Industrial Combustion Technology Roadmap

A Technology Roadmap by and for the Industrial Combustion Community

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Facilitated by the
U.S. Department of Energy

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1. Overview

Combustion has been the cornerstone of industrial development for nearly two centuries. The burning of fuel to produce heat or other forms of power is an integral part of industrial processes. Although progress has been made in understanding the fundamental science of combustion over the years, regulatory and competitive forces are driving the need for combustion equipment with better performance, lower environmental impact, and greater flexibility, all at reasonable cost. Tremendous opportunities exist for companies that can develop and apply new technology responding to these needs. Unfortunately, few companies can accept the cost and risk of the research required to develop such technologies.

Instead, users and manufacturers of industrial combustion equipment have joined forces to devise and implement a unifying plan for directing future technology research into areas that best meet the needs of industry. The first step was the development of the *Industrial Combustion Vision*, a document that outlines the challenges facing industrial combustion systems and sets strategic performance targets (summarized in Exhibit 1-1 and detailed in Appendix A) for advanced technology over the next 20 years. These performance targets complement the definition of "the industrial combustion equipment of the future" provided by users and manufacturers of this equipment in the *Vision*. Substantial research expenditures will be required to attain these ambitious targets. The economic payback of any new technologies developed will need to be sufficiently favorable to ensure widespread adoption.

Exhibit 1-1. Key Performance Targets for Industrial Combustion Systems in the Year 2020

Boiler Systems

Specific to the Burner

- Reduce NOx emissions to <2 ppm (gaseous fuels)
- Reduce CO emissions to <5 ppm (gaseous fuels)
- Reduce particulate emissions to <0.003 lbs/10^6 Btu (gaseous fuels)
- Maximize system efficiency, thereby reducing CO_2 emissions
- Be able to burn different fuels simultaneously

System

- Reduce first cost and life-cycle cost of equipment
- Achieve 150ºF stack exit temperature
- Maximize integration of steam and power requirements with plant needs
- Improve system reliability by 50%
- Maintain or improve safety levels

Process Heating Systems

Specific to the Burner

- Reduce emissions of criteria pollutants by 90%
- Reduce CO_2 emissions to levels agreed upon by the international community
- Reduce specific fuel consumption by 20% to 50%
- Maximize the ability to use multiple fuels

System

- Reduce the total cost of combustion in manufacturing
- Enhance system integration
- Reduce product loss rate by 50%
- Maximize system robustness
- Zero accidents

This present document, the "technology roadmap," is the result of a collaborative effort between equipment users, manufacturers, government, academia, and other research organizations, and represents the next step in implementing the technology development plan. The technology roadmap is actually a descriptive plan of the research and development (R&D) activities necessary to achieve the performance targets identified in the *Vision*. The *Roadmap* represents the views of a group of industry experts (listed in Appendix F) who participated in the roadmapping process. Some of the R&D activities, while considered key to advancing the state of industrial combustion technology, do not address the mission of the U.S. Department of Energy (DOE, the roadmapping facilitator), and would not qualify for DOE support.

The top priority R&D activities in the areas of burners, boilers, and industrial process heating systems are summarized in Exhibit 1-2. The proposed research activities tend to fall into one of two classes of needs -- very specific needs of importance to small segments of the industry and broad needs that need to be translated into well-defined R&D activities or programs. Institutional issues such as the availability of research results and test data and improved training and education for equipment operators are also addressed. (Note that the word "combustion," used throughout the roadmap, covers all industrial processes, including furnaces, process heaters, steam generators, etc.)

The ultimate value of the roadmap is its ability to align the components of the proposed research in burners, boilers, and industrial heating systems across industry, academia, and the Federal sectors. The final step is the implementation of the research through collaborative partnerships among the various stakeholders in industrial combustion.

Exhibit 1-2. Top Priority R&D Needs for Industrial Combustion

Burners

- ★ **Burner capable of adjusting operating parameters in real time**
- ★ **Advanced burner stabilization methods**
- ★ **Robust design tools/unified code**
- ★ **Economical methods to premix fuel and air**

Boiler Systems

- ★ **New boiler/combustion technologies**
- ★ **Common technology platform for family of advanced packaged boilers**
- ★ **Energy technology clearinghouse**
- ★ **Test/demonstration programs**

Process Heating Systems

- ★ **New furnace designs**
- ★ **Advanced sensors**
- ★ **Cost-effective heat recovery processes**
- ★ **New methods to generate process heat without environmental impact**

2. Barriers to Improvement

Many technological, regulatory, and institutional barriers prevent industrial combustion systems from achieving the envisioned 2020 performance levels today. Issues common to the entire industry are discussed briefly below, followed by issues specific to boiler and process heating systems, respectively. Comprehensive lists of the barriers for burners, boilers, and process heating systems are provided in Appendix B.

Industry-Wide Issues

The industries that use combustion equipment are typically conservative, and have requested relatively few innovative new technological changes over the past several decades. The financial risk associated with adoption of a new technology is considerable, and many innovations that come along are not accepted for fear they will prove unreliable. Industry is unwilling to accept the risk of the heavy financial burden that would be imposed by the inadequate performance of a new system. A company installing a new, low-emissions technology, only to have it perform below requirements, would be required to spend even more money to modify it or install conventional control equipment to meet emissions standards, with no credit given for having tried the alternative. In the current competitive economic environment, no incentive exists for either the end-user or the technology vendor to assume financial risk. At a minimum, new technologies will need to be demonstrated on a long-term basis to verify reliability.

A critical barrier to advanced furnace design is the industry's inability to predict the performance of new combustion systems. The industry has not developed a standard for measuring or reporting performance under "standard or agreed upon" operating conditions that could help predict in-use performance for combustion systems.

The availability, quantity, quality, and usability of performance data is a critical issue affecting the development and application of all types of industrial combustion systems. A wide gap exists between researchers (who often work on a relatively small scale) and the component, equipment, or systems designer. Considerable fundamental knowledge exists or is being pursued at the national laboratories and academic and other research institutions. Transfer and use of this knowledge, however, requires simplified and usable tools that are either not available or are prohibitive in terms of cost and training time. For example, although a large body of knowledge has been accumulated regarding the fundamentals of how emissions form in smaller-size gas flames, it is often difficult for the suppliers to design low-emission furnaces because of an inability to apply any detailed understanding about the formation of emissions to the assignment.

The lack of detailed data regarding the general performance of combustion systems is further complicated by inadequate technologies for measuring key combustion parameters. In addition, industry does not take advantage of existing state-of-the-art combustion laboratories because of the nature of the results (detailed, micro-level data that need to be interpreted), the size and type of equipment available, and costs.

The variety of existing systems, fuel types, and applications will require a broad spectrum of technology options to meet the potential demand for retrofits. The capital outlay for new technology designed to reduce NOx to very low levels must be less if these levels become mandatory. Domestic industries would likely move offshore if the cost of meeting regulations puts them in a potentially non-competitive economic position.

Boiler System Issues

Some key barriers in boiler system technology include the following:

- The wide variety of boilers in use is a barrier to the development of combustion technologies that reduce emissions uniformly; an advanced burner developed for a particular boiler design may not transfer successfully to other boilers.

- The turndown instability of lean pre-mixed combustion systems is a barrier to reducing NOx emissions. Various fuels have different requirements for NOx control, which is a barrier to achieving NOx goals as well as to meeting targets for systems operations and fuel flexibility.

- It is conceivable that the concentration of the particulates entering the burner may be higher than the concentration that would be allowed to exit a stack under more stringent regulations. This may require the installation of a particulate control system on either the front end or the back end. However, commercial and developing technologies have not been adequately demonstrated as effective options for controlling fine particulate (<10 microns) emissions for a wide variety of process stream conditions.

Process Heating System Issues

As already indicated, the industrial heating industry has been relatively slow to develop and adopt new technologies. This is primarily due to certain characteristics of the industry, including:

- the relatively small size of the companies offering industrial heating systems
- the lack of synergy between the equipment suppliers and the users
- the high level of integration of industrial heating equipment with the other process steps and equipment within a plant
- the strong dependency of the heating equipment with the operation of the entire plant
- the user’s requirements for system flexibility, which often puts final performance beyond the control of equipment suppliers
- difficulties in translating results of laboratory-scale tests into the design of production-scale equipment

3. Burners

"The burner of the future will be robust, energy-efficient, compliant with emissions regulations, and process-friendly. It will have multi-fuel capability and will use advanced flame management control features, making it user-friendly, highly reliable, and very safe." *Industrial Combustion Vision*, May 1998

Burners are integral parts of boiler and industrial heating systems, and consequently are used in a wide variety of industrial combustion applications. This diversity makes it difficult to define common performance targets for burners, particularly emissions reductions targets. The performance targets for burners (derived from the boiler and process heater targets in the *Industrial Combustion Vision* and shown in Appendix A) are not meant to apply to every burner application.

The "burners of the future" may not be capable of meeting specified emission levels or other targets when installed in existing boiler and furnace systems. It cannot be predicted that all regions of the country will need to have emissions reduced to the same level in the future. Traditionally, it has been difficult to achieve high thermal efficiency and low NOx emissions simultaneously. Without discounting these and other complexities, the targets in the *Vision* are meant to indicate a desired level of improvement that is dependent on the specific end-use application, plant design, and combustion system. Improvements to the overall combustion or heating system will require integrated approaches that consider all components of the system, including burners and eventually the entire manufacturing process.

Research and Development Needs

The research and development activities that could significantly advance the state of burner technology are shown in Exhibit 3-1. The information falls under one of six categories, related to the performance targets in the *Vision*:

- Environmental Quality
- Fuel Flexibility
- Energy Efficiency
- Process Improvement
- Health, Safety, and Reliability
- Materials

Most of the research needs are specifically for burners, but some of them relate to integrated combustion systems. Exhibit 3-1 shows how the R&D will address the performance targets in the *Vision*. The shadings in the exhibit indicate the priority of the R&D, and the exhibit also provides the time frame in which useable results could be anticipated from the various research projects, assuming initiation in the near future. The R&D needs are also listed in Appendix C by technology.

All of the research activities listed in Exhibit 3-1 will help maintain the United States as the world leader in manufacturing that requires combustion-based process heat, a key component of the *Vision*. The design and application of advanced equipment and systems, as well as cost reductions and performance improvement, will lead to an increased market for U.S. equipment.

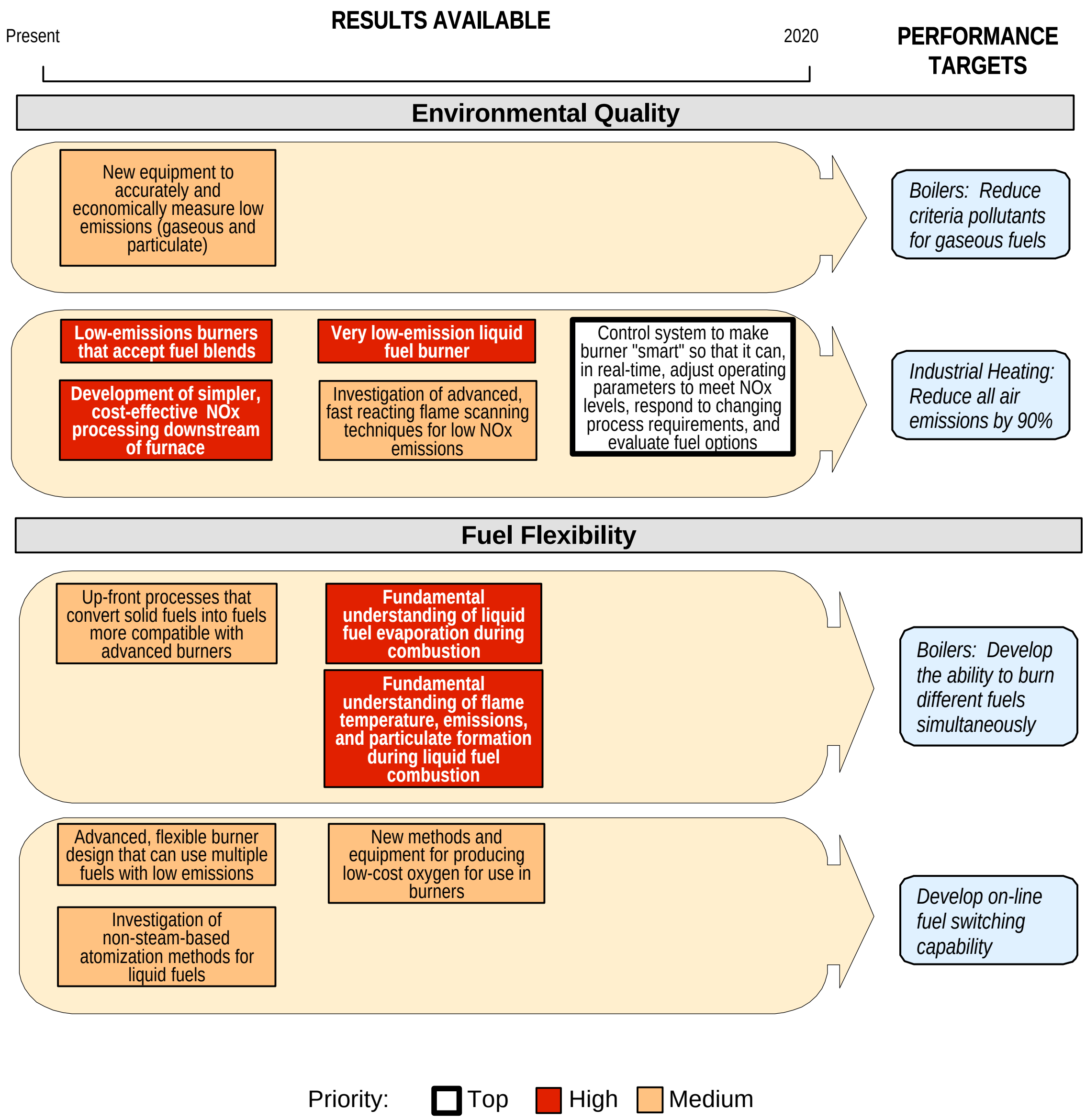

Exhibit 3-1. R&D Activities to Advance Burner Technology

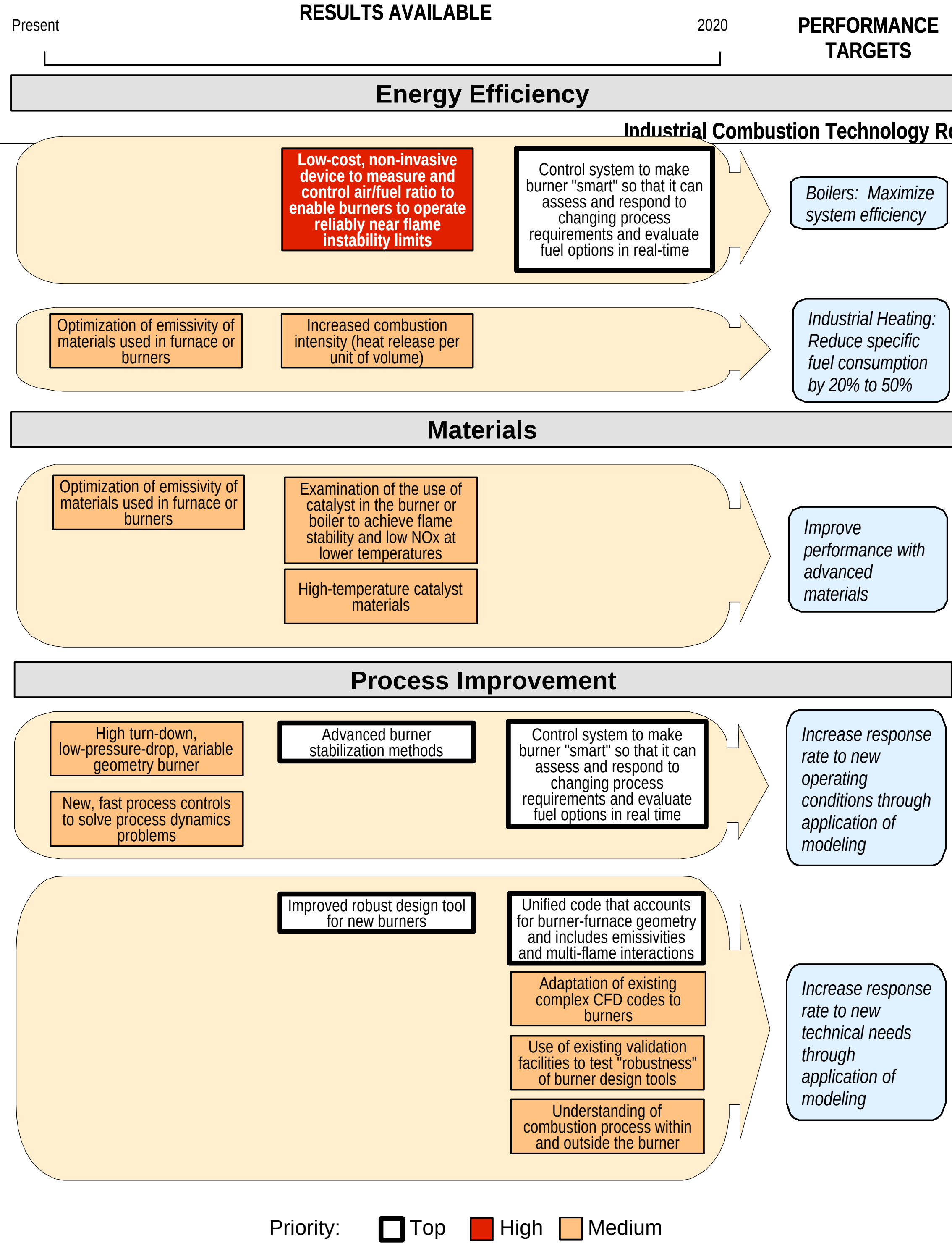

Exhibit 3-1. R&D Activities to Advance Burner Technology (cont.)

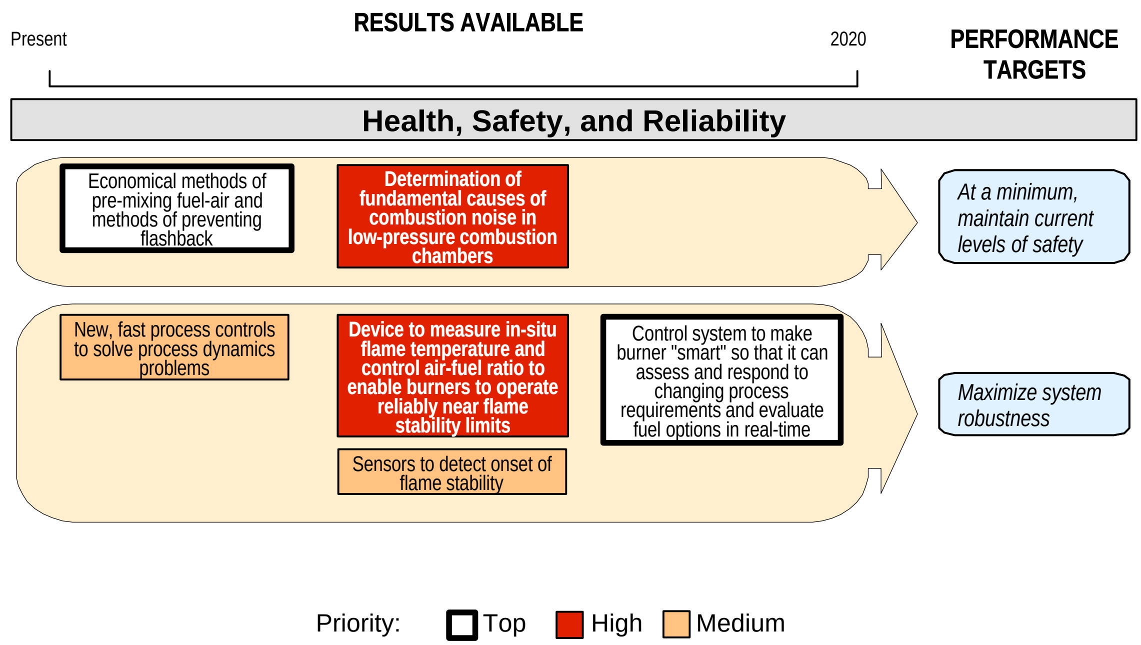

Exhibit 3-1. R&D Activities to Advance Burner Technology (cont.)

The highest-priority R&D needs in burner technology have been further analyzed to determine key technical hurdles, issues and benefits of system integration, and the impact of new technologies on energy efficiency (Exhibit 3-2). Systems-integration issues have been identified because of the difficulty in separating burners from the overall combustion system in which they operate.

As shown in Exhibit 3-2, the development of better design tools, a unified code, and smart burners could significantly increase combustion efficiency. Advanced burner stabilization methods and premix techniques would have minimal impact on energy use, but have substantial safety benefits.

Advanced Burner. A top-priority research activity that will contribute to many performance targets is the development of an advanced burner control system with the capability to determine process requirements and evaluate fuel options in real-time, and adjust its operation accordingly. This type of burner would be able to assess the energy required and delivered to the process; the load or work at the desired location with the necessary heat flux; and the level of emissions to be met, considering the combustion system. These burners would also be able to change the flame pattern or heat delivery from the burner. One concept of a "smart" burner incorporates non-steady-state combustion where fluctuations are controlled rather than random.

A related top-priority need is the development of associated combustion control algorithms incorporating emission considerations as the basis for control. The improved monitoring and control of the combustion process made possible by advanced burner systems would lead to higher energy efficiency and lower emissions and allow better response to changing thermal-process needs.

Exhibit 3-2. Top-Priority R&D Needs for Burners

R&D Need	Impact on System Energy Efficiency	Key Technical Hurdles	System Integration Issues(s)/Benefits
Develop a burner capable of adjusting operating parameters in real time (e.g., determines process requirements and evaluates fuel options)	Very high	• Non-availability and cost of sensors and controls • Lack of knowledge about how burner operates with different fuels or compositions	• Such a "smart" burner is incorporated into the system • Entirely a system integration issue
Develop advanced burner stabilization methods	None to moderate	• Lack of understanding of mixing and recirculation • Fundamental understanding of flame stabilization • Physics of fuel burning	• Simplification of flame stabilization by furnace design • Integration of controls • Adequate turndown • Appropriate heat flux • Retrofit geometry limitations • Acoustic coupling
Develop a better, robust design tool for new burners *and* **Develop a unified code that accounts for burner-furnace geometry and includes emissivities and multi-flame interactions**	Very high	• Lack of experimental data • Lack of large testing facilities • Inadequate computer resources	• Enhancement of capability for analyzing systems integration opportunities • Acceptance by users of a need for integration • Need for tools to work in both retrofit and new equipment markets
Find ways to premix fuel and air thoroughly and economically	No impact	• Lack of understanding of turbulent mixing • Potential for flashback created by laws of thermodynamics • High energy requirements to do this mixing • Unsafe conditions may be dictated by time, pressure drop, physical size requirements • Control elements not sufficiently accurate • No control of system or detection of deviations in the field with use over time	• Potential influence of system on flashback characteristics • Fewer technology hurdles at some levels of integration • Combustion control • Potential elimination of need for premixing with a greater combustion volume • Acoustic coupling between combustion system and system • Potential elimination of need for premixing by alternative low-NOx systems

Advanced Burner-Stabilization Methods. The "process improvement" targets for burners can be met with technological advancements that allow faster adjustments to changing process needs. In addition to the smart burner, these advancements include better process controls, improved design and performance-prediction models, advanced burner- stabilization methods, and other new burner systems. Advanced burner controls also contribute to health, safety, and reliability targets. New technologies will need to be supplemented by increased training of design and operating personnel.

Design Tools and a Unified Code. Research in tools, models, and algorithms will facilitate the design of advanced burners. New, robust, burner design tools should incorporate both CFD codes used in other industries and a better understanding of the combustion occurring outside the burner. Finally, a unified code is needed that accounts for burner-furnace geometry and includes emissivities and multi-flame interactions.

Economical Premixing of Fuel and Air. The development of economic methods for pre-mixing fuel and air and methods for preventing flashback during the entire range of burner operations are also key to achieving safety targets.

4. Boilers

"The boiler of the future will be an energy-efficient, low-emissions steam generator that is fuel-flexible, cost-effective, reliable, and safe. It will incorporate improved materials and smart technology, including modern automated controls, allowing total integration into process and energy systems with minimal operator involvement." Industrial Combustion Vision, May 1998

The industrial boiler community has set performance targets for itself in energy efficiency and environmental quality, fuel flexibility, cost-effectiveness, process/energy compatibility, safety/reliability, and materials. As outlined in the *Industrial Combustion Vision*, these targets indicate the level of performance that the industry believes can be achieved if sufficient research dollars are directed at the priorities contained in this technology roadmap. Boiler performance targets that refer specifically to the burner systems within the boiler itself were discussed in Section 3. Other targets consider the entire boiler system, including burners, emissions control equipment, and other auxiliary equipment. A key theme of the *Vision* is the need to look at combustion equipment as part of an overall system, accounting for the complex interrelationships between the various -- and often unpredictable -- system inputs in order to optimize system efficiency and environmental performance.

Research and Development Needs

As shown in Exhibit 4-1, the industrial boiler community will require research addressing the following areas in order to achieve the performance goals it has set for itself in the *Industrial Combustion Vision*:

- Environmental Quality
- Fuel Flexibility
- Energy Efficiency
- Process/Energy Compatibility
- Safety/Reliability/Maintainability
- Materials
- Cost Effectiveness

In addition, non-R&D actions are recommended to address institutional and policy issues. Exhibit 4-1 shows how the R&D will address the performance targets in the *Vision*. The shadings in the exhibit indicate the priority of the R&D, and the exhibit also provides the time frame in which useable results could be anticipated from the various research projects, assuming initiation in the near future. The types of activities that need to occur are listed in Appendix D by type of research.

The research needs that are most critical to achieving the industry's goals for 2020 are shown in Exhibit 4-2. Each of these needs was evaluated for its impact on the combustion system's energy efficiency, its role in meeting performance targets in the *Vision*, and the key hurdles to its success.

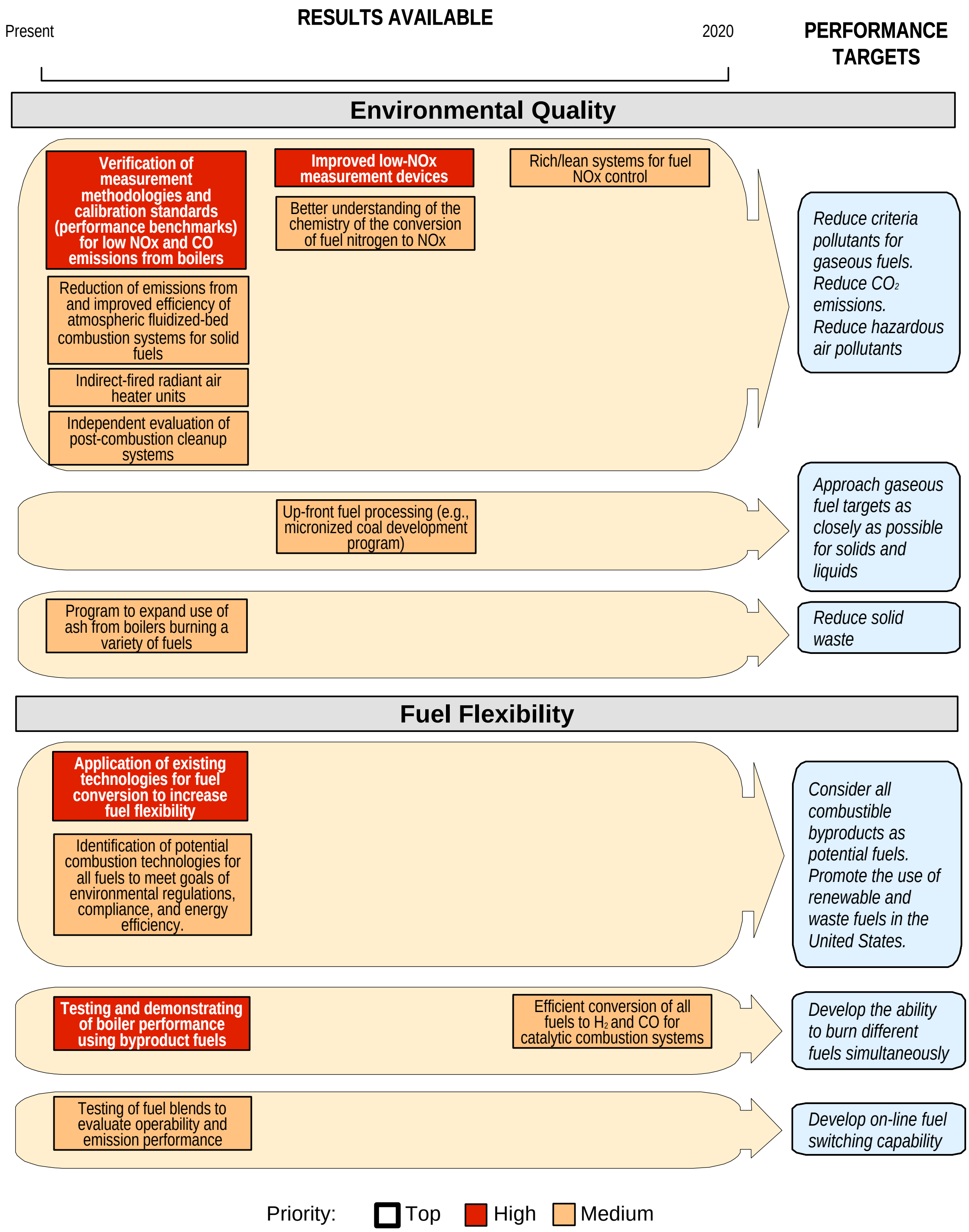

Exhibit 4-1. R&D Activities To Advance Boiler Technology

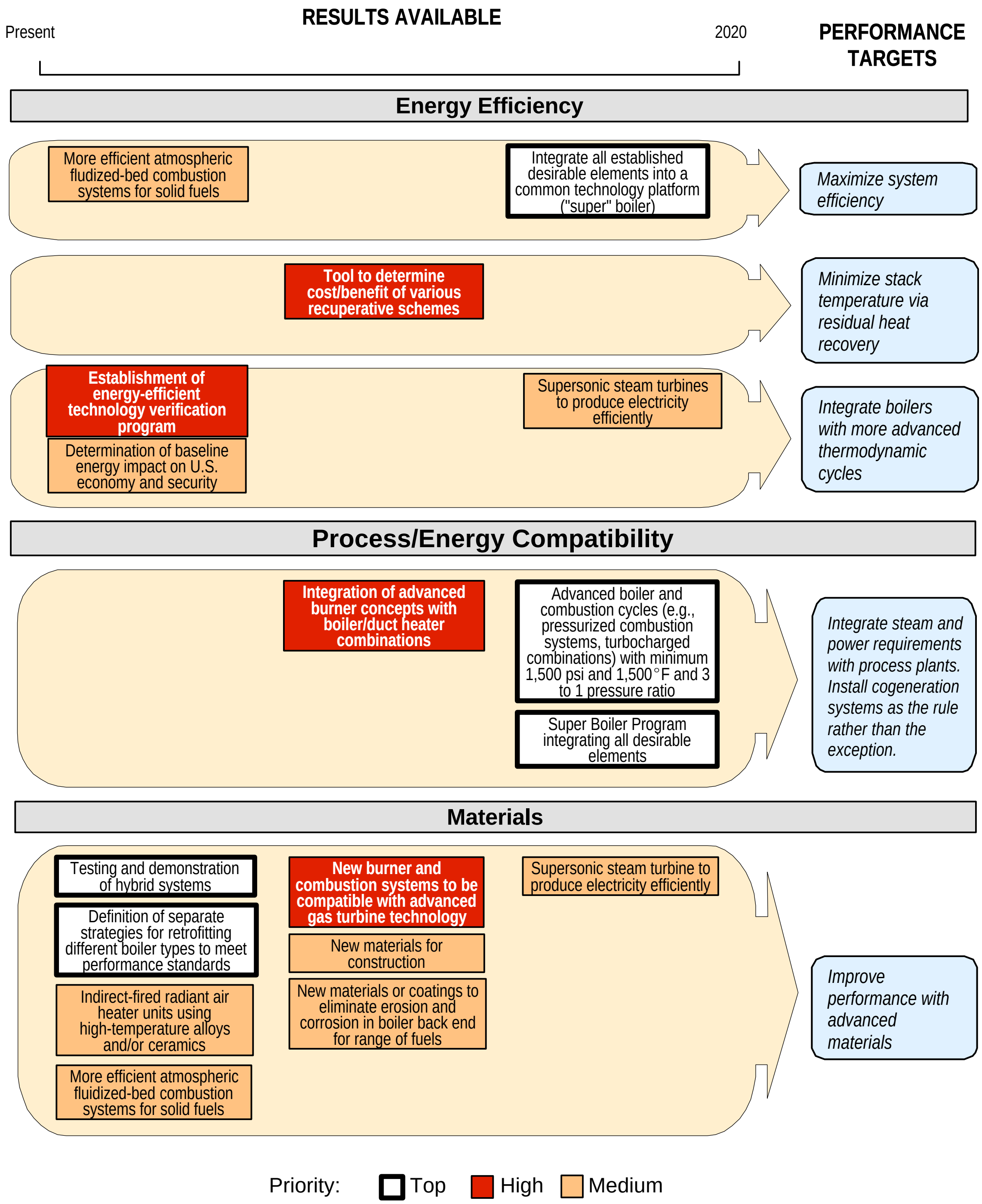

Exhibit 4-1. R&D Activities To Advance Boiler Technology (cont.)

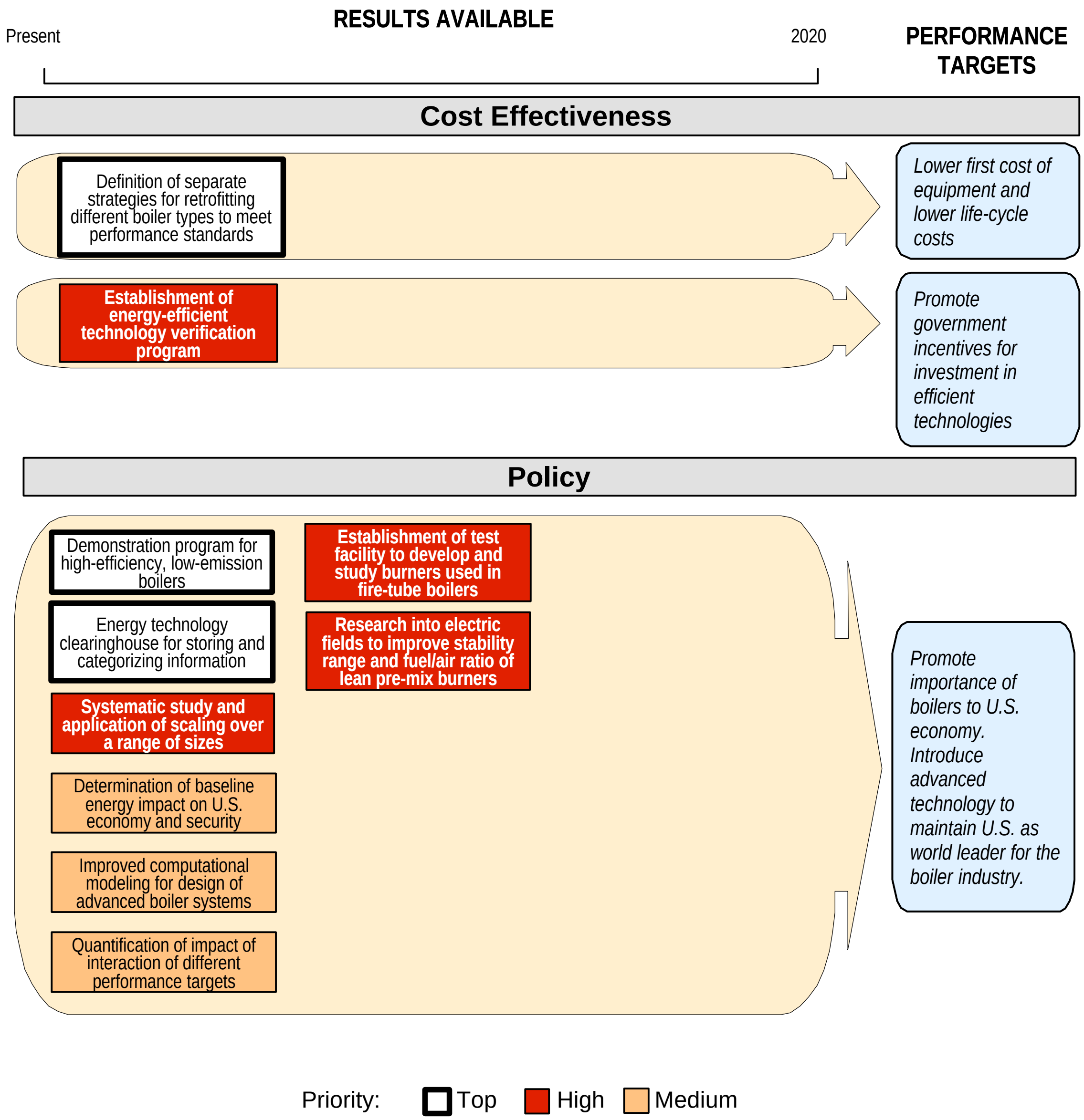

Exhibit 4-1. R&D Activities To Advance Boiler Technology (cont.)

Exhibit 4-2. Top-Priority R&D Needs for Boilers

R&D Need	Impact on System Energy Efficiency	Contributes To Which Targets	Key Technical Hurdles*	Key Non-Technical Hurdles	Risk	Pay-off
Completely new boiler and combustion cycles	Very high	Environmental, energy efficiency, fuel flexibility	• Materials • Thermody-namic design	• Inertia	High	High
Energy technology clearinghouse to store and categorize information	Low	Environmental, fuel flexibility, energy efficiency, process/energy compatibility, safety/reliability, cost effectiveness	• No major	• Lack of info vehicle • Confidential-ity (intellectual property)	Low	Low to medium
Common technology platform for a family of advanced packaged boilers	Very high	Environmental, fuel flexibility, energy efficiency, process/energy compatibility, safety/reliability, materials cost effectiveness	• Materials • Measurement • Controls • Component integration	• No single company has the capability	High	High
High-efficiency, low-emission boiler demo program	High	Environmental, energy efficiency	• Materials • Measurement • Controls • Component integration	• No major	High	High
Separate strategies for retrofitting different boiler types to meet performance stds	Moderate	Environmental fuel flexibility safety/reliability	• Component integration	• Inertia	Low	Low to medium
Test and demo of hybrid pollution control systems	Low	Environmental, fuel flexibility, possibly safety	• Component and subsystem integration	• No major	Medium	Medium

Burner and combustion systems compatible with advanced gas turbines *and* **Integration of advanced burner concepts with boiler/duct heater combinations**	Very high	Environmental, energy efficiency, process/energy compatibility	• Materials • System integration	• No major	Medium	Medium

*Low emissions (ultra-low) burner/component development (applies to all but clearinghouse)

New Boiler Technologies. The development of completely new boiler technologies and combustion cycles will help meet industry's goals in process/energy compatibility. The "boiler of the future" (an energy-efficient, low-emission, fuel-flexible, cost-effective, reliable, and safe system) will likely consist of new designs for boilers and combustion systems. Research into new systems could include examinations of pressurized combustion systems and turbocharged systems, as well as efforts to increase pressures and temperatures in the boiler (minimum of 1,500 psi and 1,500^{o}F) and to reduce the footprint. These types of systems will be needed if boilers are to meet demanding performance requirements at significantly higher pressures and temperatures than today's systems. The coupling of such systems with steam turbines will further improve system efficiency.

A related high-priority need is acceleration of the application, testing, and commercialization of new construction materials for heat exchangers, burners, and construction. Associated joining/welding technologies must also be developed. New materials or coatings to eliminate erosion and corrosion in the boiler back end for a broad range of fuels are also needed to meet the goal of achieving 150^{o}F or less stack temperature. (New materials are also important to achieving the objectives of the Super Boiler Program, and to ensuring and the compatibility of burner and combustion systems with advanced gas turbines.) An obvious key to successful commercialization of new materials is relative cost.

Energy Technology Clearinghouse. An important step would be the establishment of an energy technology clearinghouse allowing easy access to technical information on boiler technologies and the results of research. Information on advances in boiler design, selection, and operation should be easily accessible through a clearinghouse, allowing researchers to build on existing information, reducing duplication of efforts.

Common Technology Platform for Family of Advanced Packaged Boilers. An effort to integrate various desirable elements into a common technology platform for advanced boilers is considered to have a high chance of failure but also a very high potential payoff to industry if successful. The program could serve as a vehicle for coordinating a number of related boiler R&D efforts to maximize the results of research funding. The goal of this program would be to develop a family of advanced boilers that incorporate advanced materials (e.g., alloys and ceramics) to meet the broad range of industry needs. Standardization of the technology will allow low-cost manufacture of advanced, packaged boilers with significantly improved energy and environmental performance over current boiler technology.

This "super" boiler program could be structured and performance objectives developed based on fuel type (i.e., gas, liquid, solid). An alternative approach would be to conduct the effort on an industry-by-industry basis according to the needs of individual industries. Existing technology options may be used if they prove to be capable of meeting the performance targets in the *Vision*. Specific program objectives will need to be developed by representatives of industrial boilers users and manufacturers, as well as funding sources.

Testing and Demonstration Programs. Testing and demonstration programs of advanced combustion systems will establish their performance and reliability and promote industry's confidence in new technologies. For example, demonstration of high-efficiency, low-emission boiler technologies at full scale could identify limitations and quantify performance with variable loads and fuels, mitigating the risk associated with new technologies. The market penetration of existing, state-of-the-art technologies could be expanded if there was adequate information on their performance based on large-scale demonstrations of specific applications. Testing of technology being developed over the long term could be included in the development of the technology platform for advanced boilers.

It is unlikely that individual technologies will be capable of meeting the strict regulatory limits anticipated for the wide variety of boilers that will be used. Hybrid systems that combine different yet compatible pollution control technologies will have a greater chance at achieving emissions goals cost-effectively. Such combinations of technologies are already being used to meet current NOx regulations. Multiple demonstrations of hybrid system combinations will be necessary to evaluate their potential for success in a wide variety of industrial boiler settings.

Retrofit Strategies. Many boilers operate well beyond their planned lives. Separate strategies will thus be needed to technically and economically achieve boiler performance targets related to fuel flexibility, energy efficiency, and environmental improvements. Although the strategies may appear similar, differences will exist based on boiler design, primary fuel type, boiler operating history and future plans, boiler age and conditions, and overall boiler integration into the process facility. As a result, it will be critical for the boiler owners and boiler/technology vendors to cooperatively define strategies for individual and families of boilers in order to minimize both capital and life-cycle costs.

Integration of Advanced Burner Concepts. Another key to improving process energy/compatibility is to integrate advanced burner concepts with boiler/duct heater configurations. Each system element should be examined according to the fluid-flow path to ensure that assumptions made about downstream elements are based on fact rather than conjecture.

Other. The design and application of advanced equipment and systems will lead to an increased worldwide market share for U.S. equipment, helping maintain U.S. leadership in industrial boiler technology. Many other activities, including basic combustion research, the development and application of advanced tools and models, and establishment of demonstration programs will also contribute to this goal. Specific high-priority needs include a study of the scaling of design over a range of sizes, research to investigate the use of electric fields to enhance the stability of lean (air-fuel) pre-mix burners, and improved availability of research results and other technical information.

The industry should regularly examine existing technologies that can be applied to fuel conversion or fuel reforming, which are critical to achieving fuel flexibility. Boiler systems are not generally designed to allow switching from a gas to a solid fuel, requiring a decision as to whether to refit the system for burning a solid fuel or to reform the solid fuel to meet the specifications of the existing burner/boiler combination.

Fuel conversion processes may at the same time be able to remove unwanted constituents and trace elements.

5. Industrial Process Heating Systems

> *"The furnace of the future will process uniform, high-quality end products at high rates of production with low specific fuel consumption and minimal environmental impact. This cost-effective furnace will be fully automated and adaptable to changing process needs and fuel availability. It will be safe, reliable, and easy to install, maintain, and operate."* *Industrial Combustion Vision*, May 1998

The *Industrial Combustion Vision* outlined performance targets that shaped the research strategy for industrial process heating systems. Some of the targets, especially in environmental areas, may be difficult to achieve because of the cross-cutting nature of the industry and the wide range of applications in which the equipment is used. However, technology will afford opportunity, especially in the environmental area, and aggressive goals are needed to guide the industry toward the advanced technology development that will ensure U.S. global leadership in supplying process heat and steam.

Market forces dictate that the performance targets must be met in a cost-effective manner. It is unlikely that every industrial heating system in every application will achieve the specific quantitative targets, and individual companies are not expected to achieve 90 percent reduction in emissions of criteria pollutants at the expense of cost-competitiveness. However, most plants will benefit from reducing emissions from each furnace, especially if the plant has high-temperature furnaces.

Research and Development Needs

The performance targets established in the *Vision* will be met through research and other activities (Exhibit 5-1) in the following categories:

- Environmental Quality and Greenhouse Gases
- Fuels Flexibility
- Energy Efficiency
- Process Improvement
- Safety and Reliability
- Research and Education
- Cost

Exhibit 5-1 shows how the R&D will address the performance targets in the *Vision*. The shadings in the exhibit indicate the priority of the R&D, and the exhibit also provides the time frame in which useable results could be anticipated from the various research projects, assuming initiation in the near future. complete listing of the R&D needs (categorized by technology) is given in Appendix E.

The highest-priority R&D needs have been further analyzed to determine their impact on energy efficiency, contribution to performance targets, key technical hurdles, and current level of research activity (Exhibit 5-2).

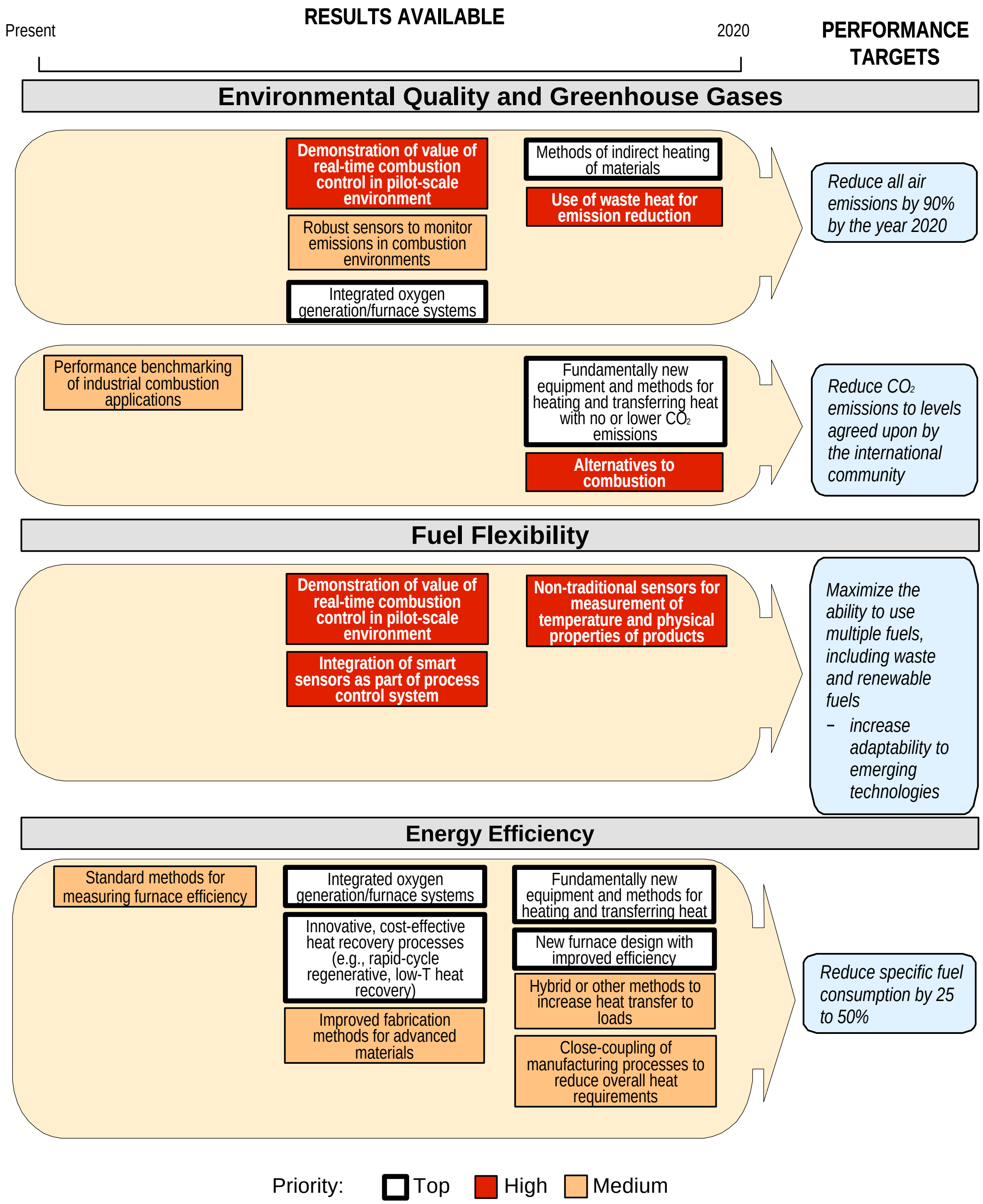

Exhibit 5-1. R&D Activities To Advance Industrial Process Heating Systems

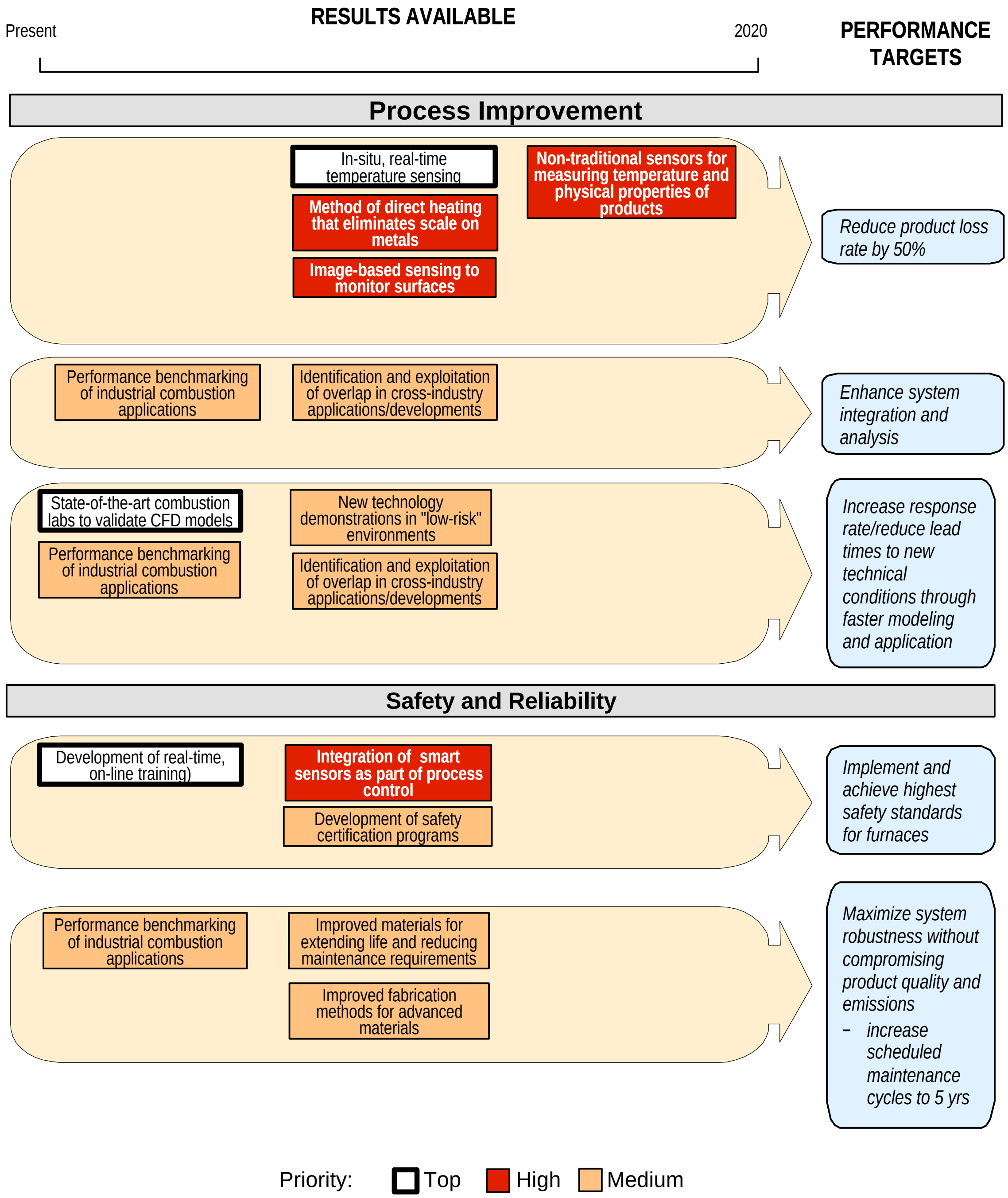

Exhibit 5-1. R&D Activities To Advance Industrial Process Heating Systems (cont.)

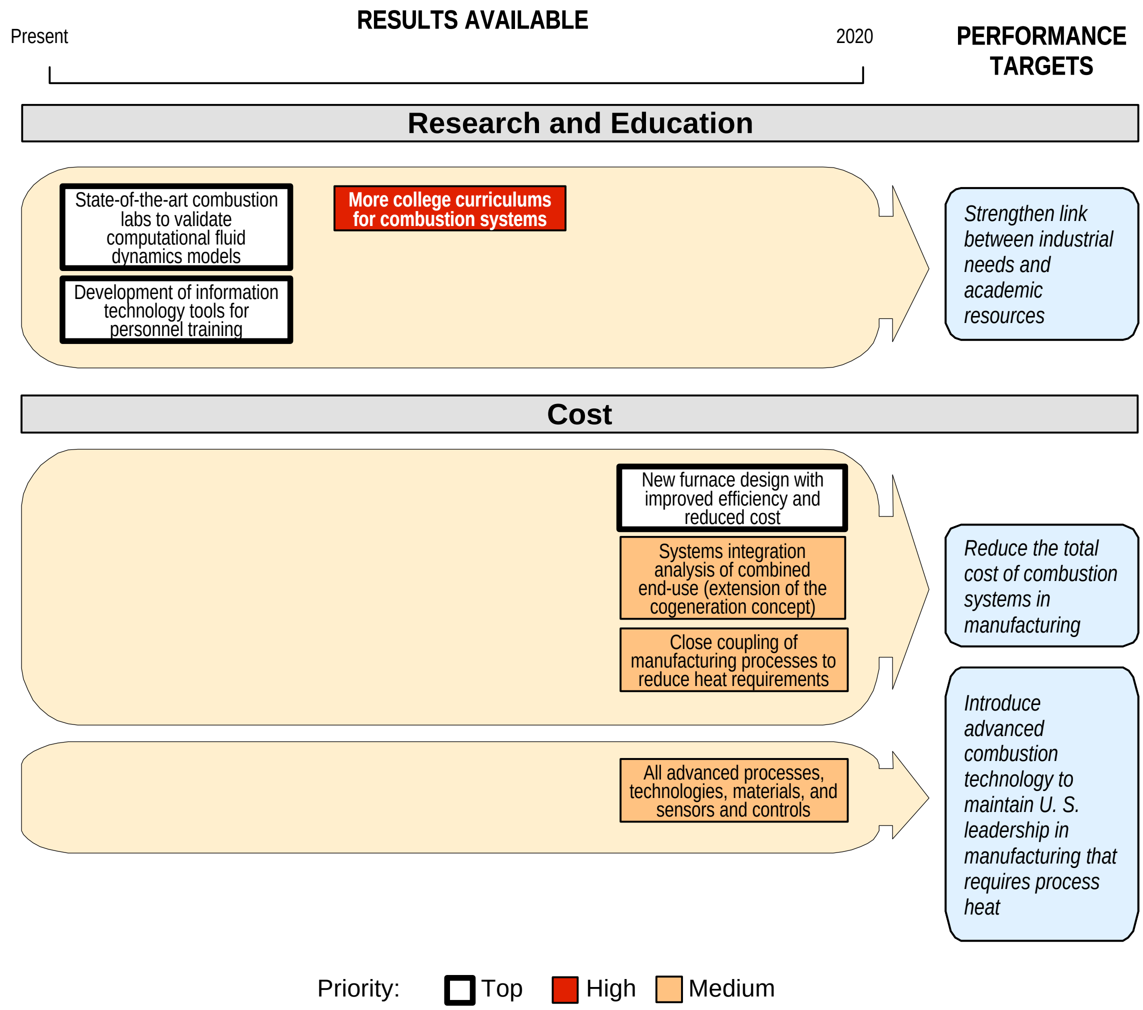

Exhibit 5-1. R&D Activities To Advance Industrial Process Heating Systems (cont.)

While each of these high-priority needs contributes to numerous performance targets, the most commonly addressed targets are reduced air emissions; improved energy efficiency; and increased product quality, yield, and productivity. The most common technical barriers in the way of successful completion of these research needs are

- process integration issues;
- materials issues; and
- lack of collaboration and cooperative efforts between equipment manufacturers, users, academia, and government agencies supporting research in this area.

Exhibit 5-2. Highest-Priority R&D Needs in Industrial Heating

R&D Need	Impact on System Energy Efficiency	Contributes To Which Targets	Key Technical Hurdles
New furnace designs for improved efficiency and reduced emissions	Very high	• CO_2 reduction • Energy efficiency • Lower costs • U.S. competitiveness	• Process-specific • Integrated into manufacturing process • Physical limits of heat transfer
In-situ, real-time sensing (e.g., tube temperature) *and* **Non-traditional sensors for measurement of temperature and physical properties**	Moderate	• Safety • Reduced product loss • Lower air emissions • CO_2 reduction • Lower costs • U.S. competitiveness	• Reliability • Interference • Survivability • Integration of technology • Communication between developers on application
Innovative, cost-effective heat recovery processes	High	• Energy efficiency • Lower air emissions • CO_2 reduction	• Heat transfer techniques • Materials
State-of-the-art combustion laboratory to validate computational fluid dynamics models	Moderate	• Stronger link between industry & researchers • Systems integration • U.S. competitiveness	• Computational limits (computer) • Communication between researchers and equipment manufacturers
New and improved method to generate process heat (without environmental impact)	Unknown	• Lower air emissions • CO_2 reduction • Reduced product loss • Reduced fuel consumption	• Innovative ideas • Materials

New Furnace Designs. The energy efficiency goal for industrial heating equipment stated in the *Vision* is to reduce specific fuel consumption by 20 to 50 percent. The most critically needed research to accomplish this includes the development of new, more efficient furnaces, as well as integrated oxygen generation/furnace systems. The objective of research into new furnaces would be to reduce the size of the furnace (and thus the energy requirements) without reducing capacity or productivity. Once an industrial heating system is designed, overall manufacturing processes should be reevaluated and possibly modified to optimize the entire process and fully capitalize on the advanced capabilities of the system. Low-cost means of producing oxygen-enriched air will result in wider usage of oxygen in combustion systems, leading to greater energy efficiency.

Sensors. While a good deal of basic and laboratory-scale research is being done regarding sensing needs, more companies need to focus on intelligent sensor design in their R&D plans. High-priority research needs include in-situ, real-time temperature sensing, image-based sensing to monitor surfaces, and non-traditional sensors for measuring the temperature and other physical properties of products being processed. The demonstration of real-time combustion controls for multiple fuel applications would also contribute to the goal of achieving maximum fuel flexibility.

Safety and reliability goals can be achieved by integrating smart sensors into process control systems, and using information-technology tools such as on-site, on-demand safety training for operating personnel. Personnel training may also be enhanced by using “packaged” programs on the fundamentals of heating equipment design, start-up, operation, and maintenance adapted for individual users. Additional courses are needed to train personnel to apply the fundamental physical science they learned in college to the design of heating equipment and processes in order to maintain the necessary performance standards. Teams of both equipment users and manufacturers to monitor safety and performance can help optimize performance without compromising safety standards.

Heat Recovery Processes. The use of innovative, cost-effective heat recovery processes, such as rapid-cycle regenerative systems and methods of recovering low-temperature heat, will also increase system energy efficiency. The economic application of materials and designs that can withstand dirty, contaminated, unpredictable combustion flue gases will accelerate high-temperature heat recovery in industrial heating applications. Low-temperature heat recovery (e.g., recovering the heat in warm process water) also presents a significant opportunity to save energy and reduce costs.

Even with the successful development of new equipment and heat recovery processes, however, there are certain limits of efficiency beyond which the furnace of the future will not advance. Revolutionary technologies may be needed to capture the secondary, low-temperature heat that is not recovered. Process improvements can reduce loss of product and increase processing flexibility while helping improve energy efficiency and environmental performance. Advanced sensors and controls are needed for better monitoring of the heating process, which will improve product quality and furnace/heater productivity.

Combustion Laboratories. State-of-the-art combustion laboratories that can simulate actual process conditions, particularly high-temperature processes, will be needed to validate computational fluid dynamics models.

New Methods to Generate Process Heat. The development of new and improved methods to generate process with no or reduced environmental impact is a high-risk, long-term activity whose potential impact is difficult to estimate.

6. Conclusions and Next Steps

The industrial combustion community has adopted the "Industries of the Future" approach promoted by the U.S. Department of Energy to plan for future technology development. This approach provides a three-step process for devising and implementing a comprehensive plan for advanced technologies. The *Vision* and the *Roadmap* represent the first two steps. The third step is the implementation of the research specified in the *Roadmap*. It is anticipated that this implementation will take place through collaborative partnerships among private companies, suppliers, trade associations, national laboratories, academia, private research institutions, and government agencies.

The U.S. Council on Competitiveness, in a recent assessment of industry's technology needs, has identified these types of partnerships as the single most important step toward meeting tomorrow's technology and market challenges. Many issues, including the oversight of partnerships between competing companies and the sharing of results developed with private-sector contribution, will need to be resolved if cooperative efforts are to be established. By articulating its own technology strategy, however, the industrial combustion community hopes to motivate all of the stakeholders in industrial combustion to refocus their research efforts in line with industry's needs.

Appendix A. Performance Targets

Burner Targets

Boiler Targets Directly Related to Burners

Environmental Quality

- Reduce criteria pollutants for gaseous fuels
  - Reduce NOx emissions to <2 ppm
  - Reduce CO emissions to <5 ppm
  - Reduce particulate matter emissions to <0.003 lbs/10^6 Btu
  - Reduce volatile organic compounds and hydrocarbons emissions to <1 ppm
- Approach gaseous fuel targets as closely as possible for solids and liquids
  - Achieve >98 percent SO_2 removal
- Shift toward fuel-neutral, output-based standards
- Reduce hazardous air pollutants
  - Meet or exceed requirements
- Reduce solid waste
  - Maximize by-product utilization

Fuel Flexibility

- Consider all combustible byproducts as potential fuels
- Develop the ability to burn different fuels simultaneously
- Develop on-line fuel switching capability

Boiler Targets for Which Burner Is One of Several Factors

Environmental Quality

- Reduce CO_2 emissions
  - Respond to worldwide CO_2 reduction pressures by maximizing system efficiency

Energy Efficiency

- Maximize system efficiency

Safety/Reliability/Maintainability

- At minimum, maintain current levels of safety
- Improve system reliability by 50 percent
- Increase time between scheduled outages by 100 percent

Materials

- Integrate catalysts within the boiler itself

Burner Targets

Cost Effectiveness
- Lower first cost of equipment
- Lower life-cycle costs

Industrial Heating Equipment Targets Directly Related to Burners

Environmental Quality
- Reduce emissions of criteria pollutants by 90 percent by 2020

Fuels and Oxidants
- Maximize the ability to use multiple fuels, including waste and renewable fuels
  - Increase adaptability to emerging technologies

Process Improvements
- Increase response rate/reduce lead times to new technical conditions through faster modeling and application
  - Shorten lead-time from concept to saleability by 50 percent
  - Educate industry about the limitations of models

Industrial Heating Equipment Targets for Which Burner Is One of Several Factors

Environmental Quality
- Reduce CO_2 emissions to levels agreed upon by the international community
  - Increase efficiency
  - Achieve higher hydrogen-to-carbon ratio
  - Practice carbon sequestration
  - Increase use of biomass

Energy Efficiency
- Reduce specific fuel consumption (Btu/constant dollar of product) by 20 to 50 percent by 2020

Process Improvements
- Reduce product loss rate by 50 percent

Safety/Reliability
- Maximize system robustness without compromising product quality and emissions
  - Increase scheduled maintenance cycle to five years

Cost
- Reduce the total cost of combustion in manufacturing to maintain its status as the preferred choice of energy services
- Introduce advanced combustion technology to maintain the United States as the world leader in

Boiler System Targets

Environmental Quality
- Reduce criteria pollutants for gaseous fuels
  - Reduce NOx emissions to <2 ppm
  - Reduce CO emissions to <5 ppm
  - Reduce particulate matter emissions to <0.003 lbs/10^6 Btu
  - Reduce volatile organic compounds and hydrocarbons emissions to <1 ppm
- Approach gaseous fuel targets as closely as possible for solids and liquids
  - Achieve >98 percent SO_2 removal
- Shift toward fuel-neutral, output-based standards
- Reduce CO_2 emissions
  - Respond to worldwide CO_2 reduction pressures by maximizing system efficiency
- Reduce hazardous air pollutants
  - Meet or exceed requirements
- Reduce solid waste
  - Maximize by-product utilization
- Reduce wastewater
  - Maximize water reuse (zero discharge)
  - Meet all environmental regulations

Fuel Flexibility
- Consider all combustible byproducts as potential fuels
- Develop the ability to burn different fuels simultaneously
- Develop on-line fuel switching capability
- Promote use of renewable and waste fuels in the United States

Energy Efficiency
- Maximize system efficiency
- Minimize stack temperatures via residual heat recovery
  - Achieve 150°F stack temperature
- Integrate boilers with more advanced thermodynamic cycles (including alternative working fluids)

Process/Energy Compatibility
- Integrate steam and power requirements with process plants
- Install cogeneration systems as the rule rather than the exception

Safety/Reliability/Maintainability
- At minimum, maintain current levels of safety
- Improve system reliability by 50 percent
- Increase time between scheduled outages by 100 percent
- Eliminate trips due to control malfunction

Boiler System Targets

Materials
- Develop reduced-cost materials able to exceed 1,050°F in superheater and higher operating pressure
- Develop inexpensive, corrosion-resistant materials that are able to function below 140°F
- Improve the heat transfer coefficient
- Improve performance (erosion and corrosion) at higher temperatures and pressures
- Improve material welding/joining
- Enhance refractory performance
- Integrate catalysts within the boiler itself

Cost Effectiveness
- Lower first cost of equipment
- Lower life-cycle costs
- Promote government regulations that encourage adoption of new technologies
- Promote government incentives for investment in efficient technologies

Policy
- Promote importance of boilers to U.S. economy; maintain U.S. leadership. Introduce advanced technology to maintain United States as world leader for the boiler industry.

Industrial Process Heating System Targets

Environmental Quality
- Reduce emissions of criteria pollutants by 90 percent by 2020
- Reduce CO_2 emissions to levels agreed upon by the international community
  - Increase efficiency
  - Achieve higher hydrogen-to-carbon ratio
  - Practice carbon sequestration
  - Increase use of biomass

Fuels and Oxidants
- Maximize the ability to use multiple fuels, including waste and renewable fuels
  - Increase adaptability to emerging technologies

Energy Efficiency
- Reduce specific fuel consumption (Btu/constant dollar of product) by 20 to 50 percent by 2020

Process Improvements
- Reduce product loss rate by 50 percent
- Enhance system integration and analysis
- Increase response rate/reduce lead times to new technical conditions through faster modeling and application
  - Shorten lead-time from concept to saleability by 50 percent
  - Educate industry about the limitations of models

Safety/Reliability
- Implement and achieve highest safety standards for furnaces to attain zero accidents
- Maximize system robustness without compromising product quality and emissions
  - Increase scheduled maintenance cycle to five years

Research and Education
- Strengthen link between industrial needs and academic resources

Cost
- Reduce the total cost of combustion in manufacturing to maintain its status as the preferred choice of energy services
- Introduce advanced combustion technology to maintain the United States as the world leader in manufacturing that requires process heat

Appendix B. Barriers

Exhibit B-1. Barriers to Achieving Burner Performance Targets (most critical barriers boldfaced)
Fundamental Understanding

- **Burner stability limits for low-NOx burners**
  - dynamics and vibration at those limits
  - understanding of the coupling of oscillations between burner and system
- **Poor understanding of mixing momentum characteristics in fuels/oxidants**
  - air/fuel mixing over a high turndown range to achieve low emission
- **Poor understanding of noise as a pollutant both from combustion and mechanical components**
- **Limited ability to predict changes in properties (emissivity of refractory materials, emissivity for in-flight particles, gaseous heat transfer, etc.)**
- Poor understanding of the vaporization of liquid fuels to allow burning them at sufficiently low temperatures to avoid particulates
- Inability to handle multi-burner flame interactions
- No techniques for converting fuel nitrogen to N_2
- Poor understanding formation, growth, and capture/control of particulates
- Knowledge gained at small scale not transferable to large scale
- Inability to calculate theoretical limits (of NOx, etc.)
- Poor understanding of radiation furnaces

Heating Equipment Design
- **Mismatched burner/process heater design** - **Lack of robust design tool for new burners** - Poor compatibility of solid and gas fuel burners
Controls and Measurements
- **Limited dynamic accuracy of controls** - **Lack of real-time, fast-responding measurement of fuel/air ratio in the flame** - **Poor measurement capability of low-level emissions** - Inability to change fuels in real-time based on customer demand
Emissions
- **Unclear if $PM_{2.5}$ poses a problem to burners fueled with process or product gas** - Inability to maintain emission requirement over range of turndown - Trade-offs between NOx and VOC and CO emissions (not possible to reduce both) - Issues related to emissions of sulfur trioxide (SO_3)

Exhibit B-1. Barriers to Achieving Burner Performance Targets **(most critical barriers boldfaced)**
Composition of Fuels and Oxidants
- **Limited flammability characteristics of most fuels and oxidants** - Presence of fuel nitrogen and fuel sulfur - Excessive cost of generating oxygen
Design and Application Tools
- **Availability and cost of models to perform calculations** - Weak computational fluid dynamic codes to describe physics, specifically radiation
High-Temperature Materials
- **Cost-effective, high-temperature materials (ceramics) unable to handle excursions** - Thermal inertia created by materials and system design
Business Issues
- **Shortage of people educated in combustion (lack of interest in universities)** - Difficulty educating customers to gauge their expectations - Limited space at front of burner for retrofit applications
Policy
- **Inflexibility of regulations for short excursions in fuel, temperature, etc.**

Exhibit B-2. Barriers to Achieving Boiler Performance Targets **(most critical barriers boldfaced)**
Technology
- **Broad variety of equipment (no standardization within industry)** - **Performance targets not all compatible** - **Footprint size in advanced systems** - **Difficulty duplicating manufacture claims for some equipment** - **Stability of lean pre-mix combustion systems to achieve NOx goals** - **Compatibility issues between burners/boilers (interface issues)** - Condition of input air - Interface with the electrical grid - Ability of equipment to perform to specifications - Wide range of storage and handling needs for different fuels - Differences in NOx control for different fuels - Wide range of specs and conditions over which goals are met - Reliability and corrosion issues - Lack of technology in small sizes - Particulates entering burner of higher concentration than allowed to exit stack - cost-effective particulate control technology options not adequately demonstrated for a variety of process streams
Fundamental Knowledge
- Lack of knowledge of thermal gas dynamic phenomena occurring in the system (velocities, fundamental gas dynamics) leading to inability to scale technology up and down - Nitrogen content of the fuel (barrier especially to fuel flexibility)
Control, Measurement, and Instrumentation

- **No or limited experience with measurement of and calibration standards for NOx and CO at low concentrations in various process streams**
    - interferences to measurement of low NOx and CO concentrations
    - no methodology for specification
- **Lack of verified gas-conditioning and measurement technologies, and environmental measurement technologies overall**
- Variety of techniques for monitoring and controlling emissions

Materials
- Cost and risk of using new materials (e.g.,ceramics, alloys) - Difficulty building recuperators because of conditions and temperatures that must be withstood - Lack of application experience with new materials for heat exchangers, burners, and construction

Exhibit B-2. Barriers to Achieving Boiler Performance Targets
(most critical barriers boldfaced)

Knowledge/Education

- **Shortage of people educated in combustion**
- **Scientifically incomplete definition of new technology**
  - undetermined variability in operation
- Lack of technology solutions that reduce both CO_2 and NOx
- Incompatibility of some goals with operability
- Lack of operator training and loss of operator experience
- Lack of industry awareness of new technologies

Institutional

- **Lack of infrastructure for collaborative industry R&D**
- **Technology push inhibited by regulations**
- **Confidentiality of data concerning new developments**
- **Lack of incentives for people (government, private sector) to spend dollars on research and development**
- **Lack of incentives for developing "brilliant ideas"**
- Only some areas of country with the capacity/ability to meet goals
- Few incentives for common lobbying (e.g., boiler companies that are subsidiaries of large corporations)
- Actions to improve constrained by "words" of anti-trust laws
- Users that avoid being first to install and use prototype equipment
- Scope of R&D too broad for a single company

Economics

- **Avoidance of risk by industry**
  - availability/reliability constraints that heighten risks
  - time to accept new technologies and understand limitations
- **Problems in retrofitting the installed base of equipment**
  - cost and variability of equipment
- Reduction in capital cost of NOx systems capable of <2ppm
- No risk mitigation for using new technologies

Regulatory

- No early reduction credit for improved environmental performance
- Sacrifice in energy efficiency to achieve low NOx,
- Lack of solution not pitting efficiency versus economics or environment
- Regulatory classification of waste streams for potential use as fuels
- No requirement for <2 ppm NOx in current U.S. policy

Exhibit B-3. Barriers to Achieving Process Heating Performance Targets
(most critical barriers boldfaced)

Predicting and Understanding Properties and Performance

- **Poor ability to predict the performance of combustion devices (modeling)**
- Lack of understanding of formation of emissions
- Lack of CFD models as design tools
- Lack of knowledge of metrics and parameters for alternate fuels

Measurement and Data

- **Lack of detailed data on the performance of combustion systems**
- **Inability to measure heat uniformity and rate in multiple burner systems**
- **Deficiency of overall tube temperature measurements**
- **Inability to measure physical properties at temperature while heating**
- Inability to accurately measure process performance properties
- Inability to accurately measure fuel efficiency and establish baselines

Technology Innovation

- **Lack of process innovation (leap frog technology)**
- **High cost of oxygen**
- **Lack of real-time controls (e.g., for flame stabilization, emissions)**
- **Lack of cost-effective waste heat recovery**
  - insufficient heat transfer to reduce cost of heat recovery
  - inability to utilize energy in low-temperature heat recovery
- Lack of high-temperature heat transfer process without flame
- Non-attention to new designs, system integration, manufacturability, operational protocol, and fuel specification

Education and Training

- **Few qualified personnel attracted to combustion industry**
- Insufficient training for control operators
- Few incentives to encourage new human resources into combustion
- Lack of curriculum for combustion in undergraduate programs

Non-Technical/Infrastructure

- **High combined risk of pursuing new technical solutions**
- **Different industries working in isolation and limiting information transfer**
- **Limited scope of industrial combustion R&D programs**
- Time constraints on product manufacturer and customers
- Unwillingness of customers to try new approaches because of possible loss of production in short- term
- Lack of coordination in siting facilities to improve overall efficiency
- No immediate reflection of returns on long-term research on bottom line

Appendix C. Burner R&D Needs by Technology

Exhibit C-1. Burner R&D Needs
(in relative order of priority; highest priority needs boldfaced)

Fuels Processing

- **Assisted combustion using a combination of fuels (hybrid systems)**
- **Inexpensive methods to separate nitrogen from liquid fuels**
- Method for producing economical oxygen as an oxidant

Process Controls and Sensors

- **Low-cost, robust, non-intrusive device for in-flame measurement of temperature and fuel-air ratio for control use**
- **New combustion control algorithms for "smart" burner incorporating emissions numbers**
- **Advanced fast- reacting flame scanning for low-NOx burners**
- Fast process controls to solve process dynamics (e.g., neural network process control)
- Equipment to measure low emissions and oxygen levels economically and accurately
- Dynamic coupling of near limit flames with fuel-air ratio variance in particular system configuration

Burner Design and Development

- **Advanced burner stabilization methods**
  - seed stabilization with other fuels, catalysts, oxygen, chemical injection
  - coupling of combustion with other energy sources (e.g. electric, acoustics) for enhancing heat transfer and stability
- **Methods to thoroughly, economically pre-mix fuel and air while preventing flashback**
- **Control system that makes burner "smart" so that it that determines process requirements and evaluates fuel options in real time**
- **Ultra-low-emission, liquid fuel burner**
  - examining fundamental properties of pre-vaporized liquid fuel flame (flame temperatures, emissions, and particulates)
- **Low emission burners that accept fuel blends (i.e. hydrogen, biofuels, etc.)**
- **High turndown, low-pressure-drop, variable geometry burner**
- Burner with variable heat flux capability
- Flexible burner to deal with future modifications (e.g. multiple fuels, wastes)
- Non-steam ways to atomize liquid fuels economically with gaseous fuels
- Better understanding of how catalysts can be used in product development with conventional staging approaches to achieve flame stability, low NOx, low temperatures
- High-temperature catalytic materials (1,400ºC)
- Ceramics for new cost-effective burner materials
- Device to measure fuel-air ratio and a burner compatible with this device

Exhibit C-1. Burner R&D Needs **(in relative order of priority; highest priority needs boldfaced)**
Tools, Models, and Algorithms
• **More robust design tool for new burners** - adapting existing complex CFD codes to burners - studying combustion outside of burner to gather data for input into models - increasing availability of existing facilities for validation - modeling for furnace heat transfer - developing more accurate CFD codes for prediction of radiation characteristics • **Determination of fundamental causes of combustion noise in low pressure combustion chambers** • Unified code that accounts for burner-furnace geometry that includes emissivities and multi-flame interactions
Other
• **Simpler, more cost-effective NOx processing downstream of furnace** • Optimized emissivity of materials - (effective heat transfer) for energy efficiency • Economic analysis of long-term outlook for burners • Creation of partnership between burner manufacturers, universities, and users (Partnership for a New Generation Burner) • Methods to increase volumetric heat of release • Tailoring of spectral characteristics of radiation

Appendix D. Boiler R&D Needs by Type of Research

Exhibit D-1. Boiler R&D Needs (in relative order of priority; highest priority needs boldfaced)
Fundamental Research
• **New boiler and combustion cycles** - pressurized combustion systems - turbo-charged (combinations) recuperated - min 1,500 psi, 1,500^{0}F; 3:1 pressure ratio • **Use of electric fields to improve stability range and equivalence (fuel/air ratio) of lean pre-mix burners** • **Improved low-NOx measurement devices** • **Equivalent of a Burner Engineering/Research Laboratory (BERL) for fire-tube boilers** • **Efficient conversion of all fuels to H_2 and CO (for catalytic combustion systems)** • **Acceleration of the application, testing, and commercialization of new materials** • Understanding of the chemistry of fuel nitrogen to NOx (conversion)
Developmental Research
• **Integration of all established, desirable elements into a common technology platform ("super" boiler program) to develop family of advanced packaged boilers** • **Integrated advanced burner concepts and boiler/duct heater combinations** • **Burner and combustion systems that are compatible with advanced gas turbine technology More efficient atmospheric fluidized-bed combustion systems for solid fuels** • **Exploration of stability of lean pre-mix systems using different stabilization procedures in standard boilers (2-7 MMBTU/hr)** • **Stable combustion systems to accommodate rapid load changes** • Indirect-fired radiant air heater units and required materials developments • Non-invasive techniques for the removal of solids from boiler tubes
Knowledge and Education
• **Energy technology clearinghouse to store and categorize information** • **Examination of existing technologies that can be applied to fuel reforming to increase fuel flexibility** • Better explanation of combustion industry's priorities to specialized R&D communities • More expertise in trouble-shooting • Training and education program for operators and users

Exhibit D-1. Boiler R&D Needs **(in relative order of priority; highest priority needs boldfaced)**
Institutional
• **Definition of separate strategies for retrofitting different boiler types to meet performance standards** • **Establishment of high-level, government/industry group to set priorities for combustion technology research and joint funding** • **Determination of cost/benefit of various recuperative schemes (user-friendly tool)** • **Consistent government standards for energy and environment for all fuels and all industries** • Baseline energy impact on U.S. economy, security, and sovereignty • Identification of potential combustion technologies for all fuels to meet goals • Identification of impacts of one goal on another and examination of interactions
Testing and Demonstration Programs
• **Testing and demonstration of hybrid systems (e.g., low-NOx burners plus post-combustion cleanup equipment) to determine their potential for meeting environmental targets** • **High-efficiency, low-emission boiler demonstration program (like CCT Program but not specifically associated with coal)** • **Testing and demonstration of fuel use (looking at emission control and operability issues)** • **Energy-efficient technology verification program** • Program to expand use of ash from boilers (particularly those using low-NOx burners) burning a variety of fuels • Independent evaluation of post combustion clean-up systems • Continued testing of fuel blends

Appendix E. Industrial Process Heating System R&D Needs by Technology

Exhibit E-1. Industrial Process Heating System R&D Needs
(in relative order of priority; highest priority needs boldfaced)

Modeling/Analytic Tools

- **Computational tools that contain validated, high-fidelity combustion models**
- **Reliable, efficient model of turbulent, reacting flow**
- Common method for measuring furnace efficiency

Process Controls and Sensors

- **Non-traditional sensors for measurement of temperatures and physical properties**
- **In-situ, real- time (tube temperature) sensing**
- **Image-based sensing to monitor surfaces**
- **Demonstration of real-time combustion control in pilot-scale environment**
- **Integration of smart sensors as part of process control system**
- **Robust sensors to measure critical parameters in combustion environments**

Innovative Furnace Design

- **Fundamentally new equipment and methods for heating and transferring heat (i.e., exothermic chemical reaction)**
- **New furnace design with improved efficiency (a smaller box)**
- **Integrated oxygen generation/furnace system (temperature- swing adsorption) such as ceramic membrane**
- **Enhanced heat transfer in furnaces**
- **Methods of indirect heating of materials**
- **Demonstration of atmosphere control for direct firing/heating (e.g., eliminates scale on steel)**
- **Alternatives for heat processing**
- **Hybrid systems or other methods to increase heat transfer to loads**

Heat Recovery

- **Innovative, cost-effective, heat recovery process**
  - rapid cycle regenerative system
  - low-temperature heat recovery (e.g. warm water)
- Uses of waste heat for emission reduction

Exhibit E-1. Industrial Process Heating System R&D Needs (in relative order of priority; highest priority needs boldfaced)
Materials
• Improved materials for extending furnace life/reducing maintenance requirements • Improved fabrication methods for advanced materials (i.e., for irregular shapes)
Manufacturing System Issues
• **Combustion alternatives (e.g. induction heating)** • Systems integration analysis of combined end use to extend the cogeneration concept • Close coupling of manufacturing processes to reduce heat requirements
Research Approaches/Education/Training
• **State -of-the-art combustion labs to validate CFD models** • **Using information technology tools for personnel training** • **Creation of development teams among users, researchers, and equipment manufacturers to focus on specific needs** • **College curriculum for combustion engineers** • Characterization of state of the industries (benchmarking) • Development of opportunities for international cooperation on combustion technology research • Industry certification program for safety • Demonstration of technology developments in low-risk method/environment • Identification and use of technical overlap in various industry applications

Appendix F. Contributors to the Roadmap

This roadmap document was prepared by Energetics, Incorporated, based on input provided by the following participants in a facilitated workshop held in June 1998. Energetics would like to acknowledge the special guidance provided by Gideon Varga of the U.S. Department of Energy, Arvind Thekdi of CSGI, Inc. and Greg Weber of the Energy and Environmental Research Center of the University of North Dakota.

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