMPROVED HIGH-TEMPERATURE MATERIALS										
Improve performance of high-temperature materials including alloy composites	✓	✓	✓	✓	✓			✓	✓	
Improved, cost-effective materials for heat recovery	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Composite materials with enhanced properties compared to existing material	✓	✓	✓	✓	✓		✓	✓	✓	
DESIGN TOOLS AND SYSTEMS INTEGRATION										
Predictive models of heat process system	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Better material property data for design	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Models for heat recovery equipment/systems	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Top and High Priority R&D Goals	Industries Impacted									
	Primary Steel	Heat Treating	Forging	Metal Casting	Aluminum	Pulp and Paper	Glass	Petroleum	Chemical	Food Products
HEAT GENERATION SYSTEMS										
Improve methods for stabilizing low emission flames	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Combustion technologies that simultaneously reduce emissions, increase efficiency and increase heat transfer	✓	✓	✓	✓	✓		✓	✓		
Heavy oil burner with gas emissions profile	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Better ultra-low NO_x burners	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Smart burners that adjust heat release profile	✓	✓	✓	✓	✓		✓	✓		
Develop the next generation of heating methods										
Hybrid gas/electric heating systems										
HEAT TRANSFER SYSTEMS										
Minimize air volume of convection ovens		✓		✓	✓	✓		✓	✓	
Enhance heat transfer (e.g., coefficients)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
HEAT RECOVERY SYSTEMS										
Low-cost, low-temperature heat recovery	✓	✓			✓	✓		✓	✓	✓
EMISSIONS CONTROLS										
Reduce the capital and operating cost of environmental equipment	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cost-effective and compact emission scrubbers and catalytic converters for industry	✓		✓	✓	✓		✓	✓		
Advanced incineration, pyrolysis, and/or gasification technologies for by product reuse (e.g., solid waste)						✓		✓	✓	✓
Cost-effective N_2 filter for combustion air and fuel	✓	✓	✓	✓	✓		✓	✓		
AUXILLIARY INPUTS/SERVICES										
Generate low-cost process atmospheres and oxidants	✓	✓	✓		✓		✓	✓	✓	
HEAT CONTAINMENT										
Improve cooling technology to avoid water use/cooling	✓	✓	✓	✓	✓		✓	✓		✓

6 Priority Near-Term Non-Research Goals

The near-term, non-research goals needed to overcome the institutional, regulatory, and market barriers are shown in Exhibit 6.1. The priority activities needed to achieve each goal are listed in Exhibit 6.2. Individual activities are categorized as top-, high-, and medium-priority but the goals themselves are not prioritized per se. The time frame indicates when useful achievements and/or results could be expected, assuming that the activities begin within the next year. These activities could be completed within the next five years, although sustained follow-on efforts will be necessary in some cases. The performer of each activity will be identified during the implementation phase of this roadmap. Achievement of the goals is expected to have a significant impact on process heating throughout industry in the near term and will contribute collectively to achieving the performance targets by 2020.

The non-research goals and activities represent a comprehensive portfolio that can help meet the needs of end users and overcome barriers presented in Section 4. The high-priority activities, considered the most critical to achieving the targets for 2020, are discussed below.

Exhibit 6.1 Goals for Near-Term Non-Research

- Establish R&D and non-research priorities based on end-user input
- Promote rational and consistent policies
- Develop voluntary conventions/practices for equipment manufacturers
- Educate end-users
- Develop incentives for new technology purchases
- Expand the number of applications using advanced technology
- Develop R&D incentives for equipment manufacturers and end users
- Foster the use of advanced enabling technology (i.e., technologies used to make improvements possible) in new process heating equipment
- Develop the workforce
- Educate the public

Exhibit 6.2 Priority Near-Term Non-Research Goals and Activities

Near-Term Non-Research Activities	Goal and Timeframe
Assess end-user interest in innovative R&D ideas Collaborative industry teams to help achieve Roadmap goals (e.g., incorporate electric process heat, provide grassroots support, lobbying) Benchmarks to determine baselines and priorities Rule-making advisory group (end users, manufacturers, and legislators) to coordinate with EPA and other federal agencies	2001 2003 2005 ***Establish R&D and non-research priorities based on end-user input***
Consistent measuring and reporting of NO_x International harmonization of emission standards Environmental regulations that encourage "systems" approach & innovative technology solutions Nation-wide permitting guide for emissions EPA-endorsed expert system that provides how-to-steps and models impacts of specific applications Product liability and torte reform	2001 2003 2005 ***Promote consistent and rational policies***
Voluntary standards for fail-safe controls especially when system controls are by-passed Equipment test protocols to develop a common basis of comparison – "consumer report" Voluntary uniform national equipment safety standards and enforcement Technology information tools to measure effects of retrofits Promote move to metric	2001 2003 2005 ***Develop voluntary conventions/practices for equipment manufacturers***
Interactive Internet site to promote awareness of training, analysis tools, case studies, demonstrations, and available technology Showcase demonstrations and case studies Equipment supplier "yellow pages" for end users Educate end users on the need for training Encourage operators to participate in plant improvement	2001 2003 2005 ***Educate end users***
Financial incentives to install state-of-the-art equipment (e.g., investment tax credit for heat recovery) Communicate benefits of new technology to end users	2001 2003 2005 ***Develop incentives for new technology purchases***
Apply process heating technology to new industry applications Promote use of energy-flexible back-up for critical electrical processes	2001 2003 2005 ***Expand the number of applications using advanced technology***

Exhibit 6.2 Priority Near-Term Non-Research Goals and Activities *(continued)*

Near-Term Non-Research Activities	Goal and Timeframe
R&D tax credits for equipment manufacturers and end users; Partnerships to ease risk of trying new technology; Sliding-scale cost-share requirement based on stage of technology development and company size	2001 2003 2005 — ***Develop R&D incentives for equipment manufacturers and end users***
Promote demonstrations of new technologies; Encourage technology transfer to small manufacturers; Assess material needs and university/ laboratory approaches; **Sensors:** Performance and cost benchmarks for available sensors; Sensor forum to develop roadmap with end-users, manufacturers and National Laboratories; **Materials:** Materials forum to provide guidance/set targets for application development; Promote the use of Federal material centers for material development and testing; Promote use of emerging material technology	2001 2003 2005 — ***Foster the use of advanced enabling technology[1] in new equipment***
Up-to-date hands-on training workshops for operating and maintenance staff; Technical education for elementary and high school (with local industry partners) to develop manpower for today's industries; Process heating engineering curriculum at recognized universities; Funding for graduate student fellowships and internships; Training labs around country with links to internships/ fellowships	2001 2003 2005 — ***Develop the workforce***
Public relations activities to educate media on industry and environmental issues	2001 2003 2005 — ***Educate the public***

Priority: Top High Medium

[1] Innovations and technologies used to make improvements possible

Consistent measuring and reporting of NO_x. NO_x emissions are a byproduct of combustion and the fuels and oxidants used for combustion. Process heating equipment is one of the major contributors of industrial NO_x emissions. The equipment and component suppliers are developing methods to reduce NO_x emissions to meet applicable regulations. Currently, NO_x measurement and reporting requirements vary by region, state, and country. Equipment must be tested and modeled to meet the requirements of various heat processes and the specific locations of operation. Some heating processes are not conducive to utilizing the most advanced low-emission combustion systems; therefore, post-combustion reactors or scrubbers must be employed, at significant capital costs, to meet emission requirements. Prioritizing processes most suitable to cost-efficient emission reduction and then establishing consistent emission measuring and reporting procedures would reduce the cost of customizing and testing the equipment, as well as increase the accuracy of reporting data. The process heating community will need to work with organizations and agencies to develop consistent measuring and reporting methods and ultimately provide guidance for the best application of emission reducing technologies.

Voluntary standards for fail-safe controls especially when system controls are by-passed. Most process heating systems have controls and safety interlocks that prevent operation in unsafe zones. In some instances these controls may be by-passed by the operator or repair and maintenance personnel. In addition, different standards exist in various countries relative to approved safety devices and fail-safe control schemes. This disparity can result in accidents and damage to property and personnel. Uniform fail-safe controls and procedures must be adopted and promoted to ensure that systems will not be operated under unsafe conditions.

Interactive Internet site to promote awareness of training, analysis tools, case studies, demonstrations, and technology availability. Information related to different aspects of process heating is currently dispersed and hard to find or use. A dedicated Internet site would serve the needs of all stakeholders, end users, equipment suppliers, and developers of supporting technologies by functioning as an organizing informational resource for the process heating community. As part of this roadmapping effort, new training tools and case studies will be developed and posted to this site for easy access and use. The proposed Internet site will be a "one-stop" resource that provides the latest information on new development tools, case histories, and best practices collected from various sources to help each industry achieve its goals. The site needs to be interactive to allow information exchange and be maintained to provide up-to-date information.

R&D tax credits for equipment manufacturers and end users. Although R&D efforts are necessary to ensure U.S. industrial competitiveness, they are also high-risk endeavors. High rates of return required in today's business environment prohibit or severely reduce the levels of investment in R&D. Most companies supplying process heating equipment are relatively small and have limited resources for allocation to R&D efforts. In the United States, private expenditure for R&D in process heating area is low, in most cases less than one percent of revenue. Tax credits for R&D investments would provide a significant incentive for investing in the advancement of process heating. Ensuring the development of effective tax credit legislation will require a strategic effort by both the process heating and manufacturing community.

Partnerships to ease the risk of implementing new technology. The risks and start-up costs associated with the use of new technology are significant barriers to investment, both in the use of new enabling technologies used to improve process heating equipment and in the purchase of new equipment by end users. Facilitating the development of partnerships could significantly impact the transfer of technology and sharing of risks. New partnerships can draw from the lessons learned from previous partnership arrangements and agreements. To foster partnerships for process heating, information and resources can be made available to process heating equipment manufacturers and end users.

Promote new technology demonstrations. Process heating equipment is one of the most critical systems in a manufacturing plant; any disruption in its operation can result in the shutdown of a process line, often with significant losses. End users are cautious and, in many cases, reluctant to experiment with the new, unproven systems. The challenge associated with demonstrations is selecting priority technologies to demonstrate and identifying end users willing to share their experience and operation with the public. Another difficulty is finding test sites to provide data that can be used to project the impact of a given technology in other application areas. To demonstrate the value of the new technology, a systematic approach for cost- and risk-sharing must be developed for field demonstrations so that performance, reliability, process disruptions, and other factors can be documented.

Performance and cost benchmarks for available sensors. Many sensors for specialized processes used by industry are available commercially, but standards for performance, testing protocols, and measurement and reporting of the results do not exist. As a result, it is difficult for equipment suppliers and end users to compare and promote effective use of the sensors. Voluntary performance standards and benchmarks are needed to facilitate the selection of sensors and to get the maximum benefit from their capabilities. Sensor suppliers, equipment suppliers, and end users will need to identify industry-specific requirements and work together to develop performance standards.

Sensor forum to develop a roadmap with end users, manufacturers, and National Laboratories. Cost-effective, reliable sensors are needed throughout process heating operations to meet needs in a diverse range of applications. A separate forum on sensors is needed to assess the challenges and requirements of sensor technology in each industry, identify areas of overlapping need as well as unique needs, and develop a strategy and plan for a focused research effort.

Materials forum to provide guidance and set targets for application development. Cost-effective materials development is an essential link to increasing the performance and productivity of process heating. A materials forum is needed to develop material specifications for industry-specific applications, identify existing candidate materials at the National Laboratories, and identify research areas that will have the most impact on energy efficiency and improved productivity. A separate research plan will be developed to implement a targeted research effort.

Up-to-date, hands-on training workshops for operating and maintenance staff. Significant efficiency savings can be realized from efficient and effective operation of existing process heating equipment. To optimize equipment performance, up-to-date training for staff is needed that includes general information relating to energy efficiency, emissions, control, and safety – all the factors that affect operation and maintenance of equipment. Training should also include information on specific equipment used by major industries. All available training options and tools will be considered, ranging from classroom and hands-on training to web-based training. Joint efforts involving end users, equipment suppliers, major component suppliers, and training specialists will be required to accomplish this goal.

7 Next Steps for Roadmap Implementation

Implementing the Roadmap

This roadmap sets forth the priority goals and direction for how the process heating community will provide end users the equipment they need over the next 20 years. The process heating community will use this roadmap as a foundation for pursuing collaborative projects to achieve the priority goals, which can be accomplished both by focused research and development (R&D) and non-research activities. In the months ahead, a detailed strategy for implementing this roadmap will be established.

Major improvements in process heating are feasible but achieving them will require the participation of the diverse range of stakeholders. These stakeholders include:

- End-users who purchase, operate, repair, and maintain process heating systems
- Equipment and component designers and suppliers
- Process and system engineering designers and consultants
- Energy suppliers
- R&D/technology development community
  - End-user R&D centers
  - Universities
  - Research institutions
  - National Laboratories
  - Government research programs
- Trade associations
- Other government programs
- Other contributors

Special efforts will be made to link the pursuit of these roadmap goals with the research programs of the DOE Office of Industrial Technologies (OIT). As a cosponsor of this roadmapping effort, OIT recognizes the importance of process heating to U.S. industrial productivity and energy efficiency. Large energy-intensive industries that use process heating in numerous applications participate in OIT's *Industries of the Future* (IOF) strategy—a strategy that ensures that Federal R&D and other resources are aligned with industry priorities. Advancements in process heating, as outlined in this roadmap, could significantly impact the achievement of targets for 2020 set by IOF vision industries for energy efficiency and environmental improvements. IOF vision industries and supporting processes that use process heating are listed in Exhibit 7.1, while the IOF enabling technology research areas important to process heating advancements are shown in Exhibit 7.2. The process heating community, however, is committed to meeting the process heating needs of all U.S. industries, not only those addressed in the IOF strategy.

Exhibit 7.1
IOF Vision Industries and Supporting Processes[1]

Vision Industries:
- Agriculture
- Aluminum
- Chemicals
- Forest products
- Glass
- Metalcasting
- Mining
- Petroleum
- Steel

Supporting Processes:
- Welding
- Forging
- Heat Treating
- Powder Metallurgy

Exhibit 7.2
IOF Enabling Technology Areas

- Advanced Industrial Materials
- Combustion[2]
- Sensors and Controls
- Continuous Fiber Ceramic Composites
- Combined Heat and Power

[1] Roadmaps are available at www.oit.doe.gov

[2] The *Industrial Combustion Roadmap* identifies important priorities for furnace controls and burner research.

Opportunities for Process Heating with DOE-OIT Industries of the Future

Opportunities for process heating advancement through the IOF strategy exist in two areas: R&D activities in collaboration with companies in major industries that can be achieved over a period of 5 to 20 years; and non-R&D activities that can begin to achieve results in 3 to 5 years and contribute to industry's near-term goals.

DOE-OIT supports R&D activities through the major energy-consuming industries to help them achieve their vision and roadmap goals. The process heating community is encouraged to initiate collaborative R&D efforts with companies from IOF industries in pursuit of mutual priority goals.
To identify opportunities for collaboration:

1. Review the IOF industry roadmaps. They are available from the DOE-OIT web site www.oit.doe.gov or through the DOE-OIT Resources Center at 202-586-2090.
2. Identify goals with direct impact and benefit to the respective industry that can be addressed through advancements in process heating.
3. Contact one or more organizations associated with the particular industry of interest and form a collaborative partnership.
4. Respond to DOE-OIT solicitations that are targeted for industry-specific priorities. These solicitations are available at www.oit.doe.gov.

In addition to industry-specific R&D, DOE-OIT funds R&D in enabling technology areas with broad industry applications such as sensors and controls and advanced materials. These solicitations are available at www.oit.doe.gov.

DOE-OIT supports non-R&D activities through the IOF BestPractices effort. Information on IOF BestPractices is available at www.oit.doe.gov/bestpractices. A Process Heating Advisory Committee has been established to guide DOE-OIT process heating activities. This Committee includes representation from process heating equipment and component suppliers and from process heating-intensive IOF industries.

Measuring Progress Toward Achieving Process Heating Goals

Progress toward achieving the goals identified in this roadmap must be measured over time so achievements can be monitored. Seven preliminary metrics to measure performance are identified in Exhibit 7.3 along with definitions and potential performance improvements that were identified by stakeholders. These metrics can be drawn upon when developing project-specific performance measures.

Exhibit 7.3 Preliminary Metrics to Measure Performance and Potential for Improvement

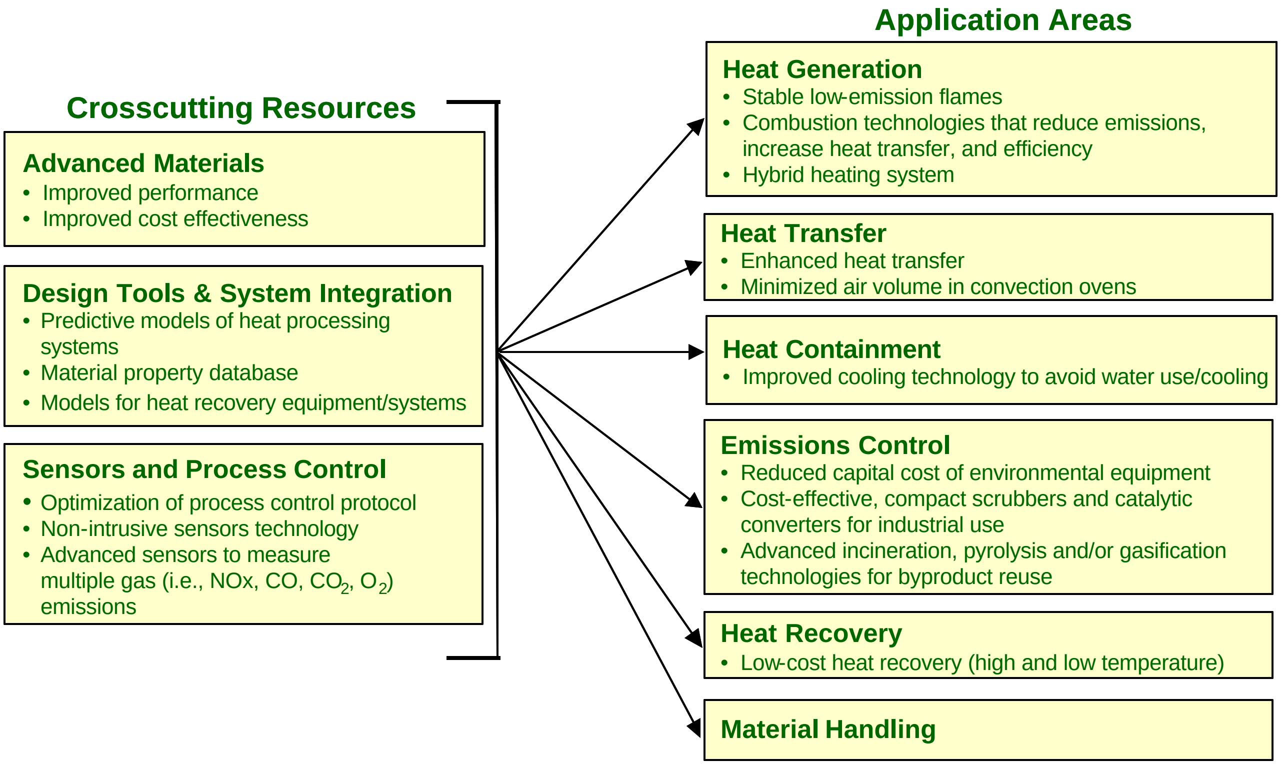
Performance Measure	Proposed Definition	Potential Performance Improvements
Productivity Gain	Increase in yield/reduction or elimination of scrap or reject product	5% to 25%
Quality	Improvement in quality as measured by using standard quality process measurement	Up to 90% reduction in rejects or post processing
Safety	Recorded incidents that affect personnel, property, and production	Up to 90% reduction in safety violations related to process heating system
Emission Reduction	Reduction in solid, liquid, and gaseous waste generated and discharged from the process	15% to 100%
Energy Savings	Savings in use of primary energy per unit of production	25% to 60%
Capital Cost*	Reduction in capital cost per unit of production or other defined measurable parameter	Continuous with above gains
Operating (O&M) Cost*	Total cost per unit of production	Continuous with above gains

* These measures are associated with the first five measures.

R&D Implementation Approach

To develop an approach for implementing the R&D goals identified in Exhibit 5.2, the Top and High priority R&D goals have been grouped into two topic areas: Application Areas and Crosscutting Resources (see Exhibit 7.4). The Application Areas are the six major components and processes used in any process heating equipment: heat generation, heat transfer, heat containment, heat recovery, emission reduction, and material handling. Crosscutting Resources includes Top and High priority activities related to the development of advanced materials, sensors and controls, and models and tools. R&D in Crosscutting Resources can improve the performance of the components and processes in the Application Areas. The nine sub areas listed in Exhibit 7.4 can be used to focus R&D implementation efforts.

Exhibit 7.4 Implementation Approach for Top and High Priority R&D



The processes or components included in the Application Areas have the following function in process heating equipment: *Heat Generation* through direct combustion of fuels, use of electricity, or use of hot fluids (steam, hot-oils, hot water); *Heat Transfer* from heat sources to the material being processed; *Heat Containment* within the heating system through proper furnace construction and use of refractories/insulation, covers, door design, etc.; *Heat Recovery* through use of recuperators, regenerators to preheat combustion air and fuel, heat recovery systems such as charge preheating, steam generation, cascading of available heat, etc.; *Emission Control* through the use of internal or external design innovations or devices; and *Material Handling Systems* that reduce heat requirements for trays, fixtures, baskets, conveyors, belts, water-cooled parts, etc.

Crosscutting Resources can impact the performance of many different parts or sub-systems of a heating system. For example, **Advanced Materials** are important to improving the performance of each of the following sub-systems of a heater or a furnace: *Heat Generation Systems* – burners or electrical heating elements; *Heat Transfer Systems* – recirculating fans, jets, radiation surfaces such as walls; *Heat Containment Systems* – insulation and refractories for furnaces or heaters, water cooled parts within a furnace; *Emission Control Systems* – materials that can withstand high temperatures in the presence of reactive gases with sulfur or chlorine, or abrasion of particulate; *Heat Recovery Systems* – high temperature recuperators or regenerators that can withstand high temperature, contaminated gases or liquids, and offer higher heat recovery efficiency; and *Material Handling Systems* – light weight, high strength conveyors, trays and fixtures.

Advanced Sensors and Controls could significantly improve the major sub-systems of a heater or a furnace. Developments in areas such as temperature measurement and controls, gas or liquid composition monitoring, and flame and emissions monitoring and management can be applied to all industries. Examples of applications of crosscutting sensors and controls to process heating systems include: *Heating System* – flame detection, emission control, temperature and heating rate control, safety, etc.; *Heat Transfer Systems* – enhancement and rate control for heat transfer systems, temperature uniformity, selective heating, etc.; *Heat Containment Systems* – control of heat losses, personnel and property safety, improved maintenance and repairs, etc.; *Emission Control System* – measurement, monitoring, and control of flue gas emissions, analysis and control of other plant emissions, etc.; *Heat Recovery Systems* – maximum or optimum heat recovery through monitoring and control of heat recovery systems; and *Material Handling Systems* – operation of the material handling system or components to reduce heat losses, improve system efficiency, and reduce cost. In addition to crosscutting sensors and controls, several sensors and controls that are specific to a particular industry or process within one industry were identified in Exhibit 5.1, such in-site melt chemistry, non-contact non-destructive in-situ carbon analyzer, transformation structure detection.

Design Tools and System Integration includes efforts to improve the sizing of equipment and components, selection of optimum materials and operating methods, models for performance prediction, and simulation software for each of the components and assemblies of the Application Areas mentioned above.

Non-R&D Implementation Approach

To develop an approach for implementing the non-R&D activities identified in Exhibit 6.2, the Top and High priority non-R&D activities have been grouped into six action areas. These action areas and the interrelationship among them are presented in Exhibit 7.5. Industry stakeholder collaboration is necessary to develop benchmarks that eventually can be used in the development of voluntary test protocols. Benchmarking is also necessary to identify the existing capability of sensors and materials, and to identify the technology to pursue and demonstrate in the future. Training and education needs will be determined by the activities of the industry stakeholder collaboration, benchmarking, and voluntary test protocols. Ultimately, the six action areas will help create the process heating of the future. R&D activities that advance process heating will influence and be affected by non-R&D activities. The non-R&D activities included in each, along with possible participants, timeframes, and preliminary implementation concepts are presented in Exhibit 7.6 through 7.11. The

Suggested Approach to Implementing Non-R&D Activities

1. Select top and high priority non-R&D and related R&D activities/goals from the roadmap.
2. Identify non-R&D activities that lead to a common goal and expected results. Group these activities into actionable topic areas that can be implemented by the process heating industry.
3. Define performance measures to be used for tracking progress and project completion
4. Define the connection and interdependent relationship among non-R&D projects as well as R&D efforts.
5. Define actions and the expected impact from results.
6. Identify participants, funding organizations, and stakeholders.
7. Establish a timeline with milestones for results.

action areas and additional information will be used to develop more detailed implementation approaches for non-R&D by industry stakeholders.

In addition to the six action areas, an Industry Action Group was identified as an important implementation approach for priority non-R&D activities. These activities include:

- Rule making advisory group to coordinate with EPA and other federal agencies
- Environmental regulations that encourage a systems approach to innovative technology solutions
- Financial incentives to install state-of-the art equipment
- R&D tax credits for equipment manufacturers and end users

To avoid conflicts of interest associated with lobbying while pursuing federal funding support for key non-R&D activities, the activities of the Industry Action Group will be supported and independently pursued by process heating industry stakeholders, separate from the Industry Stakeholder Collaboration effort.

Exhibit 7.5 Implementation Approach for Top and High Priority Non-R&D And Interrelationships Among Action Areas

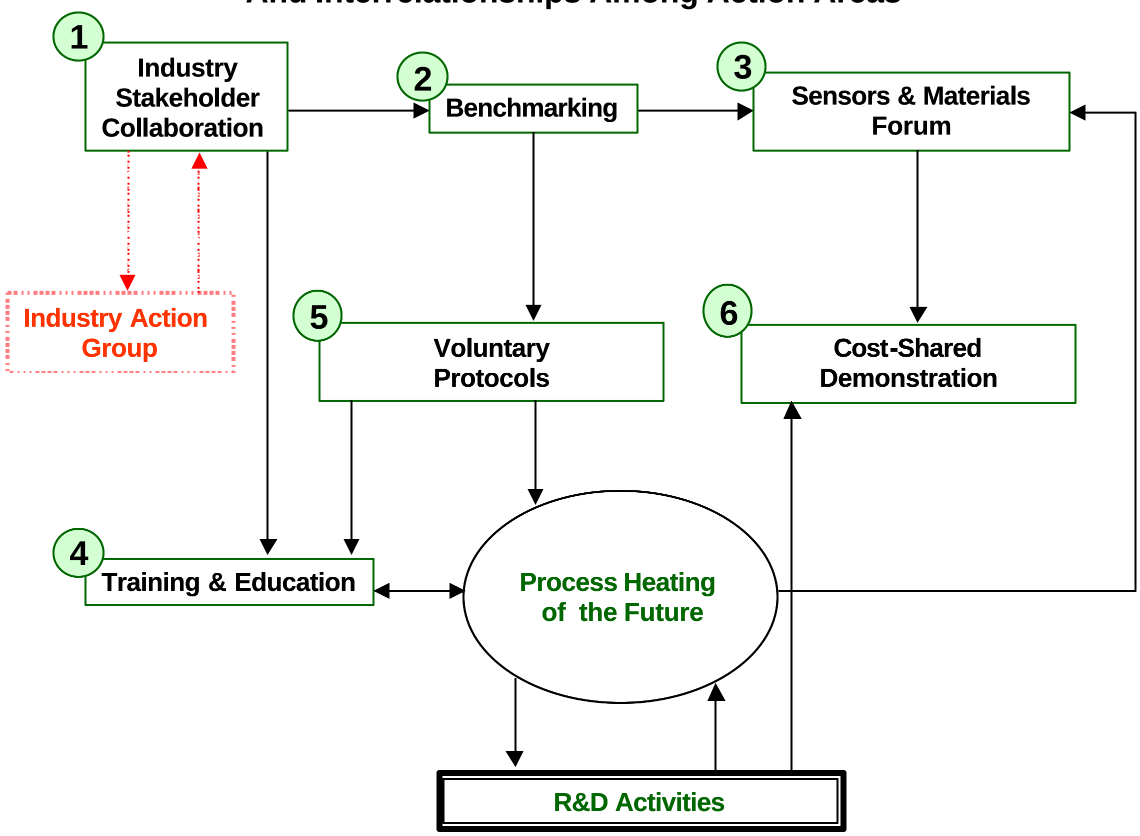


Exhibit 7.6 Action Area: Industry Stakeholder Collaboration

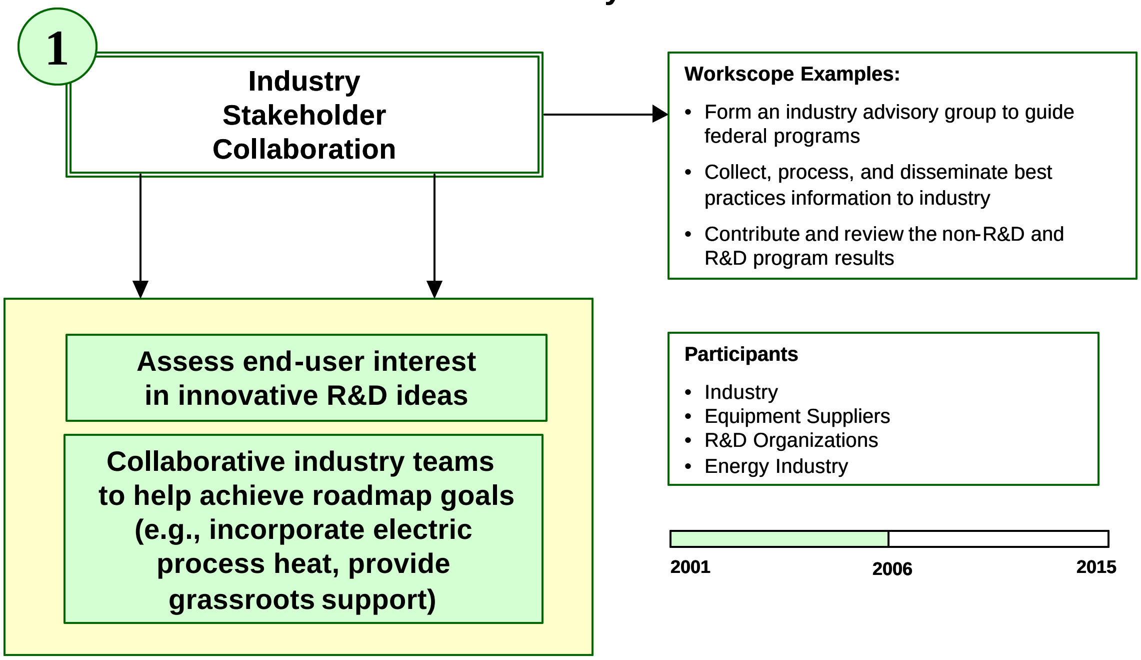


Exhibit 7.7 Action Area: Benchmarking

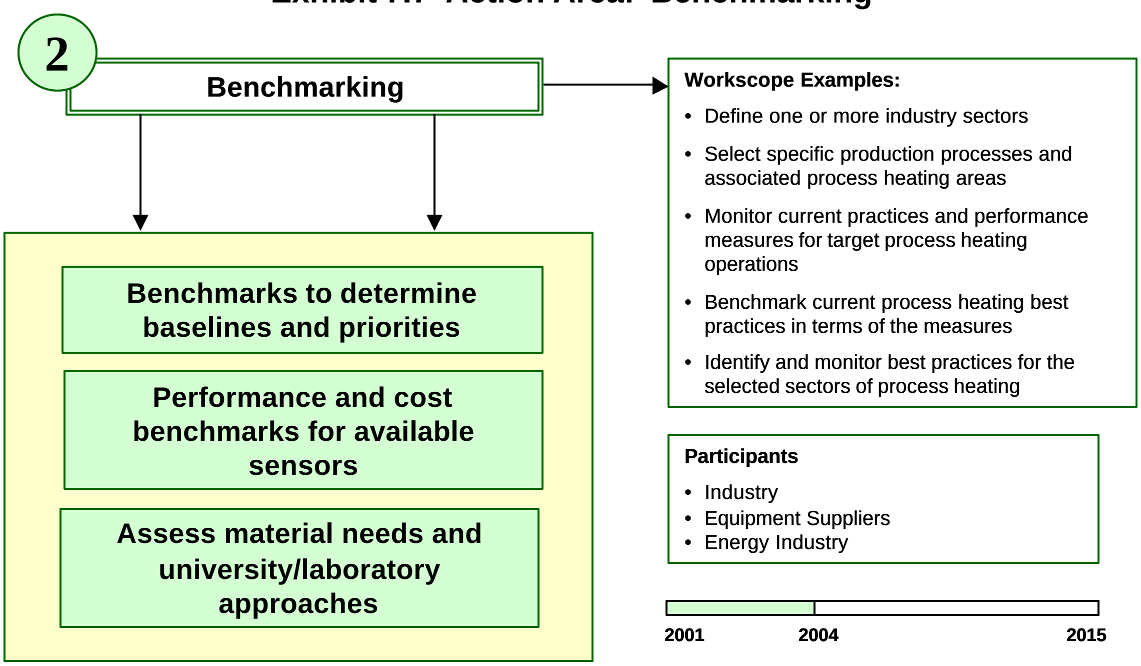


Exhibit 7.8 Action Area: Sensors and Materials Forums

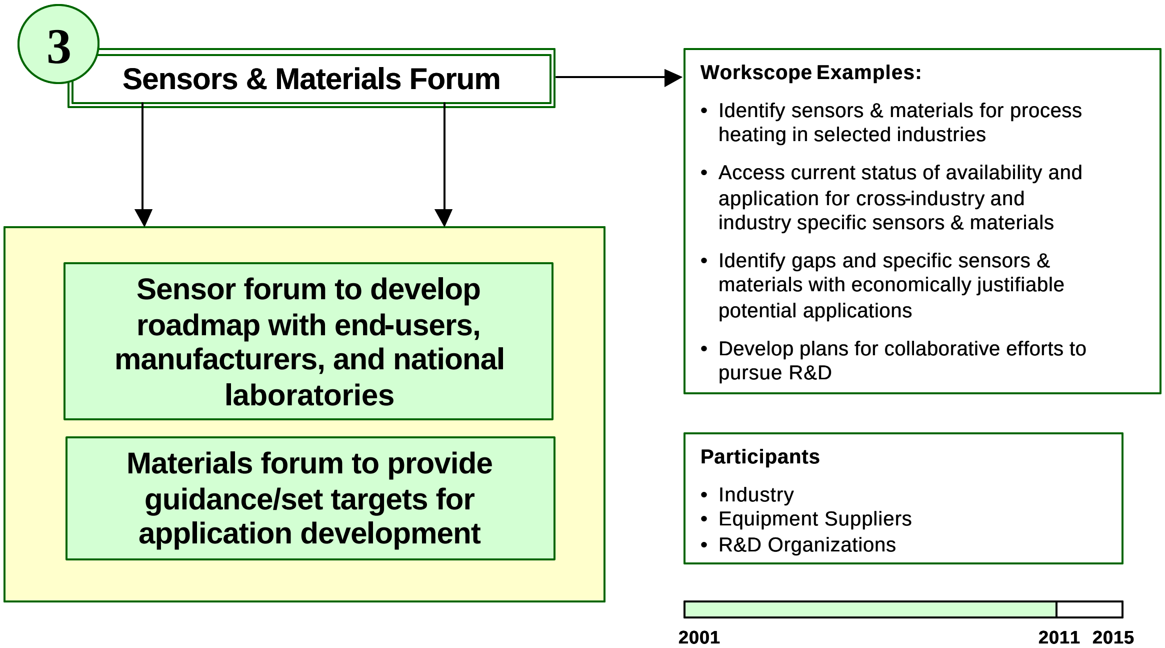


Exhibit 7.9 Action Area: Training and Education

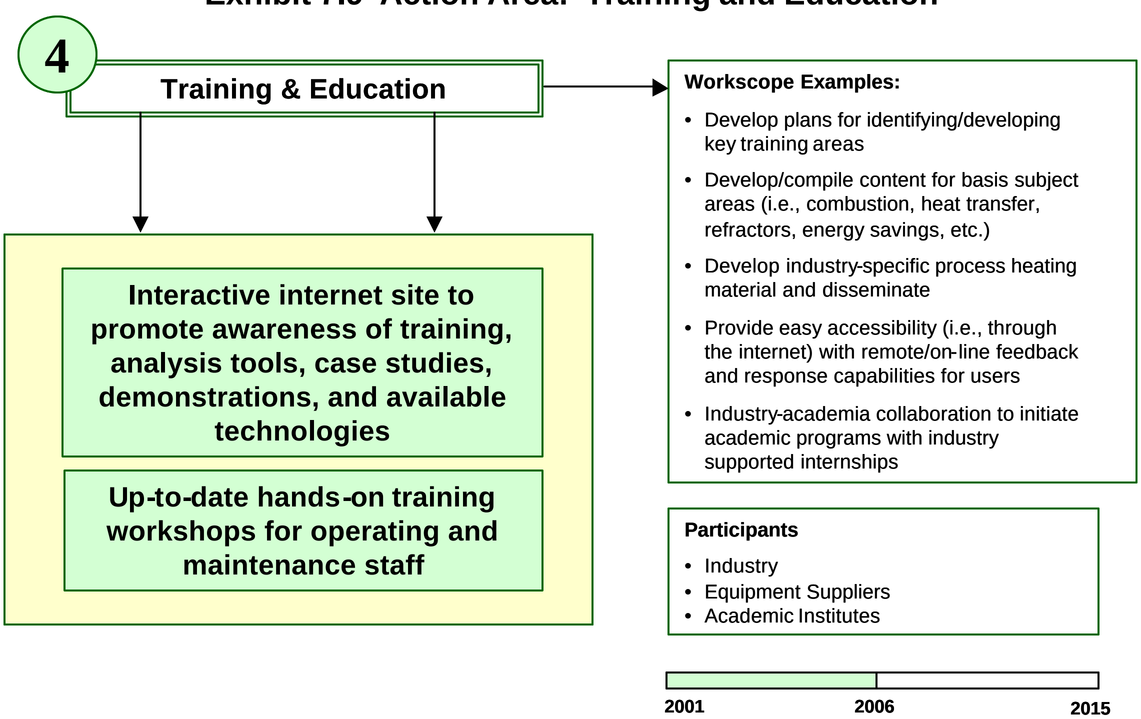


Exhibit 7.10 Action Area: Test Protocols & Voluntary Standards

5

Voluntary Protocols

- **Consistent measuring and reporting of NO_x**
- **Equipment test protocols to develop a common basis of comparison “consumer reports”**
- **Voluntary standards for fail-safe controls especially when system controls are by-passed**

Workscope Examples:

- Collect best practices used by the industry for testing, reporting, and application of performance of furnace equipment and critical components
- Compile and disseminate information on test protocols and test reporting format for performance of components (i.e., burners for NO_x
- Develop voluntary standards for process heating equipment performance in areas such as minimum efficiency and emissions

Participants

- Industry
- Equipment Suppliers
- Energy Industry

2001 2006 2015

Exhibit 7.11 Action Area: Cost-Shared Demonstrations

6

Cost-Shared Demonstrations

- **Promote demonstrations of new technologies**
- **Partnerships to ease risk of trying new technology**
- **Showcase demonstrations and case studies**
- **Sliding-scale cost-share requirements based on stage of technology development and company size**

Workscope Examples:

- Monitor new technology developments and application potential through communications with the process heating industry group, trade associations, and federal programs
- Evaluate demonstration project proposals
- Collect and disseminate information on demonstration project results

Participants

- Industry
- Equipment Suppliers
- Government
- Energy Industry

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Appendix

Workshop Overview and Participants

The Industrial Heating Equipment Association (IHEA) on behalf of the process heating community began a dialog with DOE's Office of Industrial Technologies (OIT) to develop a strategy for incorporating process heating into the *Industries of the Future* framework. Developing a roadmap was recognized as the best way to obtain a cross-industry perspective on process heating priorities.

To initiate this effort, IHEA and OIT invited representatives from the process heating community to a 1½-day workshop on November 18 and 19, 1999, in Orlando Florida. At the workshop, 35 participating experts, representing manufacturers, end-users, and researchers, worked in three professionally facilitated groups to identify the specific needs and challenges for process heating in three temperature ranges: lower than 1250 °F, between 1250 °F and 1800 °F, and higher than 1800 °F. Each group identified R&D needs to achieve desired characteristics by 2020. Immediate opportunities to improve performance and apply best management practices were also identified. The output from each group was compiled and analyzed. In the roadmap, the priority R&D goals are organized around process heating operation areas rather than temperature because the priorities are applicable across temperature ranges. Priority near-term non-research activities are organized around goals derived from the workshop results.

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Background on the Industrial Heating Equipment Association

The *Industrial Heating Equipment Association (IHEA*) is a national trade association representing major segments of the industrial heat processing equipment industry. IHEA was established in 1929 to meet the need for effective group action in promoting the interests of industrial furnace manufacturers. Since then, the organization has expanded and currently includes designers and manufacturers of all types of industrial heat processing equipment used for the melting, refining, and the heat processing of ferrous and non-ferrous metals, as well as certain non-metallic materials and the heat-treatment products made from them. The products considered include (but is not limited to):

- Furnaces
- Ovens
- Dryers
- Heaters
- Heating equipment
- Kilns
- Induction and dielectric apparati
- Coke ovens
- Tanks for melting glass
- Salt bath or salt bath furnaces
- Oil, chemical, and petrochemical processing equipment
- Industrial combustion equipment
- Accessories for all the aforementioned products
- Auxiliary equipment such as atmosphere generators, process controls, quenching apparati, equipment for heat recovery, and industrial washers

IHEA's mission is to provide services to member companies that will enhance their ability to serve end users in the industrial heat processing industry and improve their business performance.

IHEA's objectives are to:

- Promote the interest of the industrial heat processing industry before the legislative, executive, and regulatory branches of the Federal government, and the standard setting groups relevant to this industry.

- Educate member companies with regard to government regulations, industry standards, codes, and other matters that impact the industrial heat processing industry.
- Enhance the end user's image of member companies by stressing quality as viewed from the end user's perspective, and promote this as a benefit of interacting with member companies.
- Raise the level of professionalism within the industrial heat processing industry and member companies by promoting career opportunities for undergraduate engineers and other disciplines.
- Provide a forum for optimizing end-user operation of heat processing equipment via technical seminars and training sessions.
- Develop and maintain relationships with related trade associations, domestic and foreign, in order to assimilate global information about the industry.
- Engage in lawful activities that will promote the common good of member companies such as gathering and disseminating non-competitive employment and statistical information, and providing educational programs for member-company employee improvement.

Additional information on IHEA can be found at www.IHEA.org.

Background on the DOE Office of Industrial Technologies

The *DOE's Office of Industrial Technologies* has been working with major U.S. industries to improve energy efficiency, environmental performance, and productivity through an innovative partnership known as the *Industries of the Future*. This strategy has already led to successful technology partnerships and projects with key industries such as steel, aluminum, metalcasting, glass, mining, agriculture, chemicals, forest products, petroleum, forging, and heat treating. An industrial combustion technology roadmap has also been developed to guide combustion research needs in boilers, burners, and furnaces. Each of these industries have identified the critical technology and research needs that will help them achieve the long-range strategic goals they established in their strategic visions. The Office of Industrial Technologies is committed to applying its available programs and resources to help implement the research agenda contained in the technology roadmaps developed by each industry. *Industries of the Future BestPractices* provides resources to help companies identify *near-term* opportunities to reduce energy use and cut costs plant-wide. Information (including the roadmaps) is available at www.oit.doe.gov. To request a publication and get on the mailing list, contact the *OIT Resources Center* at 202-586-2090. To learn more about OIT products and technical and financial assistance, contact the *Information Clearinghouse* at 1-800-862-2086 or www.oit.doe.gov/clearinghouse.