INDUSTRY-IDENTIFIED COMBUSTION RESEARCH NEEDS

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ABSTRACT

This report discusses the development and demonstration of innovative combustion technologies that improve energy conservation and environmental practices in the U.S. industrial sector. The report includes recommendations by industry on research and development needed to resolve current combustion-related problems. These views are based on information from industry sources and on reviews of previous studies contained in DOE's Office of Industrial Technology (OIT) Vision Studies, previous OIT combustion research assessments, and private research programs. Both fundamental and applied R&D needs are presented. The report assesses combustion needs and suggests research ideas for seven major industries, which collectively consume approximately 78% of all energy used by industry. Included are the glass, pulp and paper, refinery, steel, metal casting, chemicals, and aluminum industries. Information has been collected from manufacturers, industrial operators, trade organizations, and various funding organizations and has been supplemented with expertise at the Idaho National Engineering Laboratory to develop a list of suggested research and development needed for each of the seven industries.

Section 5 presents a summary list of the research areas in each industry. Some of the technologies proposed for research are specific to certain industries; others are cross-cutting technologies. In general, the technologies cover the research and development in

- Fundamental combustion kinetics
- Development and demonstration of new generation combustion devices
- Emissions monitoring and control technologies
- Improved diagnostic devices and control systems
- Combustion modeling and optimization concepts
- Improved heat transfer concepts.

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INDUSTRY-IDENTIFIED COMBUSTION RESEARCH NEEDS

1.0 INTRODUCTION

American industry relies heavily on energy and machines to drive industrial processes. U.S. industry consumes about 13-15 quadrillion Btu (quads) of fuel each year (excluding electrical imports). Industry's appetite for energy translates to costs of about \$100 billion/year. Since this sum amounts to only about 3% of industry's total cost of doing business, many companies do not pay sufficient attention to controlling energy use.

Despite the drive for energy efficiency in the late 1970s, the potential for implementing additional energy efficiency in U.S. industries is still significant. For example, a typical integrated steel plant in the United States consumes 39% more energy than a *best practice* plant that uses state-of-the-art processing and technology. Industry's research staff and research funding has decreased since the 80s owing to smaller profit margins.

The Department of Energy's (DOE's) Office of Industrial Technology (OIT) has been a major contributor to improved energy efficiency over the past two decades. Energy saving and environmentally benign technologies such as oxy-fuel combustion, electrochemical dezincing of steel scrap, and direct steelmaking were considered too risky by industry for development and were championed by OIT. They are considered factors that contributed to renewed U.S. competitiveness. OIT-sponsored technologies helped reduce industrial energy costs by about \$400 million in 1993 (DOE/GO 1995 a). For future programs, OIT is seeking methods that streamline the technology selection process and pursue those technologies that have significant economic and energy payback but are beyond the resources of any one company to develop. By combining interests and resources of industry and DOE, future leading edge technologies can be pursued through a cooperative approach that would otherwise be considered as too high risk. Using this development strategy, scarce research and development (R&D) resources can be shared among cooperative members while benefiting U.S. industry as a whole. The objective of this report is to present industry-identified combustion needs of the major energy consuming industries and to define the type of research needed to satisfy these needs.

DOE's two OIT combustion activities are aimed at improving energy, environmental, and economic efficiency and providing cost-effective attainment of environmental goals: the Industrial Combustion Technology Program and the Industrial Combustion Equipment Program. Historically the OIT combustion programs have focused on fundamental and end-use activities. The orientation of the projects funded have followed the needs of industry as recommended by industry and by independent assessment studies.

2.0 APPROACH

To enhance DOE's responsiveness to long range R&D needs of U.S. industry, OIT launched an important initiative known as the Industries of the Future. This initiative strengthens the collaborative efforts between industry and government and leverages scarce R&D resources to the greatest extent possible. Industries of the Future purposefully concentrates on seven energy intensive industries, because these industries consume the greatest quantities of energy and are likely to possess the greatest opportunities for saving large quantities of energy and energy costs. Vision studies are being developed by each industry to define potential research that is necessary to maintain them in competitive positions in the international marketplace.

The seven major industries are surveyed in this report: the glass, refineries, steelmaking, chemicals, pulp and paper, aluminum, and metal casting industries. These industries consume approximately 78% of all energy used by industry and produce more than 90% of the waste generated in manufacturing. The information contained in the vision documents served as a basis upon which specific combustion-related needs could be defined. Contacts within each industry and appropriate trade organizations were developed to define the industrial combustion needs. Consultants were also used to summarize the needs in their area of expertise and to provide a recommended list of research areas.

Input from key industrial contacts, DOE-OIT Vision Statement documents, existing combustion programs, and resources available at the Idaho National Engineering Laboratory (INEL) were used to identify the combustion research and development needs presented. Three subcontractors provided initial research inputs for the glass, steel, refineries, and aluminum industries (attached as appendices). This study also used the results of a workshop, *Fundamental Combustion Research in Support of Industrial Applications*, conducted October 10, 1994 (Penner and Berlad 1995). Over 43 persons attended this two-day workshop, representing industrial, academic, national laboratory, and corporations. Numerous inputs from attendees were received and summarized.

The research recommendations for each industry are summarized in Section 5.

3.0 INDUSTRIAL COMBUSTION

Combustion is a process that generates heat from the oxidation of solid, liquid, or gaseous fuels. Inefficiencies occur during the conversion process, in the transfer of the heat to industrial loads, and through emissions of unwanted byproducts. A reduction in the amount of energy consumed in industrial processes is a major aim of the OIT combustion activities. This reduction can occur through improvements in efficiency or through conversion to other fuels such as coal, low Btu gas, or waste products.

The overall efficiency in the combustion of fuels and the transfer of the heat generated to industrial processes can be improved either by modifications to the existing combustion process

during retrofits and new installations or through new, innovative processes. In the first case, modifications will result in incremental energy savings. In the second case, the energy savings potential can be greater, but the risks and implementation costs are higher. Potential methods to improve the energy efficiency of combustion processes and to reduce energy use include the following:

- Reduced heat loss from the combustion system
- Increased heat transfer to the load
- Use of alternate fuels.

The OIT combustion programs concentrate on the activities involved in conversion of the chemical energy in the fuel to heat, the transfer of this heat to the load, and the discharge of the products of combustion. Reducing the energy exhausted to the stack (over 40 to 50% of the available heat in some applications) is a key element of the OIT program. This can be accomplished by increasing the energy efficiency of the process (improved heat transfer to the load, reducing heat transferred to walls, operating at optimum stoichiometry, avoiding overheating the load, etc.). For example, advanced methods of diagnostics is an integral program element because sensors can convey information and allow precise control of the combustion process. Sensors may also provide opportunities to reduce the heat losses noted and may provide an additional benefit of improved product quality.

To ensure comprehensive results, the OIT combustion activities target both specific applications and technologies that cross-cut several industries. Industry-specific technologies (e.g., recovery boilers used in the forest products industry) require specific research objectives. Other technology research objectives are much broader, for example, burners, refractory materials, diagnostics, and boilers.

4.0 INDUSTRIAL RESEARCH NEEDS ASSESSMENT

Following are the results of an assessment to define the combustion-related industrial needs and to list potential research projects that could resolve them. For each of the seven major industries, a status of the industry, an identification of combustion related problems, and a list of selected research opportunities are presented.

4.1 Petroleum Refining Industry

The petroleum refining industry produces transportation fuels and raw materials for industry. It supplies energy to fuel more than 190 million automobiles and other vehicles, plus all aircraft. The number of operating refineries has declined 34% in several decades, from 285 in the 1960s to 187 in 1993. No grassroots refineries have been built in the United States for over a decade. Among the 10 largest refinery capacity owners in the United States, four are foreign companies. Overall, imports of foreign crude and refined oil products supply almost half the U.S. market.

Petroleum refining consumes about 6 quads of energy, more than any other U.S. industry. Over half of the industry's energy comes from refinery gas produced in-house. Energy efficiency has decreased 9% since 1985, largely because of lower quality crudes that require additional processing energy due to higher sulfur content and other constituents.

An evaluation of research needs for the petroleum industry was made using several sources. These sources have included past evaluations of industrial research needs (Penner 1994, Chase et al. 1989, Chase et al. 1988). Another source was a survey of petroleum industry research needs recently conducted by Energy and Environmental Research Corporation (EER). EER has participated directly in this research needs evaluation effort and has conducted combustion research on behalf of government agencies (including DOE and EPA), petroleum companies, and trade associations [(including the Western States Petroleum Association (WSPA) and the Petroleum Environmental Research Forum (PERF)] for several years. Results of this survey are summarized in this section, and the full report is included in Appendix A. The survey included not only petroleum refinery companies but also companies that depend on and are knowledgeable of petroleum industry research needs. These included natural gas distribution companies (Southern California Gas and Pacific Gas and Electric), combustion and heating equipment manufacturers for the refinery industry (process furnace manufacturers-KTI and burner manufacturers, Selas and John Zink), a number of refinery end users, both corporate and plant engineering and the architectural and engineering firms who support them (Fluor, Brown & Root, and C.F. Braun). Trade associations such as the American Petroleum Institute (API), WSPA, and PERF were also important sources of data.

The survey included a questionnaire used with a limited but diverse subset of the population surveyed. Nineteen potential interviewees were identified and contacted. R&D for improved process control (sensors), emission (acid gas and air toxic) control, and enhanced heat transfer through improved convective and radiative heat transfer were explored. Generic petroleum industry combustion equipment that processes significant amounts of product and/or consumes large quantities of fuel was identified.

4.1.1 About the Industry

Refineries vary quite widely in crude feed characteristics, complexity, and product mix. Most large refineries produce a high yield of gasoline and middle distillate fuel as well as lube oil from crude oil. The most energy intensive refinery unit operations include initial crude distillation, desulfurization of some of the intermediate products, and their upgrading through catalytic cracking, naphtha reforming, alkylation, and coking. Sources of energy for these operations are primarily natural gas, refinery fuel gas, and petroleum coke. These operations account for more than 80% of the energy consumed.

The distillation of crude requires fluid heating in a process heater to about 800°F. Crude separation via distillation into intermediate products varies, but typically results in high and low sulfur liquids, gases, and off gas. Sulfur typically concentrates in the liquids and residuum,

which need to be further upgraded in additional unit operations. Natural gas and refinery gas blends are burned in crude heaters to supply process heat to the column feeds. Steam produced in boilers is used to provide heat and stripping media to various components of the distillation equipment.

Catalytic hydrogenation of the sulfur-containing liquids (naphtha and gas oil) requires H_2 addition and heating to between 650 and 800°F in a process heater. The feed is then passed through a fixed bed catalytic reactor, producing desulfurized liquid streams and H_2S off gas. H_2 is produced on site through purification of off gas from catalytic cracking and reforming of crude feedstocks, or through catalytic reforming of a fossil fuel, usually natural gas. H_2 reforming requires large furnaces that incorporate both concurrent process heating and catalytic cracking of the feed at moderately high temperatures of about 1,600°F. Large amounts of steam are co-fed and used in downstream shift reactors to improve H_2 yield. Refinery gas and natural gas are usually used as furnace and boiler fuels.

Coking of the low-end cut distillates such as residuum is performed to improve gasoline yields. Coker products include coke, olefins, gas oils, and naphtha, which must be further processed or sold as intermediate product. Coker feed is reheated in a process heater firing refinery fuels and off gases.

Catalytic reforming upgrades nonaromatics and naphthas to aromatics for octane improvement. The unit operations of catalytic cracking and alkylation further upgrade feed stock intermediates. They are less energy intensive than crude heating, requiring heating feed from low to moderate temperatures in a process heater train. Catalytic reforming unit operations include (a) catalytic cracking where gas, oil, and catalyst are mixed, heated to about 900°F and reacted, and the components separated through distillation, and (b) alkylation where isobutane reacts to form olefin streams over a catalyst.

Typical large fuel burning combustion equipment includes (a) process heaters providing heated fluids to unit operations such as distillation, reforming, cracking, and hydrotreating, (b) large boilers providing process and heat steam, high pressure, superheated steam to turbine drives, and in some refineries gas turbines operating in cogeneration configurations providing power, steam, and process heat. All of this equipment is generally capable of firing a wide range of gaseous and liquid fuels, usually blends of process off gases of widely varying heating value and more traditional fossil fuels.

Process heaters are very predominant and consume the most fuel in a complex refinery. Unit operations that use large process heaters include the majority of refinery operations. Feed, liquid or gaseous, is preheated against product gases and finish heated in a process heater or furnace to temperatures between 200 and 1,600°F. Furnaces may be top or bottom fired with a few large burners or side wall or with a large array of small burners. Heat inputs will vary between 20 and 500 MMBtu/hr. Burners may be natural draft or forced draft (sometimes with air preheat). The primary mode of furnace heat transfer is by radiation, with furnace flue gases

exiting at as high as 1,800°F. Down stream convective passes either preheat feed or a heat transfer fluid to improve unit thermal efficiency. Fluids heated vary widely in physical and chemical composition and are sometimes prone to cracking in the furnace tubes because of uneven furnace wall heating. Air emissions include the acid gases (NO_x and SO_x), and air toxics.

Steam is generated in large water tube, direct-fired packaged or field-erected boilers. Boilers are also sometimes fired or co-fired with refinery fuel gas, CO, or natural gas for purposes of thermal destruction. Air emissions include acid gases and air toxics, and particulates smaller than 10 microns (PM10). Boilers typically have heat inputs of 100 to 1,000 MMBtu/hr. Burners are forced draft, multi-fuel, frequently with combustion air preheat in their larger sizes.

Large frame and aero-derivative gas turbines are now frequently found in large (>100,000 Bbb/day) refineries and produce power sufficient for minimum operation, typically 40 to 200 MW. Most are equipped with NO_x control technologies including steam or water injection, CO and NO_x catalytic control, and more recently with dry, low NO_x combustors. They typically burn a blend of refinery and natural gas. Turbine exhaust heat is recovered in heat recovery steam generators or specially designed process heaters.

4.1.2 Research Needs

There are a number of research needs identified in this evaluation. The greatest single focus was on research for improving the product or purpose of the combustion equipment. For example, research to improve heat transfer to the heated fluid in process heaters by enhancing flame radiation heat transfer was considered most important for process heaters and burners used in process heaters. Short-term (within 3 years) research was considered more important than longer-term research, because of the belief (especially in environmental concerns such as air emissions) that changing regulatory requirements make the longer term too uncertain.

General types of combustion equipment technologies were suggested to the survey respondents as initial starting points from which to identify combustion needs. The survey respondents considered multiple burner arrays, catalytically assisted combustion, fluidized beds, mass burn, suspended circulation, and porous media.

Practically any research that focuses on the performance and air emissions [especially acid gases (primarily NO_x) and air toxics] for multiple burner arrays and catalytically assisted combustion is considered to be a high priority. Most process heaters are multiple burner arrays, and catalytically assisted processes such as catalytic cracking and reforming are very important refinery operations. However, there were several major research needs that were important not only for multiple burner arrays and catalytically assisted combustion, but were cross-cutting for most or all of the different general combustion technologies. These are, in order of priority;

- High-temperature furnace efficiency improvements through flame radiation enhancement and oxygen enrichment

- Heat release profiling to optimize energy transfer from the energy source to the load
- Refractory improvements
- Acid gas (primarily NO_x) control, especially for conventional multiple burner arrays and catalytically assisted combustion
- Flame safety and stability.

Furnace efficiency is important for the process heaters that dominate refinery combustion processes, as well as other combustion equipment. Efficiency and performance improvements for process heaters can result in significant energy and operating cost savings and higher safety. Control of radiant section temperatures are very important for maximizing efficiency and for minimizing catastrophic tube failures and other problems such as tube-side coking of heated crude.

Inasmuch as lower quality and alternative feedstocks and fuels are used in refineries worldwide, energy conservation and versatility of combustion equipment is also important. Heat release profiling is one of the tools used to improve furnace efficiency and determine the ability to fire alternate fuels under various conditions in furnaces, while maintaining operating safety.

Reduced maintenance and downtime are always important issues in refinery operation. Research on materials of construction, especially for high-temperature refractories, is important to improve refractory lifetime.

Some respondents considered research to improve control of air emissions to be very important, others considered this to be less important than performance of the combustion equipment to perform its primary task such as heat production, heat transfer, steam generation, or power generation. The importance of flame safety and stability was also inconsistent but did rank high enough to be placed in a priority position. This topic was considered to be important for combustion equipment using mass burn or multiple burner arrays, but was less important for other types of combustion equipment.

4.2 Steel Industry

The steel industry is divided into two major segments: (1) large, integrated producers that smelt iron ores to molten iron in blast furnaces and refine the iron in basic oxygen furnaces, and (2) nonintegrated producers that rely primarily on scrap for their raw materials. The steel industry has undergone drastic restructuring over the last decade by investing heavily in continuous casting, adopting new management styles, closing many outmoded plants, improving quality, and boosting productivity at a 7% annual rate since 1984. Such changes helped 1993 industry shipments reach their highest level since 1981, while import market penetration was at

its lowest since 1980. Also, the industry returned to profitability during 1993—94 after sustaining a cumulative deficit of \$3.5 billion between 1989—92.

Annual energy use in the steel industry is about 1.7 quads, or about 21 million Btu/ton of finished steel. The industry spent \$4.8 billion on purchased energy in 1991—8.7% of its value of shipments. Coal supplies about 50% of the industry's energy, and natural gas supplies about 25%. Electricity is the dominant energy source among scrap-based minimills.

The main priorities of the steel industry are production capacity, customer service, quality, environmental control, and cost. Use of energy in the production of steel therefore is a matter of concern. Modernization programs that improve production, quality, or both will frequently improve fuel use and reduce the overall Btu/ton of crude steel produced. Reduction of fuel consumption also has a positive effect on the environment. Prime examples of projects that improved capacity and quality and affected major fuel economies are the installation of continuous casters and the new generation of walking beam reheat furnaces recently installed in many steel plants.

There is an ongoing concern that many of the combustion processes used in producing steel involve the generation of carbon dioxide and nitrogen oxides, unwanted byproducts. The Clean Air Act of 1990 provides impetus to improve combustion efficiency and minimize the generation of unwanted emissions. A reduction of fuel consumption is viewed as a way to achieve significant reductions in the generation of these undesirable byproducts. The improvement of fuel rates in various steel producing processes help achieve this goal.

The desire of the industry is to have research efforts directed toward combustion process improvements that will achieve significant tangible improvements in the near term. Projects that are likely to stay in the laboratory for five to ten years before commercial use is initiated are not of great interest.

The projects discussed, in nonprioritized order, below are considered possible application research work. The succeeding sections were developed in discussions with two integrated steel companies, two burner manufacturers, one furnace builder, one oxygen supplier, and industry energy experts. The complete recommendations for this industry are discussed in Appendix B.

4.2.1 Candidate Research Projects

4.2.1.1 Reduction of the Use of Coke. Coke batteries have high initial capital cost, continued operating and maintenance costs related to the nature of oven design, and challenging environmental problems. The standard coke oven furnace design presently in use is the same design used for the last 70 years. While size of the furnaces has changed, the principle is the same: coal is indirectly heated by transferring heat through thin, fragile refractory walls to make coke. The coke making process must either be replaced with one that overcomes the current problems, or the ironmaking process must be modified to reduce or eliminate the requirement for

coke. Past efforts to develop new cokemaking processes to overcome the problems of the existing coke oven design have not been successful. Therefore, reduction in coke usage represents the most direct path to reducing cost and environmental problems.

The majority of North American furnaces inject natural gas, and in recent years much higher gas injection rates have been achieved. Natural gas injection at these new higher levels greater than 100-lb per ton hot metal (THM) has proven to be beneficial in reducing coke consumption while increasing productivity at minimal capital cost. However, from a long-term strategic viewpoint it is believed that natural gas can replace at most 25% of the furnace coke requirement. Coal injection, on the other hand, could replace up to 40% and perhaps more of the furnace coke requirement. Accordingly, the largest steel plants in the Chicago area and several others have installed coal injection. At present, coal injection is installed on 12 furnaces, representing almost 20 million tons or about 40% of the U.S. hot metal production.

The major difference between the recent North American coal injection projects and those elsewhere is that these North American projects are all designed to inject at high levels, 400 lb/THM. This level is economically essential in order to justify the capital investment required, as lower levels of coal injection would merely replace natural gas injection already available with no capital cost.

The need for North American furnace operators to inject coal at high levels, 400 lbs/THM, to maximize coke replacement requires efficient combustion at the tuyeres. A considerable amount of research has been performed in Europe and the Far East to study the key aspects of coal combustion in the blast furnace raceway (combustion) zone. Many of these studies have used laboratory or pilot-scale single tuyere combustion furnaces; some of these have been supplemented by in-furnace measurements of raceway gas composition and temperature.

Such studies have shown how combustion efficiency is increased with higher flame temperatures, oxygen enrichment, smaller coal particle sizes, higher coal volatile content, reduced coal moisture, etc. In blast furnace operation it has also been observed that combustion efficiency and overall use is affected by tuyere velocities, injection lance design, coke quality, and raw materials distribution. These laboratory studies and furnace operating experiences have provided valuable guidance to North American ironmakers in the startup and operation of recent coal injection installations.

However, these overseas studies are not tailored to North American coals or specific blast furnace conditions. The only significant coal injection research initiative in North America is the DOE Clean Coal Program Project at the Bethlehem Steel Burns Harbor Plant. Here, a full-scale coal injection system, capable of injecting at high rates, 400 lbs/THM, has been installed on two medium-to-large size furnaces producing each about 7000 THM/day. The test program will feature the exploration of the maximum coal injection rate for a given coal grind size for up to four types of North American coals.

The Bethlehem Burns Harbor DOE test program will furnish valuable empirical information on the suitable coal grind size for various injection levels for the most typical North American coals. This program could be enhanced by a complementary laboratory scale effort with a raceway or tuyere hot model. Such a hot model could be used in a program to explore a wide array of coal injection lance configurations, blast conditions, coal types, and grind sizes. This program could also complement in-house studies and furnace experimental trials at other steel company coal injection sites.

A useful extension of the laboratory program could be the co-injection of other solid materials: waste oxides, fluxes, fine iron ores, titanium ore (to protect the furnace hearth), and plastics. The injection of plastics has been tested in Germany at Stahlwerke Bremen and holds great potential for energy efficient disposal of waste plastics that cannot be recycled by other means. The co-injection test program could also include other fuels such as oil, tar, and natural gas; such co-injection practices are already used but probably not optimized at several U.S. blast furnaces.

While the above program would initially be directed toward coal injection, the co-injection of other solid materials such as flux, ore, plastics, etc., should also be tested. Natural gas injection will continue to play a major role in North American blast furnace practice even after all companies likely to adopt coal injection have done so.

4.2.1.2 Blast Furnace Operating Improvements. The fuel used in an integrated plant's boilers accounts for a significant portion of the total plant fuel consumption. A large portion of the boilers' steam output is used to drive the turbo-blowers that provide the *wind* for the blast furnaces. The advent of larger, modern blast furnaces has resulted in larger, more powerful turbo-blowers capable of producing greater air flows at higher pressures. This results in a cost factor that could be mitigated by a process change. Technology affecting boiler efficiencies, steam cycle efficiencies, condensers, and blower efficiencies is very well understood, and there are few areas of opportunity where further research would bring energy savings not already available.

However, the following opportunity should be investigated to establish if significant energy savings can be achieved by making changes to the ironmaking processes of the integrated plants.

- Modification of the blast furnace process using heated recycled reducing gases. Russian experimental work has demonstrated a process that uses recycled blast furnace top gas enriched with 95 percent purity oxygen instead of air for blast furnace blowing purposes. The top gas would be compressed, stripped of CO₂, heated in modified blast furnace stoves, and blown into the furnace through the tuyeres. While a demonstration plant has been built in Russia, the process is untried in this country. An evaluation of the process, its economics, and a possible field test in this country is needed.

4.2.1.3 Burner Enhancement Projects - Reheat Furnaces. Reheat furnaces are generally fired with recuperative burners of various sizes using combustion air temperatures up to 900°F. While temperatures greater than 900°F have been used, the cost of burner and recuperator materials goes up appreciably, and maintenance increases disproportionately, particularly if fuels other than natural gas are used. Burners are sized and applied by carefully taking into account the furnace heat loads that must be satisfied. However, the variability of the material heated (length and thickness as well as furnace loading pattern) makes the burner selection process a series of compromises.

Modern computer control systems are now available to control furnace temperatures to respond to the varying production and temperature requirements for heated steel to be rolled by the mill. These computer programs are intended to model the radiant and convective heat transfer of the burner flames to the furnace refractory and steel.

Furthermore, there is a whole spectrum of low NO_x burners and oxy-fuel burners available in the marketplace. Additionally, there are several regenerative burner systems available. Pulse combustion burner systems are also being proposed by some suppliers for improving the efficiency of certain furnace types. Burner types supplied by the major manufacturers should be tested, evaluated, and modified, as required to:

- Improve uniformity of generation and application of heat to the steel. This includes a thorough evaluation of the heat transfer aspects of the burner types to confirm that existing computer models properly account for the burner characteristics.
- Further reduce NO_x emissions.
- Improve the range over which burners can properly apply a uniform temperature field over the steel to be heated.
- Improve burner long-term durability.

A detailed examination of the benefits or disadvantages of using oxygen enrichment of the combustion air should be conducted. This should cover the full range of combustion air oxygen from 21 to 100%. It is clear that NO_x generation rises with the increase of combustion air oxygen content and the resultant flame temperature. The question that must be addressed is whether or not the savings in fuel is a linear function of NO_x per Btu of fuel fired so that the net NO_x emission per ton of steel heated is reduced.

4.2.1.4 Direct Steel Temperature Measurement. While every major steel company now has very elaborate and complex computer models to simulate the heat transfer process that occurs in the reheat furnace and to predict the temperature of every slab in the furnace, such models require direct steel temperature measurement to calibrate the accuracy of the

computations. Positive feedback to verify and adjust for changes in emissivity, non-stoichiometric combustion, scale formation rate, burner misadjustment and other deviations from theoretical estimates is required to optimize heating practices. Several concepts have been researched but the industry claims the need has not been satisfied.

Measurement of steel temperature in a reheat furnace is subject to errors caused by the varying thicknesses of the scale layer on the steel. The measurement can be affected by the furnace atmosphere in the area where the measurement is being taken. A device is needed to directly measure the temperature of steel in the furnace as it is being heated. This device must be unaffected by the hot combustion gases surrounding the steel and the varying thicknesses of scale on the surface of the steel. Additionally, the device must be robust to withstand the unfriendly environment in which it must operate. While several manufacturers have produced and marketed such instrumentation, durability, reliability, accuracy and repeatability have not been acceptable. It is recommended that research be directed to either improve existing equipment or develop a measurement system that does not depend on optical viewing of the steel.

4.2.1.5 Combustion Completion Measurement. Combustion efficiency is maximized when the fuel is burned to completion with a minimum of excess air. A fuel cost penalty results if either too much air or too much fuel is put into the furnace. Since combustibles or excess air in the flue gas from any one zone affect the measurement of combustion in succeeding downstream zones in the furnace, each zone must be monitored and controlled separately, thereby requiring a multiplicity of instruments in a multiple zone, multiple burner furnace. Several manufacturers have marketed instrumentation to attempt to measure and control the completeness of combustion. None of these has been entirely satisfactory because they have failed to meet one or more of the criteria for durability, reliability, accuracy, or repeatability. However, if a reliable instrument is developed to look at the flame to determine completion of combustion, excess air could be better controlled, with an attendant fuel saving. It is recommended that a research effort be directed to develop an instrument capable of measuring completeness of combustion and determining proper air fuel ratio, taking into account the following:

- Flame length and size, which need not be constant as a function of fuel content and turndown ratio. The length of the flame and the point where any test instrument must be sighted changes as the rate of fuel input is varied.
- Variable fuel composition. By-product fuels are known to vary appreciably in analysis and Btu content. Similar variations occur to a larger degree in purchased fuels.
- Reliability-based design criteria, including attention to water cooling system design, clouding of lenses, and other problems inherent to the hot, dirty, vibration prone reheat furnace environment.

4.2.1.6 Continuous Annealing Furnace Burners. Continuous annealing furnaces are very large, costly, and inefficient. Expensive radiant tube burners must be used throughout because of requirements for various furnace atmospheres. A direct-fired burner that would heat the steel much more rapidly than the present radiant burners, and that would not oxidize, decarburize, or carburize the steel, would effect major fuel savings in the continuous anneal process, even if applicable in only a few furnace sections. This would not be an easy process to achieve, but it would most certainly have significant benefits, both in furnace size and thermal efficiency.

Areas that promise possible efficiency gains include

- Identifying new methods of rapidly heating strip to temperatures below those where furnace atmospheres would result in oxidation, decarburization, or carburization of the product. Pulse heating may be an application in this area.
- New direct firing methods at higher temperatures that would not cause adverse effects on the product.

4.2.1.7 Computer Modeling of Reheat Furnace Burner Flames. The accuracy of the computer models for predicting the steel temperatures developed in the furnace depends on the model for flame radiation and convection in the furnace. The advent of the many different types of low NO_x burners, as well as the low NO_x oxygen enriched burners, complicates the problem of developing accurate models to predict the heat transfer of these burners. The fact that varying firing rates and ambient temperatures occur in the reheat furnace adds to the problem. Any inaccuracies in the calculation of the heat transfer effected by the burners will affect the accuracy of the reheat furnace computer model.

Fundamental flame research is required to verify the actual heat transfer achieved by various types of burners. The results of such work could then be used to improve the accuracy of the many reheat furnace models now in existence. It is recognized that such work does not fall into the category of a process improvement that will achieve near-term results. However, it is of such importance that it is mentioned here. A program to examine possible solutions to this problem is recommended.

4.3 Metal Casting Industry

The foundry industry is primarily involved in melting metal and introducing it into a mold cavity to form complex shapes. More broadly, however, it may include premelting operations such as metal reheating, and postcasting operations such as annealing and tempering. Heat treating operations are discussed in this section, though they also pertain to the steel industry. In its narrowest definition, the foundry industry is almost totally scrap-based, converting up to 20 million tons/year of scrap into castings used in over 90% of durable goods and 100% of machine tools. About 3,000 foundries employ nearly 200,000 workers. Since

1980, about 25% of U.S. foundries have closed. Output in 1991 was about half of what it was in 1972. Casting imports and exports are each about 7% of the U.S. market. When the metal being cast is steel, the division between the combustion research needs of the foundry industry and the steel industry becomes somewhat vague. An attempt is made to keep the two industries separate. Further complicating this assessment is the melting of aluminum, which is covered in the aluminum industry section.

Foundries used 0.25 quad in 1988—66% from natural gas, and the remaining majority from electricity. Melting uses about 55% of the foundry industry's energy, but many furnaces are only about 35% efficient. The foundry industry spent \$3.3 billion for energy in 1992—17% of the value of shipments.

The metal casting industry vision notes that this industry is vulnerable to the cost of increasingly stringent environmental and occupational regulations (DOE/GO 1995 b). The vision study for this industry identifies the following combustion-related research and development needs: waste heat recovery and re-use, cupola furnace modeling and control using neural networks, advanced sensors and process controls to optimize process energy use, and melting and holding furnace optimization.

The foundry industry essentially melts scrap metal and produces a metal object of the desired shape by using a ladle to pour molten metal through a passageway into a mold and allowing the metal to cool and solidify. Melting is the single largest combustion-related processing step and can be effected in furnaces of several types, such as cupola, electric arc, induction, and gas fired. Cupolas are generally used for iron castings and account for 59% of all foundry metal. Gas fired furnaces are used for nonferrous castings.

Fundamental research needs to be conducted on coal and coke reactivity. The rate of carbon reaction within the cupola depends upon a number of factors. Production of carbon dioxide rather than carbon monoxide for cupolas is preferred because a reduction atmosphere is not required. Reactions that favor carbon dioxide production should be encouraged. Some types of carbon react faster. The active diffusivity is not well understood, but could lead to the use of less expensive coal.

About 33% of the energy of combustion in the cupola is lost through the discharge of the heat content of carbon monoxide. Foundries typically reburn the CO and recuperate as much of the energy as feasible, but the amount of CO discharge is still significant. One method to use this CO is to introduce oxygen at appropriate locations. This technique has been tried, but too much oxygen leads to melting in the upper layer which forms a sealing layer. Current research being performed for cupola modeling has increased the industry's ability to predict gas composition and exhaust stack temperatures. The use of this model to predict the location and amount of oxygen injection could lead to increased energy savings.

Sand casting is the dominant method used in the foundry industry. Die casting is the second most common. In the die casting process, molten metal is injected at high pressure into a water cooled steel die, where it solidifies as a net shape product. The life of the die is affected by materials properties and heat treating methods. Heat transfer to the die during heat treating has been a problem area. Studies that would determine improved methods of heat transfer are needed by the industry. Processes which improve heat transfer will have the effect of reducing combustion energy.

Reclamation of sand from sand casting requires further work. Regulations are increasingly limiting the amount of sand that can be disposed of in landfills. The sands contain organic and inorganic materials. One potential method of sand reclamation is the use of fluidized bed combustors where the organic is burned off. A demonstration of fluidized bed sand reclamation is needed (the heat produced could be used to preheat metal).

Off gasses from cupola melting require afterburners to reduce emissions to acceptable levels. Typically these are natural gas fired, very inefficient (without heat recovery devices), and combustion is difficult to sustain. Composition of the off gas is variable and needs to be better defined to reduce the amount of cover gas used to ensure complete destruction. Fundamental research needs to be performed to establish heating values based on chemical structure, improved combustion geometries and zoning, and emissions destruction efficiencies. Although not within the combustion program realm, the use of waste heat recovery devices should be studied for low-temperature direct applications or for the use of electrical generation where burnout of the carbon monoxide can be used. The study must include effects of particulate and gas composition suitability for generation equipment.

A significant amount of energy is lost in transfer processes as the hot metal is conveyed to casting areas. Based on the foundry site location and age, the material must be moved several times and kept hot during the transfer. Integration studies to minimize these transfers would be useful. The avoidance of reheating the metal will reduce the energy input per ton of metal produced. Combustion-related processes to replace electrical induction, or electric arc heating would be more efficient.

Competition from aluminum and other products is forcing the industry to reduce wall thickness for weight reduction. Heat treating of the castings becomes increasingly important to achieve acceptable metal attributes. The iron carbide precipitates that form when iron castings are cooled are typically burned off during heat treating processes. Improved methods to reduce these precipitates and achieve the appropriate heat treatment for thin castings is an area requiring further study. Optimization of this process will have the effect of reducing the amount of combustion energy.

The exhaust gases from cupolas lead to difficulties in the use of current-generation combustion sensors. Sensors to monitor oxygen, carbon monoxide, and carbon dioxide content would optimize combustion. Appropriate filters should be developed to allow the use of current-

generation sensors, or new sensors suitable for gas analysis in dirty environments need to be developed. Continuous measurement of the liquid metal flow out of cupolas cannot be monitored, yet this would give one necessary data point needed to optimize combustion. Monitoring of oxygen in foundries is typically accomplished with a one time use oxygen probe. Although costs for the probes are low and are used in the steel industry, they do not see use in the foundry industry because of smaller tonnage rates. The net cost of the sensor per ton of metal produced is considered too high by the metal casting industry.

4.4 Chemical Industry

The chemical industry is sometimes called the keystone industry because its products improve the productivity and quality of goods manufactured by so many other industries. It is the largest U.S. exporting industry: in 1993, exports were \$42.7 billion. The chemical industry must retain its strong competitive stance or risk aggravating the chronic U.S. trade deficit.

The chemical industry uses about 2.7 quads of fuel annually. Four of the industry's segments—inorganics, organics, plastics, and fertilizers—use almost 90% of the industry's fuel and electricity. Energy efficiency in the chemical industry has improved 51% since 1974.

Much of the growth in the chemical industry is in the specialty chemical sector. As firms in the commodity chemical market shift to the specialty market, some modifications of production practices are necessary because the sales in the specialty market are tied more closely to product quality and performance. Research developments should address these types of process improvements. In addition to improvements relating to changes in products and processes, there is always a need to reduce regulated emissions and reduce waste production. Recommendations for research to address process improvements, as they relate to combustion processes, include (a) development of advanced control algorithms for thermal reactors (fluidized-bed reactors, fluid heaters, and distillation reactors) in which combustion is used to supply energy to the process; (b) development of enhanced heat transfer methods for the transfer of combustion heat to processes such as those described above; and (c) development of high-temperature separation processes to partition the components of the combustion off-gas stream. These three topics are discussed in greater detail below.

4.4.1 Development of Advanced Control Algorithms and Equipment for Thermal Reactors

Product quality and efficiency are closely related to processing conditions, especially in the growing specialty chemical market; consequently, process control is imperative for successful production operations. Improved control algorithms are needed to meet the need for combustion processes. For externally heated fluidized-bed reactors, fluid heaters and distillation reactors, the amount of heat transferred to the reactor and the rate at which heat is transferred to the reactor are among the important process parameters. Improvements in the control of these

process parameters will result in improvements in product quality, efficiency and minimization of gaseous emissions.

For in-bed combustion fluidized bed reactors, improved control algorithms could result in significant improvements in product quality. For these processes, not only are the amount of heat supplied to the process and the rate at which it is supplied important, but the combustion process inside the reactor also directly impacts the product chemistry. Control of the combustion process results in control of product chemistry by regulation of chemical reactions involving the combustion off-gas and the product.

Improvements in the area of non-intrusive, in-situ measurements of conditions within the combustion reactor, whether it be a burner external to the reaction vessel that supplies heat to a process or an in-bed combustion process, are also needed. Run-time knowledge of combustion conditions, such as air/fuel mixtures and off-gas/effluent compositions, enhances operating efficiencies, improves product quality, and reduces regulated emissions from combustion processes, especially in situations where multiple fuel sources (such as process off-gasses, fuel oils, refinery residue, and/or natural gas) are employed.

4.4.2 Development of Enhanced Heat Transfer Mechanisms

Development of process control algorithms, and development of alternative materials and designs for vessel construction would enhance heat transfer for externally-heated processes. As the size of a process vessel increases, heat transfer limitations generally become more pronounced because while the surface area of cylindrical vessel varies proportional to the radius, the volume of the vessel varies with the square of the radius. Heat transfer limitations can negatively effect process efficiencies as vessel sizes increase, and in many processes heat transfer is the limiting constraint on reaction vessel volume.

4.4.3 High-Temperature Separation Processes

The production of high-temperature gasses during combustion processes in the chemical industry is widespread. It is sometimes necessary to perform a separation on these streams, either to remove entrained particulate or to remove one or more gaseous components from the stream. Most often, separations involving gasses are performed at temperatures that require cooling of the gaseous stream. If a portion of this cooled stream is to be used subsequent to the separation, it is often necessary to reheat the gas. This cooling-heating cycle loses heat that might have been used during the cooling step and requires additional heat during the heating step. These inefficiencies could be eliminated by using of high-temperature separation processes.

One high-temperature gas separation concept involves the use of high-temperature membranes or molecular sieves, or both, to separate gasses at near the process temperature, thus eliminating the loss of heat during cooling and the consumption of heat during reheating of the

separation product(s). It is likely that technology development in this area would include developing new materials and advanced process design and control.

4.5 Glass Industry

Glass was one of this country's first industries, locating here from Europe owing to abundant energy and raw material. Today's glass industry is a major user of energy. The glass industry constitutes one of the principal markets for natural gas, consuming over 188 billion cubic feet in 1994. This fuel has been preferred over other fossil fuels because of its operational cleanliness and flexibility. About 85 percent of the total energy used in the glass industry is supplied from natural gas, and about 14 percent comes from electricity. A small amount of oil is used in melting; however, its use is restricted to situations where gas is purchased on an interruptible basis and has been curtailed. Because of air emission concerns and some operating difficulties, oil use is usually discontinued as soon as gas again becomes available. The full report used as input to this discussion on glass can be found in Appendix C.

Overall, about 75 percent of the natural gas consumed by the glass industry is used for melting; the balance is used for (a) downstream operations, which consist of fabrication into containers, flat glass, fiberglass, or a variety of objects (such as dinnerware, kitchenware, television tubes, and laboratory ware), that are pressed and blown, and (b) finishing operations such as annealing and tempering. However, in the fiberglass segment, 55 to 60 percent of gas consumption is used for melting and refining; in the other segments, melting and refining account for 85 percent or more.

The fabrication processes are different for each product category, but they use combustion processes for controlling the molten glass temperature. Many products are thermally or chemically treated after fabrication by tempering, annealing, labeling, coating, or decorating. Tempering of flat glass is very energy intensive. For the annealing of flat glass or containers, energy intensity depends on the efficiency of the annealing lehrs.

The major use for gas in the container glass sector is in melting, with some consumption in annealing and finishing. Average fuel consumption for melting is about 4.5 to 6 MMBtu/ton. The flat glass segment also consumes energy for laminating, autoclaving, annealing, and tempering. Typical furnace fuel consumption is in the range of 8 to 10 MMBtu/ton melted. Fuel consumption in the fiberglass melting furnaces also run in the 8- to 10-MMBtu range. Unlike the container and flat glass segments, a large amount of energy is used in fabrication. Fiberizing can consume 6 to 10 MMBtu/ton. Pressed and blown glass melting furnaces have a capacity of about 5 to 25 TPD. Fuel consumption in these plants can run 12 to 16 MMBtu/ton shipped.

The basic design of conventional fuel-fired furnaces has remained unchanged for many years. The raw material charge is melted in large gas-fired reverberatory type furnaces. High heat losses and inefficient regenerator designs formally resulted in thermal efficiencies of less than 30 percent in many older furnaces. The efficiency of these types of furnaces has been

increased significantly in the last 15 years in response to the rapid increase in energy costs. Fuel consumption has decreased by more than 25 percent through a variety of design changes. More efficient regenerators have been used to increase combustion preheat temperatures to 2,200 to 2,300°F. This may require the use of more expensive refractories in the hot end of the regenerator and some increase in size and design complexity to obtain the higher effectiveness. More efficient insulation of the furnace itself reduces heat loss and decrease its fuel consumption, but the savings are limited by the size of the furnace.

4.5.1 Combustion-Related Problems

4.5.1.1 Environmental. With melting energy representing approximately 15% of manufacturing costs and considerable efforts necessary to meet expanding environmental regulations, the industry must find alternative melting technologies to remain competitive. Environmentally driven process changes for reducing emissions of criteria air pollutants (HC, CO, NO_x, and particulate matter) sometimes do not lead to increases in productivity and thus have increased operating costs. Investments in environmental control equipment are viewed as nonproductive and as leading to further pressures on the industry's low operating margins. Therefore, there are real opportunities for the development of technologies that can meet applicable regulations without increases in capital requirements or operating costs.

One key issue for combustion space characterization and modeling for glass melting furnaces involves understanding the heat input to the batch/glass, the relationship with pollution production (NO_x) and combustion products, and glass fluid dynamics (refractory erosion resulting from flow, entrainment of particulates, etc.). Present combustion models are limited in their ability to accurately predict chemical reactions, radiant heat transfer (spectral effects, etc.), and the turbulent reacting flow. For example, the Fluent, Inc., code is frequently used by many organizations but it has limited sub models and a simplified radiation heat transfer sub-model. There is very limited *linkage* between the combustion environment and chemical species interaction at the melt interface. Another major issue is that there are very few experimental data to validate numerical models.

An effort in the glass industry is underway to gather detailed measurements within an operating glass melter. Measurements will include the collection of local gas compositions, including O₂, CO₂, CO, NO_x, and SO_x, their temperatures and gas velocities. Measurements of wall radiant and convective heat flux will also be made. Process variables will be altered (such as different burner angles, gas flow rates, etc.). The local data will be used to experimentally validate computer models. The validated model will then be used to optimize present operating conditions, examine possible design changes, and investigate innovative concepts and examine possible design changes, such as gas reburn, staged combustion, oxygen/fuel combustion, etc. These validated models will allow an investigation of the effects of changing conditions and geometry on both the combustion process and molten glass.

Although the concept behind low NO_x burners may be applicable to glass melting, the burners cannot be directly retrofitted to glass furnaces. This is a consequence of a basic difference between industrial boilers and glass furnaces. In boilers, mixing of fuel and air takes place within the burner itself. In a glass furnace, however, the burner is really a fuel injector, injecting fuel into the flow of combustion air entering the furnace. The mixing of fuel and air takes place within the furnace. Consequently, there are no off the shelf low NO_x burners available for glass melting furnaces.

In natural gas-fired regenerative glass furnaces, NO_x is essentially formed by thermal oxidation of nitrogen in combustion air (thermal NO_x). Thermal NO_x depends upon the time-temperature history of the flame and increases with increasing residence time and increasing peak flame temperatures. Furnace operating temperatures and flame temperatures—and, consequently, NO_x generation—are quite high. NO_x emissions over 10 lb/ton glass are not uncommon. Thermal NO_x also increases significantly with increasing availability of oxygen in the high-temperature zone. To reduce NO_x formation during natural gas combustion, both the peak flame temperatures and the oxygen availability must be reduced. California is the most aggressive in terms of regulating NO_x emissions. Current regulations specify less than 4 lbs NO_x/ton of glass produced. Some conversions to oxy-fuel sponsored by DOE have resulted in NO_x emission of less than 1 lb NO_x/ton.

At this time, the use of oxy-fuel firing is viewed by the glass industry as the leading melting technology to lower NO_x emissions. Implementation of this technology for meeting future environmental compliance will initiate a significant driving force to integrate waste heat recovery schemes, such as batch/cullet preheating, co-generation, or gas reformer technology. This technology is being rapidly accepted by the glass industry because it uses many similar operating principles as conventional furnaces, especially unit melters, and provides solutions to a variety of other requirements.

Several NO_x control methods, including air staging, were developed and successfully tested on a pilot-scale glass tank simulator in the early 1980s. The Gas Research Institute and DOE are presently continuing this effort for side-port-fired regenerative furnaces.

Gas reburn technology and low excess air firing as a prerequisite to air staging are other methods of NO_x reduction where some previous testing has been carried out. Several types of secondary oxidants required for staging have been considered in previous testing and current field tests.

There is an interest to have modeling tools to better quantify various aspects of these conditions for combustion modifications.

Approximately 1,200 - 1,500 lb of CO₂ are emitted from combustion for each ton of glass melted. An additional 300 lb of CO₂ come from raw material calcination for each ton of glass. Reduction of CO₂ to address concerns with global warming has not been of significant concern

for the glass industry to date. Consequently, such fuels as hydrogen are not presently considered for study.

4.5.2 Suggested Research Opportunities

Comparing the glass industry's vision of the future with the present situation provides insight on the important issues that must be addressed through improvements in technology. The following technologies associated with combustion issues have been identified.

4.5.2.1 Environmental Performance. The challenge is to cost effectively meet the requirements of expected environment regulations (air staging, etc). Combustion of fossil fuel is far from optimized when considering the need to balance heat transfer for melting and to minimize pollutants, especially NO_x . Fuel or air staging and gas reburn have been identified as being a potentially cost effective means of reducing NO_x in conventional regenerative melters. Gas reforming as an integrated component of waste heat recovery may be used for increasing flame luminosity, including oxy-fuel furnaces.

4.5.2.2 Improved Emissions Controls. Developing improved, more cost-effective air emissions control technology is necessary to meet the more stringent environmental regulations expected. Compliance using integrated process improvements are preferred over add-on devices.

4.5.2.3 Improved Process Control. In production processes where flame jet impingement is attractive, an understanding of the local distribution of heat flux, partitioning between convective and radiative transfer, stability of the flame, optimum geometric configuration, pollutant formation and control, etc., is vital to the achievement of highest product quality and the minimization of energy consumption. Improved comprehension of the transport mechanisms and generalization of heat fluxes to the load will also permit advance of the modeling of the various fabrication processes. There is a need to characterize the fundamental transport mechanisms in flame jet impingement heat transfer. An experimental investigation of mechanisms governing heat transfer to the load (stock) rather than the detailed kinetics and mechanisms of the chemical reaction is needed. Previous work-related momentum-driven flame jet impingement heat transfer has investigated premixed flames, but very few have measured the local heat transfer characteristics.

4.5.2.4 Reduced Particulates. Particulate emissions in soda lime glass (container and flat glasses) are the result of using sulfates in the bath as a melting and refining aid. The SO_x content of glass being recycled varies by source and type. As higher levels of recycled glass are reached, some particulate control problems may occur. Alternative materials or furnace designs might reduce or eliminate particulates, thereby lowering the cost of add-on capital equipment. Combustion research would relate to the conversion of SO_2 gas to sulfate particulates, altering emission control strategies.

4.5.2.5 Forming/Tempering Optimization. Improvements will be necessary in furnace design and operation to achieve increased efficiency. The forming and tempering of flat glass in gas hearth processing is far from optimized. The glass is heated with radiant combustion cups. There is little or no knowledge about spectral response or effects on heat flux distribution (such as height, flow rate fuel/air ratio, etc.) for the individual cups, and no information on heat transfer with arrays of combustion cups. Unlike metals, glass is not opaque at wavelengths below 4.5×10^{-6} meters. It may be feasible to optimize the spectral characteristics of burners for heating the glass uniformly and efficiently, which relates to major quality issues for forming and stress levels.

4.5.2.6 Optimizing Combustion and Process Control. The melter's combustion process consumes a large portion of the total facility's energy. Although significant progress in control has been made in this area, design optimization requires better understanding of the process fundamentals. Furnace design features that affect flame development (fuel and air mixing) and optimize heat transfer to the melt need to be better understood. Changes in design involve significant risks, especially when air emission control is also required. Research is needed to enhance productivity and quality through improvements in process control and equipment performance.

Develop combustion process control with real-time capabilities, heat flux (transfer) sensors, and CEMSs (continuous emission monitoring systems).

Develop and apply fuzzy logic and neural network control strategies to improve productivity, quality, and output.

4.5.2.7 Oxy-Fuel Evolution. A significant trend is developing to convert to furnaces that use nearly 100% oxygen combustion as a means of reducing NO_x production and particulate emissions. Since the application of this technology is relatively new, process optimization is needed. Operating economics are higher than conventional furnaces because of the cost of oxygen. Some new methods of on-site generation have been developed. Waste heat recovery has not been applied to the high-temperature exhaust gases from oxy-fuel firing (the exhaust contains up to one-third of the heat input). Required add-on equipment for particulate and SO_x emissions should be integrated into waste heat recovery schemes.

4.5.2.8 Process Monitoring and Control Instrumentation. Information from advanced instrumentation can be used to control combustion parameters and improve process control. Strategies to further improve the manufacturing of glass products require obtaining representative and reliable data from yet to be developed sensors within key areas of the processes.

Thermocouples that are cost effective to use in relative large numbers (nonprecious metal coated) are needed to provide multiple molten glass temperature measurements in the distributor

and forehearth areas, where controlled temperature conditioning using combustion processes is recognized as being deficient.

Noncontact temperature measurement sensors should be developed to determine glass temperature profiles in the furnace and throughout the glass fabrication processes. These sensors must detect temperature rapidly, so the information can be used in control processes.

More reliable and cost effective sensors (for temperature and gaseous species) should be developed that can be used to monitor the molten glass and combustion space, so that relatively large arrays can be used to provide information to improve process control.

Also needed are lower cost, high-reliability air emission monitoring equipment that can detect SO_x, NO_x, CO, O₂, and particulates.

4.5.2.9 Waste Heat Recovery. Further expenditures for more insulation or larger regenerator systems are not cost effective for today's modern furnaces. Significant additional waste heat recovery may be possible by preheating the cullet and batch raw materials. Although heat recovery is not usually considered part of the combustion program, preheating cullet and batch reduces required from the combustion process.

4.5.2.10 Process Modeling. There is a strong need for improved capabilities to model and control the complex process of glass melting and fabrication to provide consistency and high quality at high production rates.

All-electric furnaces are more thermally efficient than fossil-fired furnaces. They are limited in size (under 300 tons of glass per day) and because of the high cost of electricity their energy cost per ton of glass is higher than fossil furnaces. As a result, use of electric heating for container production is generally limited to partially replace (boost) fossil fuels. Electric boosting increases furnace productivity, improves glass quality, and minimizes furnace emissions. The glass industry has generally relied on operating experience with actual equipment for developing new and improved furnace designs using electric boost. As a result, improvements have been slow to evolve. Development of improved furnace models would increase understanding of the melting process and the influence of electric boost. Both physical and mathematical models should be reviewed to determine their applicability to the type of glass melted, glass product produced, and furnace type and geometry. Detailed computer models should then be developed to aid in furnace design and process optimization.

4.5.3 Furnace Computer Modeling

The glass industry needs integrated furnace models that can calculate transient thermal and chemical behavior and can be used to develop methods to optimize energy use and reduce air emissions. Models should link the dynamics of combustion, heat transfer, glass flow and temperature, and furnace throughput. Models should be developed to (a) optimize fuel

combustion and heat release parameters based on furnace design factors, (b) calculate glass melting and temperature conditioning (distribution), (c) include improved combustion models for prediction of pollutant production (SO_x , NO_x , and particulates) and the effects of gaseous bubbles in the melt, and (d) improve understanding of glass chemistry, including chemical kinetics of batch melting and reactions in glass, chemical equilibrium and solubility data, and chemical kinetics influenced by variables in the combustion environment.

Additionally, computer modeling of oxy-fuel melting in large float glass furnaces should be developed. Work needs to be continued to correlate numerical data and operating parameters and use them for development of expert control systems, including systems for melting, processing, and emissions.

4.5.4 Equipment

Optimize furnace designs to reduce NO_x , SO_x , and particulate emissions. This may include improved burners and means of reducing the particulates entrained in the combustion products.

Develop equipment and techniques for promoting enhanced heat transfer.

Develop equipment that will improve energy recovery from the melter by preheating batch materials and cullet. The design should include the capability to install equipment to remove NO_x , SO_x , and particulate emissions.

4.6 Aluminum Industry

An evaluation of research needs for the aluminum industry was made using several sources. These sources have included past evaluations of industrial research needs (Penner 1994, Chace 1989, Choce 1988). Another source was a survey of aluminum industry research needs recently conducted by Energy and Environmental Research Corporation (EER). Results of this survey are summarized in this section, and the EER report is included in Appendix D. The survey included not only aluminum company representatives (Kaiser Aluminum, Gas Research Institute) but also companies that depend on and are knowledgeable of aluminum industry research needs. These included aluminum furnace and burner equipment manufacturers (KVS, Hauck, Lindberg, Surface Combustion, Maxon, CEC, and MPH Ind.), and natural gas and merchant gas companies (Southern California Gas Co., Air Products, and British Oxygen Company).

4.6.1 About the Industry

While aluminum was not produced for commercial use until the 20th century, it is now one of the world's most critical primary metals, supplying manufacturing, construction, automotive, aerospace, beverage, and other industries. It has many attractive features, including

a high strength to weight ratio, high corrosion resistance, alloyability for various properties, and recyclability. Even though aluminum is very common in its oxide form (comprising 7% of the earth's crust), aluminum metal was not produced in a relatively pure state until the 1820s (Williams 1993). The aluminum industry is separated into a primary industry (conversion of bauxite ore to basic metal) and a secondary industry (metal recycling, shaping, fabrication, finishing, and treating).

Aluminum production did not become a major industry until the 1900s, following the development of the Hall-Heroult and Bayer processes, and the establishment of a market for the aluminum. By the end of World War II, aluminum production had peaked at 2 million tons per year. Following the post war slump caused by reduced aircraft aluminum demand, aluminum production continued to increase to 4 million tons per year by 1960 and 25 million tons per year today. Current aluminum production is second only to steel (which is over 700 million tons per year) (Teissier-duCros 1995).

Most important, of all current industrial metals, aluminum has the strongest growth potential, since it is an industrialized nation's metal. For example, the world aluminum consumption would increase to 140 million tons per year if it matched Japan's per capital consumption. However there is a significant shift between primary and secondary aluminum production and national dominance in these industries.

The U.S. market dominance in worldwide primary aluminum production has decreased from 41% in 1960 to 21% today. The primary causes for this shift are locations of bauxite resources (primarily outside the United States), energy costs, oversupply, and increased use of recycled or secondary aluminum. Between 1987 and 1992, about 1.1 million tons of high-cost U.S. aluminum capacity (nearly 25% of the U.S. total) were closed. Lower power costs in competing countries make it unlikely that new primary aluminum smelters will be built in the United States. Domestic aluminum firms are more likely to retrofit existing plants with incrementally improved technologies. Increased investment in the U.S. aluminum fabrication and recycling facilities (secondary aluminum industry) has also occurred and is expected to continue. Energy savings and waste disposal concerns boosted aluminum recycling from 0.4 million tons in 1960 to 2.8 million tons in 1992.

Primary aluminum smelting is one of the most energy-intensive manufacturing processes. Even with efficiency improvements in recent decades, smelters require about 7 kWh/lb of aluminum produced, and account for 70% of energy use for primary aluminum production. The annual primary aluminum energy consumption is about one quad.

Recycled aluminum production is much more energy efficient (because the smelting step is eliminated) and requires only about 5% of the energy needed to make primary aluminum. The aluminum industry spends about \$2 billion on energy, about 8.6% of the value of shipments. For primary production, the costs were \$1.55 billion, or 22% of its value of shipments. A complete description of recommendations is contained in Appendix D.

4.6.1.1 Primary Aluminum Industry. Ore, most commonly bauxite, is processed to high purity Al in the primary industry. Limestone is processed to hydrate in a rotary kiln, and then combined with ore and caustic soda. This mixture is fed to steam-heated digestors that convert the Al to a hydrate. The weak caustic solution for this process is also concentrated in steam-heated evaporators for chemical recovery. The separated and dried alumina trihydrate is then calcined to alumina in a second, direct-fired rotatory kiln. Natural gas is the preferred fuel, since the hydrate is susceptible to contamination. Electrolytic reduction of the alumina with carbon electrodes converts the feed to high purity Al in the final smelting process. Most primary processing to alumina for U.S. consumption is done off-shore at the ore mines and is not considered in this report. Most alumina is transported to locations of low power cost (usually hydro derived) such as the North Western states as the smelting process is very electrically energy intensive. Carbon electrodes are sacrificially consumed during the reduction process, producing CO₂ and molten aluminum. Electrodes are fabricated on site in bake ovens, the major combustion process at U.S. smelters.

Hazardous wastes from the smelting process are significant. These wastes include aluminum dross and spent pot lining material (pot liner). Pot liner consists of anthracite coal and graphite, with alumina and refractory brick insulation. During operation, the liner absorbs fluorides and cyanides from carbon in the liner, fluorine in the process materials, and nitrogen from the air. The pot liner may also become contaminated with heavy metal oxides and salts from the petroleum coke powder of the anode as it is consumed during electrolysis. The pot must be relined every 2,000 to 3,000 operating days. Spent pot liner is designated as hazardous waste KO88 by the Resource Conservation and Recovery Act (RCRA).

Recommended solutions for this waste generation include (a) purification of the carbon anode to prevent heavy metals contamination of the pot liner, and (b) thermal treatment or vitrification of the dross and spent potliner to recover aluminum, destroy hazardous organics, and enable recycling of the refractory materials (A. R. Teissier-duCros, 1995).

4.6.1.2 Secondary Aluminum. The fabrication begins with the melting of scrap and ingot in a reverberatory furnace or directly from the primary smelting process. Feed that is remelted is further refined to remove impurities and alloyed with other metals to achieve the required end-use metallurgical properties such as ductility, hardness, or strength. This typically requires metal assays before and after the secondary smelting operation. Reverberatory furnaces are usually directly fired with natural gas, and furnace temperatures are about 2,400°F. These are the most energy intensive combustion processes in Al fabrication. Fluxing salts and Cl gas injection are used during this processing step. Molten metal is poured into a foundry mold for ingots or casting final shapes. The cast metal typically undergoes a homogenizing heat treating step previous to additional processing, e.g., machining or cold rolling. Depending on the final shape desired, the cold metal may be cold or hot rolled for sheet product, or remelted in smaller furnaces, typically indirect fired crucible, and investment or die cast to net shape.

Aluminum is heat treated at several stages in the fabrication process in small, direct fire to very large muffle furnaces. Typical heat treating steps include homogenation and reheating at about 1,000°F, usually after casting operations; annealing at 460 to 775°F, usually after hot milling; and aging at 250 to 460°F, usually after metal working.

Heat treating generally requires close control of temporal and spatial temperature distributions within the work and, therefore, accurate measurements and control of furnace temperature. Thermocouple arrays are used, sometimes in conjunction with instrumented work pieces to control and confirm temperature histories. Natural gas is almost exclusively used in these furnaces.

Of lesser interest are aluminum anodizing and painting (coating) operations since these are less energy intensive, smaller, and more disperse processing operations. These typically involve boilers for providing steam heat for chemical cleaning and plating tanks or direct heat to paint drying booths.

Aluminum die casting and foundries and strip mills are large single point users of energy, since large quantities of metal are heated/melted to high temperatures. Metals are typically batch melted in pots (indirect fired crucibles) or direct-fired reverberatory furnaces (the latter sometimes with heat recovery). Heat treating and anodizing operations are energy intensive at the plant level, though energy use is widely distributed among a number of unit operations, e.g., heat treating and reheat furnaces and heated chemical tanks. Research and development for improved process control (sensors), emission (acid and air toxic) control, improved high-temperature insulation packages and heat transfer enhancements, and cost effective high- and low-grade heat recovery are important areas to explore.

4.6.1.3 Combustion Equipment. Large gas-fired rotary kilns are used in the primary aluminum industry to produce high purity alumina, which is subsequently reduced electrolytically to aluminum in electrically heated smelters. Nearly all primary processing in kilns is done off-shore at the ore mines. Electrically heated smelting is practiced at low-cost U.S. hydro sites. These rotary kilns are typically configured like cement kilns with feed preheat sections, and have heat inputs of 50 to 150 MMBtu/hr. However, gas-fired furnaces to produce carbon electrodes used in the smelting process are more significant combustion equipment in the U.S. primary metals industry than rotary kilns. Petroleum-derived coke is used to manufacture carbon electrodes. The prebake process requires that the electrodes be temperature-treated in a ring furnace to volatilize residual hydrocarbons and develop structural rigidity. The furnaces are gas fired, recuperated during the cooling cycle, and the most fuel intensive of the process steps practiced at U.S. smelters.

In the secondary aluminum industry, reverberatory furnaces are batch charged, moderately large (25-MMBtu/hr heat input) furnaces, which operate cyclically. Once metal is charged, burners are set to high fire for melting. The metal is held at intermediate fire, assayed and withdrawn nearly continuously. Melt temperatures are less than 1,400°F, requiring high

temperature, corrosive resistant refractories for containment. Furnace thermal efficiencies are generally poor, 20 to 30%. Furnaces are usually gas fired, though the feasibility of pulverized coal firing has been demonstrated. Oxygen enrichment has also been practiced to improve melter throughput. Thermal efficiencies tend to be low because of the difficulty in applying heat recovery. Cost effectiveness is further compromised by the moderate potential for combustion air preheat (about 800°F) resulting from the moderate furnace gas exhaust temperatures. Preheating the feed by charging through the stack or a separate heat recovery unit is, therefore, sometimes practiced.

Heat treating furnaces of the direct and indirect (muffle) type are frequently used to prepare work for further processing or to change its metallurgy. The work requires extremely even heating leading to the use of highly radiant furnace walls and/or improved convective heat transfer with high-velocity burners. These furnaces are moderately thermally efficient, 30 to 50%, depending on furnace temperatures. Natural gas is almost exclusively fired to avoid contamination of the product. Direct firing is not used for annealing but may be used for other types or work heating. Furnace surface heat losses tend to be more significant for these furnaces, stack sensible heat losses less so, compared to the reverberatory furnace.

4.6.2 Combustion Research Survey Results

There are a number of research needs identified in this evaluation. The greatest single focus was on research for improving productivity of the combustion equipment. Short-term (within 3 years) research was considered more important than longer-term research because of the belief (especially relating to environmental concerns such as air emissions) that changing regulatory requirements make the longer term too uncertain. The highest priority combustion issues are clustered in the following categories, in order of priority:

- Furnace efficiency and productivity improvements through flame radiation for secondary aluminum melters and heat treating furnaces, enhancement and O₂ enrichment for reverberatory furnaces
- Improved refractories for hot burner parts such as burner blocks, radiant tubes, and burner tips
- NO_x reduction technologies for oxygen-enhanced combustion
- Multipoint, low-cost sensors for monitoring composition (gas and metals), and temperature (gas and aluminum product)
- NO_x control and enhanced production with acoustic (pulsed) or catalytically assisted combustion technologies

- Waste control technologies, especially advanced thermal treatment (vitrification) of dross and spent pot liner.

Significant cost savings may be achieved through improved efficiency of combustion equipment. Expected energy savings (including electrical energy) by the year 2000 is estimated to be 2—3% through improvements in monitoring and control, 10—15% through retrofit improvements on current equipment, and 15-30% through installation of new technologies (Hulgen and Kvande 1994). While the large portion of these savings may be from smelter improvements, commensurate improvements in combustion equipment are also desired.

The research areas of improved refractories, NO_x reduction technologies for oxygen-enhanced combustion and enhanced production, and multipoint low-cost sensors are also of interest in order to reduce capital and operating costs and improve aluminum product quality and amounts while meeting current and impending regulations. Aluminum product quality is a growing concern for secondary production, with increasing amounts of recycled aluminum. The recycled aluminum contains variable, unassayed alloys, and it also contains paint, solvents, and other contaminants that increase pollutant off-gas emissions and can affect the quality of the aluminum product.

New and emerging hazardous waste control technologies are important owing the need to meet hazardous waste treatment and disposal requirements at the lowest cost. The most promising technologies are thermal treatment of the dross to recover and recycle the aluminum, and vitrification of (a) the secondary wastes from the dross treatment and (b) spent pot liner.

4.7 Forest Products Industry

The forest, wood, and paper industry is a major contributor to the nation's economy. It employs 1.4 million people directly and produces products valued at more than \$200 billion per year. It ranks among the nation's top 10 manufacturing industries. Mills range from large, state-of-the-art facilities to small family-owned sawmills.

The U.S. pulp and paper industry segment includes 547 mills in 42 states, produces 82 million tons of paper and paperboard and 10 million tons of market pulp. The industry has long been a leader in recovery and recycling (recycling, composting, and energy recovery). About 40% of all the paper used in the U.S. is currently being recovered for recycling, and the industry intends to increase this rate to 50% by the year 2000 (AFPA 1994). About 73% of all mills use recovered paper as raw material for papermaking, and more than 37% rely upon it entirely.

The industry faces strong competitive challenges from abroad. More demanding environmental requirements are also a major burden for the future. In order to comply with new regulatory initiatives, the industry is facing increases in capital expenditures, operating costs, and energy use. The pulp and paper industry is the nation's most capital intensive manufacturing industry (on the basis of investment dollar per employee) and is very energy intensive. The

resulting economic consequences of the need for major capital equipment replacement tends to limit experimentation, development, and application of large, new core technologies. The industry is currently 57% energy self-sufficient through the use of byproduct black liquor, wood, and wood waste fuels. The industry expects that more energy-efficient processes will evolve and that a larger amount of energy will be self-generated, with excess energy marketed in the form of electricity and (perhaps) liquid fuels.

The pulp and paper industry uses about 3 quads of energy per year, or about 31 million Btu/ton of product produced. Because it relies heavily on byproduct black liquor, bark, and wood wastes to meet its energy needs, it uses two-thirds of all renewable fuels consumed by U.S. industry. It also accounts for 40% of all power cogenerated by U.S. manufacturing. Still, it spends \$5.5 billion on energy — 4.3% of the value of its shipments. Even with the extensive use of energy byproducts and renewable energy resources, the industry is still the fourth largest user of fossil fuels in the industrial sector.

Based on the work conducted in generating the Vision 2020 document, the high-priority research efforts identified by the industry include sustainable forest management, environmental performance, energy performance, improved capital effectiveness, recycling, and sensors and controls. In the area of energy performance, the industry believes that biomass and black liquor gasification will play an increasingly important role as components of advanced cogeneration technologies. These technologies will be incorporated to optimize the generation of electricity and process heat. Compliance with air regulations will necessitate effective combustion control and accurate continuous monitoring.

4.7.1 Combustion-Related Problems

Combustion is the primary means for producing needed process steam and electricity from various fuel resources available to the industry. In addition to the traditional fossil fuels (coal, fuel oil, and natural gas), wood, wood waste, bark, byproduct black liquor, sludge, and waste paper are also used as fuels in boilers to generate needed process steam and (by means of a steam turbine) electricity. Combustion is also used for lime calcination and direct heating of air in paper coating dryers. As part of the process for regenerating needed pulping chemicals, limestone is calcined in rotary kilns or fluidized bed calciners. Although the calcination process is combustion related, it is not considered to be a significant problem area.

The chemical recovery boiler is a steam generator that uses byproduct black liquor as its fuel. Combustion of black liquor provides two key benefits. Steam is generated by the combustion of the fuel source, and inorganic chemicals are recovered for reuse in the pulping process. In a modern kraft mill, approximately 95—97% chemical recovery is achieved. Because the byproduct black liquor fuel contains a large quantity of water (about 30% by weight) and because endothermic chemical reactions occur in the boiler, these units typically operate at about 66 to 75% efficiency.

Black liquor combustion is different than combustion of other low-energy streams. The black liquor is a low value Btu fuel (5,400—6,600 Btu/lb) and is sprayed, rather than atomized, into the combustion zone, forming very coarse droplets (1—5 mm in diameter). The black liquor must be concentrated to above 60% solids so that it will burn without supplemental fuel. Typical solids concentrations of black liquor are about 70%, though some new boilers have operated at as high as 80% solids. The black liquor solids consists of about two-thirds organic material (dissolved from the wood during pulping) and one-third inorganic pulping chemicals. Once concentrated, the material is sprayed into the combustion chamber, partially combusting in flight, with particles either impacting the furnace walls, or falling to a char bed at the bottom of the unit. Air injection at several stages achieves multilevel stoichiometric control. A reducing atmosphere is provided in the lower furnace to maximize the endothermic reduction of sulfur compounds to the form needed for pulping chemical regeneration. This is followed by secondary air injection at a higher level, and then a tertiary air rich zone to complete combustion.

Combustion of the char occurs in the lower furnace area, either on the furnace walls or the char bed at the base of the unit. The chemical reactions and transport phenomena occurring in char combustion are not well understood. The measurement of the temperature of the char bed would provide one means of control of the process, but the measurement of even this simple parameter has presented a significant challenge to current sensor systems. After the organic material has burned from the char, the inorganic chemicals are recovered as a molten smelt that flows out of the furnace through smelt spouts. The smelt is then dissolved in recycled water to regenerate the needed pulping chemicals.

During flight, some of the inorganic material is volatilized and carried with the exhaust gases and can end up depositing on the heat transfer surface areas of the recovery boiler. These deposits can sinter, which make them more difficult to remove with soot blowers. In certain situations, the buildup may force a decrease in firing rate or even a shutdown to clean the passages (Alkaline Pulping Committee 1992).

Overall, the detailed chemical reactions and transport phenomena associated with the combustion of black liquor in a recovery boiler are not well understood. Computer modeling of the process has been attempted and is the focus of an existing OIT financial assistance grant. However, the work has proven to be difficult. More research is still considered necessary, and, if a more fundamental understanding of the combustion process were obtained, better boiler controls could be devised to optimize the process.

Alternatively, another method of chemical recovery is the use of gasification technology. Gasification processes have been researched intensely for several years, and a foreign manufacturer has commercialized one process. Further development of other gasification technologies could be warranted to provide alternatives to the existing recovery process.

Finally, in general, corrosion is a problem in both recovery boiler combustion and gasification processes. Also, research to reduce the variability and control the properties of the black liquor fuel can be a benefit to both combustion and gasification processes.

4.7.2 Research Needs

Several projects are currently sponsored by DOE in the areas of black liquor, gasification, and sensor technologies. The following research needs are intended as outgrowths:

- **Understanding Combustion in Black Liquor Fired Boilers.** The generation of steam by combustion of fuels provides a significant amount of energy to this industry. The boilers used are similar to other industrial boilers if fired by natural gas, coal, fuel oil, wood, or biomass, for example, but are significantly different when fired by black liquor. In this regard, the pulp and paper industry has distinct combustion research needs. A more fundamental understanding of the black liquor combustion process (reaction rates, combustion species, velocities, residence time, etc.) needs to be developed. Understanding of the combustion of black liquor is not as developed as the understanding of the combustion of coal, for example.
- **Gasifier Demonstration and Advanced Research.** The industry has expressed the need for the development of lower-cost, safer, and more efficient alternatives to the existing chemical recovery process. It is noted that black liquor gasification has significant potential in this regard. The development of black liquor gasification can also be combined with the further development of combined cycle cogeneration systems — another need expressed by the industry.
- **Air Emissions.** Air emissions from all combustion sources (especially from recovery boilers) must meet present and future regulations, including nitrogen oxides, sulfur oxides, toxic air emissions, and (particularly for the kraft pulp mill) odor. The combustion air environment in the recovery boiler can partially reduce nitrogen oxide emissions, but if changes are made to the combustion process to optimize recovery (especially higher solids firing), these emissions can be adversely affected. A better understanding of the fundamental combustion process can provide the means for both attaining air emission standards and optimizing the operation of the recovery boiler.
- **Sensors and Controls.** Development of effective combustion control with black liquor fired fuels is needed. In particular, better measurements of temperature of the char bed and temperatures in the combustion furnace is needed. A more fundamental understanding of reactions and transport properties occurring in and around the char bed is also needed.

- Fouling and Plugging. Research to understand the deposition mechanism of volatilized inorganic in the flue gases needs to be conducted. Also, improved methods of removing these deposits need to be determined.
- Modeling. Because the process of black liquor combustion involves multilevel air introduction under somewhat special geometric conditions, modeling efforts to better understand the process need to be continued. This can lead to improved equipment designs.
- Biomass Fired Boilers. Emissions from biomass fired boilers, especially dioxins when biomass is mixed with chlorinated sludge, has not been considered a problem in Canadian pulp and paper mills. Combustion of biomass mixed with chlorinated sludge has not been tried in the United States and stiffer emissions regulations may preclude it.

5.0 SUMMARY OR RESEARCH NEEDS BY INDUSTRY

Following is a simplified list of proposed research and development activities for each of the seven industries surveyed:

Refinery Industry

- Heat release profiling
- Oxygen enrichment
- Refractories
- Multiple burner arrays
- Catalytically assisted combustion acid gases (primarily NO_x)
- Flame safety and stability
- Fluidized beds
- Mass burn
- Suspended circulation
- Porous media
- Acid gas control

Steel Industry

- Laboratory testing of blast furnace coal injection techniques
- Continuation of investigation into smelting of iron ore pellets using coal
- New top gas recycling process for blast furnaces
- Reheat furnace burner enhancement investigation
- Direct steel temperature measurement
- Combustion completion measurement
- Continuous annealing furnace burner improvement

- Computer modeling of rehear furnace burner flames

Metal Casting Industry

- Carbon dioxide burnout using oxygen injection
- Active diffusivity studies
- Fluidized bed sand reclamation
- Gas-fired melting furnaces
- Heat treating (specific grain structure)
- Heat treating of materials for dies (long life)
- Combustion sensors
- Metal flow rate sensors
- Low-cost oxygen sensor for molten metal
- Maintaining ladle temperatures/conditions

Chemical Industry

- Development of advanced control algorithms and equipment for thermal reactors
- Development of enhanced heat transfer mechanisms
- Environmental performance

Glass Industry

- Improved emissions controls
- Combustion optimization
- Improved Productivity - (flame jet impingement, transport mechanisms, and generalization of heat fluxes to the load)
- Reduced particulates
- Energy efficiency - furnace design and operation
- Development (fuel and air mixing) and optimization of heat transfer to the melt
- Oxy-fuel evolution - process optimization
- Process monitoring and control instrumentation
- Waste heat recovery - cullet and batch preheating
- Process modeling - improved capabilities to model and control glass melting and fabrication.
- Furnace computer modeling - integrated furnace models
- Emissions equipment

Aluminum Industry

- Furnace efficiency and productivity improvements through flame radiation enhancement and O₂ enrichment

- Improved refractories for hot burner parts such as burner blocks, radiant tubes, and burner tips
- NO_x reduction technologies for oxygen enhanced combustion.
- Multipoint, low-cost sensors for monitoring composition (gas and metals) and temperature (gas and work)
- NO_x control and enhanced production with acoustic or catalytically assisted combustion technologies.
- Waste control technologies, especially advanced thermal treatment (vitrification) of dross and spent pot liner

Pulp and Paper Industry

- Understanding combustion in black liquor fired boilers
- Gasifier demonstration and advanced research
- Air emissions
- Sensors and controls
- Fouling and plugging research
- Modeling
- Biomass fired boilers.

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APPENDIX A - REFINERY INDUSTRY

**NEAR TERM COMBUSTION RESEARCH NEEDS IN THE
REFINERY INDUSTRY**

Prepared by:

Energy and Environmental Research Corporation

October 1995

NEAR TERM COMBUSTION RESEARCH NEEDS IN THE REFINERY INDUSTRY

Objectives

The objectives of this survey were to define the near term combustion research priorities through discussions with the refinery industry stakeholders. These include those that are directly involved in refinery operations and the infrastructure which supports them, specifically the merchant gas industry, burner, boiler, and process heater vendors, engineering and A&E firms, and the natural gas industry.

Approach

EER has used its familiarity with the refinery industry to establish an appropriate data base, and the develop knowledgeable industrial contacts. We specifically relied upon our contacts with various gas distribution company industrial account executives, specifically those large organizations who have significant relevant industrial customer gas loads such as So. Cal. Gas Co., and Pacific Gas and Electric. We also contacted combustion and heating equipment manufactures for the refinery industry including process furnace manufactures KTI and Foster Wheeler, and burner manufactures Selas and John Zink. EER also has access to a number of end users, both corporate and plant engineering and the A&E's who support them, Fluor and Brown & Root Braun. Trade associations such as the American Petroleum Institute, Western States Petroleum Association and the Petroleum Environmental Research Forum were also important sources of data.

The first step was to identify generic combustion equipment within each industrial sector which processes significant amounts of product and/or consumes large quantities of fuel, as these would benefit the most from DOE sponsored R&D. Candidate refinery equipment typically would be large process heaters commonly found in hydrotreating, reforming and cracking operations, and large energy converting equipment such as steam boilers and gas turbines. R&D for improved process control (sensors), emission (acid gas and air toxic) control, and enhanced heat transfer through improved convective and radiative heat transfer were explored. To assure an internally consistent and systematic approach a targeted-industry questionnaire was first developed internally, and reviewed with a limited, but diverse subset of the population surveyed. The final questionnaire, Attachment I, was composed of two parts:

- A profile page which describes the position and function of the interviewee, the market served by his company, and his major combustion issues
- A list of research topics for major combustion technologies found in the industry, and their prioritization by the interviewee

The protocol was to first contact the interviewee (Table 1) and generally discuss the objectives of the survey and to request his support. Nineteen potential interviewees were identified. Several of these were unavailable within the time period of this effort, or otherwise unavailable. For those willing to participate the questionnaire was then submitted by facsimile transmission for review and consideration. A subsequent follow-up call was made during which the questionnaire was discussed and responses filled in by EER.

About the Industry

The results of the questionnaire must be interpreted within the context of the type and use of

combustion equipment within the refinery industry. A brief description of the major process operations therefore, follows.

The energy intensive unit operations found in the hydrocarbon processing industry are shown in block diagram in Figure 1. Refineries vary quite widely in crude feed characteristics, complexity, and product mix. Most large refineries produce a high yield of gasoline and lube oil from crude oil. The primary energy consumption results from the initial crude distillation, desulfurization of some of the intermediate products, and their upgrading through catalytic cracking, naphtha reforming, alkylation, and coking. Sources of energy for these operations are primarily natural gas, refinery gas, petroleum coke, and fuel oil. These operations account for more than 80 % of the energy consumed.

The distillation of crude requires fluid heating in a process heater to about 800 F. Crude separation via distillation into intermediate products varies, but typically results in high and low sulfur components in liquids, gases and off gases. Sulfur typically concentrates in the liquids and residuum which need to be further upgraded in additional unit operations. Natural and refinery gas blends are burned in crude heaters to supply process heat to the column feeds. Steam produced in boilers is used to provide heat and stripping media to various components of the distillation equipment.

Catalytic hydrogenation of the sulfur containing liquids (naphtha and gas oil) requires H_2 addition and mixture heating to between 650 and 800 F in a process heater. The feed is then passed through a fixed bed catalytic reactor, producing desulfurized liquid streams and H_2S off gas. H_2 is produced on site through purification of off gases from catalytic cracking and reforming of components, or through catalytic reforming of a fossil fuel, usually natural gas. H_2 reforming requires large furnaces which incorporate both concurrent process heating and catalytic cracking of the feed at moderately high temperatures, about 1600 F. Large amounts of steam are co-fed and used in downstream shift reactors to improve H_2 yield. Refinery and natural gas are usually used as furnace and boiler fuels.

Coking of the low end cut distillates such as residuum is performed to improve gasoline yields. Coker products include coke, olefins, gas oils, and naphtha which must be further processed or sold as intermediate product. Coker feed is reheated in a process heater firing refinery fuels and off gasses.

Catalytic reforming upgrades non-aromatics and naphthas to aromatics for octane improvement. The unit operations of catalytic cracking and alkylation further upgrade feed stock intermediates. They are less energy intensive than crude heating, requiring heating feed from low to moderate temperatures in a process heater train. Unit operations include:

- Fluid catalytic cracking where gas oil and catalyst are mixed, heated to about 900 °F and reacted, and the components separated through distillation
- Alkylation where isobutane reacts to form olefin streams over a catalyst

Typical large fuel burning combustion equipment are found in the shaded unit operation boxes of Figure 1 and include the following, Figure 2:

- Process heaters providing heated fluids to unit operations such as distillation, reforming, cracking and hydrotreating

Figure 1. Materials flow of petroleum refinery.

A-8

- Large boilers providing process and heating steam, and high pressure, superheated steam to turbine drives
- Gas turbines operating in cogeneration configurations providing power, steam, and process heat.

All of this equipment is generally capable of firing a wide range of gaseous and liquid fuels, usually blends of process off gases of widely varying heating value and more traditional fossil fuels. Process heaters consume the most fuel in a complex refinery and are typically configured as shown in Figure 2. Feed, liquid or gaseous, is preheated against product gases and finish heated in a process heater or furnace to temperatures between 200 and 1600 °F. Furnaces may be top or bottom fired with a few large burners or side wall fired with a large array of small burners. Heat inputs will vary between 20 and 500 MMBtu/hr. Burners may be forced draft (sometimes with air pre-heat) or natural draft. The primary mode of furnace heat transfer is by radiation, with furnace flue gases exiting at as high as 1800 °F. Downstream convective passes either pre-heat feed or a heat transfer fluid to improve unit thermal efficiency. Fluids heated vary widely in physical and chemical composition and are sometimes prone to cracking in the furnace tubes because of uneven furnace wall heating. Air emissions include the acid gases (NO_x & SO_x), and air toxics (currently being characterized).

Steam is generated in large water tube, direct fired packaged or field erected boilers. Boilers are also sometimes co-fired with small amounts of waste gases and liquids for purposes of thermal destruction. Air emissions include acid gases and air toxics, and PM 10. Boilers typically have heat inputs of 100 to 1000 MMBtu/hr. Burners are forced draft, multi-fuel, frequently with combustion air preheat in their larger sizes.

Large frame and aero-derivative gas turbines are now frequently found in large scale (100,000 Bbb/day) refineries and produce power sufficient for minimum operation, typically 40 to 200 MW. Most are equipped with NO_x control technologies including steam or water injection, CO and NO_x catalytic control, and more recently with dry, low NO_x combustors. They typically burn more premium refinery and natural gas fuel blends. Turbine exhaust heat is recovered in heat recovery steam generators or specially designed process heaters.

Combustion Research Survey Results

Major stakeholder industries were identified for inclusion into the data base and specific, potential contacts currently known to EER staff were selected for the interview process. Because of the very short time and constrained budget no attempt was made at a randomized, statistical sample. The following stakeholders were polled:

- Combustion equipment manufactures, specifically burner and furnace
- Fuel and merchant gas suppliers
- Oil refiners
- Associations supporting the industry

At least two contacts in each of the above groups, Table 1, were identified and vigorously pursued with the questionnaire, somewhat modified depending on the group solicited. The first page of the interview identifies and profiles the interviewee and his organization and was used to focus the acquisition of the priority combustion research topics from their perspective. Combustion Issues were listed in the first column by major categories, environmental mitigation, furnace efficiency, flame/furnace compatibility, operations, and materials of construction. Combustion technologies

TABLE 1. REFINERY CONTACTS

	Name	Company	Telephone/FAX	Status ¹				Comments
				PL	RT	QC	FAX	
1	Buddy Eleazer	Alr Products	(610) 481-8082/5136	✓			✓	In process
2	Arun Basu	Amoco	(708) 420-4602/3848	✓			✓	unavailable
3	Robert Gemmer	GRI	(312) 399-8313/8170	✓				call on monday
4	Wayne Gensler	Selas	(215) 282-8338/646-3536	✓	✓	✓	✓	
5	Greg Croce	KTI	(510) 798-2940/2944	✓				call on monday
6	Jim Ng	Brown Root	(818) 300-2033	✓	✓	✓	✓	
7	Wayne Thomson	Fluor	(714) 975-4817	✓	✓	✓	✓	
8	Harry Tang	Shell	(510) 313-3272/5536	✓	✓	✓	✓	call on friday
9	Fred Kessler	KTI	(909) 592-4455/ 5347/3399	✓	✓	✓	✓	In process
10	Rick Cain	Arco	(610) 359-3292/2264	✓				
11	Larry Carlo	So. Cal Gas	(310) 803-7356	✓			✓	In process
12	Bruce Bolduc	BOC Gases	(908) 371-1613/1708	✓	✓	✓	✓	
13	Miriam Lev-On	Arco	(213) 486-2610/2021	✓			✓	
14	Jim Seebold	Chevron	(510) 242-3313/5947	✓				call on monday
15	Bob Andrew	Mobil	(609) 737-4516	✓				unavailable
16	Karen Ritter	A.P.I.	(209) 682-8472	✓				unavailable
17	Gary Robbins	Exxon	(713) 656-5049/6677	✓				unavailable
18	Michael DiCostanzo	Unocal	(213) 977-5132/5227	✓			✓	call on monday
19	Richard Walbel	John Zink Co.	(918) 234-5744/422-2851	✓				call on monday
20	John Winter	Texaco	(310) 699-0948/7408	✓				unavailable

Notes: ¹ Placed call (PL), Call Returned (RT), Questionnaire Completed (QC), Fax Questionnaire (FAX)

(conventional or emerging) were rated by the interviewee on a priority scale of 0 (no opinion) to 3 (high priority) for each of the aforementioned issues. All but the burner manufacturers had a very broad view of needs across the technologies list. Burner manufactures tended to want to focus on specific burner embodiments, eg: direct, radiant tube, or indirect immersible.

Results of the survey are shown in the following two tables. Table 2 shows a tabulation of the responses. This provides an indication of the agreement or lack thereof between different respondents on a given subject. Table 3 shows a statistical analysis of the responses. In this analysis the weight given to each respondents opinion was averaged and a standard deviation (σ^2) calculated on the mean.

Due to the way in which questions were posed to the interviewees, a mean response of greater than 2.00 with $\sigma^2 < 1$ should be considered a significant area for research. Heat release profiling, oxygen enrichment and refractories were consistently ranked high among refinery stakeholders. For conventional multiple burner arrays and catalytically assisted combustion acid gases (primarily NOx) was found an area of concern.

Surprisingly, air toxics were not consistently of concern. Several respondents thought air toxics were a high priority, while others were comfortable that it is or will be a non-issue for combustion in their industries. Flame safety and stability was another area in which mixed responses were received. In the areas of mass burn and multiple burner arrays, respondents rated these topic as high priorities. In other areas, however, the response was mixed. some of the respondents considered safety and stability to be issues that could be handled by appropriate equipment specifications, while others rated these issues highly.

In considering these analyses two important factors must be understood. First, if a respondent chose to respond in a particular technology area (*e.g.* fluid bed combustion, or multiple burner arrays) then that respondent's rating was factored into the mean for each question in that technology area, even if it was a "no opinion". The reason for this was that if a respondent felt qualified to comment on a particular technology area, even a "no opinion" should be considered significant in determining whether that topic was worthy of research funding. On the other hand, if a respondent did not care to comment on an *entire* technology area, then that respondent's lack of opinion was not considered in calculating the mean. This was justified on the basis that a respondent's opinion would not be representative of a technology area in which the respondent did not conduct business.

Completed respondent profiles and questionnaires are attached as appendix to this report.

**Table 2. Combustion System Refinery Stakeholder Questionnaire
Summary of Respondents' Opinions**

Research Topics/Priority'	Combustion Technology																																									
	1							2							3							4							5							6						
	Suspended Circulation							Fluid Bed							Porous Media							Mass Burn							Multiple Burner Arrays							Catalytically Assisted Combustion						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
1 Environmental Mitigation (Combustion Generated)																																										
1 - Noise	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	3	2	3	3	0	0	1	0	0	3	2	0
2 - Acid Gas (NOx, SOx)	2	0	0	0	0	0	0	2	3	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	2	0	0	2	3	2	3	3	3	0	2	3	0	0	3	2	0
3 - Greenhouse Gases	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	1	0	3	3	0	0	1	0	0	3	2	0	
4 - Air Toxics	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	3	2	1	3	3	0	0	3	0	0	3	2	0	
2. High Temperature Furnace Efficiency																																										
1 - Flame Radiation Enhancement	2	0	0	0	0	0	0	2	2	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	3	0	0	2	2	1	3	2	3	0	2	2	0	0	1	0	0
2 - O ₂ Enrichment	3	0	0	0	0	0	0	3	1	0	0	0	3	0	3	0	0	0	0	0	0	3	0	0	0	3	0	0	3	1	1	1	2	3	0	3	1	0	0	1	2	0
3. Flame/Furnace Compatibility																																										
1 - Heat Release Profiling	3	0	0	0	0	0	0	3	3	0	0	0	0	0	3	0	0	0	0	0	0	3	0	0	0	3	0	0	3	3	3	3	3	3	0	3	3	0	0	1	2	0
2 - Flame Confinement	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	3	1	3	3	3	0	0	3	0	0	1	2	0	
3 - Flame Safety/Stability	2	0	0	0	0	0	0	2	3	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	3	0	0	2	3	3	2	3	3	0	2	3	0	0	1	2	0
4. Operations																																										
1 - Ultra High Turndown	2	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	1	2	3	3	0	0	1	0	0	1	2	0	
2 - Fuel Flexibility	2	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	3	2	3	3	0	0	2	0	0	1	2	0	
3 - Multipoint Sensors																																										
a Temperature	2	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	1	2	3	3	0	0	2	0	0	1	2	0	
b Composition	2	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	1	2	3	3	0	0	2	0	0	1	2	0	
4 - Productivity Enhancements	2	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	3	2	3	3	0	0	1	0	0	1	2	0	
5. Materials of Construction																																										
1 - Refractories	3	0	0	0	0	0	0	3	3	0	0	0	0	0	2	0	0	0	0	0	0	3	0	0	0	3	0	0	3	3	3	2	3	3	0	2	3	0	0	2	3	0
2 - Insulation Package	0	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	3	2	2	3	3	0	0	3	0	0	2	3	0	
3 - High-T Alloys	0	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	3	2	3	3	3	0	0	3	0	0	2	3	0	
' 3 = highest priority, 2 = medium priority, 1 = low priority, 0 = not of importance or no opinion.																																										

¹ 3 = highest priority, 2 = medium priority, 1 = low priority, 0 = not of importance or no opinion.

**Table 3. Combustion System Refinery Stakeholder Questionnaire
Statistical Analysis of Respondents' Opinions**

Research Topics	Combustion Technology																	
	1			2			3			4			5			6		
	Suspended Circulation			Fluid Bed			Porous Media			Mass Burn			Multiple Burner Arrays			Catalytically Assisted Combustion		
	Mean	σ^2	n	Mean	σ^2	n	Mean	σ^2	n	Mean	σ^2	n	Mean	σ^2	n	Mean	σ^2	n
1 Environmental Mitigation (Combustion Generated)																		
1 - Noise	0.00	0.00	1	0.33	0.22	3	0.00	0.00	1	1.00	1.00	2	2.00	1.33	6	1.50	1.25	4
2 - Acid Gas (NO _x , SO _x)	2.00	0.00	1	1.67	1.56	3	2.00	0.00	1	2.00	0.00	2	2.67	0.22	6	2.50	0.25	4
3 - Greenhouse Gases	0.00	0.00	1	0.33	0.22	3	0.00	0.00	1	1.00	1.00	2	1.33	1.56	6	1.50	1.25	4
4 - Air Toxics	0.00	0.00	1	1.00	2.00	3	0.00	0.00	1	1.00	1.00	2	2.00	1.33	6	2.00	1.50	4
2. High Temperature Furnace Efficiency																		
1 - Flame Radiation Enhancement	2.00	0.00	1	1.33	0.89	3	2.00	0.00	1	2.50	0.25	2	2.17	0.47	6	1.25	0.69	4
2 - O ₂ Enrichment	3.00	0.00	1	2.33	0.89	3	3.00	0.00	1	3.00	0.00	2	1.83	0.81	6	1.75	0.69	4
3. Flame/Furnace Compatibility																		
1 - Heat Release Profiling	3.00	0.00	1	2.00	2.00	3	3.00	0.00	1	3.00	0.00	2	3.00	0.00	6	2.25	0.69	4
2 - Flame Confinement	0.00	0.00	1	1.00	2.00	3	0.00	0.00	1	1.50	2.25	2	2.17	1.47	6	1.50	1.25	4
3 - Flame Safety/Stability	2.00	0.00	1	1.67	1.56	3	2.00	0.00	1	2.50	0.25	2	2.67	0.22	6	2.00	0.50	4
4. Operations																		
1 - Ultra High Turndown	2.00	0.00	1	1.00	0.67	3	0.00	0.00	1	1.00	1.00	2	1.67	1.22	6	1.00	0.50	4
2 - Fuel Flexibility	2.00	0.00	1	1.33	0.89	3	0.00	0.00	1	1.00	1.00	2	2.17	1.14	6	1.25	0.69	4
3 - Multipoint Sensors																		
a Temperature	2.00	0.00	1	1.33	0.89	3	0.00	0.00	1	1.00	1.00	2	1.83	1.14	6	1.25	0.69	4
b Composition	2.00	0.00	1	1.33	0.89	3	0.00	0.00	1	1.00	1.00	2	1.83	1.14	6	1.25	0.69	4
4 - Productivity Enhancements	2.00	0.00	1	1.00	0.67	3	0.00	0.00	1	1.00	1.00	2	2.00	1.33	6	1.00	0.50	4
5. Materials of Construction																		
1 - Refractories	3.00	0.00	1	2.00	2.00	3	2.00	0.00	1	3.00	0.00	2	2.83	0.14	6	2.50	0.25	4
2 - Insulation Package	0.00	0.00	1	1.67	1.56	3	0.00	0.00	1	1.50	2.25	2	2.17	1.14	6	2.00	1.50	4
3 - High-T Alloys	0.00	0.00	1	1.67	1.56	3	0.00	0.00	1	1.50	2.25	2	2.33	1.22	6	2.00	1.50	4

COMBUSTION SYSTEM REFINERY STAKEHOLDER QUESTIONNAIRE

Respondent #1

CONTACT: Bruce Bolduc Company BOC Gases

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☐ 1. Corporate/General Mgmt.	☐ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☒ 8. Mktg./Sales
☐ 3. R&D/Development	☐ 6. Estimating	☐ 9. Other (Specify)

B. What is the principal activity at this location?

☐ 10. Manufacturing	☐ 13. Central Engineering
☐ 11. Corporate HQ	☐ 14. Research & Development
☒ 12. Division HQ	☐ 15. Other (Specify)

C. What is the principal business - *Primary - Industrial Gases, but supply oxy-fuel*

- ☐ 16. Refinery Operations
☐ 17. Furnace Vendor
☒ 18. Burner Vendor

D. Do you manufacture/use floor-fired burners, wall-fired burners or both?

☐ 19. Natural Draft	☐ 20. Forced Draft	☐ 21. Air Preheat

E. Which are emission requirements:

☒ 22. NOx	☒ 23. SOx	☐ 24. Air Toxics
☐ 25. CO	☐ 26. Other (Specify)	

F. Do you manufacture or use:

☐ 27. Rotary Kilns	☐ 28. Process Heaters	☐ 29. Boilers
☐ 30. Crackers	☐ 31. Gas Turbines	☒ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☐ 33. Design Performance?	☐ 34. Durability?	☒ 35. Reliability?
☒ 36. Process Temperature?	☐ 37. Fuel Efficiency?	☐ 38. Fuel Flexibility?
☒ 39. Process Control?		

RESEARCH TOPICS/PRIORITY:

Respondent: Bruce Bolduc

	Combustion Technology					
	1	2	3	4	5	6
	Suspended Circulation	Fluid Bed	Porous Media	Mass Burn	Multiple Burner Arrays	Catalytically Assisted
1. Environmental Mitigation (Combustion Generated)						
1-Noise	0	0	0	0	0	0
2-Acid Gas (NO _x & SO _x)	2	2	2	2	2	2
3-Hot House Gas	0	0	0	0	0	0
4-Air Toxic	0	0	0	0	0	0
2. High Temperature Furnace Efficiency						
1-Flame Radiation Enhancement	2	2	2	2	2	2
2-O ₂ Enrichment	3	3	3	3	3	3
3. Flame/Furnace Compatibility						
1-Heat Release Profiling	3	3	3	3	3	3
2-Flame Confinement	0	0	0	0	0	0
3-Flame Safety/Stability	2	2	2	2	2	2
4. Operations						
1-Ultra High Turndown	2	2	0	0	0	0
2-Fuel Flexibility	2	2	0	0	0	0
3-Multipoint Sensors						
a Temperature	2	2	0	0	0	0
b Composition	2	2	0	0	0	0
4-Productivity Enhancements	2	2	0	0	0	0
5. Materials of Construction						
1-Refractories	3	3	2	3	3	2
2-Insulation Package	0	2	0	0	0	0
3-High T Alloys	0	2	0	0	0	0

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

COMBUSTION SYSTEM REFINERY STAKEHOLDER QUESTIONNAIRE

Respondent #2

CONTACT:

Name Wayne Thomson Company Fluor-Daniel

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☐ 1. Corporate/General Mgmt.	☐ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☐ 8. Mktg./Sales
☐ 3. R&D/Development	☐ 6. Estimating	☒ 9. Other (Specify)
<i>Technical Consultant</i>

B. What is the principal activity at this location?

☐ 10. Manufacturing	☒ 13. Central Engineering
☐ 11. Corporate HQ	☐ 14. Research & Development
☐ 12. Division HQ	☐ 15. Other (Specify)

C. What is the principal business

☐ 16. Production	
☐ 17. Furnace Vendor	☒ X
☐ 18. Burner Vendor	

D. Do you manufacture/use floor-fired burners, wall-fired burners or both?

☒ 19. Natural Draft	☒ 20. Forced Draft	☒ 21. Air Preheat

E. Which are emission requirements:

☒ 22. NO _x	☒ 23. SO _x	☒ 24. Air Toxics
☒ 25. CO	☐ 26. Other (Specify)	

F. Do you manufacture or use:

☐ 27. Rotary Kilns	☐ 28. Process Heaters	☐ 29. Boilers
☐ 30. Crackers	☐ 31. Gas Turbines	☐ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☒ 33. Design Performance?	☐ 34. Durability?	☒ 35. Reliability?
☒ 36. Process Temperature?	☒ 37. Fuel Efficiency?	☒ 38. Fuel Flexibility?
☒ 39. Process Control?		

Durability not a primary issue

RESEARCH TOPICS/PRIORITY:

Respondent: Wayne Thomson

Main area of concern is process heaters and power boilers

	Combustion Technology					
	1	2	3	4	5	6
	Suspended Circulation	Fluid Bed	Porous Media	Mass Burn	Multiple Burner Arrays	Catalytically Assisted
1. Environmental Mitigation (Combustion Generated)						
1-Noise	0	1	0	0	1	1
2-Acid Gas (NO _x & SO _x)	0	3	0	0	3	3
3-Hot House Gas	0	1	0	0	1	1
4-Air Toxic	0	3	0	0	3	3
2. High Temperature Furnace Efficiency						
1-Flame Radiation Enhancement	0	2	0	0	2	2
2-O ₂ Enrichment	0	1	0	0	1	1
3. Flame/Furnace Compatibility						
1-Heat Release Profiling	0	3	0	0	3	3
2-Flame Confinement	0	3	0	0	3	3
3-Flame Safety/Stability	0	3	0	0	3	3
4. Operations						
1-Ultra High Turndown	0	1	0	0	1	1
2-Fuel Flexibility	0	2	0	0	2	2
3-Multipoint Sensors						
a Temperature	0	2	0	0	2	2
b Composition	0	2	0	0	2	2
4-Productivity Enhancements	0	1	0	0	1	1
5. Materials of Construction						
1-Refractories	0	3		0	3	3
2-Insulation Package	0	3		0	3	3
3-High T Alloys	0	3		0	3	3

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

COMBUSTION SYSTEM REFINERY STAKEHOLDER QUESTIONNAIRE

Respondent #3

CONTACT:

Name Wayne Gensler Company Selas Corporation

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☐ 1. Corporate/General Mgmt.	☐ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☐ 8. Mktg./Sales
☒ 3. R&D/Development	☐ 6. Estimating	☐ 9. Other (Specify)

B. What is the principal activity at this location?

☒ 10. Manufacturing	☐ 13. Central Engineering
☒ 11. Corporate HQ	☒ 14. Research & Development
☐ 12. Division HQ	☐ 15. Other (Specify)

C. What is the principal business

- ☐ 16. Refinery Operations
☒ 17. Furnace Vendor
☒ 18. Burner Vendor

D. Do you manufacture/use floor-fired burners, wall-fired burners or both?

- ☒ 19. Natural Draft ☒ 20. Forced Draft ☒ 21. Air Preheat

E. Which are emission requirements:

☒ 22. NOx	☐ 23. SOx	☐ 24. Air Toxics
☒ 25. CO	☐ 26. Other (Specify)	

F. Do you manufacture or use:

☐ 27. Rotary Kilns	☐ 28. Process Heaters	☐ 29. Boilers
☐ 30. Crackers	☐ 31. Gas Turbines	☒ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☒ 33. Design Performance?	☒ 34. Durability?	☒ 35. Reliability?
☐ 36. Process Temperature?	☐ 37. Fuel Efficiency?	☒ 38. Fuel Flexibility?
☐ 39. Process Control?		

RESEARCH TOPICS/PRIORITY:

Respondent: Wayne Gensler

Priority according to buyer specifications

	Combustion Technology					
	1 Suspended Circulation	2 Fluid Bed	3 Porous Media	4 Mass Burn	5 Multiple Burner Arrays	6 Catalytically Assisted
1. Environmental Mitigation (Combustion Generated)						
1-Noise	0	0	0	0	3	0
2-Acid Gas (NO _x & SO _x)	0	0	0	0	2	0
3-Hot House Gas	0	0	0	0	1	0
4-Air Toxic	0	0	0	0	2	0
2. High Temperature Furnace Efficiency						
1-Flame Radiation Enhancement	0	0	0	0	1	0
2-O ₂ Enrichment	0	0	0	0	1	0
3. Flame/Furnace Compatibility						
1-Heat Release Profiling	0	0	0	0	3	0
2-Flame Confinement	0	0	0	0	1	0
3-Flame Safety/Stability	0	0	0	0	3	0
4. Operations						
1-Ultra High Turndown	0	0	0	0	1	0
2-Fuel Flexibility	0	0	0	0	3	0
3-Multipoint Sensors						
a Temperature	0	0	0	0	1	0
b Composition	0	0	0	0	1	0
4-Productivity Enhancements	0	0	0	0	3	0
5. Materials of Construction						
1-Refractories	0	0	0	0	3	0
2-Insulation Package	0	0	0	0	2	0
3-High T Alloys	0	0	0	0	2	0

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

COMBUSTION SYSTEM REFINERY STAKEHOLDER QUESTIONNAIRE

Respondent #4

CONTACT:

Name Jim Ng Company Brown & Root

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☐ 1. Corporate/General Mgmt.	☐ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☐ 8. Mktg./Sales
☐ 3. R&D/Development	☐ 6. Estimating	☒ 9. Other (Specify)
<i>Engineering Design</i>

B. What is the principal activity at this location?

☐ 10. Manufacturing	☒ 13. Central Engineering
☐ 11. Corporate HQ	☐ 14. Research & Development
☐ 12. Division HQ	☐ 15. Other (Specify)

C. What is the principal business

☐ 16. Refinery Operations	<i>Design Engineering Firm</i>
☐ 17. Furnace Vendor	
☐ 18. Burner Vendor	

D. Do you manufacture/use floor-fired burners, wall-fired burners or both?

☒ 19. Natural Draft	☒ 20. Forced Draft	☒ 21. Air Preheat

E. Which are emission requirements:

☒ 22. NOx	☒ 23. SOx	☐ 24. Air Toxics
☒ 25. CO	☐ 26. Other (Specify)	

F. Do you manufacture or use:

☐ 27. Rotary Kilns	☒ 28. Process Heaters	☒ 29. Boilers
☒ 30. Crackers	☒ 31. Gas Turbines	☒ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☒ 33. Design Performance?	☒ 34. Durability?	☒ 35. Reliability?
☐ 36. Process Temperature?	☐ 37. Fuel Efficiency?	☐ 38. Fuel Flexibility?
☐ 39. Process Control?		

RESEARCH TOPICS/PRIORITY:

Respondent: Jim Ng

	Combustion Technology					
	1 Suspended Circulation	2 Fluid Bed	3 Porous Media	4 Mass Burn	5 Multiple Burner Arrays	6 Catalytically Assisted
1. Environmental Mitigation (Combustion Generated)						
1-Noise	0	0	0	0	2	0
2-Acid Gas (NO _x & SO _x)	0	0	0	0	3	0
3-Hot House Gas	0	0	0	0	0	0
4-Air Toxic	0	0	0	0	1	0
2. High Temperature Furnace Efficiency						
1-Flame Radiation Enhancement	0	0	0	0	3	0
2-O ₂ Enrichment	0	0	0	0	1	0
3. Flame/Furnace Compatibility						
1-Heat Release Profiling	0	0	0	0	3	0
2-Flame Confinement	0	0	0	0	3	0
3-Flame Safety/Stability	0	0	0	0	2	0
4. Operations						
1-Ultra High Turndown	0	0	0	0	2	0
2-Fuel Flexibility	0	0	0	0	2	0
3-Multipoint Sensors						
a Temperature	0	0	0	0	2	0
b Composition	0	0	0	0	2	0
4-Productivity Enhancements	0	0	0	0	2	0
5. Materials of Construction						
1-Refractories	0	0	0	0	2	0
2-Insulation Package	0	0	0	0	2	0
3-High T Alloys	0	0	0	0	3	0

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

COMBUSTION SYSTEM REFINERY STAKEHOLDER QUESTIONNAIRE

Respondent #5

CONTACT:

Name Fred Kessler Company KTI Corporation

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☒ 1. Corporate/General Mgmt.	☐ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☐ 8. Mktg./Sales
☐ 3. R&D/Development	☐ 6. Estimating	☐ 9. Other (Specify)

B. What is the principal activity at this location?

☐ 10. Manufacturing	☒ 13. Central Engineering
☐ 11. Corporate HQ	☐ 14. Research & Development
☐ 12. Division HQ	☐ 15. Other (Specify)

C. What is the principal business

- ☒ 16. Refinery Operations
☒ 17. Furnace Vendor
☐ 18. Burner Vendor

D. Do you manufacture/use floor-fired burners, wall-fired burners or both?

- ☒ 19. Natural Draft ☒ 20. Forced Draft ☒ 21. Air Preheat

E. Which are emission requirements:

☒ 22. NOx	☒ 23. SOx	☐ 24. Air Toxics
☐ 25. CO	☒ 26. Other (Specify)
Particulates	

F. Do you manufacture or use:

☐ 27. Rotary Kilns	☒ 28. Process Heaters	☒ 29. Boilers
☒ 30. Crackers	☒ 31. Gas Turbines	☒ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☒ 33. Design Performance?	☐ 34. Durability?	☒ 35. Reliability?
☐ 36. Process Temperature?	☐ 37. Fuel Efficiency?	☐ 38. Fuel Flexibility?
☐ 39. Process Control?		

RESEARCH TOPICS/PRIORITY:

Respondent: Fred Kessler

	Combustion Technology					
	1	2	3	4	5	6
	Suspended Circulation	Fluid Bed	Porous Media	Mass Burn	Multiple Burner Arrays	Catalytically Assisted
1. Environmental Mitigation (Combustion Generated)						
1-Noise	0	0	0	2	3	3
2-Acid Gas (NO _x & SO _x)	0	0	0	2	3	3
3-Hot House Gas	0	0	0	2	3	3
4-Air Toxic	0	0	0	2	3	3
2. High Temperature Furnace Efficiency						
1-Flame Radiation Enhancement	0	0	0	3	2	1
2-O ₂ Enrichment	0	0	0	3	2	1
3. Flame/Furnace Compatibility						
1-Heat Release Profiling	0	0	0	3	3	1
2-Flame Confinement	0	0	0	3	3	1
3-Flame Safety/Stability	0	0	0	3	3	1
4. Operations						
1-Ultra High Turndown	0	0	0	2	3	1
2-Fuel Flexibility	0	0	0	2	3	1
3-Multipoint Sensors						
a Temperature	0	0	0	2	3	1
b Composition	0	0	0	2	3	1
4-Productivity Enhancements	0	0	0	2	3	1
5. Materials of Construction						
1-Refractories	0	0	0	3	3	2
2-Insulation Package	0	0	0	3	3	2
3-High T Alloys	0	0	0	3	3	2

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

COMBUSTION SYSTEM REFINERY STAKEHOLDER QUESTIONNAIRE

Respondent #6

CONTACT:

Name Harry Tang Company Shell

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☐ 1. Corporate/General Mgmt.	☐ 4. Production Engr.	☐ 7. Purchasing
☒ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☐ 8. Mktg./Sales
☐ 3. R&D/Development	☐ 6. Estimating	☐ 9. Other (Specify)

B. What is the principal activity at this location?

☒ 10. Manufacturing	☐ 13. Central Engineering
☐ 11. Corporate HQ	☐ 14. Research & Development
☐ 12. Division HQ	☐ 15. Other (Specify)

C. What is the principal business

☒ 16. Refinery Operations
☐ 17. Furnace Vendor
☐ 18. Burner Vendor

D. Do you manufacture/use floor-fired burners, wall-fired burners or both?

☒ 19. Natural Draft	☒ 20. Forced Draft	☒ 21. Air Preheat

E. Which are emission requirements:

☒ 22. NOx	☒ 23. SOx	☒ 24. Air Toxics
☒ 25. CO	☐ 26. Other (Specify)	

F. Do you manufacture or use:

☐ 27. Rotary Kilns	☒ 28. Process Heaters	☒ 29. Boilers
☒ 30. Crackers	☒ 31. Gas Turbines	☒ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☐ 33. Design Performance?	☐ 34. Durability?	☒ 35. Reliability?
☐ 36. Process Temperature?	☒ 37. Fuel Efficiency?	☒ 38. Fuel Flexibility?
☐ 39. Process Control?		

RESEARCH TOPICS/PRIORITY:

Respondent: Harry Tang

Main worry about materials for catalytic systems

	Combustion Technology					
	1	2	3	4	5	6
	Suspended Circulation	Fluid Bed	Porous Media	Mass Burn	Multiple Burner Arrays	Catalytically Assisted
1. Environmental Mitigation (Combustion Generated						
1-Noise	0	0	0	0	3	2
2-Acid Gas (NOx & SOx)	0	0	0	0	3	2
3-Hot House Gas	0	0	0	0	3	2
4-Air Toxic	0	0	0	0	3	2
2. High Temperature Furnace Efficiency						
1-Flame Radiation Enhancement	0	0	0	0	3	0
2-O ₂ Enrichment	0	3	0	0	3	2
3. Flame/Furnace Compatibility						
1-Heat Release Profiling	0	0	0	0	3	2
2-Flame Confinement	0	0	0	0	3	2
3-Flame Safety/Stability	0	0	0	0	3	2
4. Operations						
1-Ultra High Turndown	0	0	0	0	3	2
2-Fuel Flexibility	0	0	0	0	3	2
3-Multipoint Sensors						
a Temperature	0	0	0	0	3	2
b Composition	0	0	0	0	3	2
4-Productivity Enhancements	0	0	0	0	3	2
5. Materials of Construction						
1-Refractories	0	0	0	0	3	3
2-Insulation Package	0	0	0	0	3	3
3-High T Alloys	0	0	0	0	3	3

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

APPENDIX B - STEEL INDUSTRY

STEEL INDUSTRY COMBUSTION ASSESSMENT

Report

for

Idaho National Engineering Laboratory

Submitted by

**E & E Corporation
Bethlehem, PA**

October 20, 1995

Steel Industry Combustion Assessment

Draft 10-20-95

1. Introduction

The purpose of this report is to review the steel industry opportunities for combustion research that would reduce industry energy consumption or otherwise improve process cost. Energy costs for the industry are high, comprising approximately 20 percent of the total cost of producing finished steel in an integrated steel plant. This cost includes electric power purchased from the local utility grid as well as that produced within the plant from byproduct as well as purchased fuels.

The main priorities of the steel industry are production capacity, customer service, quality, environmental control and cost. Use of energy in the production of steel therefore is a matter of concern. Modernization programs that improve production, quality, or both will frequently improve fuel utilization and reduce the overall BTU/ton of crude steel produced. Reduction of fuel consumption also has a positive effect on the environment. Prime examples of such projects that involve improved capacity and/or quality while at the same time effecting major fuel economies are the installation of continuous casters and the new generation of walking beam reheat furnaces recently installed in many steel plants.

There is an on-going concern that many of the combustion processes used in producing steel involve the generation of carbon dioxide and nitrous oxides as unwanted byproducts. The Clean Air Act of 1990 provides impetus to improve combustion efficiency and minimize the generation of unwanted emissions. A reduction of fuel consumption is viewed as a way to achieve significant reductions in the generation of these undesirable byproducts. The improvement of fuel rates in various steel producing processes help achieve this goal.

The desire of the industry is to have research efforts directed towards combustion process improvements that will achieve significant tangible improvements in the near term. Projects that are likely to stay in the laboratory for five to ten years before commercial use is initiated are not of great interest.

These projects must meet several of industry's requirements for acceptance. The equipment developed must be durable and resistant to the hostile environments (heat, cold, and dirt) found in the steel industry. Use of laboratory-type equipment that is prone to repeated failures is not acceptable. Equipment or instrumentation must achieve repeatable results as well as being robust. In other words, plant operator acceptance must be achieved through the demonstration of reliable performance and must not be the cause of frequent operational interruptions.

The projects listed below are not listed in order of priority. They are stated as possible application research work that could be performed now in various areas of the plant. The contents of the succeeding sections were developed in discussions with two integrated steel companies, two burner manufacturers, one furnace builder, one oxygen supplier and industry energy experts. It is likely that there are several equipment suppliers, oxygen suppliers, furnace builders, and/or steel companies that would be interested in participating in these various projects.

2. Candidate Research Projects

2.1 Reduction of the Utilization of Coke.

Coke batteries have high initial capital cost, continued operating and maintenance costs related to the nature of oven design, and challenging environmental problems. The standard coke oven furnace design presently in use is the same design used for the last 70 years. While size of the furnaces has changed, the principle is the same: coal is heated by pushing heat through thin, fragile refractory walls to make coke. The coke making process must either be replaced with one that overcomes the above problems, and/or the ironmaking process must be modified to reduce or eliminate the requirement for coke. Past efforts to develop new cokemaking processes to overcome the problems of the existing coke oven design have not been successful. Therefore, reduction in coke usage represents the most direct path to reducing cost and environmental problems.

The majority of North American furnaces inject natural gas, and in recent years much higher gas injection rates have been achieved. Natural gas injection at these new higher levels greater than 100 lb/NTHM has proven to be beneficial in reducing coke consumption while increasing productivity at minimal capital cost. However, from a long term strategic viewpoint it is believed that natural gas can replace at most 25 % of the furnace coke requirement. Coal injection, on the other hand, could replace up to 40 % and perhaps more of the furnace coke requirement. Accordingly, the largest steel plants in the Chicago area and several others have installed coal injection. At present coal injection is installed on 12 furnaces representing almost 20 million tons or about 40 % of U.S. hot metal production.

The major difference between the recent North American coal injection projects and those elsewhere is that these North American projects are all designed to inject at high levels, 400 lb/NTHM. This level is economically essential in order to justify the capital investment required as

lower levels of coal injection would merely replace natural gas injection, already available with no capital cost.

The need for North American furnace operators to inject coal at high levels, 400 lbs/NTHM, to maximize coke replacement requires efficient combustion at the tuyeres. A considerable amount of research has been performed in Europe and the Far East to study the key aspects of coal combustion in the blast furnace raceway (combustion) zone. Many of these studies have utilized laboratory or pilot-scale single tuyere combustion furnaces; some of these have been supplemented by in-furnace measurements of raceway gas composition and temperature.

Such studies have shown how combustion efficiency is increased with higher flame temperatures, oxygen enrichment, smaller coal particle sizes, higher coal volatile content, reduced coal moisture, etc. In blast furnace operation it has also been observed that combustion efficiency and overall utilization is affected by tuyere velocities, injection lance design, coke quality and raw materials distribution. These laboratory studies and furnace operating experiences have provided valuable guidance to North American ironmakers in the start-up and operation of recent coal injection installations.

However, these overseas studies are not tailored to North American coals or specific blast furnace conditions. The only significant coal injection research initiative in North America is the DOE Clean Coal Program Project at the Bethlehem Steel Burns Harbor Plant. Here a full scale coal injection system, capable of injecting at high rates, 400 lbs/NTHM, has been installed on two medium to large size furnaces producing each about 7000 NTHM/day. In this project DOE contributed about 30 million dollars to the construction and test program. The test program will feature the exploration of the maximum coal injection rate for a given coal grind size for up to four types of North American coals.

- A. The Bethlehem Burns Harbor DOE test program will furnish valuable empirical information on the suitable coal grind size for various injection levels for the most typical North American coals. This program could be enhanced by a complementary laboratory scale effort with a raceway or tuyere hot model. Such a hot model could be used in a program to explore a wide array of coal injection lance configurations, blast conditions, coal types and grind sizes. This program could also complement in-house studies and furnace experimental trials at other steel company coal injection sites.

A useful extension of the laboratory program could be the co-injection of other solid materials: waste oxides, fluxes, fine iron ores, titanium ore (to protect the furnace hearth), and plastics. The injection of plastics has been tested in Germany at Stahlwerke Bremen and holds great potential for energy efficient disposal of waste plastics which cannot be recycled by other means. The co-injection test program could also include other fuels such as oil, tar and natural gas; such co-injection practices are already utilized but probably not optimized at several U. S. blast furnaces.

While the above program would initially be directed towards coal injection, the co-injection of other solid materials such as flux, ore; plastics, etc, should also be tested. Natural gas injection will continue to play a major role in North American blast furnace practice even after all companies likely to adopt coal injection have done so.

- B. Work on direct ironmaking - steelmaking processes would be in order, with particular attention to follow-up on the DOE/AISI Direct Steelmaking efforts including adaptation of the process to the smelting of iron-bearing solid waste.

2.2 Blast Furnace Operating Improvements.

The fuel used in an integrated plant's boilers accounts for a significant portion of the total plant fuel consumption. A large portion of the boilers' steam output is used to drive the turbo-blowers which provide the "wind" for the blast furnaces. The advent of larger, modern blast furnaces has resulted in larger, more powerful turbo-blowers capable of producing greater air flows at higher pressures. This results in a cost factor that could be mitigated by a process change. Technology affecting boiler efficiencies, steam cycle efficiencies, condensers, and blower efficiencies is very well understood, and there are few areas of opportunity where further research would bring energy savings not already available.

However, the following opportunities should be investigated to establish if significant energy savings can be achieved by making changes to the ironmaking processes of the integrated plants.

- A. The smelting of coal and iron pellets in a new process to eliminate or reduce the energy requirements related to ironmaking.

- B. Modification of the blast furnace process using heated recycled reducing gases. Russian experimental work has demonstrated a process that uses recycled blast furnace top gas enriched with 95 percent purity oxygen instead of air for blast furnace blowing purposes. The top gas would be compressed, stripped of its CO₂ constituents in an MEA process, heated in modified blast furnace stoves, and blown into the furnace through the tuyeres. While a demonstration plant has been built in Russia, the process is untried in this country. An evaluation of the process, its economics, and a possible field test in this country should be explored.

2.3 Burner Enhancement Projects - Reheat Furnaces.

Reheat furnaces are generally fired with recuperative burners of various sizes using combustion air temperatures up to 900 deg. F. While temperatures greater than 900 deg. F. have been used, the cost of burner and recuperator materials goes up appreciably, and maintenance increases disproportionately, particularly if fuels other than natural gas are utilized. Burners are sized and applied by carefully taking into account the furnace heat loads that must be satisfied. However, the variability of the material heated (length and thickness as well as furnace loading pattern) makes the burner selection process a series compromises.

Modern computer control systems are now available to control furnace temperatures to respond to the varying production and temperature requirements for heated steel to be rolled by the mill. These computer programs include models of the radiant and convective heat transfer of the burner flames to the furnace refractory and steel.

Furthermore, there is a whole spectrum of low NO_x burners and oxygen enriched burners available in the marketplace. Additionally, there are several regenerative burner systems available. Pulsed combustion burner systems are also being proposed by some suppliers for improving the efficiency of certain furnace types. Burner types supplied by the major manufacturers should be tested, evaluated, and modified as required to:

- A. Improve uniformity of generation and application of heat to the steel. This includes a thorough evaluation of the heat transfer aspects of the burner types to confirm whether existing computer models properly account for the burner characteristics.
- B. Reduce NO_x.

- C. Improve the range over which burners can properly apply a uniform temperature field over the steel to be heated.
- D. Improve burner long term durability.

The above may require a detailed examination of the benefits or disadvantages of using oxygen enrichment of the combustion air. This should cover the full range of combustion air oxygen from 21% to 100%. It is clear that NO_x generation rises with the increase of combustion air oxygen content and the resultant flame temperature. The question that must be addressed is whether or not the savings in fuel offsets the increase in NO_x per BTU of fuel fired so that the net NO_x emission per ton of steel heated is reduced.

At least one and probably all burner manufacturers have ongoing research addressing the above mentioned areas. Furthermore, research in this area has proceeded with DOE Funding. The scope of this work should be expanded, particularly with respect to the items listed above.

2.4 Direct Steel Temperature Measurement.

While every major steel company now has very elaborate and complex computer models to simulate the heat transfer process that occurs in the reheat furnace and to predict the temperature of every slab in the furnace; such models require direct steel temperature measurement to calibrate the accuracy of the computations. Positive feedback to verify and adjust for changes in emissivity, non-stoichiometric combustion, scale formation rate, burner misadjustment and other deviations from theoretical estimates is required to optimize heating practices.

Measurement of steel temperature in a reheat furnace is subject to errors caused by the varying thicknesses of the scale layer on the steel. The measurement can be affected by the furnace atmosphere in the area where the measurement is being taken. A device is needed to directly measure the temperature of steel in the furnace as it is being heated. This device must be unaffected by the hot combustion gases surrounding the steel and the varying thicknesses of scale on the surface of the steel. Additionally, the device must be robust to withstand the unfriendly environment in which it must operate. While several manufacturers have produced and marketed such instrumentation, durability, reliability, accuracy, and repeatability have not been acceptable. It is recommended that research be directed to either improve existing equipment or develop a measurement system not dependent on optical viewing of the steel.

2.5 Combustion Completion Measurement.

Combustion efficiency is maximized when the fuel is burned to completion with a minimum of excess air. A fuel cost penalty results if either too much air or too much fuel is put into the furnace to assure complete combustion. Since combustibles or excess air in the flue gas from any one zone affect the measurement of combustion in succeeding downstream zones in the furnace, each zone must be monitored and controlled separately, thereby requiring a multiplicity of instruments in a multiple zone, multiple burner furnace. Several manufacturers have marketed instrumentation to attempt to measure and control the completeness of combustion. None of these has been entirely satisfactory because they have failed to meet one or more of the criteria for durability, reliability, accuracy or repeatability. However, if a reliable instrument is developed to look at the flame to determine completion of combustion, excess air could be better controlled with an attendant fuel saving. It is recommended that a research effort be directed to develop an instrument capable of measuring completeness of combustion and determining proper air fuel ratio taking into account:

- A. Flame length and size not being constant as a function of fuel content and turndown ratio. The length of the flame and the point where any test instrument must be sighted changes location as the rate of fuel input is varied.
- B. Variable fuel composition. By-product fuels are known to vary appreciably in analysis and BTU content. Similar variations occur to a larger degree in purchased fuels.
- C. Mill-worthy design criteria including attention to water cooling system design, clouding of lenses and other problems inherent to the hot, dirty, vibration prone reheat furnace environment.

2.6 Continuous Annealing Furnace Burners

Continuous annealing furnaces are very large, costly, and inefficient. Expensive radiant tube burners must be used throughout because of requirements for various furnace atmospheres. A direct fired burner that would heat the steel much more rapidly than the present radiant burners, and that would not oxidize, decarburize, or carburize the steel, would effect major fuel savings in the continuous anneal process, even if applicable in only a few furnace sections. This would not be an easy process to achieve, but it would most certainly have significant benefits, both in furnace size and thermal

efficiency. One possible solution may be the application of high heat head pulse firing.

Areas that promise possible efficiency gains include:

- A. Identifying new methods of rapidly heating strip to temperatures below those where furnace atmospheres would result in oxidation, decarburization or carburization of product. Pulse heating may be an application in this area.
- B. New direct firing methods at higher temperatures that would not cause adverse effects on the product.

2.7 Computer modeling of Reheat Furnace Burner Flames

The accuracy of the computer models for predicting the steel temperatures developed in the furnace (see Section 2.4) is dependent on the model for flame radiation and convection in the furnace. The advent of the many different types of low NO_x burners as well as the low NO_x oxygen enriched burners complicates the problem of developing accurate models to predict the heat transfer of these burners. The fact that varying firing rates and ambient temperatures occur in the reheat furnace adds to the problem. Any inaccuracies in the calculation of the heat transfer effected by the burners will affect the accuracy of the reheat furnace computer model.

Fundamental flame research is required to verify the actual heat transfer achieved by various types of burners. The results of such work could then be utilized to improve the accuracy of the many reheat furnace models now in existence. It is recognized that such work does not fall in the category of a process improvement that will achieve near term results. However, it is of such importance that it is mentioned here.

A program to examine possible solutions to this problem is recommended.

3. Summary

To summarize, the following programs are recommended:

- 3.1 Laboratory testing of blast furnace coal injection techniques (2.1A).
- 3.2 Continuation of investigation into smelting of iron ore pellets using coal (2.1B).

- 3.3 New top gas recycling process for blast furnaces (2.2B).
- 3.4 Reheat furnace burner enhancement investigation (2.3).
- 3.5 Direct Steel Temperature measurement (2.4).
- 3.6 Combustion Completion Measurement (2.5).
- 3.7 Continuous annealing furnace burner improvement (2.6).
- 3.8 Computer modeling of reheat furnace burner flames (2.7).

APPENDIX C - GLASS INDUSTRY

Issues of Fundamental Research in Support of Glass Industry Combustion Needs

U.S. Glass Industry

Glass was one of this Country's first industries, locating here from Europe due to abundant energy and raw material sources. Today's glass industry is a major user of energy (about 205 trillion BTUs per year). The glass industry constitutes one of the principal markets for natural gas, consuming over 188 billion cubic feet in 1994. This fuel has been preferred over other fossil fuels because of its operational cleanliness and flexibility. About 85 percent of the total energy used in the glass industry is supplied from natural gas and about 14 percent comes from electricity. A small amount of oil consumed is used in melting; however, its use is restricted to situations where gas is purchased on an interruptible basis and has been curtailed. Because of air emission concerns and some operating difficulties, oil use is usually discontinued as soon as gas again becomes available.

Glass manufacturing is a mature, highly competitive industry. It has been pressured by the penetration of competitive materials such as metals, plastic, and papers (all using less energy for their manufacture than glass). Past drivers for manufacturing process improvements relate to a number of important issues associated with combustion. The formation of glass involves complex chemical reactions between glass forming raw materials at high temperatures in a refractory lined chamber involving intense combustion. Such concerns as resultant glass quality, production rates, refractory life, fuel conservation, and cost effectiveness continue to hold significant attention.

Overall, about 75 percent of natural gas consumed by the glass industry is used for melting; the balance is used for:

- a) Downstream operations, which consist of fabrication into containers, flat glass, fiberglass, or a variety of objects (such as dinnerware, kitchenware, television tubes, and laboratory ware), and which are pressed and blown, and
- b) Finishing operations such as annealing and tempering. However, in the fiber segment only 55 to 60 percent of gas consumption is used for melting and refining; in the other segments, melting and refining account for 85 percent or more.

The fabrication processes are specific for each product category, and utilize combustion based processes for controlling the molten glass temperature. Many products are thermally or chemically treated after fabrication by tempering, annealing, labeling, coating, and/or decorating. Tempering of flat glass is very energy intensive, for the annealing of flat glass or containers, energy intensity depends on the efficiency of the annealing lehrs.

The U.S. glass industry consists of four principle segments: Containers (SIC 3221), Flat (SIC 3211), Insulating Fiber (SIC 3229), Textile Fiber (SIC 3296), and Pressed and Blown (SIC 3229).

Container Glass

The container segment is by far dominant and accounts for over 50 percent of the total glass tonnage melted in the United States. It is continuously fighting the competition of other materials, and, in 1994, shipped 41 billion units per year out of about 180 billion rigid container units of all kinds per year in the United States.

The major use for gas in the container glass sector is in melting, with some consumption in annealing and finishing. This sector has encountered significant inter-material competition and loss of market share; less efficient producers have shut down and production is concentrated in relatively newer, more efficient plants. Average fuel consumption for melting is about 4.5 to 6 mmBTU/ton.

Flat Glass

The Flat Glass segment is important and is primarily supported by the demand of the Transportation and Construction industries. In 1992 about 3.9 million tons of flat glass, equivalent to about 4.6 billion square feet, were shipped from U.S. factories.

The major use for natural gas in the flat glass sector is in the melting furnaces. Furnaces are generally very large, ranging from 400 to 800 TPD. Some consumption is in the downstream laminating, autoclaving, annealing, and tempering steps. Typical furnace fuel consumption is in the range of 8 to 10 mmBTU/ton melted, depending on the age and size of the furnace/regenerator system.

Fiberglass

The fiberglass segment is subdivided into a) Wool Insulation - used primarily by the construction industry and b) Textile - used principally by the production of polymer based, continuous filament reinforced composites. It is further subdivided into "low technology" (e.g., furniture and boats) and "high technology" (e.g., electronics, automotive, and aerospace components) areas. Neither product can support the cost of long-range transportation, and therefore international trade is negligible.

Most Textile production is from continuous, on-line melting furnaces primarily fueled by natural gas. The melting furnaces have a capacity of 150-200 TPD. Insulating Wool is more typically made in electric furnaces. Some re-melting is performed in electric furnaces from marbles made in gas-fired furnaces. This less common process consumes 50% more energy. Some of the gas consumed in fiberizing is used to produce steam, and some is used to supply heat directly to the fiberizing process.

The unit consumption of natural gas for melting is now in the 8 to 10 mmBTU range. Unlike in the container and flat glass segments, a large amount of energy is used in the fabrication step. Fiberizing can consume 6 to 10 mmBTU/ton.

Pressed and Blown Glass

The Pressed and Blown segment of the glass industry is a significant "catch all" for glassware not otherwise classified. A large fraction of this segment consists of owner managed, small labor-intensive manufacturers. The pressed and blown segment generally depends on several post forming operations including annealing, tempering, and/or decorating. Many plants in this sector are small and relatively inefficient in energy use, so

unit energy consumption for melting is 12 to 16 mmBTU/ton shipped. In these shops the melting furnaces have small capacity (on the order of 5 to 25 TPD).

The few companies that manufacture machine made table and kitchenware and certain industrial products such as light and electric components, used primarily gas-fueled large furnaces (typically of 100 to 200 TPD capacity). Their furnaces are more similar to Container and Fiber Glass types.

Conventional Fuel-Fired Furnace Designs

The basic design of conventional fuel fired furnaces has remained unchanged for many years. The raw material charge is melted in large gas fired reverberatory type furnaces. A typical furnace would have a plan area of about 4 square feet per ton per day of production and be about 35 feet long and 20 feet wide with sidewalls 6 feet in height. The dominant mechanism for the heat transfer necessary to carry out the glass making reactions is radiation. Energy is recovered from the combustion off gases using regenerators that preheat combustion air.

High heat losses and inefficient regenerator designs resulted in thermal efficiencies of less than 30 percent in many older furnaces. The efficiency of these types of furnaces has been increased significantly in the last 15 years in response to the rapid increase in energy costs. Fuel consumption has been decreased by more than 25 percent through a variety of design changes. More efficient regenerators have been used to increase combustion preheat temperatures to 2200 to 2300°F. This may require the use of more expensive refractories in the hot end of the regenerator and some increase in size and design complexity to obtain the higher effectiveness. More efficient insulation of the furnace itself reduces heat loss and decrease its fuel consumption, but the savings are limited by the size of the furnace.

Present Industry Problems/Needs

Environmental

With melting energy representing approximately 15% of manufacturing costs and considerable requirements to meet expanding environmental regulations, this industry must find alternative melting technologies to remain competitive. Environmentally driven process changes for reducing emissions of criteria air pollutants (HC, CO, NO_x, and particulate matter) have not generally led to increases in productivity; and thus have increased operating costs. Investments in environmental control equipment are viewed as nonproductive and as leading to further pressures on the industry's low operating margins. Therefore, there are real opportunities for the development of technologies that can meet applicable regulations without increases in capital requirements or operating costs.

One key issue for combustion space characterization and modeling for Glass Melting furnaces involves understanding the heat input to the batch/glass with pollution production (NO_x) and fluid dynamics (refractory erosion due to flow, entrainment of particulates, etc.). Present combustion models are limited in their ability to accurately predict chemical reactions, radiant heat transfer (spectral effects, etc.) and the turbulent reacting flow. As example, the Fluent, Inc. code is a frequent use by many organizations but it has limited sub models and a simplified radiation heat transfer sub-model). There is very limited "linkage" between the combustion environment and chemical species interaction at the melt interface. Another major issue is that there is very limited experimental data to validate numerical models.

An effort in the glass industry is underway to gather detailed measurements within an operating glass melter. Measurements will include the collection of local gas compositions including O_2 , CO_2 , CO , NO_x , and SO_x . Their temperatures and gas velocities are planned for acquisition. Measurements of wall radiant and convective heat flux will also be made. Process variables will be altered (such as different burner angles, gas flow rates, etc.). The local data will be used to experimentally validate computer models. The validated model will then be used to optimize present operating conditions, examine possible design changes, and investigate innovative concepts and examine possible design changes - such as gas reburn, staged combustion, oxygen/fuel combustion, etc. The validated model will allow an investigation of the effects of changing conditions/geometry on both the combustion process and molten glass.

Although the concept behind low NO_x burners may be applicable to glass melting, the burners cannot be directly retrofitted to glass furnaces. This is a consequence of a basic difference between industrial boilers and glass furnaces. In boilers, mixing of fuel and air takes place within the burner itself. In a glass furnace, however, the burner is really a fuel injector, injecting fuel into the flow of combustion air entering the furnace. The mixing of fuel and air takes place within the furnace. Consequently, there are no "off the shelf" low NO_x burners available for glass melting furnaces.

In natural gas fired regenerative glass furnaces, NO_x is essentially formed by thermal oxidation of nitrogen in combustion air (thermal NO_x). Thermal NO_x depends upon the time temperature history of the flame and increases with increasing residence time and increasing peak flame temperatures. Furnace operating temperatures and flame temperatures - and, consequently, NO_x generation - are quite high. NO_x emissions over 10 lb/ton glass are not uncommon. Thermal NO_x also increases significantly with increasing availability of oxygen in the high temperature zone. To reduce NO_x formation during natural gas combustion, both the peak flame temperatures and the oxygen availability must be reduced.

At this time, the use of Oxy-Gas firing is viewed by the glass industry as the leading melting technology to lower NO_x emissions. The implementation of this technology for meeting future environmental compliance will initiate a significant driving force to integrate waste heat recovery schemes - such as batch/cullet preheating, co-generation, or gas reformer technology.

This technology is being rapidly accepted by the glass industry because it utilizes many similar operating principles as conventional furnaces, especially Unit Melters, and provides solutions to a variety of other requirements. A recent review on the status of Oxy-Fuel technology shows ~50 glass melting furnaces in North America being converted or being considered for conversion. Current motivations to convert to Oxy-Fuel involve finding methods of meeting environmental compliance conditions. The glass industry expresses significant interest in pursuing more understanding of combustion issues with this technology.

Several NO_x control methods, including air staging, were developed and successfully tested on an IGT pilot scale glass tank simulator in the early 1980s. The furnace was equipped with scaled melter ports. The glass tank load was simulated by a heat silk that consisted of a top layer of molten glass. Furnace temperatures and port operating parameters were maintained within the limits of commercial container glass melter operation.

Low excess air firing tests, as a prerequisite to air staging tests, were carried out on the IGT glass tank simulator, as well as on two commercial glass melters. Air staging tests with ambient air as the secondary oxidants injected near the exhaust port to maintain an overall stoichiometric ratio of 1.15 were carried out

also. The data show that decreasing the excess air from 15 to 5% reduced NO_x by 35%. This is a very effective NO_x reduction method - even more so because of the added benefit of improved heat transfer. In the tests at IGT, there was a significant increase in heat transfer by operating the port at a stoichiometric ratio of 1.0 to 1.06.

Several types of secondary oxidants required for staging have been considered in previous testing and current field tests. A typical option in which a portion of the hot combustion air that is normally supplied to the burners is withdrawn, using an oxygen driven ejector, to create an oxygen deficient flame condition that inhibits NO_x formation. The oxygen enriched hot air is then injected into the furnace as the secondary oxidant, at strategic locations downstream of the flame, to effectively complete the combustion without forming additional NO_x .

There is an interest to have modeling tools to better quantify various aspects of these conditions for combustion modifications.

1. Complete coverage of the exhaust stream inside the melter
2. Sufficient penetration without impinging into the main flame (primary zone)
3. Complete burnout of CO and other unburned THC (total hydrocarbon) within the melter
4. Avoidance of high temperature regions in the melter that encourage additional NO_x formation
5. Computational fluid dynamics (CFD) models for O_2 injection locations with secondary oxidants
6. Species concentration changes which influence glass formation (H_2O , CO & CO_2 partial pressures)
7. Alkali vapor formation differences with Oxy-Fuel options (refractory attack concerns)

Gas Reburning is a NO_x control technology which has successfully been demonstrated on utility boilers to provide moderate to high NO_x removal efficiencies at a moderate cost per ton of NO_x abated and is an appropriate technology for retrofit applications.

A feasibility study has been performed to evaluate the effectiveness of gas reburning for NO_x control from glass furnaces. In the feasibility study, preliminary conceptual designs have been prepared for application of gas reburning to model glass furnaces representing typical furnaces used in the manufacturing of container and flat glass. Computational models have been used to evaluate the impacts of gas reburning on NO_x emissions, and on furnace fuel usage and temperatures.

Bench and pilot scale research programs have been conducted on Gas reburn by EER under funding from U.S. EPA, the Gas Research Institute, and the U.S. Department of Energy. These studies have quantified the impact of process parameters on reburning effectiveness and provided scaling methodologies.

Approximately 12 - 1500 lb. of CO_2 are emitted from combustion for each ton of glass melted. An

additional 300 lb. of CO₂ come from raw material calcination for each ton of glass. Serious concerns with CO₂ reduction to address concerns with global warming have not been of significant concern for the glass industry to date. Consequently, such fuels as Hydrogen, are not presently considered for study.

The forming and tempering of flat glass in Gas Hearth processing is far from optimization. The glass is heated with radiant combustion cups. There is little or no knowledge about spectral response, effects on heat flux distribution (such as height, flow rate fuel/air ratio, etc.) for the individual cups and no information on heat transfer with arrays of combustion cups. Unlike metals, glass is not opaque at wavelengths below 4.5×10^{-6} meters. It may be feasible to optimize the spectral characteristics of burners for heating the glass uniformly and efficiently, which relates to major quality issues for forming and stress levels.

Flame jet impingement heating has been used in the glass fabricating industry for many years. Chemically reacting jets are playing an increasingly important role in such impingement heating applications in other industries. In this case, the energy required to heat the load comes largely from the heat of reaction of the fuel.

It has been recognized for its high transport characteristics and is emerging as an attractive method for rapid heating to replace conventional radiant heating. Rapid heating of materials in a variety of industries is emerging as a cost-effective step resulting in reduced production time, and is a potential replacement for more conventional radiant heating. Other advantages include reduction of thermal inertia of the furnace, reduced capital costs, and in some cases improved spacial control in situations where localized heating is required.

In production processes where flame jet impingement is attractive, an understanding of the local distribution of heat flux, partitioning between convective and radiative transfer, stability of the flame, optimum geometric configuration, pollutant formation and control, etc., is vital to the achievement of highest product quality and the minimization of energy consumption. The potential for savings is high, both from efficiency and reduced product reject basis. Improved comprehension of the transport mechanisms and generalization of heat fluxes to the load will also permit advancement of the modeling of the various fabrication processes.

There is a need to characterize the fundamental transport mechanisms in flame jet impingement heat transfer. An experimental investigation of mechanisms governing heat transfer to the load (stock), rather than the detailed kinetics and mechanisms of the chemical reaction is needed. However, since the reaction is critical in the determination of the local combustion gas temperature, characterization of the extent of reaction, heat release, oxidizer/fuel mixing, etc. will be a key facet of the research. The influence of local reaction chemistry, pollutant formation, turbulence, system geometric parameters, burner configuration, etc., on the local transport to the impingement surface will then be supporting elements of the investigation. Theoretical modeling of the flame jet impingement will also play a role in the improved understanding of the problem.

Previous work related momentum-driven flame jet impingement heat transfer has investigated premixed flames, but very few have measured the local heat transfer characteristics. Further, few studies have attempted to correlate the local heat flux, generalizing the results for use elsewhere. Little study has been devoted to the problem of diffusion flames. In many industrial applications, however, diffusion flames are preferred due to safety considerations. There are also a variety of different burner geometry's investigated in the previous work, making the results difficult to generalize.

The dependence of an optimal burner-plate distance on jet Reynolds number and equivalence ration has not been fully characterized even for limiting oxidizer delivery configurations, i.e., premixed and diffusion flames. While most studies have indicated that the radiation transfer is negligible for non-luminous flames, only one study (Beer and Chigier, 1986) has attempted to quantify the partitioning between convective and radiative heat transfer at the impingement plate.

There is a critical need for a comprehensive study which integrates the local flow structure, chemistry, temperature, etc., and correlates their influence on the local heat transfer at the impingement plate. Among others, some critical questions which remain to be answered include:

1. What is the partitioning between convective and radiative heat transfer for those conditions where radiation transfer is important (i.e., luminous flames)?
2. What is the appropriate temperature for correlating the variation in local heat transfer coefficient?
3. What is the influence of turbulence on transport?
4. Can the local heat transfer be correlated for different fuels with a wide range of heating values?
5. Can the dependence of local heat transfer on fuel equivalence ration (for premixed or coaxial flow diffusion flames), jet Reynolds number, burner-plate spacing, etc. be generalized for use in design settings?
6. Can the local heat be predicted as a function of fuel and burner operating conditions using established theoretical models?

Consolidation of corporate staffs and reduced earnings have exacted a toll in the Glass Industry for conducting combustion research internally. The Glass Industry does still have a variety of mechanisms for proactive involvement with external R&D activities, especially those supported by government co-funding programs. Consortiums have been formed through trade associations, as well as cooperative groups driven by individual glass companies, vendors, or technology developers.

Successful, cost effective R&D activities require the glass industry's following participation:

1. Address specific industry requirements to be of timely benefit
2. Identify existing and emerging technologies, technical hurdles, past activities, relevant patents, and other on-going research
3. Decide what research activities will be undertaken and evaluation of the research project
4. Support a demonstration phase and conduct trials at their facilities to accomplish or validate the research
5. Promote technology transfer for broad acceptance.

Researcher Interests

A review of the DOE Workshop on Fundamental Research in Support Of Industrial Combustion Needs (October 10, 1994) document identified the following items consistent with current problems relating to combustion that are faced by the Glass Industry (as identified by phone survey, direct contacts at meetings, and recent literature searches).

Diagnostic Devices

- Rugged or non-intrusive, inexpensive, easy to use & interpret
- Combustion Process Control/real time capabilities
- Soot radiative characterization/quantification
 - Heat flux (transfer) sensors
- CEMS (Continuous Emission Monitoring Systems)

Industrial Specific Processes

- Modeling/design
- User friendly software for equipment and process design development
- Integrated process control (sensors, software, actuators)

Combustion

- Computer Model/Simulations
 - Fuel/Air Mixing relative to Furnace Design & Burner Variables
 - Chemical Kinetics & Dynamics (interaction with Glass chemistry species)
 - Heat transfer dynamics with melting batch/1st liquid phase
- Safety of premixed systems
- Oxygen Enrichment
- Liquid Fuel Combustion

Burner Issues

- Multi-burner process scaling
- Radiative Burners
- Enhanced heat transfer
- Pulsed Combustion
- Precessing Jet

Air Toxics

- Low NO_x combustion processes
- Trace compounds from new processes
- PM₁₀ (Sulfate Particulate vs SO_x gases)

DOE Vision Issues

The U.S. Department of Energy's Office of Industrial Technology "*Vision of the Future*" activities has identified a broad range of technical opportunities of interest for the Glass Industry. The results of the Glass Vision of the Future will be used by the DOE to assist in defining their programs to support industry.

Assistance is being developed to provide bridging mechanisms to support collaborations between Universities, Government sponsored Laboratories, and Industry.

Comparing the glass industry's vision of the future with the present situation provides insight on the important issues that must be addressed through improvements in technology. Technologies associated with combustion issues were identified which should be advanced in the following key areas.

Environmental Performance - Cost effectively meet the requirements of expected environment regulations.

Improved emissions controls - Developing improved, more cost effective air emissions control technology is necessary to meet the more stringent environmental regulations expected. Compliance using integrated process improvements are preferred over add-on devices.

Combustion optimization - Combustion of fossil fuel is far from optimized when considering the need to balance heat transfer for melting and to minimize pollutants, especially NO_x. Fuel or air staging and gas reburn have been identified as being a potentially cost effective means of reducing NO_x in conventional regenerative melters. Gas Reforming as an integrated component of waste heat recovery may be used for increasing flame luminosity, including oxy-fuel furnaces.

Reduced particulates - Particulate emissions in soda lime glass (container and flat glasses) are the result of using sulfates in the bath as a melting and refining aid. The SO_x content of glass being recycled varies by source and type. As higher levels of recycled glass are reached, some particulate control problems may occur. Alternative materials or furnace designs might reduce or eliminate particulates, thereby lowering the cost of add-on capital equipment. Combustion issues may relate to the conversion of SO₂ gas to Sulfate particulates, altering emission control strategies.

Energy Efficiency - Increase energy efficiency in manufacturing by efficient use of energy to conserve resources and minimize future costs.

Furnace Technology - Improvements will be necessary in furnace design and operation to achieve increased efficiency.

Optimizing electric boost - Some glass furnaces are all-electric or use significant levels of electric boost. This approach is often used to minimize losses of volatile batch components (borates and fluorides) and to enhance meter output. In addition to the higher cost of electrical energy, electric melters tend to suffer more rapid loss of refractories, resulting in shorter, unbalanced melter campaigns. Optimizing the relationship between fossil fuels and electric boost consumption has significant impact on energy efficiency and melting costs. Improved melter designs, temperature sensors for vulnerable areas, and advanced control systems are needed.

Optimizing combustion control - The melter's combustion process consumes a large portion of the total facility's energy. Although significant progress in control has been made in this area, design optimization requires better understanding of the process fundamentals. Furnace design features that affect flame development (fuel and air mixing) and optimize heat transfer to the melt need to be better understood. Changes in design involve significant risks, especially when air emission control is also

required.

Oxy-fuel evolution - A significant trend is developing to convert to furnaces that use nearly 100% oxygen combustion as a means of reducing NO_x production and particulate emissions. Since the application of this technology is relatively new, process optimization is needed. Operating economics are higher than conventional furnaces because of the cost of oxygen. Some new methods of on-site generation have been developed. Waste heat recovery has not been applied to the high temperature exhaust gases from oxy-fuel firing (the exhaust contains up to one-third of the heat input). Required add-on equipment for particulate and SO_x emissions should be integrated into waste heat recovery schemes.

Process Control - Enhance productivity and quality through improvements in process control and equipment performance.

Process Monitoring and Control Instrumentation - Information from advanced instrumentation can be used to improve process control. Strategies to further improve the manufacturing of glass products require obtaining representative and reliable data from yet to be developed sensors within key areas of the processes.

Thermocouples that are cost effective to use in relative large numbers (non-precious metal coated) are needed to provide multiple molten glass temperature measurements in the distributor and forehearth areas, where controlled temperature conditioning is recognized as being deficient.

Non-contact temperature measurement sensors should be developed to determine glass temperature profiles in the furnace and throughout the glass fabrication processes.

Waste heat recovery - Further expenditures for more insulation or larger regenerator systems are not cost effective for today's modern furnaces. Significant additional waste heat recovery may be possible by preheating the cullet and batch raw materials.

Process Modeling - There is a strong need for improved capabilities to model and control the complex process of glass melting and fabrication to provide consistency and high quality at high production rates.

All-electric furnaces are more thermally efficient than fossil fired furnaces but they are limited in size (under 300 tons of glass per day) and their energy cost per ton of glass is higher than fossil furnaces. As a result, use of electric heating for container production is generally limited to partially replace (boost) fossil fuels. Electric boosting increases furnace productivity, improves glass quality, and minimizes furnace emissions. The glass industry has generally relied on operating experience with actual equipment for developing new and improved furnace designs using electric boost. As a result, improvements have been slow to evolve. Development of improved furnace models would increase understanding of the melting process and the influence of electric boost. Both physical and mathematical models should be reviewed to determine their applicability to the type of glass melted, glass product produced, and furnace type and geometry. Detailed computer models should then be developed to aid in furnace design and process optimization.

Computer software that simulates glass melters and has the capability to correlate design parameters and operation history information would aid the industry in its pursuit of more consistent glass quality. Such simulation will require a better understanding of the heat transfer mechanisms of glass in the furnace, a correlation between the calculated glass temperature and velocity profiles and the actual glass quality, and an indication of locations within the melter where bubbles or sand grains originate.

Research opportunities have been identified based on their capability to provide a direction for the entire industry rather than for a single sector or company. Following is a list of research and development identified at the *Glass Vision of the Future Workshop*, conducted in Washington, DC in February 1995, which should be performed to overcome barriers and identified technical challenges.

Computer Modeling

We need integrated furnace models that can calculate transient thermal and chemical behavior and can be used to develop methods to optimize energy use and reduce air emissions. Models should link the dynamics of combustion, heat transfer, glass flow and temperature, and furnace throughput. We need to:

- Develop models to optimize fuel combustion and heat release parameters based on furnace design factors.

- Develop furnace heat transfer models for the furnace to calculate glass melting and temperature conditioning (distribution).

- Expand current furnace models to include improved combustion models for prediction of pollutant production (SO_x , NO_x , and particulates) and the effects of gaseous bubbles in the melt.

- We need to develop models to improve understanding of glass chemistry, including chemical kinetics of batch melting and reactions in glass, chemical equilibrium and solubility data, and chemical kinetics influenced by variables in the combustion environment.

- Study the influences and concerns with oxy-fuel melting in large float glass furnaces.

- Correlate numerical data and operating parameters and use them for development of expert control systems, including systems for melting, processing, and emissions control.

Instrumentation and Control

- Develop more reliable and cost effective sensors (for temperature and gaseous species) that can be used to monitor the molten glass and combustion space, so that relatively large arrays can be used to provide information to improve process control.

- Develop non-contact sensors that will determine the glass temperature during the fabrication processes. These sensors must detect temperature rapidly so the information can be used in control processes.

- Develop lower cost, high reliability air emission monitoring equipment that can detect SO_x , NO_x , CO ,

O₂, and particulates.

Develop and apply fuzzy logic and neural network control strategies to improve productivity, quality, and output.

Equipment

Optimize furnace designs to reduce NO_x, SO_x, and particulate emissions. This may include improved burners and means of reducing the particulates entrained in the combustion products.

Develop equipment and techniques for promoting enhanced heat transfer.

Develop equipment that will improve energy recovery from the melter by preheating batch materials and cullet. The design should include the capability to install equipment to remove NO_x, SO_x, and particulate emissions.

Glass Industry Interests

The objectives of maximizing combustion efficiency and minimize emissions to reduce net costs are generally accepted by the Glass industry. Recent applied research activities for combustion applications in the Glass industry include the following areas:

- Oxy-Fuel combustion and furnace atmosphere content changes
- Oxygen Enriched Combustion (Primary & Secondary Air enrichment)
- Air Staging
- Gas Reburn (Fuel Staging)
- Gas Cracker (thermal cracking)
- High Radiation Burners (Plasma assisted)
- Enhanced Sensors.

Another related area involves waste heat recovery integration, especially from Oxy-Fuel melting furnaces.

- Sensible heat from exhausting gases for
 - fuel/air preheating
 - reformer

- Natural gas substitution for electricity (lowering the effective cost per BTU)
 - Fabrication (Bending & Tempering)
 - porous solid/muffled radiators

APPENDIX D - ALUMINUM INDUSTRY

NEAR TERM COMBUSTION RESEARCH NEEDS IN THE
ALUMINUM INDUSTRY

Prepared by:

Energy and Environmental Research Corporation

October 1995

NEAR TERM COMBUSTION RESEARCH NEEDS IN THE ALUMINUM INDUSTRY

Objectives

The objectives of this survey were to define the near term combustion issues and the research priorities required to resolve them through discussions with the aluminum industry stakeholders. These include those that are directly involved in primary and secondary manufacturing operations and the infrastructure which supports them, specifically the merchant gas industry, burner , boiler, and heat treating and melting furnace vendors, and the natural gas industry.

Approach

EER has used its familiarity with the subject industries' to establish an appropriate data base, and the develop knowledgeable industrial contacts. We specifically relied upon our contacts with various gas distribution company industrial account executives, eg: those large organizations who have significant relevant industrial customer gas loads such as S. Ca. Gas Co., and Pacific Gas and Electric. We also contacted combustion and heating equipment manufactures . EER also has access to a number of end users, both corporate and plant engineering.

The first step was to identify generic combustion equipment within each industrial sector which process significant amounts of product and/or consume large quantities of fuel as these would benefit the most from DOE sponsored R&D. The aluminum industry is typically characterized as primary (the conversion of ore to basic metal) and secondary (metal recycling, shaping, fabrication, finishing and treating). Both sectors were evaluated, although the USA primary metals industry is fundamentally a user of electro-technologies. Aluminum die casting and foundries, and strip mills are large single point users of energy, eg: large quantities of metal are heated/melted to high temperatures. Metals are typically batch melted in pots (indirect fired crucibles) or direct fired reverberatory furnaces (the latter sometimes with heat recovery). Heat treating and anodizing operations are energy intensive at the plant level, although energy use is widely distributed among a number of unit operations, eg: heat treating and reheat furnaces and heated chemical tanks. R&D for improved process control (sensors), emission (acid and air toxic) control, improved high temperature insulation packages and heat transfer enhancements, and cost effective high and low grade heat recovery may be important areas to explore. To assure an internally consistent and systematic approach a targeted industry questionnaire was first developed internally, and reviewed with a limited, but diverse subset of the population surveyed. The final questionnaire, Attachment 1, was composed of two parts:

- A profile page which describes the position and function of the interviewee, the market served by his company, and perceived major combustion related issues
- A list of research topics for major combustion technologies found in the industry, and their prioritization by the interviewee

The protocol was to first contact the interviewee and generally discuss the objectives of the survey and to request his support. The questionnaire was then FAX'd for his review and consideration. A follow-up call was made several days latter in which the questionnaire was verbally walked through and completed by EER .

About the Industry

typically configured like cement kilns with feed pre-heat sections, and have heat inputs of 50 to 150 MMBtu/hr. Petroleum derived coke is used to manufacture carbon electrodes. The pre-bake process requires that the electrodes be temperature treated in a ring furnace to volatilize residual hydrocarbons and develop structural rigidity. These furnaces are gas fired, recuperated during the cooling cycle, and the most fuel intensive of the process steps practiced at USA smelters.

Reverberatory furnaces are batch charged, moderately large (25 MMBtu/hr heat input) furnaces which operate cyclically. Once metal is charged burners are set to high fire for melting. The metal is held at intermediate fire, assayed and withdrawn nearly continuously. Melt temperatures are less than 1400 F, requiring high temperature, corrosive resistant refractories for containment. Furnace thermal efficiencies are generally poor, of order 20 to 30 %. Furnaces are usually gas fired although the feasibility of pulverized coal firing has been demonstrated. Oxygen enrichment has also been practiced to improve melter through-put. Thermal efficiencies tend to be low because of the difficulty in applying heat recovery. Cost effectiveness is further compromised by the moderate potential for combustion air preheat (about 800 F) resulting from the moderate furnace gas exhaust temperatures. Pre-heating the feed by charging through the stack or a separate heat recovery unit is, therefore, sometimes practiced.

Heat treating furnaces of the direct and indirect (muffle) type are frequently used to prepare work for further processing or to change its metallurgy. The work requires extremely even heating leading to the use of highly radiant furnace walls and/or improved convective heat transfer with high velocity burners. These furnaces are moderately thermally efficient, 30 to 50%, depending on furnace temperatures. Natural gas is almost exclusively fired to avoid contamination of work surfaces. Direct firing is not used for annealing, but may be used for other types of work heating. Furnace surface heat losses tend to be more significant for these furnaces and stack sensible heat losses less so, as compared to the previously discussed reverberatory furnace.

Combustion Research Survey Results

Major stakeholder industries were identified for inclusion into the data base and specific, potential contacts currently known to EER staff were selected for the interview process. Because of the very short time and constrained budget no attempt was made at a randomized, statistical sample. The following stakeholders were polled:

- Combustion equipment manufactures, specifically burner and furnace
- Fuel and merchant gas suppliers
- Aluminum manufactures, both primary and secondary industries
- Associations supporting the industry

At least two contacts in each of the above groups, Table 1, were identified and vigorously pursued with the questionnaire, somewhat modified depending on the group solicited. The first page of the interview identifies and profiles the interviewee and his organization and was used to focus the acquisition of the priority combustion research topics (second page of questionnaire) from their perspective. Combustion "Issues" were listed in the first column by major categories, environmental mitigation, furnace efficiency, flame/furnace compatibility, operations, and materials of construction. Combustion technologies (conventional or emerging) were rated by the interviewee on a priority scale of 0 (no opinion) to 3 (high priority) for each of the aforementioned issues. All but the burner manufacturers had a very broad view of needs across the technologies list. Burner manufactures tended to want to focus on specific burner embodiments, eg: direct, radiant tube of face, or indirect immersible. To make these categories tractable burner manufacturer responses were assigned one of the following three categories, radiant, direct, or

enhanced (acoustic, oxy enrichment or catalytic).

The results have been tallied by combustion issue/technology in statistical chart form, Figure 3. Priority selections have been made on the basis of the product value of the number of response (n) and the mean statistical mean rating in each category. The results incorporate nine (9) respondents, four from gas utility and merchant gas suppliers, two burner manufacturers, one primary AI manufacturer, and two combustion equipment suppliers. The highest priority combustion issues appear to be clustered in the following categories:

- Furnace efficiency and productivity improvements through flame radiation enhancement and O₂ enrichment
- Improved refractories for hot burner parts such as burner blocks, radiant tubes, and burner tips.
- NO_x reduction technologies for oxygen enhanced combustion

Lower priorities were assigned to the following issues:

- Multipoint, low cost sensors for monitoring composition (gas and metals), and temperature (gas and work).
- NO_x control and enhanced production with acoustic or catalytically assisted combustion technologies

There was very little interest articulated in flame safety and stability, heat release profiling or flame containment issues. Technologies of primary concern were multiple, oxygen enhanced and radiant burners, and combustion processes incorporating solid phase media, eg: porous media and suspended materials/fuels.

Figure 1. Materials flow of primary and secondary aluminum.

Figure 2. Large energy using combustion equipment commonly found in the aluminum industry.

Figure 3. Combustion System Aluminum Stakeholder Questionnaire
Summary of Respondents' Opinions

Research Topics/Priority	Combustion Technology																																			
	1									2									3									4								
	Suspended Circulation									Fluid Bed									Porous Media									Mass Burn								
	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
1 Environmental Mitigation (Combustion Generated)																																				
1 - Noise	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
2 - Acid Gas (NOx, SOx)	0	0	0	3	0	2	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	3	0	2	0	0	0	0	0	0	0	0	2	0	0	0
3 - Greenhouse Gases	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	
4 - Air Toxics	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
2. High Temperature Furnace Efficiency																																				
Enhancement	0	0	0	3	3	2	0	2	0	0	0	0	0	0	2	1	3	0	0	0	0	3	0	2	3	0	0	0	0	0	0	0	2	0	0	0
2 O2 Enrichment	0	0	0	3	2	3	0	2	0	0	0	0	0	0	3	1	3	0	0	0	0	3	0	3	1	0	0	0	0	0	0	0	3	0	0	0
3. Flame/Furnace Compatibility																																				
1 - Heat Release Profiling	0	0	0	3	0	3	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	3	0	3	1	0	0	0	0	0	0	3	0	0	0	0
2 - Flame Confinement	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0
3 - Flame Safety/Stability	0	0	0	3	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	3	0	2	1	0	0	0	0	0	0	2	0	0	0	0
4. Operations																																				
1 - Ultra High Turndown	0	0	0	2	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	3	0	0	0	0	0	0	0	0	0	0	0
2 - Fuel Flexibility	0	0	0	2	0	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0
3 - Multipoint Sensors																																				
a Temperature	0	0	0	1	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	3	0	0	0	0	0	0	0	0	0	0	0
b Composition	0	0	0	1	3	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
4 - Productivity Enhancements	0	0	0	3	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0
5. Materials of Construction																																				
1 - Refractories	0	0	0	1	3	3	0	0	0	0	0	0	0	0	3	0	2	0	0	0	0	3	0	2	2	0	0	0	0	0	0	3	0	0	0	0
2 - Insulation Package	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
3 - High-T Alloys	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	2	0	0	0	0	0	0	0	0	0	0	0

**Figure 3. (continued) Combustion System Aluminum Stakeholder Questionnaire
Summary of Respondents' Opinions**

Research Topics/Priority	Combustion Technology																																				
	5									6									7									8									
	Multiple Burner Arrays									Oxygen, Acoustically Assisted									Direct Burners									Radiant Burners									
	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	
1 Environmental Mitigation (Combustion Generated)																																					
1 - Noise	0	0	3	2	0	0	0	0	0	0	1	3	2	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0
2 - Acid Gas (NOx, SOx)	0	0	3	3	0	2	3	0	2	0	3	3	3	0	2	3	0	0	3	3	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0
3 - Greenhouse Gases	0	0	3	1	0	0	0	0	2	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4 - Air Toxics	0	0	3	2	0	0	0	0	3	0	2	3	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2. High Temperature Furnace Efficiency																																					
Enhancement	0	0	3	3	0	2	3	0	3	0	2	3	3	0	2	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2 O2 Enrichment	0	0	3	3	0	3	1	0	0	0	0	3	3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3. Flame/Furnace Compatibility																																					
1 - Heat Release Profiling	0	0	3	3	0	3	0	0	2	0	2	3	3	0	3	0	0	0	2	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
2 - Flame Confinement	0	0	3	3	0	0	0	0	1	0	2	3	3	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
3 - Flame Safety/Stability	0	0	3	3	0	2	0	0	1	0	0	3	3	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
4. Operations																																					
1 - Ultra High Turndown	0	0	3	2	0	0	2	0	1	0	0	3	2	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0
2 - Fuel Flexibility	0	0	0	2	0	0	1	0	1	0	0	0	2	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0
3 - Multipoint Sensors																																					
a Temperature	0	0	3	1	0	0	3	0	1	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b Composition	0	0	3	1	0	0	1	0	1	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4 - Productivity Enhancements	0	0	3	3	0	0	3	0	1	0	0	3	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0
5. Materials of Construction																																					
1 - Refractories	0	0	1	1	0	3	3	0	3	0	3	1	1	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	3	2	0	0	0	0	0	0	0
2 - Insulation Package	0	0	1	1	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
3 - High-T Alloys	0	0	1	1	0	0	3	0	0	0	3	1	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0

Figure 3. (continued) Combustion System Aluminum Stakeholder Questionnaire
Statistical Analysis of Respondents' Opinions

1		2			3			4			5			6			7			8				
Suspended Circulation		Fluid Bed			Porous Media			Mass Burn			Multiple Burner Arrays			Oxygen, Acoustically Assisted			Radiant Burners			Direct Burners				
		Mean	σ^2	n	Mean	σ^2	n	Mean	σ^2	n	Mean	σ^2	n	Mean	σ^2	n	Mean	σ^2	n	Mean	σ^2	n		
0.50		0.75	4	0.33	0.22	3	0.67	0.89	3	0.00	0.00	1	1.00	1.60	5	1.20	1.36	5	2.00	1.00	2	2.00	1.00	2
1.25		1.69	4	1.00	0.67	3	1.67	1.56	3	2.00	0.00	1	2.60	0.24	5	2.80	0.16	5	3.00	0.00	2	3.00	0.00	2
0.25		0.19	4	0.33	0.22	3	0.33	0.22	3	0.00	0.00	1	1.20	1.36	5	0.80	1.36	5	0.00	0.00	2	0.00	0.00	2
0.50		0.75	4	0.33	0.22	3	0.67	0.89	3	0.00	0.00	1	1.60	1.84	5	1.80	0.96	5	0.00	0.00	2	0.00	0.00	2
2.50		0.25	4	2.00	0.67	3	2.67	0.22	3	2.00	0.00	1	2.80	0.16	5	2.00	1.20	5	1.50	2.25	2	0.00	0.00	2
2.50		0.25	4	2.33	0.89	3	2.33	0.89	3	3.00	0.00	1	2.00	1.60	5	1.80	2.16	5	0.00	0.00	2	0.00	0.00	2
1.50		2.25	4	1.00	2.00	3	2.33	0.89	3	3.00	0.00	1	2.20	1.36	5	2.20	1.36	5	1.50	0.25	2	1.00	1.00	2
1.50		2.25	4	0.00	0.00	3	1.33	1.56	3	0.00	0.00	1	1.40	1.84	5	1.60	1.84	5	1.50	0.25	2	1.00	1.00	2
1.25		1.69	4	0.67	0.89	3	2.00	0.67	3	2.00	0.00	1	1.80	1.36	5	1.60	1.84	5	1.00	1.00	2	0.50	0.25	2
1.00		1.00	4	0.67	0.89	3	1.67	1.56	3	0.00	0.00	1	1.60	1.04	5	1.00	1.60	5	2.00	0.00	2	1.50	0.25	2
0.75		0.69	4	0.67	0.89	3	1.00	0.67	3	0.00	0.00	1	0.80	0.56	5	0.40	0.64	5	1.50	0.25	2	2.00	0.00	2
0.75		0.69	4	0.67	0.89	3	1.33	1.56	3	0.00	0.00	1	1.60	1.44	5	0.80	1.36	5	0.00	0.00	2	0.00	0.00	2
1.50		1.25	4	0.67	0.89	3	0.67	0.22	3	0.00	0.00	1	1.20	0.96	5	0.80	1.36	5	0.00	0.00	2	0.00	0.00	2
1.25		1.69	4	0.67	0.89	3	2.00	2.00	3	0.00	0.00	1	2.00	1.60	5	1.20	2.16	5	1.50	2.25	2	1.50	2.25	2
1.75		1.69	4	1.67	1.56	3	2.33	0.22	3	3.00	0.00	1	2.20	0.96	5	1.40	1.04	5	0.50	0.25	2	2.50	0.25	2
0.25		0.19	4	0.67	0.89	3	0.67	0.22	3	0.00	0.00	1	0.60	0.24	5	0.40	0.24	5	0.00	0.00	2	1.00	1.00	2
0.25		0.19	4	0.67	0.89	3	1.00	0.67	3	0.00	0.00	1	1.00	1.20	5	1.00	1.20	5	1.00	1.00	2	1.50	2.25	2

ALCOC

TABLE 1. ALUMINUM CONTACTS AND STATUS

Name	Company	Telephone	Status ¹				Comments
			PL	RT	QC	FAX	
Bill Zimmer	KVS	(717) 271-7700 F-275-6789	X		X	X	Rotary Kiln Mfg
Rick James	Kaiser Alum	(509) 468-1101 F-467-1728	X	X	X	X	Primary Al Mfg
David Emerson	Kaiser Alum	(509) 468-1176	X	X			Primary Al Mfg
Bill Rogers	Consultant	(310) 377-4411	X				
Robert Frick	S. Ca Gas Co.	(310) 803-7423 F(909) 394-4252	X		X	X	Al Accts
Ed Moore	Hauck	(717) 272-3051 F-273-7618	X	X	X	X	Burners Mfg
Anil Lingras	GRI	(312) 349-8363 F-8170	X	X	X	X	Metals Industry
Scott Becker	Air Products	(610) 481-7363 F-7822	X	X	X	X	Metals Acct Merchant Gas
Bruce Bolduc	BOC	(908) 771-1613	X	X	X	X	Merchant Gas
Paul McCarren	Lindberg	(714) 893-6561	X				Heat Treater
Tom Schultz	Surface Combustion	(919) 891-7126 F-7151	X			X	Furnace Mfg
Bill Coppin	Maxon	(317) 284-3304 F-286-8344	X	X	X	X	Burner Mfg.
Pal Crafton	CEC	(404) 422-5100	X				Furnace Mfg.
Pat McKenna	MPH Ind.	(616) 849-2700 F-3021	X	X	X	X	Furnace Mfg.

Notes:

1, Placed call (PL), Call Returned (RT), Questionnaire Completed (QC), Fax Questionnaire (FAX) to respondent

COMBUSTION SYSTEM ALUMINUM STAKEHOLDER QUESTIONNAIRE

Respondent #1

CONTACT:

Name Edward E. Moore Company Hauck Mfg. Co.

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☐ 1. Corporate/General Mgmt.	☐ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☐ 8. Mktg./Sales
☒ 3. R&D/Development	☐ 6. Estimating	☐ 9. Other (Specify)

B. What is the principal activity at this location?

☒ 10. Manufacturing	☒ 13. Central Engineering
☒ 11. Corporate HQ	☒ 14. Research & Development
☐ 12. Division HQ	☐ 15. Other (Specify)

C. What is the principal business

- ☐ 16. Production
☐ 17. Furnace Vendor
☒ 18. Burner Vendor

Primary melter applications

D. Do you manufacture/use floor-fired burners, wall-fired burners or both?

☐ 19. Natural Draft	☒ 20. Forced Draft	☒ 21. Air Preheat

E. Which are emission requirements:

☒ 22. NOx	☐ 23. SOx	☐ 24. Air Toxics
☒ 25. CO	☒ 26. Other (Specify)
THC	

F. Do you manufacture or use:

☐ 27. Rotary Kilns	☐ 28. Reverberatory Furnaces	☐ 29. Boilers
☐ 30. Heat Treating furnaces	☐ 31. Fluid Beds	☒ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☒ 33. Design Performance?	☐ 34. Durability?	☒ 35. Reliability?
☐ 36. Process Temperature?	☒ 37. Fuel Efficiency?	☒ 38. Fuel Flexibility?
☐ 39. Process Control?		

RESEARCH TOPICS/PRIORITY:

Respondent: #1

Combustion Issues	Combustion Technology							
	1	2	3	4	5	6	7	8
	Suspended Circulation	Fluid Bed	Porous Media	Mass Burn	Multiple Burner Arrays	Oxygen, Acoustically Assisted	Radiant Burners	Direct Burners
1. Environmental Mitigation (Combustion Generated)								
1-Noise	0	0	0	0	0	0	3	3
2-Acid Gas (NO _x & SO _x)	0	0	0	0	0	0	3	3
3-Hot House Gas	0	0	0	0	0	0	0	0
4-Air Toxic	0	0	0	0	0	0	0	0
2. High Temperature Furnace Efficiency								
1-Flame Radiation Enhancement	0	0	0	0	0	0	3	0
2-O ₂ Enrichment	0	0	0	0	0	0	0	0
3. Flame/Furnace Compatibility								
1-Heat Release Profiling	0	0	0	0	0	0	2	2
2-Flame Confinement	0	0	0	0	0	0	2	2
3-Flame Safety/Stability	0	0	0	0	0	0	0	0
4. Operations								
1-Ultra High Turndown	0	0	0	0	0	0	2	2
2-Fuel Flexibility	0	0	0	0	0	0	2	2
3-Multipoint Sensors								
a Temperature	0	0	0	0	0	0	0	0
b Composition	0	0	0	0	0	0	0	0
4-Productivity Enhancements	0	0	0	0	0	0	3	3
5. Materials of Construction								
1-Refractories	0	0	0	0	0	0	0	3
2-Insulation Package	0	0	0	0	0	0	0	0
3-High T Alloys	0	0	0	0	0	0	0	0

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

COMBUSTION SYSTEM ALUMINUM STAKEHOLDER QUESTIONNAIRE

Respondent #2

CONTACT:

Name Bill Coppin Company Maxon Corporation

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☒ 1. Corporate/General Mgmt.	☒ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☐ 8. Mktg./Sales
☒ 3. R&D/Development	☐ 6. Estimating	☒ 9. Other (Specify)
Mfg Engr.

B. What is the principal activity at this location?

☒ 10. Manufacturing	☒ 13. Central Engineering
☒ 11. Corporate HQ	☒ 14. Research & Development
☐ 12. Division HQ	☐ 15. Other (Specify)

C. What is the principal business

- ☐ 16. Production
☐ 17. Furnace Vendor
☒ 18. Burner Vendor & Valves

D. Do you manufacture/use floor-fired burners, wall-fired burners or both? *NO*

- ☐ 19. Natural Draft ☐ 20. Forced Draft ☐ 21. Air Preheat

E. Which are emission requirements:

☒ 22. NO _x @ 8% O ₂	☐ 23. SO _x	☐ 24. Air Toxics
☒ 25. CO PPM	☐ 26. Other (Specify)	

F. Do you manufacture or use:

☐ 27. Rotary Kilns	☐ 28. Reverberatory Furnaces	☐ 29. Boilers
☐ 30. Heat Treating furnaces	☐ 31. Fluid Beds	☒ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☒ 33. Design Performance?	☒ 34. Durability?	☒ 35. Reliability?
☐ 36. Process Temperature?	☒ 37. Fuel Efficiency?	☒ 38. Fuel Flexibility?
☐ 39. Process Control?		

RESEARCH TOPICS/PRIORITY:

Respondent: #2

Combustion Issues	Combustion Technology							
	1	2	3	4	5	6	7	8
	Suspended Circulation	Fluid Bed	Porous Media	Mass Burn	Multiple Burner Arrays	Oxygen, Acoustically Assisted	Radiant Burners	Direct Burners
1. Environmental Mitigation (Combustion Generated)								
1-Noise	0	0	0	0	0	1	1	1
2-Acid Gas (NO _x & SO _x)	0	0	0	0	0	3	3	3
3-Hot House Gas	0	0	0	0	0	0	0	0
4-Air Toxic	0	0	0	0	0	2	0	0
2. High Temperature Furnace Efficiency								
1-Flame Radiation Enhancement	0	0	0	0	0	2	0	0
2-O ₂ Enrichment	0	0	0	0	0	0	0	0
3. Flame/Furnace Compatibility								
1-Heat Release Profiling	0	0	0	0	0	2	1	0
2-Flame Confinement	0	0	0	0	0	2	1	0
3-Flame Safety/Stability	0	0	0	0	0	0	2	1
4. Operations								
1-Ultra High Turndown	0	0	0	0	0	0	2	1
2-Fuel Flexibility	0	0	0	0	0	0	1	2
3-Multipoint Sensors								
a Temperature	0	0	0	0	0	0	0	0
b Composition	0	0	0	0	0	0	0	0
4-Productivity Enhancements	0	0	0	0	0	0	0	0
5. Materials of Construction								
1-Refractories	0	0	0	0	0	3	1	2
2-Insulation Package	0	0	0	0	0	0	0	2
3-High T Alloys	0	0	0	0	0	3	2	3

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

COMBUSTION SYSTEM ALUMINUM STAKEHOLDER QUESTIONNAIRE

Respondent #3

CONTACT:

Name J. McKenna or Andy Wisdom Company Linberg/MPH

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☐ 1. Corporate/General Mgmt.	☐ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☒ 8. Mktg./Sales
☐ 3. R&D/Development	☐ 6. Estimating	☐ 9. Other (Specify)

B. What is the principal activity at this location?

☒ 10. Manufacturing	☒ 13. Central Engineering
☐ 11. Corporate HQ	☐ 14. Research & Development
☐ 12. Division HQ	☐ 15. Other (Specify)

C. What is the principal business

☐ 16. Production
☒ 17. Furnace Vendor
☐ 18. Burner Vendor

D. Do you manufacture/use floor-fired burners, wall-fired burners or both?

☐ 19. Natural Draft	☐ 20. Forced Draft	☐ 21. Air Preheat

E. Which are emission requirements:

☒ 22. NOx	☐ 23. SOx	☐ 24. Air Toxics
☐ 25. CO	☐ 26. Other (Specify)	

F. Do you manufacture or use:

☐ 27. Rotary Kilns	☐ 28. Reverberatory Furnaces	☐ 29. Boilers
☒ 30. Heat Treating furnaces	☐ 31. Fluid Beds	☐ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☒ 33. Design Performance?	☒ 34. Durability?	☒ 35. Reliability?
☒ 36. Process Temperature?	☒ 37. Fuel Efficiency?	☐ 38. Fuel Flexibility?
☒ 39. Process Control?		

RESEARCH TOPICS/PRIORITY:

Respondent: #3

Combustion Issues	Combustion Technology							
	1	2	3	4	5	6	7	8
	Suspended Circulation	Fluid Bed	Porous Media	Mass Burn	Multiple Burner Arrays	Oxygen, Acoustically Assisted	Radiant Burners	Direct Burners
1. Environmental Mitigation (Combustion Generated								
1-Noise	0	0	0	3	3	0	0	0
2-Acid Gas (NO _x & SO _x)	0	0	0	3	3	0	0	0
3-Hot House Gas	0	0	0	3	3	0	0	0
4-Air Toxic	0	0	0	3	3	0	0	0
2. High Temperature Furnace Efficiency								
1-Flame Radiation Enhancement	0	0	0	3	3	0	0	0
2-O ₂ Enrichment	0	0	0	3	3	0	0	0
3. Flame/Furnace Compatibility								
1-Heat Release Profiling	0	0	0	3	3	0	0	0
2-Flame Confinement	0	0	0	3	3	0	0	0
3-Flame Safety/Stability	0	0	0	3	3	0	0	0
4. Operations								
1-Ultra High Turndown	0	0	0	3	3	0	0	0
2-Fuel Flexibility	0	0	0	0	0	0	0	0
3-Multipoint Sensors								
a Temperature	0	0	0	3	3	0	0	0
b Composition	0	0	0	3	3	0	0	0
4-Productivity Enhancements	0	0	0	3	3	0	0	0
5. Materials of Construction								
1-Refractories	0	0	0	1	1	0	0	0
2-Insulation Package	0	0	0	1	1	0	0	0
3-High T Alloys	0	0	0	1	1	0	0	0

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

COMBUSTION SYSTEM ALUMINUM STAKEHOLDER QUESTIONNAIRE

Respondent #4

CONTACT:

Name Anil Lingras Company GRI

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☐ 1. Corporate/General Mgmt.	☐ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☐ 8. Mktg./Sales
☒ 3. R&D/Development	☐ 6. Estimating	☒ 9. Other (Specify)
<i>Commercialization</i>

B. What is the principal activity at this location?

☐ 10. Manufacturing	☐ 13. Central Engineering
☒ 11. Corporate HQ	☒ 14. Research & Development <i>Management</i>
☐ 12. Division HQ	☒ 15. Other (Specify)
<i>Commercialization</i>

C. What is the principal business

☐ 16. Production	
☐ 17. Furnace Vendor	See A&B
☐ 18. Burner Vendor	

D. Do you manufacture (*develop*)/use floor-fired burners, wall-fired burners or both?

☒ 19. Natural Draft	☒ 20. Forced Draft	☒ 21. Air Preheat

E. Which are emission requirements:

☒ 22. NOx	☒ 23. SOx	☒ 24. Air Toxics
☒ 25. CO	☒ 26. Other (Specify)
PM10	

F. Do you manufacture (*develop*) or use:

☒ 27. Rotary Kilns	☒ 28. Reverberatory Furnaces	☒ 29. Boilers
☒ 30. Heat Treating furnaces	☒ 31. Fluid Beds	☒ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☒ 33. Design Performance?	☒ 34. Durability?	☒ 35. Reliability?
☒ 36. Process Temperature?	☒ 37. Fuel Efficiency?	☒ 38. Fuel Flexibility?
☒ 39. Process Control?		

RESEARCH TOPICS/PRIORITY:
Respondent: #4

Combustion Issues	Combustion Technology							
	1	2	3	4	5	6	7	8
	Suspended Circulation	Fluid Bed	Porous Media	Mass Burn	Multiple Burner Arrays	Oxygen, Acoustically Assisted	Radiant Burners	Direct Burners
1. Environmental Mitigation (Combustion Generated)								
	2	0	2	0	2	2	0	0
	3	0	3	0	3	3	0	0
	1	0	1	0	1	1	0	0
2. High Temperature Furnace Efficiency								
	2	0	2	0	2	2	0	0
	3	0	3	0	3	3	0	0
	3	0	3	0	3	3	0	0
3. Flame/Furnace Compatibility								
	3	0	3	0	3	3	0	0
	3	0	3	0	3	3	0	0
	3	0	3	0	3	3	0	0
4. Operations								
	2	0	2	0	2	2	0	0
	2	0	2	0	2	2	0	0
	1	0	1	0	1	1	0	0
5. Materials of Construction								
	1	0	3	0	1	1	0	0
	1	0	1	0	1	1	0	0
	1	0	1	0	1	1	0	0

Notes: '1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

COMBUSTION SYSTEM ALUMINUM STAKEHOLDER QUESTIONNAIRE

Respondent #5

CONTACT:

Name Bill Zimmer Company KVS

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☐ 1. Corporate/General Mgmt.	☒ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☐ 8. Mktg./Sales
☐ 3. R&D/Development	☐ 6. Estimating	☐ 9. Other (Specify)

B. What is the principal activity at this location?

☒ 10. Manufacturing	☒ 13. Central Engineering
☐ 11. Corporate HQ	☐ 14. Research & Development
☐ 12. Division HQ	☐ 15. Other (Specify)

C. What is the principal business

- ☐ 16. Production
☒ 17. Furnace Vendor
☒ 18. Burner Vendor

D. Do you manufacture/use floor-fired burners, wall-fired burners or both?

☐ 19. Natural Draft	☒ 20. Forced Draft	☒ 21. Air Preheat

E. Which are emission requirements:

☐ 22. NOx	☐ 23. SOx	☐ 24. Air Toxics
☐ 25. CO <i>Could be problem in NE</i>	☒ 26. Other (Specify)
PM	

F. Do you manufacture or use:

☒ 27. Rotary Kilns	☐ 28. Reverberatory Furnaces	☐ 29. Boilers
☐ 30. Heat Treating furnaces	☐ 31. Fluid Beds	☐ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☒ 33. Design Performance? <i>tonnage</i>	☐ 34. Durability?	☐ 35. Reliability?
☐ 36. Process Temperature?	☒ 37. Fuel Efficiency?	☐ 38. Fuel Flexibility?
☐ 39. Process Control?	<i>Most Important</i>	☒ <i>Other</i>
<i>Mechanical</i>
<i>Warranties</i>
<i>Refractory</i>

RESEARCH TOPICS/PRIORITY:

Respondent: #5

Intense flame, better burner FCT has new gas burner, sooting

O₂ analyzer for high, dustFluxing resistance Al₂O₃ MgO/Cr expensive to dispose of

	Combustion Technology							
	1	2	3	4	5	6	7	8
	Suspended Circulation	Fluid Bed	Porous Media	Mass Burn	Multiple Burner Arrays	Oxygen, Acoustically Assisted	Radiant Burners	Direct Burners
1. Environmental Mitigation (Combustion Generated								
1-Noise	0	0	0	0	0	0	0	0
2-Acid Gas (NO _x & SO _x)	0	0	0	0	0	0	0	0
3-Hot House Gas	0	0	0	0	0	0	0	0
4-Air Toxic	0	0	0	0	0	0	0	0
2. High Temperature Furnace Efficiency								
1-Flame Radiation Enhancement	3	0	0	0	0	0	0	0
2-O ₂ Enrichment	2	0	0	0	0	0	0	0
3. Flame/Furnace Compatibility								
1-Heat Release Profiling	0	0	0	0	0	0	0	0
2-Flame Confinement	0	0	0	0	0	0	0	0
3-Flame Safety/Stability	0	0	0	0	0	0	0	0
4. Operations								
1-Ultra High Turndown	0	0	0	0	0	0	0	0
2-Fuel Flexibility	0	0	0	0	0	0	0	0
3-Multipoint Sensors								
a Temperature	0	0	0	0	0	0	0	0
b Composition	3	0	0	0	0	0	0	0
4-Productivity Enhancements	0	0	0	0	0	0	0	0
5. Materials of Construction								
1-Refractories	3	0	0	0	0	0	0	0
2-Insulation Package	0	0	0	0	0	0	0	0
3-High T Alloys	0	0	0	0	0	0	0	0

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

COMBUSTION SYSTEM ALUMINUM STAKEHOLDER QUESTIONNAIRE

Respondent #6

CONTACT:

Name Bruce Bolduc/Ken Griesham Company BOC Gases

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☐ 1. Corporate/General Mgmt.	☐ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☒ 8. Mktg./Sales
☐ 3. R&D/Development	☐ 6. Estimating	☐ 9. Other (Specify)

B. What is the principal activity at this location?

☐ 10. Manufacturing	☐ 13. Central Engineering
☐ 11. Corporate HQ	☐ 14. Research & Development
☒ 12. Division HQ	☐ 15. Other (Specify)

C. What is the principal business

☐ 16. Production
☐ 17. Furnace Vendor
☒ 18. Burner Vendor

D. Do you manufacture/use floor-fired burners, wall-fired burners or both?

☐ 19. Natural Draft	☐ 20. Forced Draft	☐ 21. Air Preheat

E. Which are emission requirements:

☒ 22. NOx	☒ 23. SOx	☐ 24. Air Toxics
☒ 25. CO	☐ 26. Other (Specify)	

F. Do you manufacture or use:

☐ 27. Rotary Kilns	☐ 28. Reverberatory Furnaces	☐ 29. Boilers
☐ 30. Heat Treating furnaces	☐ 31. Fluid Beds	☒ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☒ 33. Design Performance?	☒ 34. Durability?	☒ 35. Reliability?
☒ 36. Process Temperature?	☒ 37. Fuel Efficiency?	☐ 38. Fuel Flexibility?
☒ 39. Process Control?		

RESEARCH TOPICS/PRIORITY:

Respondent: #6

Combustion Issues	Combustion Technology							
	1	2	3	4	5	6	7	8
	Suspended Circulation	Fluid Bed	Porous Media	Mass Burn	Multiple Burner Arrays	Oxygen, Acoustically Assisted	Radiant Burners	Direct Burners
1. Environmental Mitigation (Combustion Generated								
1-Noise	0	0	0	0	0	0	0	0
2-Acid Gas (NO _x & SO _x)	2	0	2	2	2	2	0	0
3-Hot House Gas	0	0	0	0	0	0	0	0
4-Air Toxic	0	0	0	0	0	0	0	0
2. High Temperature Furnace Efficiency								
1-Flame Radiation Enhancement	2	0	0	2	2	2	0	0
2-O ₂ Enrichment	3	0	3	3	3	3	0	0
3. Flame/Furnace Compatibility								
1-Heat Release Profiling	3	3	3	3	3	3	0	0
2-Flame Confinement	0	0	0	0	0	0	0	0
3-Flame Safety/Stability	2	2	2	2	2	2	0	0
4. Operations								
1-Ultra High Turndown	2	2	0	0	0	0	0	0
2-Fuel Flexibility	2	2	0	0	0	0	0	0
3-Multipoint Sensors								
a Temperature	2	2	0	0	0	0	0	0
b Composition	2	2	0	0	0	0	0	0
4-Productivity Enhancements	2	2	0	0	0	0	0	0
5. Materials of Construction								
1-Refractories	3	3	2	3	3	2	0	0
2-Insulation Package	0	2	0	0	0	0	0	0
3-High T Alloys	0	2	0	0	0	0	0	0

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

COMBUSTION SYSTEM ALUMINUM STAKEHOLDER QUESTIONNAIRE

Respondent #7

CONTACT:

Name Robert Frick Company S. CA Gas Co. Metals Accts

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☐ 1. Corporate/General Mgmt.	☐ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☒ 8. Mktg./Sales
☐ 3. R&D/Development	☐ 6. Estimating	☐ 9. Other (Specify)

B. What is the principal activity at this location?

☐ 10. Manufacturing	☐ 13. Central Engineering
☐ 11. Corporate HQ	☒ 14. Research & Development
☒ 12. Division HQ	☒ 15. Other (Specify)
<i>Research Ctr.</i>

C. What is the principal business

☐ 16. Production	☒ Other
☐ 17. Furnace Vendor	<i>Gas Utility</i>
☐ 18. Burner Vendor	

D. Do you manufacture/use floor-fired burners, wall-fired burners or both?

☐ 19. Natural Draft	☐ 20. Forced Draft	☐ 21. Air Preheat

E. Which are emission requirements:

☒ 22. NOx	☐ 23. SOx	☒ 24. Air Toxics
☒ 25. CO	☒ 26. Other (Specify)
VOC	

F. Do you manufacture or use:

☒ 27. Rotary Kilns	☒ 28. Reverberatory Furnaces	☐ 29. Boilers
☒ 30. Heat Treating furnaces	☒ 31. Fluid Beds	☒ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☒ 33. Design Performance?	☒ 34. Durability?	☒ 35. Reliability?
☒ 36. Process Temperature?	☒ 37. Fuel Efficiency?	☐ 38. Fuel Flexibility?
☒ 39. Process Control?		

RESEARCH TOPICS/PRIORITY:

Respondent: #7

Combustion Issues	Combustion Technology							
	1	2	3	4	5	6	7	8
	Suspended Circulation	Fluid Bed	Porous Media	Mass Burn	Multiple Burner Arrays	Oxygen, Acoustically Assisted	Radiant Burners	Direct Burners
1. Environmental Mitigation (Combustion Generated)								
1-Noise	0	1	0	0	0	0	0	0
2-Acid Gas (NOx & SOx)	0	1	2	2	3	3	0	0
3-Hot House Gas	0	1	0	0	0	0	0	0
4-Air Toxic	0	1	0	0	0	2	0	0
2. High Temperature Furnace Efficiency								
1-Flame Radiation Enhancement	0	1	3	2	3	0	0	0
2-O ₂ Enrichment	0	1	1	3	1	0	0	0
3. Flame/Furnace Compatibility								
1-Heat Release Profiling	0	0	1	3	0	0	0	0
2-Flame Confinement	0	0	1	0	0	0	0	0
3-Flame Safety/Stability	0	0	1	2	0	0	0	0
4. Operations								
1-Ultra High Turndown	0	0	3	0	2	0	0	0
2-Fuel Flexibility	0	0	1	0	1	0	0	0
3-Multipoint Sensors								
a Temperature	0	0	3	0	3	0	0	0
b Composition	0	0	1	0	1	0	0	0
4-Productivity Enhancements	0	0	3	0	3	0	0	0
5. Materials of Construction								
1-Refractories	0	0	2	3	3	0	0	0
2-Insulation Package	0	0	1	0	1	0	0	0
3-High T Alloys	0	0	2	0	3	0	0	0

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

COMBUSTION SYSTEM ALUMINUM STAKEHOLDER QUESTIONNAIRE

Respondent #8

CONTACT:

Name Scott Becker Company Air Products

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☐ 1. Corporate/General Mgmt.	☐ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☐ 8. Mktg./Sales
☒ 3. R&D/Development	☐ 6. Estimating	☐ 9. Other (Specify)

B. What is the principal activity at this location?

☐ 10. Manufacturing	☐ 13. Central Engineering
☐ 11. Corporate HQ	☒ 14. Research & Development
☐ 12. Division HQ	☒ 15. Other (Specify)
Customer Support

C. What is the principal business

☐ 16. Production
☐ 17. Furnace Vendor
☒ 18. Burner Vendor <i>O₂ Supplier</i>

D. Do you manufacture/use floor-fired burners, wall-fired burners or both?

☐ 19. Natural Draft
<i>Oxy Fuel/Job Out</i>	☐ 20. Forced Draft	☐ 21. Air Preheat

E. Which are emission requirements:

☒ 22. NOx	☐ 23. SOx	☐ 24. Air Toxics
☒ 25. CO	☐ 26. Other (Specify)	

F. Do you manufacture or use:

☐ 27. Rotary Kilns	☒ 28. Reverberatory Furnaces	<i>Some dioxin concern</i>
☒ 29. Boilers
☐ 30. Heat Treating furnaces	☐ 31. Fluid Beds	☒ 32. Burners

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☐ 33. Design Performance?	☐ 34. Durability?	☐ 35. Reliability?
☐ 36. Process Temperature?	☒ 37. Fuel Efficiency?	☐ 38. Fuel Flexibility?
☒ 39. Process Control?		

RESEARCH TOPICS/PRIORITY:

Respondent: #8

Refractories: need to develop low density filter based, wetted areas, burner & burner blocks, submerged burners

Combustion Issues	Combustion Technology							
	1	2	3	4	5	6	7	8
	Suspended Circulation	Fluid Bed	Porous Media	Mass Burn	Multiple Burner Arrays	Oxygen, Acoustically Assisted	Radiant Burners	Direct Burners
1. Environmental Mitigation (Combustion Generated)								
1-Noise	0	0	0	0	0	3	0	0
2-Acid Gas (NO _x & SO _x)	0	0	0	0	0	3	0	0
3-Hot House Gas	0	0	0	0	0	1	0	0
4-Air Toxic	0	0	0	0	0	1	0	0
2. High Temperature Furnace Efficiency								
1-Flame Radiation Enhancement	0	2	3	0	0	2	0	0
2-O ₂ Enrichment	0	2	3	0	0	3	0	0
3. Flame/Furnace Compatibility								
1-Heat Release Profiling	0	0	0	0	0	3	0	0
2-Flame Confinement	0	0	0	0	0	1	0	0
3-Flame Safety/Stability	0	0	0	0	0	1	0	0
4. Operations								
1-Ultra High Turndown	0	0	0	0	0	1 to 3 max	0	0
2-Fuel Flexibility	0	0	0	0	0	1	0	0
3-Multipoint Sensors								
a Temperature	0	0	0	0	0	3	0	0
b Composition	0	0	0	0	0	3+	0	0
4-Productivity Enhancements	0	0	0	0	0	3	0	0
5. Materials of Construction								
1-Refractories	0	0	2	0	0	3	0	0
2-Insulation Package	0	0	0	0	0	1	0	0
3-High T Alloys	0	0	0	0	0	0	0	0

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion

COMBUSTION SYSTEM ALUMINUM STAKEHOLDER QUESTIONNAIRE

Respondent #9

CONTACT:

Name Rick James Company Kaiser Al

PROFILE (Check all that apply):

A. Which of the following describes your primary job function?

☐ 1. Corporate/General Mgmt.	☐ 4. Production Engr.	☐ 7. Purchasing
☐ 2. Production/Mfg. Mgmt.	☐ 5. Quality Control	☐ 8. Mktg./Sales
☒ 3. R&D/Development	☐ 6. Estimating	☐ 9. Other (Specify)

B. What is the principal activity at this location?

☒ 10. Manufacturing	☒ 13. Central Engineering
☐ 11. Corporate HQ	☒ 14. Research & Development
☐ 12. Division HQ	☐ 15. Other (Specify)

C. What is the principal business

☒ 16. Production	
☐ 17. Furnace Vendor	<i>Primary Al - Smelting</i>
☐ 18. Burner Vendor	

D. Do you manufacture/use floor-fired burners, wall-fired burners or both?

☐ 19. Natural Draft	☐ 20. Forced Draft	☐ 21. Air Preheat
<i>Holding Furnaces</i>		

E. Which are emission requirements:

☐ 22. NOx	☐ 23. SOx	☐ 24. Air Toxics
☒ 25. CO	☐ 26. Other (Specify)	
<i>Fluoride (bath) dry scrub</i>		

F. Do you manufacture or use:

☐ 27. Rotary Kilns	☒ 28. Reverberatory Furnaces	☐ 29. Boilers
☐ 30. Heat Treating furnaces	☐ 31. Fluid Beds	☐ 32. Burners
<i>Holding Furnaces</i>		<i>Steam Plant</i>

G. What are your major concerns regarding equipment operation (capacity and heat release)?

☐ 33. Design Performance?	☐ 34. Durability?	☒ 35. Reliability?
☐ 36. Process Temperature?	☐ 37. Fuel Efficiency?	☐ 38. Fuel Flexibility?
☒ 39. Process Control?		

RESEARCH TOPICS/PRIORITY:

Respondent: #9

Indirect heating, through permeable flue which collect offgas progressively staged firing around circumference water inert and burner staging used to develop radiating flames furnaces 12 to 15' deep, six pits to battery

Combustion Issues	Combustion Technology							
	1	2	3	4	5	6	7	8
	Suspended Circulation	Fluid Bed	Porous Media	Mass Burn	Multiple Burner Arrays	Oxygen, Acoustically Assisted	Radiant Burners	Direct Burners
1. Environmental Mitigation (Combustion Generated								
1-Noise	0	0	0	0	0	0	0	0
2-Acid Gas (NOx & SOx)	0	0	0	0	2	0	0	0
3-Hot House Gas (CO ₂)	0	0	0	0	2	0	0	0
4-Air Toxic (Fl and CO)	0	0	0	0	3	0	0	0
2. High Temperature Furnace Efficiency								
1-Flame Radiation Enhancement	0	0	0	0	3	0	0	0
2-O ₂ Enrichment	0	0	0	0	0	0	0	0
3. Flame/Furnace Compatibility								
1-Heat Release Profiling	0	0	0	0	2	0	0	0
2-Flame Confinement	0	0	0	0	1	0	0	0
3-Flame Safety/Stability	0	0	0	0	1	0	0	0
4. Operations								
1-Ultra High Turndown	0	0	0	0	1	0	0	0
2-Fuel Flexibility	0	0	0	0	1	0	0	0
3-Multipoint Sensors								
a Temperature	0	0	0	0	1	0	0	0
b Composition	0	0	0	0	1	0	0	0
4-Productivity Enhancements	0	0	0	0	1	0	0	0
5. Materials of Construction								
1-Refractories	0	0	0	0	3	0	0	0
2-Insulation Package	0	0	0	0	0	0	0	0
3-High T Alloys	0	0	0	0	0	0	0	0

Notes: 1 = low priority, 2 = medium priority, 3 = high priority, 0 = no opinion