Industrial Combustion Technology Roadmap

A Technology Roadmap by and for the Industrial Combustion Community

October 2002

This roadmap document was prepared by Energetics, Incorporated based on input provided by participants in a facilitated workshop held in August 2001. (Contributors are listed in Appendix A.) The revised Combustion Roadmap represents a consolidated industry viewpoint, but not necessarily the government's top R&D focus. The Department of Energy intends to use the Combustion roadmap as one of the industry inputs as its R&D program strategy is formulated.

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Executive Summary

The U.S. combustion industry is among the most productive, efficient, and technologically sophisticated in the world and remains vital to the nation's economic competitiveness and national security. As the industry looks forward, it confronts tremendous growth opportunities but also significant technical and market challenges. Future industry success will depend on the industry's ability to respond to competitive pressures as well as public expectations for a clean and sustainable industry.

Much progress has been made in understanding the fundamental science of combustion; however, much more is needed as regulatory and competitive forces push the industry to develop combustion equipment with better performance, lower environmental impact, and greater flexibility. Immense opportunities exist for companies to develop and apply new technology responding to these needs. Unfortunately, few companies can accept the high technical and financial risk required for the research if the technology is not adopted widely enough to provide a payback on their investment.

To position itself for the future, the combustion industry has embraced a strategy for defining its performance targets for the next 20 years and for mapping out the technology pathway to accomplishing these goals. The industry outlines its challenges and long-term performance targets in the *Industrial Combustion Vision* (1998), and presents the research and development (R&D) activities needed to achieve these performance targets in the *Industrial Combustion Technology Roadmap*[1]. The roadmap guides collaborative research, development, and demonstration of technologies and processes, its ultimate value being its ability to align the components of the proposed research across industry, academia, and the federal government.

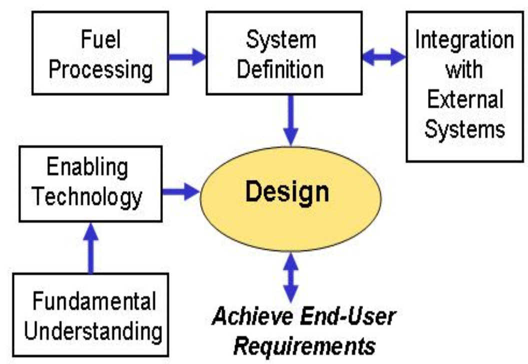

Exhibit ES-1. Combustion System Design Process

The challenges of improving combustion processes are extremely complex, and the combustion equipment industry must work with other resources to achieve them. While developments at the component level will remain important, breakthroughs in efficiency, productivity, safety, and environmental performance hinge on optimizing combustion processes from a total systems perspective. By approaching development from a total systems view, research can result in increasingly efficient, clean, fuel-flexible, and reliable combustion systems, capable of producing uniform high-quality end products at high production rates. These systems will offer benefits to

[1] The vision and previously published roadmap can be obtained through the OIT website at http://www.oit.doe.gov/combustion/vision_roadmap.shtml.

our nation, furthering energy security and environmental protection goals.
According to the roadmap, industrial combustion research is focused on three areas: Boilers, Furnaces, and Burners. The burner is the most important component within a boiler or furnace system. The burner system design process, and how it must take into account the entire system, is described in exhibit ES-1. It demonstrates the major steps in the process of designing a combustion system. To further advances in the design process, a broad spectrum of R&D opportunities leading to the boiler and furnace of the future, are comprised of low-emission, efficient components that approach fundamental energy consumption limits. The highest priority needs, as well as the end-use requirements associated with each need, are described in exhibit ES-2.

Opportunities for saving energy in industrial combustion processes involve the application of technology to measure, control, and improve combustion systems. These technologies include improving heat transfer to the load and increased waste heat recovery in the furnace or boiler system. Further opportunities lie in developing completely new and innovative furnace and boiler designs. Through better fundamental understanding, these designs could transform today's combustion system into the low-emission, productive, and efficient Boiler or Furnace of the Future.

Process control, including advanced combustion stabilization methods, is also key to the industry's progress. Application of real-time sensors and control systems could help combustion designers and end-users optimize their burner system performance. Additionally, robust computational design tools would help burner designers reduce the time and cost of development of new combustion system designs.

To meet the industry objectives, some non-technical hurdles must also be crossed. Technology development is currently slowed because of multiple technology transfer difficulties. A pathway to demonstrate and commercialize new technologies must be created to achieve the industry's R&D objectives in a timely manner. With achievement of some of its R&D initiatives, the combustion industry will meet the targets set for the years 2010 and 2020.

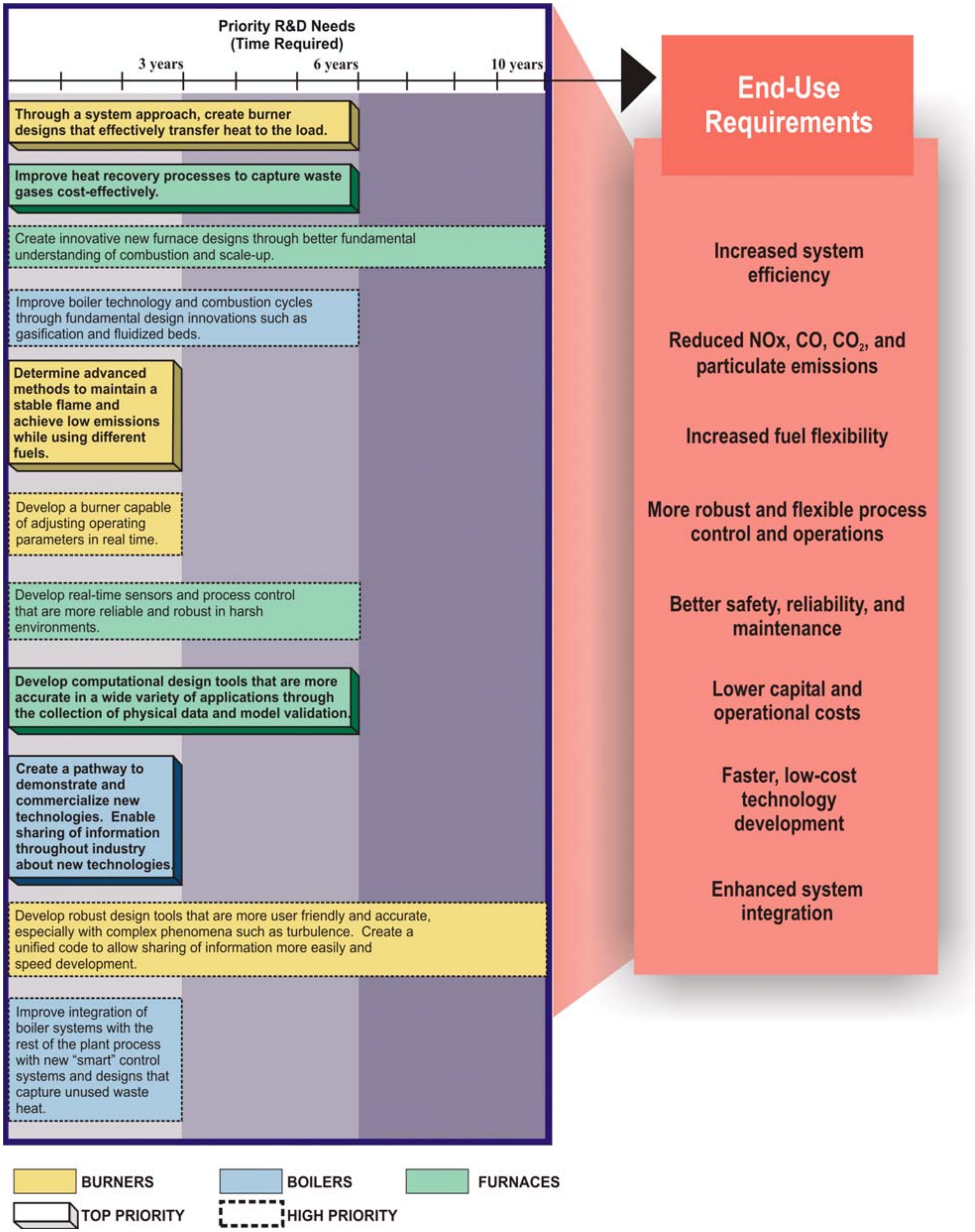

Exhibit ES-2. Top Combustion R&D Needs and Their Impacts on End-Users

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1. Overview and Introduction

The burning of fuel to produce heat or other forms of power has been the cornerstone of industrial processes for millenia. Over most of that time, there was little need to understand very much about the combustion process to achieve the desired results. In recent years, however, the need to minimize emissions while maintaining performance has focused substantial attention on the combustion process. Much progress has been made in understanding the fundamental science of combustion; however, much more is needed as regulatory and competitive forces push the industry to develop combustion equipment with better performance, lower environmental impact, and greater flexibility. Tremendous opportunities exist for companies to develop and apply new technology responding to these needs. Unfortunately, few companies can accept the high technical and financial risk required for the research in light of the economic risk that their technology might not receive sufficient adoption to provide a payback on their investment.

While the risk of research is high for individual companies, the pay off for the end-users is large. Virtually every manufacturing industry has a stake in improved combustion technologies. Boilers, furnaces, and other process heaters account for more than three-quarters of the total energy used by U.S. manufacturing industries. To meet the needs of these different industries, the design process must take into account some key factors provided by the end-users, as shown in Exhibit 1-1. First, the type of fuel and oxidant is often dictated by the end-user's facility. The system is then defined, based on the needs of the production process. With these inputs determined, the burner system can be designed based on the designer's knowledge of combustion as well as the available design tools and technology (CFD, sensors and controls, etc.). A critical factor in the design process is the understanding of fundamental combustion science which underpins the ultimate burner design. Through this process, the burner system design, whether a boiler, furnace, or process heating system, can ultimately meet the efficiency, productivity, safety, and environmental requirements of the end-user.

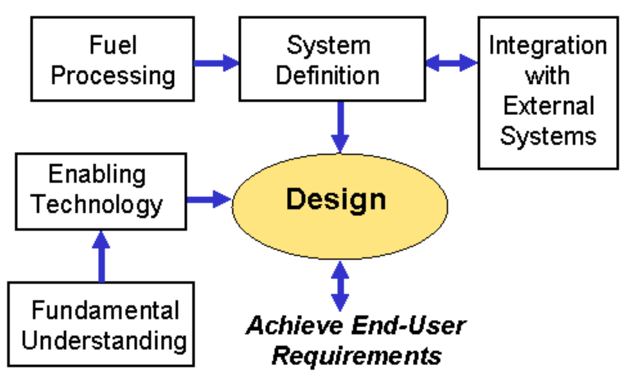

Exhibit 1-1. Combustion System Design Process

To address the research needs of the combustion community, users and manufacturers of industrial combustion equipment have joined forces to implement a strategy for directing future technology research into areas that best meet the needs of the industry as a whole. This strategy would then provide the framework for national initiatives to overcome the inherent risks of new combustion technology development. In the *Industrial Combustion Vision* [2](1998), the industry outlines the challenges facing it and sets ambitious performance targets (summarized in Exhibit 1-2) for technology developments over the next 20 years.

Exhibit 1-2. Key Performance Targets for Industrial Combustion Systems in the Year 2020
(from the *Industrial Combustion Vision*)

BOILER SYSTEMS

Specific to the Burner

- Reduce NOx emissions to <2ppm (gaseous fuels)
- Reduce CO emissions to <5 ppm (gaseous fuels)
- Reduce particulate emissions to <0.003 lbs/ 10^6 Btu (gaseous fuels)
- Enable simultaneous burning of different fuels
- Maximize system efficiency, thereby reducing CO_2

System

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

FURNACES / 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 - 50%
- Maximize the ability to use multiple fuels

System

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

- Introduce advanced combustion technology to maintain U.S. Leadership

In the *Industrial Combustion Technology Roadmap*[2], first published in 1999, equipment users, manufacturers, government agencies, academia, and research organizations, present the research and development (R&D) activities needed to achieve the performance targets identified in the Vision. The roadmap effectively guides collaborative research, development, and demonstration of technologies and processes, its ultimate value being its ability to align the components of the proposed research across industry, academia, and the federal government. However, technology and markets are not static. To address technological advances, changes in the global market, and new technical insights, the roadmap has been updated.

[2] The vision and previously published roadmap can be obtained through the OIT website at http://www.oit.doe.gov/combustion/vision_roadmap.shtml.

Towards achieving its Vision, the industry has established top priority R&D activities in the areas of burners, boilers, and furnace systems (summarized in Exhibit 1-3). Each of the eleven priority R&D Needs is analyzed in detail through a one-page summary within the appropriate burner, boiler or furnace chapter. The summaries explain the key technical elements as well as providing the time required to meet each research need. The key R&D areas can also be linked for burners, boiler systems, and furnace systems through analysis of the design process. Exhibit 1-3 shows how this process applies to the key elements of all three research areas.

The industry has also addressed institutional issues, such as the availability of research results and test data, along with improved training and education for equipment operators. (Note: the word "combustion," used throughout the roadmap, covers all industrial processes that include burners, such as furnaces, process heaters, steam generators, et cetera.)

As shown in Exhibit 1-4, the design process requires input from many different technological areas. Breakthroughs in efficiency, productivity, safety, and environmental performance hinge on optimizing combustion processes from a total systems perspective. New technologies promise increasingly efficient, clean, fuel-flexible, and reliable combustion systems, capable of producing uniform high-quality end products at high production rates.

This roadmap aligns the different research components in burners, boilers, and furnace systems across industry, academia, and the Federal sectors. The ultimate value of the roadmap will be seen through implementation of this research through collaborative partnerships among the various stakeholders in the industrial combustion community.

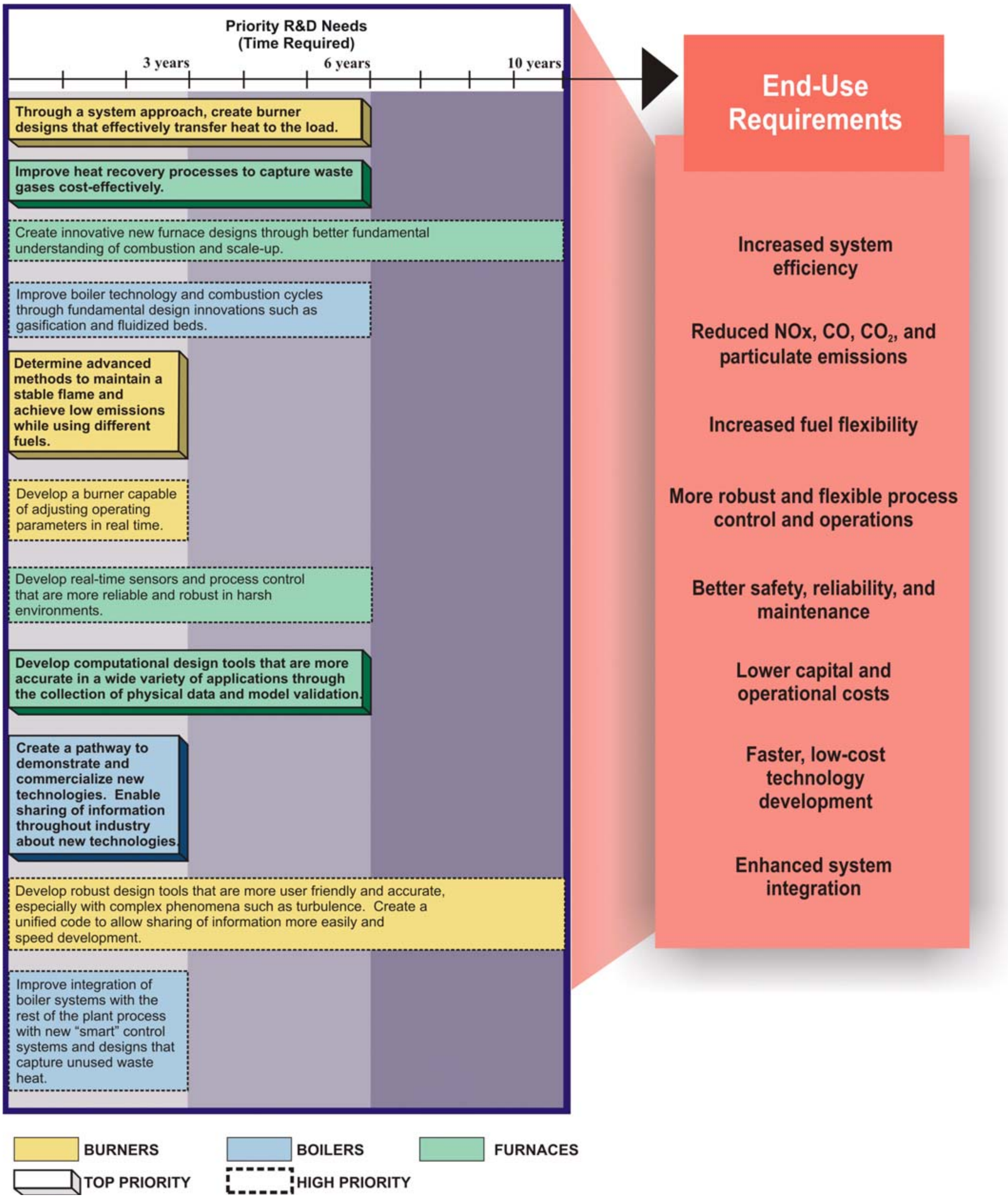

Exhibit 1-3. Top Combustion R&D Needs and Their Impacts on End-Users

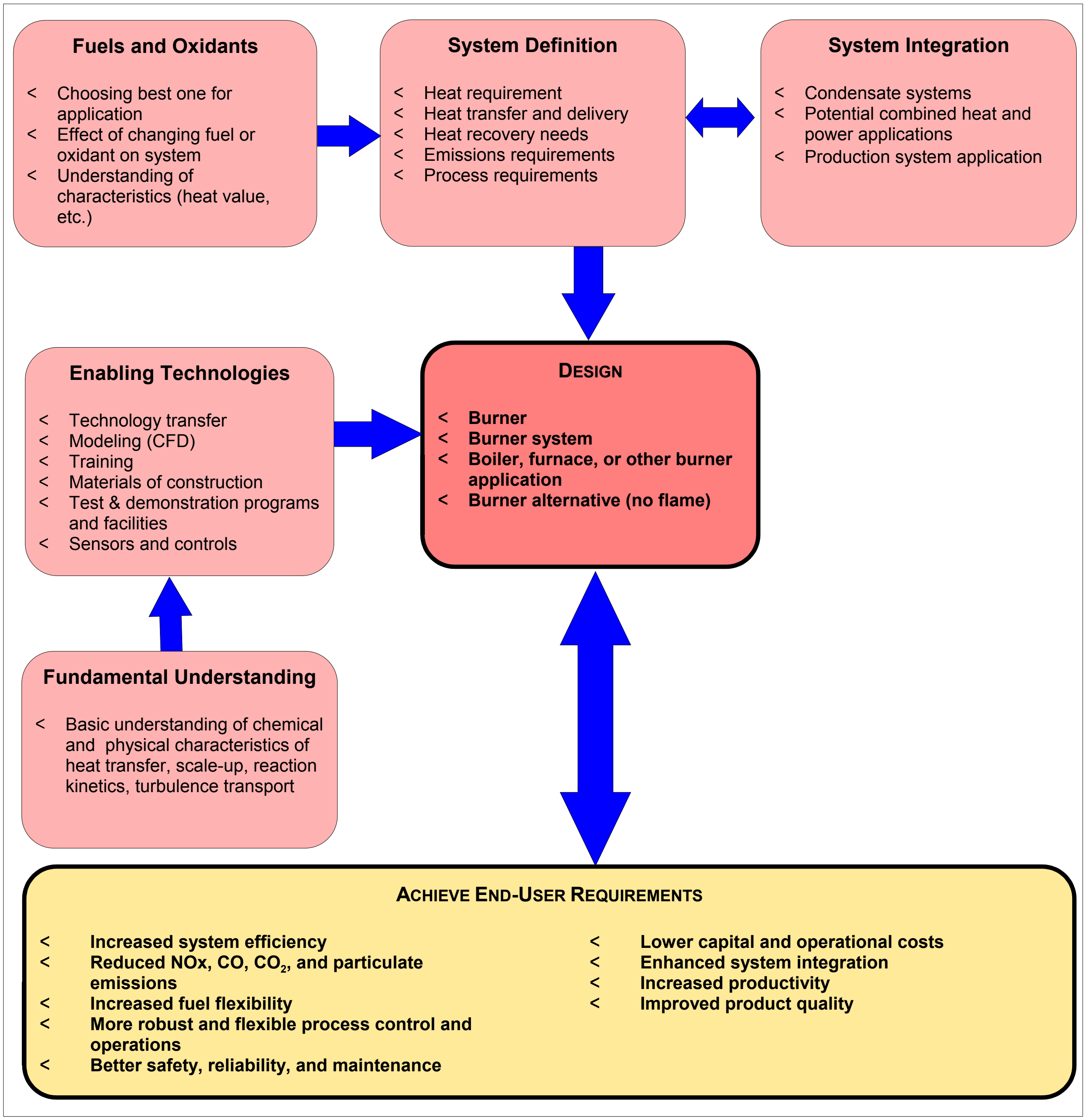

Exhibit 1-4. The Combustion System Design Process

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2. Barriers to Improvement

Many technological, regulatory, and institutional barriers prevent industrial combustion systems from achieving the envisioned 2020 performance levels today. This chapter discusses the barriers common to the entire industry, as well as those specific to boiler and process heating systems, respectively. Appendix B provides comprehensive lists of the barriers for all of the combustion systems.

Industry Wide Barriers

The **financial risk** associated with adopting a new technology is considerable in the industries that use combustion equipment. As a result, these industries are typically conservative, initiating relatively few technological changes over the past several decades. Industry, as a whole, is unwilling to risk a heavy financial burden resulting from inadequate performance of a new system. A company installing a new, low-emissions technology, only to have it not meet requirements, would be forced to spend even more money to modify it or install additional control equipment to meet emissions standards, and the company would receive no credit for having tried the alternative. In the current competitive economic environment, incentives do not exist for either the end-user or the technology vendor to assume excessive financial risk.

A further barrier to the development of new combustion system designs is the industry's **inability to accurately predict the performance** of the new systems. No standard exists for measuring or reporting performance under "standard" or agreed upon operating conditions. Additionally, technologies for measuring key combustion parameters are not adequately advanced, and industry does not take advantage of existing state-of-the-art combustion laboratories because the results are generally detailed, micro-level data that need to be interpreted. For the most part, the size and type of laboratory test equipment available are inadequate, and the costs are prohibitive.

A wide gap exists between researchers, who often work on a relatively small scale, **and the component, equipment, or systems designers**. Considerable fundamental knowledge exists or is being pursued at the national laboratories and in academic and other research institutions, but the transfer and use of this knowledge requires simplified tools that are either unavailable or prohibitive because of cost and training time. This gap creates a weak link in the design process (Exhibit 2-1). 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 translate that knowledge to the design of industrial-scale, low-emission furnaces. Similar problems exist for other important combustion characteristics, such as flame behavior and radiant heat transfer.

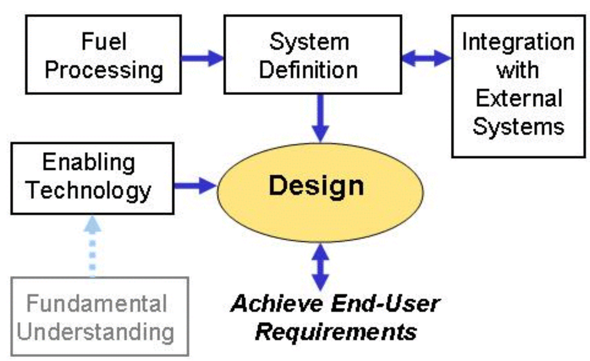


Exhibit 2-1. Combustion System Design Process

In the end, 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 emissions to very low levels, while at the same time improving system efficiency, must be less if these levels become mandatory. Domestic industries will continue to move offshore if the cost of meeting regulations puts them in a potentially non-competitive economic position.

Boiler System Barriers

The **variety of boilers** in use today is a barrier to the development of combustion technologies that reduce emissions uniformly because 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. Additionally, because various fuels have different NOx control requirements, achieving NOx goals as well as targets for systems operations and fuel flexibility is exceedingly difficult.

Another barrier to new boiler development is **particulate regulations**. Under more stringent regulations, it is conceivable that the concentration of the particulates entering a burner may be higher than the concentration allowed to exit a stack. This may require the installation of a particulate control system on either the front or back end for new installations. However, commercial and developing technologies have not been adequately demonstrated as effective options for controlling fine particulate emissions (<2.5 microns) for a wide variety of process conditions.

Furnace System Barriers

As already indicated, the furnace and industrial heating industry has been relatively slow to develop and adopt new technologies. This is primarily due to characteristics of the industry, including the relatively **small size of the companies** offering industrial heating systems and the lack of communication and integration between the equipment suppliers and the end-users.

Another barrier to furnace system development is the **high level of integration** of industrial heating equipment **with the other process steps and equipment within a plant**. The operation of the entire plant is often dependent on the furnace system. Thus, the end user is hesitant to risk production downtime that may result from a new furnace technology.

The **end user's requirement for system flexibility** may also pose a problem for furnace technology development. The end user will likely prefer a more reliable, less efficient furnace system if it meets the needs of the plant without exception, rather than risk limitations with a new technology.

3. Burner Research and Development

> "*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 form the basis for a wide variety of industrial combustion applications. Because they are used in so many diverse applications, it is difficult to set common performance targets, particularly for emissions reductions. Currently, systems are hard-pressed to achieve high thermal efficiency and, at the same time, low NOx emissions. Also, boiler and furnace systems of today will not perform at the emission levels that "burners of the future" will be designed to achieve. Together, complexities such as these affect the ability of the industry to set uniform parameters for all systems.

Industries of the Future Burner End Users

- Aluminum
- Chemicals
- Forest Products
- Glass
- Metal Casting
- Mining
- Petroleum
- Steel

The Vision's performance targets, which are derived from the boiler and process heater targets in the *Industrial Combustion Vision*, are therefore not meant for every burner application. Consequently, implementation of the industry targets must take all factors into account. Applications will vary depending on specific end-use, plant design, and combustion systems.

Research and Development Needs

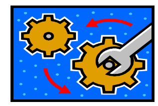
For industry to achieve its desired performance targets for industrial combustion systems, it must focus R&D efforts on improvements to the entire system, integrating approaches that consider all of the components, including burners and, eventually, the entire manufacturing process. R&D activities should be designed to improve the productivity, product quality, and efficiency of the systems as a whole, incorporating NOx emissions as one of the critical issues.

The R&D areas and activities with the highest potential to significantly advance the state of burner technology are shown in the one-page summaries at the end of this chapter. Most of the research needs are specifically for burners, but some of them relate to integrated combustion systems. Within each key R&D area, the specific activities required to achieve the performance targets in the vision are outlined in the one-page summaries. The highest priority items designated by industry are in bold type. The burner R&D needs detailed in this chapter are focused mostly on large users, since most of the Industries of the Future use a significant amount of steam and process heat.

These summaries further analyze the highest priority R&D needs, showing their impact on:


Energy Efficiency


Fuel Flexibility


Safety, Reliability, and Maintainability


Environmental Quality


Process Improvement

These summaries also describe the time frame in which employable results could be anticipated for each activity, assuming immediate initiation of research. The entire set of burner R&D needs is listed in Appendix C.

The priority key technical elements in the one page summaries (items in bold) indicate that the industry must develop new approaches and unconventional ideas, possibly involving new types of burners and furnaces (e.g. burner designs that distribute fuel injection or incorporate outside air injection). Long-term research requires this kind of radical approach to produce a substantially better boiler or heating system. To validate the products of this research, facilities and resources will be needed to ensure adequate demonstration. In addition, sensors that are adequately sensitive and robust must be developed to accurately measure results.

All of the top priority research activities will help maintain the United States as the world leader in combustion-based process heat for manufacturing processes, 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.

Priority Burner R&D Needs

Burners Capable of Adjusting Operating Parameters in Real Time

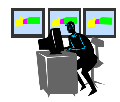
Using burners capable of adjusting operating parameters in real time, or "Smart Burners", will significantly improve system efficiency and emission control. Significant progress has been made over the last 10 years in smart control technologies. Although these technologies have been implemented in some plants, they have not yet been used in the industrial boiler or process heater area as a whole. Optimization of smart control systems may be individualized for each process to manage the overall control of NOx and CO emissions, flame stability, and heat flux to the load, as well as many other potential issues.

Impacts

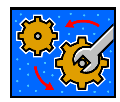
Medium: *Increased system energy efficiency through system integration*

High: *Reduced NOx and other emissions through new control schemes*

High: *Potential for increased fuel flexibility*

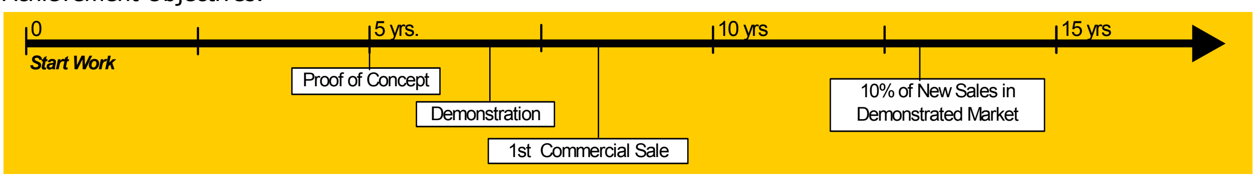


Medium: *More stable process control and operation with synergy between systems*



High: *Significant improvement in safety and reliability and reduced maintenance with integrated systems*

Achievement Objectives:



Research Areas	Key Technical Elements (Top Priority Elements in bold)	Time Frame (yrs) 0-3	4-6	7-10
Sensors and Controls for Emissions and Heat Distribution	Develop intelligent control technology and schemes	■		
	Research measurement techniques for monitoring heat flux/profile	■	■	
	Improve sensors/controls of fuel characteristics with adjustment capability (heating value, sulfur content)	■	■	
	Develop rugged sensors that can be used in harsh environments	■	■	
Fuel & Oxidant Physical and Chemical Characteristics	Develop fuel and oxidant property data that would allow more fuel/oxidant flexibility	■	■	
Fuel & Oxidant Mixing within the Burner	**Create advanced burner stabilization methods**	■		
	Improve combustion strategies for emissions control including: aerodynamic near field and far field stages; improved flue gas re-circulation; external combustion; air and fuel staging; partial premixing; heat transfer staging; and water/steam or agent injection	■	■	
	Improve turbulent transport and fuel/air mixing, both experimental and computational	■		
	Gain the capability to predict the impact of fuel/air mixing on performance	■		
	Determine methods of pre-mixing fuel-air and preventing flashback	■		
Process Interactions Within the Burner System	Improve heat recuperation capability	■		
	Improve control and validate CFD tools through reaction flow simulation	■	■	
	Research simpler, more cost-effective NOx processing downstream of furnace	■		

Priority Burner R&D Needs

Robust Design Tools/Unified Code

Development of robust design tools that incorporate a unified code would significantly improve burner design. Limit case studies would be valuable for design and troubleshooting. The code should account for burner-furnace geometry and include emissivities and multi-flame interactions. Most beneficial to burner design would be better understanding of turbulence, including the coupling of turbulence and chemical kinetics.

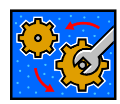
Impacts

Medium: *Increased system energy efficiency with improved burners resulting from better design tools*

High: *Reduced generation of waste energy and reduced environmental impact with improved design tools*

High: *Potential for increased fuel flexibility*

Medium: *Process control and operation stability with better troubleshooting tools*



High: *Significant improvement in safety and reliability and reduced maintenance requirements*

Achievement Objectives:

0 — *Start Work*

5 yrs. — 40% of burners sold will have used analytical tools as an integral part of design

10 yrs. — 75% of burners sold will have used analytical tools as an integral part of design

15 yrs.

Research Areas	Key Technical Elements (Top Priority Elements in bold)
Fundamental Understanding of Physical and Chemical Science	< Gain a better understanding of turbulent transport (scalar, energy release, large scale) < Develop a better understanding of turbulent chemistry interactions (small scale) < Improve understanding of chemical kinetics, especially of liquid fuel combustion < Understand oil atomization and spray distribution < Create a model of fine particle destruction
Burner System Design Models (Using Fundamentals)	< **Develop a family of limit case codes (computational tool that is focused on one combustion component) useful by itself and as a part of a more complex model** < Gain transient process modeling capabilities < Refine the model of near burner to full system through adaptive mesh technologies
Performance Targets for Models	< Develop the capability to determine process parameters from a specified flame/burner (inverse modeling) < Simulate multi-interaction of flames to load and wall < Predict emissions through CFD modeling < Improve simulation of flame dynamics and flame-to-flame interaction

Time Frame (yrs) 0-3 4-6 7-10

Priority Burner R&D Needs

More Effective Heat Transfer to Load

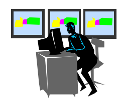
Transferring heat to the load effectively is an important aspect of a total systems approach to burner improvement. To achieve high process efficiency, the burners must distribute the energy released to the load effectively. Burner system designs need to include control of where the heat is released, how the heat is released, and how that translates to heating the load.

Impacts

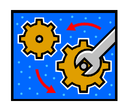
High: *Increased system energy efficiency with less energy losses during heat transfer*

Medium: *Reduced environmental impact through waste energy reduction*

High: *Potential for increased fuel flexibility*

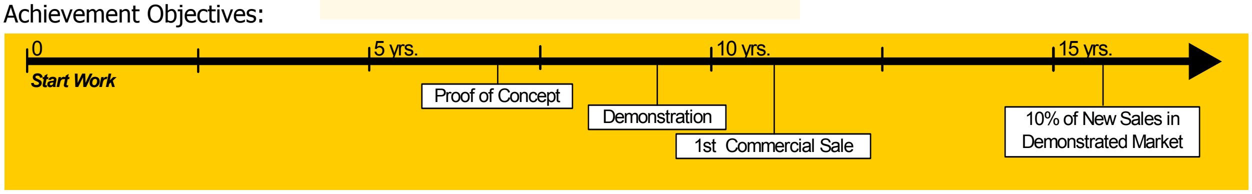


High: *More stable process control with effective heat transfer*



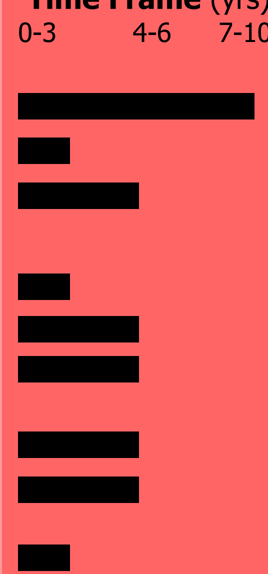
Low: *Little impact on safety, reliability, and maintenance*

Achievement Objectives:



Research Areas	Key Technical Elements (Top Priority Elements in bold)
Radiative Heat Transfer from the Flame to the Load	< Determine emissivities of high-temperature materials and/or flame-generated particulates < Assess burner material properties for heat transfer, including high temperature processes < Develop heat transfer enhancement techniques (e.g. microwave)
Heat Delivery to the Load	< **Determine best heat delivery for different flame shapes and combustion intensities** < **Develop a systems approach to combustion process design** < Design burners specific to process
Physical Modeling	< Gain a better understanding of scaling laws (radiant adsorption & length scale) < Increase understanding of heat/radiant transfer physics
Sensors and Controls	< Develop heat flux sensors

Time Frame (yrs)



Priority Burner R&D Needs

Advanced Combustion Stabilization Methods

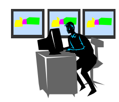
A top-priority research activity that will contribute to many performance targets is the development of an advanced burner control system capable of detecting process requirements and evaluating fuel options in real time, adjusting its operation accordingly. Advanced burner stabilization is especially important when burning non-standard fuels. The emphasis must be on how to maintain a stable flame and achieve low emissions while using different types of fuels. Capabilities must be developed to use low heat-value fuels and burn them in burners designed for natural gas.

Impacts

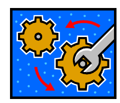
Medium: *Increased system energy efficiency*

High: *Reduced generation of emissions*

High: *Increased fuel flexibility due to improved control methods*

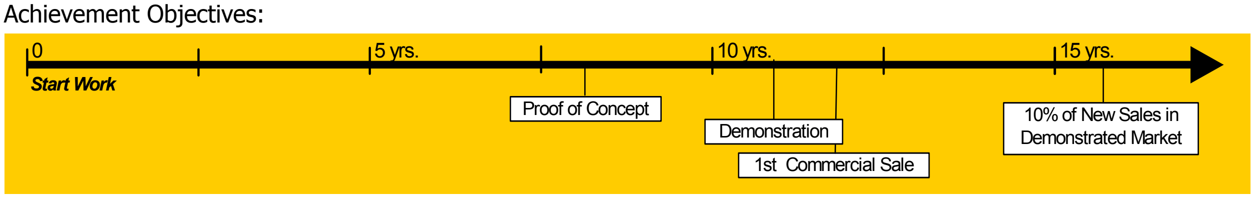


Medium: *Improved process control and operation with advanced stabilization methods*



High: *Significantly improved safety, reliability, and maintenance with more stable burner operation*

Achievement Objectives:



Research Areas	Key Technical Elements (Top Priority Elements in bold)	Time Frame (yrs) 0-3	4-6	7-10
Use of Multiple Fuels and their Characteristics	< **Improve combustion methods for non-standard, commercially available fuels with both low and high heat value**	■		
	< **Determine fuel characteristics including composition, combustion properties, and flame behavior**	■		
	< Research oil vaporization capability	■		
	< Gain the ability to design fuels	■	■	
	< Develop a low-emission liquid fuel burner that accepts different fuels and blends of fuels	■	■	
New Flame Stabilization Techniques	< **Develop advanced techniques including piloting, swirl, dump, bluff, and low swirl**	■		
	< Design a flame stability sensor	■		

4. Boiler Research and Development

> "*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, environmental friendliness, fuel flexibility, cost-effectiveness, process/energy compatibility, safety/reliability, and material use. These targets, outlined in the Vision, indicate the level of performance that can be achieved by directing sufficient research dollars towards the priorities contained in this technology roadmap. Boiler performance targets that refer specifically to the burner systems within the boiler itself were discussed in Chapter 3. Other targets consider the entire boiler system, including burners, emissions control equipment, and other auxiliary equipment. Key to the Vision is the need to look at combustion equipment as part of an overall system, to account for the complex relationships among the various — and often unpredictable — system inputs to optimize system efficiency and environmental performance.

Industries of the Future
Boiler End Users

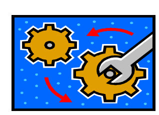
< Chemicals
< Forest Products
< Glass
< Mining
< Petroleum
< Steel

Research and Development Needs

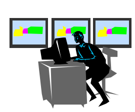
Exhibit 4-1 shows the highest priority R&D areas and specific research needs that are most critical to achieving the industry's goals for 2020. Each of these areas was evaluated to determine its impact on meeting performance targets in the Vision, and to identify the key hurdles to its success. The items designated as highest priority are in bold type. The one-page summaries further analyze the highest priority R&D needs to show their impact on:


Energy Efficiency


Fuel Flexibility


Safety, Reliability, and Maintainability


Environmental Quality


Process Improvement

These summaries also describe the time frame in which employable results could be anticipated for each activity, assuming immediate initiation of research. Appendix D provides a comprehensive list of the boiler research needs. The boiler R&D needs detailed in this chapter are focused mostly on big steam users, since most of the Industries of the Future use a significant amount of steam.

The industry should regularly examine existing technologies to see if they 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 refitting the system for burning a solid fuel or reforming the solid fuel to meet the specifications of the existing burner/boiler combination. Fuel conversion processes may also be able to remove unwanted constituents and trace elements.

The design and implementation of new, 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 fundamental research, the development and application of advanced tools and models, and the establishment of demonstration programs will also contribute to this goal. Additionally, non-R&D activities address institutional and policy issues.

Priority Boiler R&D Needs

New Boiler Technologies

Current boiler designs are thirty to forty years old. The development of completely new boiler technologies and combustion cycles will help the industry meet its process and energy improvement goals. The industry will need to research fundamental design issues, including heat transfer characteristics in boilers and alternatives to burners. Cost-effective solutions may include non-traditional fuels and oxidants. More robust, cost-effective, and reliable sensors and controls will likely further improve efficiency.

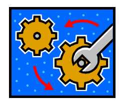
Impacts

Medium: *Maximized system efficiency*

High: *Reduced NOx and CO emission*

High: *Potential for increased fuel flexibility*

Medium: *Improved process control and operation*

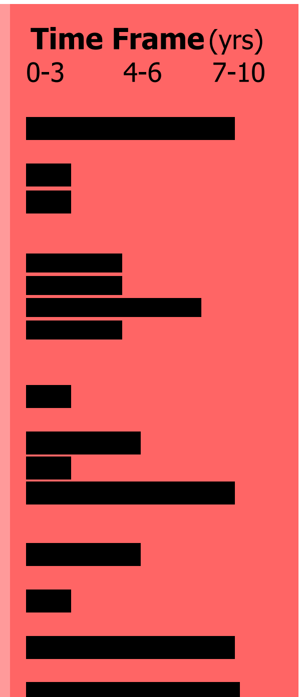


High: *Significant improvement in safety, reliability, and maintenance as a result of improved performance*

Achievement Objectives:

Research Areas	Key Technical Elements (Top Priority Elements in bold)
Sensors and Controls	< Develop durable sensors that can provide real-time measurement of combustion products < Research sensors that can withstand high temperatures < Improve sensors and software algorithms that compute heat exchanger and furnace fouling
Alternatives to Burners for Solid and Liquid Fuels	< **Investigate gasification** < **Improve fluidized beds** < Improve back-end materials for fluidized beds < Develop a high-pressure feeder
Fuel and Oxidant Flexibility	< **Increase use of oxy-enriched burners/boilers with documentation of benefits and trade-offs** < Find better and less expensive ways to store gaseous fuels < Research better multi-fuel burners < Investigate ways to significantly lower the cost of oxygen generation
Boiler System Efficiency Improvement	< Investigate heat transfer characteristics through fundamental study and flow modeling design < Increase capture of heat through better materials, applications, or designs < Research high temperature steam generation using CHP or industrial power generators < Improve alternative materials for burner components

Time Frame (yrs)



Priority Boiler R&D Needs

System Integration

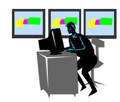
System integration issues involve the interactions of boilers with the rest of the process. Often, boiler operations are managed independently of production processes. However, process changes, both upstream and downstream, can affect the demand, stability, and efficiency of the boiler operation. In addition to production issues, support systems such as feedwater can also affect boiler performance. Integrating boiler systems with the support and production processes will lead to significant improvements in overall efficiency and energy use.

Impacts

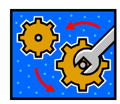
Medium: *Better system integration with more advanced thermodynamic cycles*

High: *Reduced solid waste and wastewater with system optimization*

High: *Shift toward fuel-neutral, output-based standards*



Medium: *Process plants needs integrated with steam and power requirements*



High: *Reliability improved by 25% and fewer shutdowns as a result of significantly reduced control malfunctions*

Achievement Objectives:

Research Areas	Key Technical Elements (Top Priority Elements in bold)	Time Frame (yrs) 0-3	4-6	7-10
Sensors and Controls	**Develop "smart" control systems (like neural networks) to run multiple boilers**	X		
	Improve measurement of steam use and temperature	X		
Application of Combined Heat and Power Systems (CHP)	**Create designs that balance thermal energy and electricity requirements efficiently using new equipment or methods to capture waste heat**	X	X	
	Improve heat recovery by finding a balance between product quality and heat quality and environmental clean-up	X	X	X
	Research better heat exchanger materials, both metals and ceramics, for both high and low temperatures	X	X	X
Condensate Systems Integration	Improve use of water treatment in regards to deaeration and chemistry	X		
	Develop a steam trap selection tool and better steam traps	X		
	Create system designs that prevent fouling and contamination due to poor water quality	X		
	Find ways to cost-effectively use the heat energy contained in the condensate	X		
Boiler Personnel Training	Improve the basic steam and system training for the operators	X		
	Create a simulation program or software that can be adapted to different boiler systems for training operators	X		

Priority Boiler R&D Needs

Technology Transfer

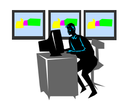
Following development, new technologies must be demonstrated and commercialized to reach the marketplace. Demonstration of new technologies at full scale can identify limitations and performance with variable loads and fuels, mitigating uncertainties associated with the new technologies. However, adequate test facilities are currently not available for use by the combustion community. Also, increased cross-industry and government cooperation is needed to speed up commercialization of new technologies. Increasing industry-government partnerships and expanding test facilities would decrease the time needed for new energy saving technologies to become commercially available.

Impacts

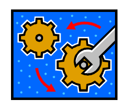
***Medium:** Energy efficiency increases with shared information and practices*

***High:** Reduced environmental impact through increased technology implementations*

***High:** Increased fuel flexibility*



***Medium:** Process control improvements through the use of best practices*



***High:** Significant improvement in safety, reliability, and maintenance*

Achievement Objectives:

Research Areas	Key Technical Elements (Top Priority Elements in bold)	Time Frame (yrs) 0-3 / 4-6 / 7-10
Test and Demonstration Programs	< **Reduce restrictions to working with government including minimizing paperwork requirements, protecting competitive information, allowing licensing of new technology, minimizing regulatory requirements and conflicts between different government agencies (EPA, DOE, FDA)**	
	< Use cross-industry cooperation to demonstrate combustion technology - possibly through consortia	
	< Identify and voice needs for test site facilities	
	< Create a good partner mix for demonstration programs- often an industry, supplier, and government collaboration	
	< Produce independent validation and verification data to increase use of new technologies	
	< Increase likelihood of success through regular interaction and communication between operation and design teams	
Speed of the Commercialization Process	< Reduce time required to move new technologies into the marketplace through government support in deployment resources and resolution of licensing issues	
	< Investigate gasification	
	< Create an energy technology clearinghouse that contains all government - and non-government - funded research would improve communication of new technologies	
	< Continue partnerships and cooperation	

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5. Furnace Research and Development

> *"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* outlines performance targets to shape the research strategy for furnaces and industrial process heating systems. Some 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, the industry needs aggressive goals to guide advanced technology development to 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. While every furnace system application may not achieve the specific quantitative targets, most plants will benefit from reducing furnace emissions , especially high-temperature furnaces.

Industries of the Future Furnace End Users

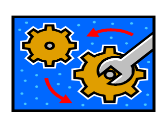
< Aluminum
< Chemicals
< Glass
< Metal Casting
< Mining
< Petroleum
< Steel

Research and Development Needs

The one-page summaries at the end of the chapter describe the top R&D needs for furnaces, while Appendix E provides a comprehensive list of Furnace R&D needs. The furnace R&D needs detailed in this chapter are focused mostly on large users, since most of the Industries of the Future use a significant amount of heat in their processes. The highest priority items designated by industry are in bold type. The summaries further analyze the highest priority R&D needs to show their impact on:


Energy Efficiency


Fuel Flexibility


Safety, Reliability, and Maintainability


Environmental Quality


Process Improvement

These summaries also describe the time frame in which employable results could be anticipated for each activity, assuming immediate initiation of research.

While each of these high-priority needs will contribute to numerous performance targets, they will most commonly address reduced air emissions, improved energy efficiency, and increased product quality, yield, and productivity. The most common technical barriers to successful completion of these research needs are process integration issues, materials issues, and lack of collaboration between equipment manufacturers, users, academia, and government agencies supporting research in this area.

Priority Furnace R&D Needs

New Furnace Designs

Only new, more efficient and low emission furnaces will reduce fuel consumption and air emissions. A better understanding of fundamentals, especially in the areas of heat transfer characteristics, fluid mechanics, and chemical kinetics will enable the development of models to help design burners and process heating systems that improve operational performance and flexibility.

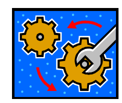
Impacts

High: *Specific fuel consumption reduced*

High: *Air emissions reduced*

Medium: *Potential for increased fuel flexibility*

Medium: *Product loss rate reduced*



High: *Increased robustness of system to maximize safety and reliability and reduce maintenance requirements*

Achievement Objectives:

0 | 5 yrs. | 10 yrs. | 15 yrs.

Provide support to IOF furnace activities: Timeline determined by each IOF.

Research Areas	Key Technical Elements (Top Priority Elements in bold)	Time Frame (yrs) 0-3 4-6 7-10
Fundamental Knowledge of Physical and Chemical Science	< **Gain a better understanding of improved heat transfer and its application**	
	< **Improve understanding of scale-up**	
	< Increase understanding of particulate generation in combustion	
	< Research mechanisms that generate heat using less volume	
	< Gain a better understanding of element properties	
Materials of Construction	< Continue development of advanced materials	
Model Validation and Technology Transfer	< **Create a combustion "Center of Excellence" to test materials and validate models**	
End-User Product Quality	< Develop a better knowledge of mechanisms of product degradation	
	< Find ways to reduce reactive product oxidation	
Process Characterization and Development	< Benchmark classification of existing processes	
	< Develop application-specific models	
	< Develop innovative furnace designs	

Priority Furnace R&D Needs

Advanced Sensors and Process Control

Process heating can be much more effective with more reliable, more robust, and less expensive sensors and process controls. High-priority research needs include reliable sensors for harsh environments and real-time measurement of chemical composition of fuel, oxidant, and flue gas. Real-time combustion controls for multiple fuel applications would contribute to achieving maximum fuel flexibility, while improved sensors in smart control systems would achieve efficiency, safety, and reliability goals.

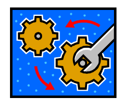
Impacts

High: *Maximum system energy efficiency through use of new sensors*

High: *CO_2 and air emissions reduced through improved process control*

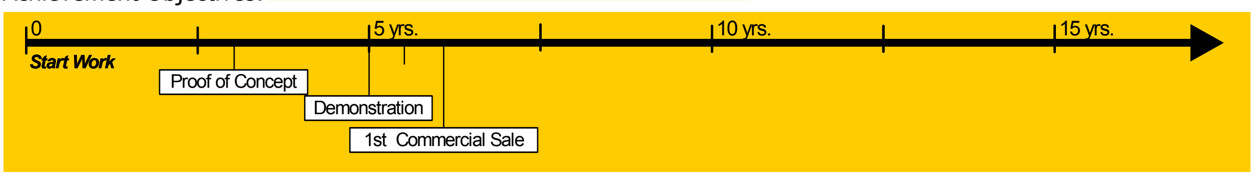
High: *Maximized use of multiple fuels, including waste fuels*

High: *Process control and operation significantly improved*



High: *Safety and reliability improved, and maintenance cycles increased to 5 years*

Achievement Objectives:



Research Areas	Key Technical Elements (Top Priority Elements in bold)	Time Frame (yrs) 0-3	4-6	7-10
Best Practices (from other industries)	< **Investigate low-cost sensors from automotive and other industries**	■		
Advanced Materials of Construction	< Research material compatibility for probes and sensors	■	■	
Application of Sensors and Controls	< **Develop self-learning and self-teaching smart control systems**	■	■	■
	< Produce reliable, continuous flue gas component analysis and temperature measurement	■	■	■
	< Measure physical properties of feedstock and products during processing, as well as product quality	■	■	
	< Develop low-cost reliable flame monitoring systems (including flame quality/stability)	■	■	■
	< Research a practical continuous heat flux meter	■	■	■
	< Improve measurement and control of flame characteristics	■	■	■
	< Improve measurement of fuel and oxidant compositional characteristics	■	■	■
	< Develop the capability to measure real-time thermal distribution	■		

Priority Furnace R&D Needs

Cost-Effective Heat Recovery

Current furnace and process heating systems release waste gases to the atmosphere because it is not cost-effective to recover their sensible and latent heat. Integration of a heat recovery system with emissions control would allow efficiency and environmental improvement, while lowering fuel use and, as a result, operating costs. Revolutionary technologies could be developed to capture the low-quality heat that is currently not recovered. Process improvements and advanced sensors and controls will be needed to enable the recovery of waste gases.

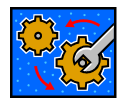
Impacts

High: *Energy efficiency significantly improved through heat recovery*

High: *Reduced emissions and fuel consumption with recovery of waste heat*

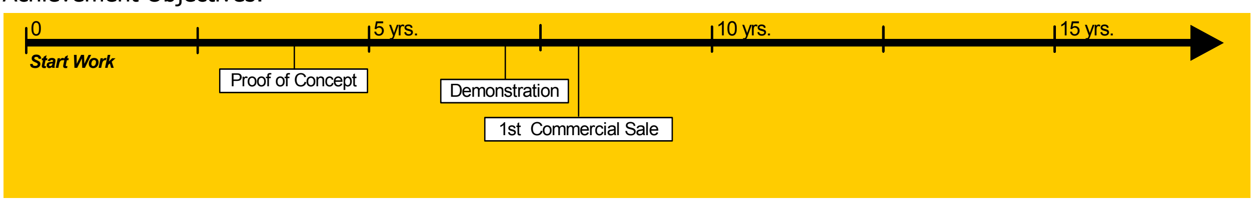
Low: *Slightly increased fuel flexibility through use of waste heat*

High: *Process control and operation significantly stablized*



Low: *Consistent safety, reliability, and maintenance levels*

Achievement Objectives:



Research Areas	Key Technical Elements (Top Priority Elements in bold)	Time Frame (yrs) 0-3	4-6	7-10
Design, Application, and Performance of Heat Recovery Systems	< **Research innovative heat recovery technology**	■	■	
	< **Develop integrated heat recovery and emission control capability**	■		
	< Improve heat recovery of oxy-fuel or oxy-enriched processes	■	■	
	< Increase effectiveness of available heat exchange systems	■		
Advanced Materials of Construction	< Improve materials of construction	■		
	< Develop better coatings	■		
Flue Gas Characterization	< Improve understanding of dioxin and furan formation in flue gas streams below 1,400 F	■		
	< Predict behavior of the flue gas stream in the heat recovery system based on gas characteristics	■		
	< Find ways to capture fine particulates	■		

Priority Furnace R&D Needs

Integrated Computational Design Tools

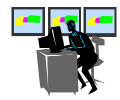
Research in tools, models, and algorithms will facilitate the design of advanced process heating and furnace systems. Computational design tools have significantly improved many industrial processes, but have not been fully utilized in burner and furnace design due to deficiencies in accuracy and robustness. To enable use of Computational Fluid Dynamics (CFD) and other design tools, physical property data must be more accurate. Also, tools need to be more user-friendly for easier application. Computational design tools are key to achieving energy, emission, and fuel flexibility goals.

Impacts

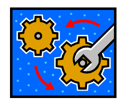
High: *Increased system energy efficiency with better designs*

High: *Reduced environmental impact due to improved designs*

High: *Increased fuel flexibility in more robust furnace systems with improved design tools*



High: *More stable process control and operation with better models*



High: *Significant improvement in safety, reliability, and maintenance due to better system design*

Achievement Objectives:

0 — ***Start Work***

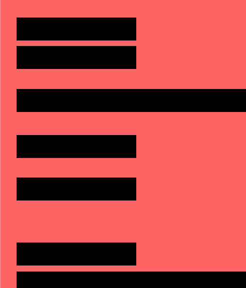
5 yrs. — 15% of new furnaces sold will have been developed with advanced analytical tools

10 yrs. — 30% of new furnaces sold will have been developed with advanced analytical tools

15 yrs.

Research Areas	Key Technical Elements (Top Priority Elements in bold)
Design Tool Characteristics	< **Develop model validation technology** < **Research more robust and accurate models to look at physical phenomena of process** < Gain the ability to calculate full chemistry and fluid mechanics at the same time (handling/integration) < Develop material property generator (physical properties) < Produce tools that handle transient phenomena
Technology Transfer	< Create user-friendly tools < Standardize the format for furnace performance data

Time Frame (yrs) 0-3 4-6 7-10



6. Conclusions and Next Steps

The challenges of improving combustion processes are extremely complex, and the combustion equipment industry has inadequate resources to tackle them alone. **While developments at the component level will remain important, breakthroughs in efficiency, productivity, safety, and environmental performance hinge on optimizing combustion processes from a total systems perspective.** By approaching development, from a total systems view, research can result in increasingly efficient, clean, fuel-flexible, and reliable combustion systems, capable of producing uniform high-quality end products at high production rates. These systems will offer benefits to our nation, furthering energy security and environmental protection goals.

The industrial combustion community has adopted the "Industries of the Future" approach promoted by the U.S. Department of Energy to plan future technology development. This approach uses a three-step process to devise and implement a comprehensive strategy for developing and implementing advanced technologies. The Vision and Roadmap represent the first two steps. The third step is the implementation of the research specified in the Roadmap.

The implementation of the strategy outlined in this Roadmap hinges on several steps. The first of these steps is the creation of partnerships among private companies, suppliers, trade associations, national laboratories, academia, private research institutions, and government agencies. The U.S. Council on Competitiveness, in an assessment of industry's technology needs, has identified the creation of 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 to establish cooperative efforts. By articulating its own technology strategy, the industrial combustion community hopes to motivate all of the stakeholders to refocus their research efforts in line with industry's needs.

The next step in implementing the strategy outlined in the Roadmap involves combustion processes themselves. Technological breakthroughs will depend on optimizing combustion processes from a total systems perspective, although developments at the component level will remain important. By approaching technology from a systems view, research can result in increasingly efficient, clean, fuel-flexible, and reliable combustion systems.

To accomplish the full systems integration that will lead to the largest productivity improvements, energy savings, and environmental benefits, all of the dependant systems that enable combustion technology development, as shown in Exhibit 6-1, need to be fully supported. For example, the type of fuel and oxidant is often dictated by the end-user's facility. Additionally, the burner system design is dependant on the industry's knowledge of the fundamental science as well as the available design tools and technology (CFD, sensors and controls, etc.). Through this process, the burner system design, whether a boiler, furnace, or process heating system, can ultimately meet the efficiency, productivity, safety, and environmental requirements of the end-user.

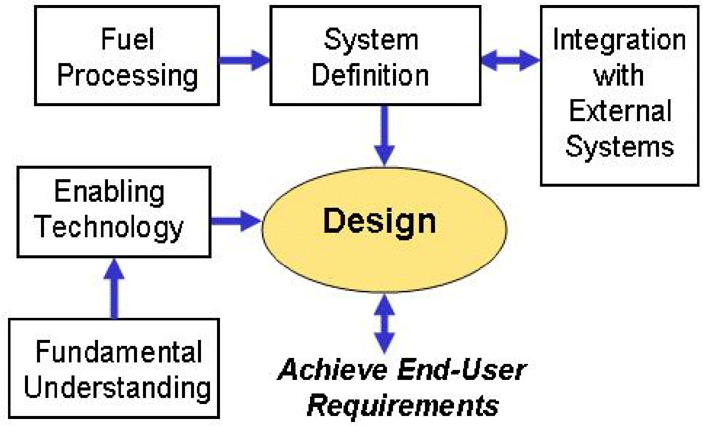


Exhibit 6-1. Burner System Design Process

The final step in the Roadmap strategy implementation involves translating the development of technology to practical use by members of the industry. Industry, academia, and government must work together to facilitate research. They must then work to convince industry to accept and apply the results in their product designs. A consortia, involving users and developers, would help legitimize and disseminate research results throughout the industry. Centers of excellence (virtual or real) would also help lower the cost of scale-up and product development. Industry partnerships could mitigate the risk and financial burden of investing in new technology.

Through the Industries of the Future approach, working together as an entire industry, and developing partnerships, the combustion community can successfully implement its strategy for future technology development. With new technologies, the community can continually improve its performance and evolve into the next generation of industrial combustion.

Appendix A
Industrial Combustion Technology Roadmap Workshop (August 2001)
Participant List

Furnace Group

Chuck Benson, *Arthur D. Little, Inc.*
San Chhotray, *ExxonMobil Research & Engineering*
Bob De Saro, *Energy Research Company*
Jeff Gorss, *Alcoa, Inc.*
Vince Henry, *Henry Technical Solutions, L.L.C.*
John Hudson, *Ipsen International*
Tom McKinnon, *Colorado School of Mines*
John Newby, *North American Manufacturing Company, Ltd.*
Elwin Rooy, *Rooy & Associates*
Roberto Ruiz, *John Zink Co.*
Shyam Singh, *SS Energy Environmental International, Inc.*
Lee Smith, *Kellogg, Brown & Root, Inc.*
Arvind Thekdi, *E3M, Inc.*

Burner Group

Hamid Abbasi, *Gas Technology Institute*
Bob Besette, *Council of Industrial Boiler Owners*
Robert Cheng, *Lawrence Berkeley National Laboratory*
Kevin Davis, *Reaction Engineering International*
Bob Gallagher, *Sandia National Laboratories*
Joe Keller, *Idaho National Engineering and Energy Laboratory*
Bill Malic, *Bloom Engineering Company*
Vince McDonell, *UCI Combustion Laboratory*
Steven Mickey, *WS Thermal Process Technology, Inc.*
John Sultzbaugh, *Hauck Manufacturing Company*
Tom Tyson, *GE Energy & Environmental Research Corporation*
Carsten Weinhold, *Schott Glass Technologies*
Charlie Westbrook, *Lawrence Livermore National Laboratory*

Boiler Group

Nathan Carpenter, *Boise Cascade Corp*
Tom Eldredge, *TODD Combustion Group of John Zink Co.*
Tom Erickson, *University of North Dakota*
Bob Keough, *Applied Process, Inc.*
David Littlejohn, *Lawrence Berkeley National Laboratory*
Ovidiu Marin, *AirLiquide*
Al Musur, *Abbott Laboratories*
Earl Pfefferkorn, *Aqua-chem*
Henri Reiher, *Industrial Combustion*
John Sullivan, *Alzeta Corp*

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Appendix B

Barriers to Achieving Performance Targets

(most critical barriers boldfaced)

Burners

Fuels and Oxidants

Limited information on flammability characteristics of most fuels and oxidants
Presence of fuel nitrogen and fuel sulfur
Excessive cost of generating oxygen

Design and Development

Mismatched burner/process heater design
Lack of robust design tool for new burners
Unclear if $PM_{2.5}$ poses a problem to burners fueled with process or product gas
Cost-effective, high-temperature materials (ceramics) unable to handle temperature excursions
Poor compatibility of solid and gas fuel burners
Inability to maintain emissions requirement over range of turndown
Trade-offs between NOx, VOC, and CO emissions (difficult to reduce all simultaneously)
Issues related to emissions of sulfur trioxide (SO_3)
Thermal inertia created by materials and system design
Limited space at front of burner for retrofit applications

Sensors and Controls

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

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 emissions

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 liquid fuel vaporization to allow burning them at low temperatures to avoid particulates
Inability to handle multi-burner flame interactions
No good 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 in furnaces

Tools and Models

Availability and cost of models to perform calculations
Weak computational fluid dynamic codes to describe physics, specifically radiation

Technology Transfer

Shortage of people educated in combustion (lack of interest in universities)
Inflexibility of regulations to accommodate excursions in fuel, temperature, etc.
Difficulty educating customers so they have real expectations

Boilers

Design and Development

Broad variety of equipment (no standardization within industry)
Performance targets not all compatible
Footprint size too large in advanced systems
Ability of equipment to perform to specifications
Stability of lean pre-mix combustion systems used to achieve NOx goals
Compatibility issues between burners/boilers (interface issues)
Condition of input air
Interface with the electrical grid
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
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

Sensors and Controls

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

Fundamental Understanding

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)

Technology Transfer

Shortage of people educated in combustion
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 R&D
Lack of incentives for developing "brilliant ideas"
Scientifically incomplete definition of new technology
- undetermined variability in operation
Lack of technology solutions that reduce <u>both</u> CO and NOx
Incompatibility of some goals with operability
Lack of operator training and loss of operator experience
Lack of industry awareness of new technologies
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 avoid being first to install and use prototype equipment
Scope of R&D too broad for a single company

Economics and Regulatory

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**

Capital cost of NOx systems capable of <2ppm
No risk mitigation for using new technologies
No early reduction credit for improved environmental performance
Sacrifice in energy efficiency to achieve low NOx,
Lack of solution that does not pit 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

Furnaces

Design and Development

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
Lack of attention to new designs, system integration, ease of manufacturing, operational protocol, and fuel specification

Sensors and Controls

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

Fundamental Understanding

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

Technology Transfer

Few qualified personnel attracted to combustion industry
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
Insufficient training for control operators
Few incentives to encourage new human resources into combustion
Lack of curriculum for combustion in undergraduate 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 of long-term research on bottom line

Appendix C

Burner R&D Needs

(in relative order of priority within each category)

Fuels and Oxidants

Improved combustion using a combination of fuels (both high and low heat value)
Inexpensive methods to separate nitrogen from liquid fuels
Advanced oxygen generation to decrease cost of using oxygen as an oxidant
Fuel and Oxidant Mixing within the Burner

- Capability to predict mixing's impact on performance
- Combustion strategies for emissions controls including aerodynamic near-field and far-field stages, induced flue gas circulation, external combustion air and fuel staging, partial pre-mixing, heat transfer staging, water/steam injection and agent injection
- Improved turbulent transport, fuel/air mixing, both experimental and computational

Fuel and oxidant interchangeability data
Capability to design fuel
Methods to thoroughly, economically pre-mix fuel and air while preventing flashback

Sensors and Controls

Low-cost, robust, non-intrusive device for in-flame measurement of temperature and fuel-air ratio
Intelligent combustion control technology for "smart" burner incorporating emissions reduction
Advanced fast-reacting flame scanning for low-NOx burners
Fast process controls to solve process dynamics (e.g., neural network process control)
Equipment sensitive enough to measure emissions and oxygen levels accurately
Dynamic coupling of near limit flames with fuel-air ratio variance in particular system configurations
Flame stability sensors
Burner that can change and maintain control over time (flow rate, swirl, tilt)
Sensitivity analysis of the impact of process variable changes
Control system that makes burners "smart" so that it determines process requirements and evaluates fuel options in real time
Measurement techniques for measuring heat flux and profile
Sensors and controls that can adjust based on measured fuel characteristics (heat value, sulfur content)
Rugged sensor technologies that can exist in harsh environments

Design and Development

Advanced burner stabilization techniques (piloting, swirl, dump, bluff, and low swirl)
Methods to thoroughly, economically pre-mix fuel and air while preventing flashback
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
Burner flexible enough to deal with multiple fuels and emissions requirements
Determination of impact of multiple fuel types on different burner designs
Ways to atomize liquid fuels economically that don't use steam or air
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 (1,400°C)
Ceramics for new cost-effective burner materials
Device to measure fuel-air ratio and a burner compatible with this device
Reaction flow simulation to improve control
Improved understanding of how design impacts burner performance
Reduction or elimination of flames from combustion (to reduce NOx)
Effective projected radiant surface (EPRS) burner design

Designs using different flame shapes and combustion intensities
Designs specific to process applications
Systems approach to combustion process design
Novel burner designs with high pressure, cool flame, and CO_2 collection capabilities

Tools and Models

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

Unified code that accounts for burner-furnace geometry that includes emissivities and multi-flame interactions
Simplified tools interface
CFD for emissions prediction
Family of limit case codes useful in itself and usable in larger models
Improved simulation of flame dynamics (noise and flame-to-flame interaction)
Adaptive mesh technologies - refine model of near burner to boiler
Adaptation of boiler configuration to optimize burner overlay
Transient process modeling capabilities
Inverse modeling and quick turnaround capability
Validation of new designs, tools, and sensors through demonstration

Fundamental Understanding

Better understanding of :
- Scaling laws (radiant absorption length scale)
- Physics of heat/radiant transfer
- Fundamental causes of combustion noise in low pressure combustion chambers
- Turbulence transport (scalar, energy release, large scale)
- Turbulent chemistry interactions (small scale)
- Chemical kinetics
- Oil atomization and spray distribution
- Large eddy simulations
- Capability to disconnect droplet & spray and furnace model
- Model of formation and destruction of fine particles
- Fundamental chemistry for large molecules
- Detailed mechanism reduction
- Advanced solvers for reduced mechanisms
- Soot chemistry
- Efficient conversion of all fuels to H2 and CO (for catalytic combustion systems)

System Integration

Simpler, more cost-effective NOx processing downstream of furnace
Optimized emissivity of materials for energy efficiency effective heat transfer
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
Heat recuperation capability
Assessment of material properties for heat transfer
Heat transfer enhancement techniques (microwave, gas)
Better understanding of load distribution impacts
Determination of emissivities of high-temperature materials and flame generated particulates (emitter/receiver emissions)

Appendix D

Boiler R&D Needs

(in relative order of priority within each category)

Fundamental Understanding

Better understanding of :

- Efficient conversion of all fuels to H2 and CO (for catalytic combustion systems)
- Chemistry of the conversion of fuel nitrogen to NOx
- Heat transfer characteristics
- Water treatment chemistry

Sensors and Controls

Improved low-NOx measurement devices
Durable sensors that can provide real-time measurement of combustion products
Sensors and software algorithms to compute heat exchanger and furnace fouling
Sensor that can provide high-temperature measurement
"Smart" control system to run multiple boilers (neural networks)
Improved measurement of steam use and temperature

Technology Transfer

Energy technology clearinghouse to store and categorize information
Better explanation of combustion industry's priorities to specialized R&D communities
More expertise in trouble-shooting
Convenient training and education program for operators and users(easily adaptable to different boiler systems)
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
Acceleration of the application, testing, and commercialization of new materials
Cross-industry consortia to demonstrate new technologies
Identify needs for demonstration sites
Reduction in time for new technologies to make it to the marketplace through governmental deployment support
Removal/reduction of restrictions to working with government (competitive information, regulatory conflicts, paperwork requirements)

Design and Development

New boiler and combustion cycles:

- Pressurized combustion systems
- Turbo-charged, recuperated combinations
- Min 1,500 psi, 1,500°F

Use of electric fields to improve stability range and equivalence (fuel/air ratio) of lean pre-mix burners
Integration of all established, desirable elements into a common technology platform ("super" boiler program) to develop family of advanced packaged boilers
Exploration of stability of lean pre-mix systems using different stabilization procedures in standard boilers
Stable combustion systems to accommodate rapid load changes
Indirect-fired radiant air heater units and associated materials developments
Non-invasive techniques for the removal of solids from boiler tubes
Improved alternative materials

High temperature steam generation (CHP or industrial power generators)
Capture of flue gas heat through improved materials
Filter systems for pressurized fluidized beds (possibly ceramic)
Combustion by-product clean-up in fluidized bed
Improved back-end materials for fluidized beds

Tools and Models

Investigation of heat transfer characteristics through flow modeling design (number of passes)
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 Clean Coal Technology Program but not specifically associated with coal)
Testing and demonstration of fuel use (looking at emissions control and operational issues)
Energy-efficient technology verification program
Equivalent of the Sandia Burner Engineering/Research Laboratory (BERL) for fire-tube boilers

Fuels and Oxidants

Low-cost oxygen generation methods
Documentation of trade-offs and benefits of oxy-enriched burners and boilers
Multi-fuel burners
Methods to pre-heat fuel
Less expensive ways to store gaseous fuels
More efficient atmospheric fluidized-bed combustion systems for solid fuels
Investigation of gasification
Development of a high pressure feeder
Examination of existing technologies that can be applied to fuel reforming to increase fuel flexibility
Program to expand use of ash from boilers (particularly those using low-NOx burners) burning a variety of fuels
Continued testing of fuel blends

System Integration

Burner and combustion systems that are compatible with advanced gas turbine technology
Integrated advanced burner concepts and boiler/duct heater combinations
Burner component research coordinated with boiler R&D
Steam-trap selection tool for condensate system and better steam traps
Condensate system design that prevents contamination due to poor water quality
Use of waste heat in condensate system
Combined heat and power (CHP) designs that balance thermal and electricity requirements efficiently
Capture of flue gas heat through improved process integration
Independent evaluation of post combustion clean-up systems

Appendix E

Furnace R&D Needs

(in relative order of priority within each category)

Tools and Models

Computational tools that contain validated, high-fidelity combustion models
Reliable, efficient model of turbulent, reacting flow
Common method for measuring furnace efficiency
Application-specific models
Tools that account for transient phenomena
Performance data for furnace equipment - in a standard format
Design tools for heat recovery device design
Robust, accurate models that consider process chemistry and fluid mechanics
More user-friendly tools

Sensors and Controls

Non-traditional sensors for more accurate measurement of temperatures and physical properties
In-situ, real-time temperature sensing
Image-based sensing to monitor surfaces
Demonstration of real-time combustion control in pilot-scale environment
“Smart” sensors and control systems (self-learning and -teaching)
Robust sensors to measure critical parameters in harsh combustion environments
Investigation of low-cost sensors used in the auto and other industries
Low-cost reliable flame monitoring systems (flame quality, stability, etc.)
Improved pressure measuring system and control device
Low-cost reliable actuators
Reliable, continuous flue gas analysis and temperature sensors
Sensors that can accurately measure fuel and oxidant compositional characteristics
Sensors to measure integrated energy use
Continuous heat flux meter
Real-time measurement of material failure

Design and Development

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., eliminate scale on steel)
Alternatives for heat processing
Hybrid systems or other methods to increase heat transfer to loads
Innovative, cost-effective, heat recovery process:

- Rapid cycle regenerative system
- Low-temperature heat recovery (e.g. warm water)
- Specific for oxy-fuel or oxy-enriched processes

Uses of waste heat for emissions reduction

Fundamental Understanding

Better Understanding of :

- Particulate generation in combustion
- Mechanisms of product degradation
- Heat transfer and its application
- Mechanisms to generate heat with less volume

- Scale-up
- Formation of dioxins and furans below 1400 F in flue gas streams
- Flue gas stream characteristics for prediction of behavior in a heat recovery system
- Mechanism for capturing fine particulates under wet conditions (NOx conversion)
- Physical properties of different materials

Materials

Improved materials for extending furnace life/reducing maintenance requirements
Investigation of material compatibility data for probes and sensors
Coatings to improve heat transfer and recovery
Improved fabrication methods for advanced materials (i.e., for irregular shapes)

System Integration

Combustion alternatives (e.g. induction heating)
Systems integration analysis of combined end use to extend the co-generation concept
Close coupling of manufacturing processes to reduce heat requirements
Ways to reduce oxidation of reactive products
Benchmarking classification of existing processes
Identification of processes that have the most difficult problems with heat exchange/furnace operation
Real-time thermal distribution

Technology Transfer

State-of-the-art combustion lab(s) to validate CFD models and test materials
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 the 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 environments
Identification and use of technical overlap in various industry applications
Data transfer standards
Combustion database integration and software engineering

Appendix F

Technology Achievement Objectives

Meeting Results & Participants - Roadmap Review

In April, 2002, a small group of industry experts met to discuss the draft combustion roadmap and develop measurable goals that indicate how well the actions developed in the Combustion Roadmap are contributing to the nation's energy objectives. The group developed milestones that the combustion community can use to measure its progress towards the Roadmap objectives. These goals are summarized in the one-page summary for each top priority R&D Need.

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Detailed Results**:**

Burners – Technology Achievements to Measure Progress

Research Need	Burners Capable of Adjusting Operating Parameters in Real-time	More Effective Radiant Heat Transfer to the Load	Robust Design Tools/ Unified Code	Advanced Combustion Stabilization Methods
Description /Objectives	• *Optimize boiler /furnace operation & performance to meet the vision's targets* • *Adjust 2 ways – flows and physical configuration*	• *Total Systems Approach* • *For Example - Radiant Burners*	• *Burner/Furnace design tool Research Needs are related.*	• *Help meet emissions targets* • *Allow multiple fuels* • *Optimize fuel input and turndown ratio*
Measure 1	Proof of Concept: 5 yrs.*	Proof of Concept: 7 yrs.*	40% of burners sold in 5 yrs* will have analytical tools as an integral part of design.	Proof of Concept: 8 yrs.*
Measure 2	Demonstration: + 2 yrs.	Demonstration: + 2 yrs.	75% of burners sold in 10 yrs* will have analytical tools as an integral part of design.	Demonstration: + 3 yrs.
Measure 3	1st Commercial Sale: +1 yr	1st Commercial Sale: +2 yrs.		1st Commercial Sale: +1 yr.
Measure 4	10% of New Sales in Demonstrated Market: +5 yrs.	10% of New Sales in Demonstrated Market: +5 yrs.		10% of New Sales in Demonstrated Market: +4 yrs.

***** From start of work***

Boilers – Technology Achievements to Measure Progress

Research Need	New Boiler Technologies	System Integration	Technology Transfer
Description /Objectives	• *Current Boiler Designs are 30-40 yrs old.*	• *Technology exists* • *Low level heat steam vs. plant integration* • *Cost-effective technologies are needed to collect low grade heat* • *Current economic climate is not conducive for investment*	• *Collaboration to promote the adoption of new technologies* • *Ultimate objectives determined by participants*
Measure 1	Completion of an analytical study/ assessment of boiler operation: 4 yrs.*	Demonstration of technical viability of steam plant integration using current technologies: 5 yrs.*	Formation of an industry and government collaboration focused on technology transfer: 2 yrs.*
Measure 2	Evaluate candidates for concept development: + 2 yrs.		
Measure 3	Proof of concept: + 5 yrs.		
Measure 4	Demonstration: + 2yrs		

**** From start of work***

Furnaces – Technology Achievements to Measure Progress

Research Need	New Furnace Designs	Advanced Sensors and Process Control	Integrated Computational Design Tools	Cost-Effective Heat Recovery
Description /Objectives	• *Furnace research is underway in each industry*	• *Real-time process sensors for combustion* • *Reliable, in-situ sensors*	• *Closely connected to burner design tool Research Need*	• *System to combine heat recovery and emissions reductions* • *Used in many industries* • *Market opportunity is substantial; difficult to estimate*
Measure 1	Provide support to IOF furnace activities: Timeline determined by each IOF	Proof of Concept: 3 yrs.*	15% of new furnaces sold in 5 yrs* will have been developed with advanced analytical tools.	Proof of Concept: 3 yrs.*
Measure 2		Demonstration: + 2 yrs.	30% of new furnaces sold in 10 yrs* will have been developed with advanced analytical tools.	Demonstration: + 2 yrs.
Measure 3		1st Commercial Sale: + 1 yr.		1st Commercial Sale: + 1 yr.

***From start of work**