Report on
the Process Heating
Advanced Materials Forum

Sponsored by

U. S. Department of Energy
Office of Energy Efficiency and Renewable Energy
and
Industrial Heating Equipment Association

Oak Ridge National Laboratory
Oak Ridge, Tennessee

February 5–6, 2003

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***Note**: Because of their large size, the presentations and research briefs are included on the CD-ROM rather than in this printed version of the report.*

Process Heating Advanced Materials Forum

Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee

February 5–6, 2003

Dear Colleague:

On behalf of The Department of Energy's Office of Energy Efficiency and Renewable Energy (DOE-EERE) and the Industrial Heating Equipment Association (IHEA), we welcome you to the Process Heating Advanced Materials Forum.

The forum agenda focuses on use of advanced materials including high-temperature alloys, ceramics and composites, and refractories and insulation to achieve greater energy efficiency, as well as to lower operating costs, increase reliability and productivity, and improve safety.

The forum attendees include representatives from the process heating industry, the associated user community, and scientists and researchers from DOE national laboratories. The agenda has been structured to allow for both formal and informal opportunities to exchange information. We encourage you to discuss and share information on your specific needs, recent research and development results, and the future research needs of the process heating industry in the area of advanced materials.

We hope that your participation in the forum activities and your visit to the Oak Ridge National Laboratory will be productive and enjoyable.

Ramesh Jain
Office of Energy Efficiency
and Renewable Energy
U.S. Department of Energy

Mario Ciampini,
President
Industrial Heating Equipment Association

Executive Summary

An advanced materials forum was held at Oak Ridge National Laboratory (ORNL) February 5–6, 2003, under the sponsorship of the Department of Energy's Office of Energy Efficiency and Renewable Energy (DOE-EERE) and the Industrial Heating Equipment Association (IHEA).

This summary report was prepared under the guidance of the Process Heating Advanced Materials Subcommittee. It identifies areas of research and development that demonstrate particular promise for the process heating industry and comments on a strategy for DOE and the national laboratories to work with the industry to proceed with the research and development (R&D) that meet future needs of the industry.

The forum was attended by 56 representative end users from Industries of the Future, equipment suppliers, and research scientists and engineers from DOE national Laboratories. The purpose of the forum was to provide an environment in which representatives from the process heating industry, the associated user community, and scientists and researchers from the national laboratories and elsewhere can share information on recent R&D and discuss the future research needs of the process heating industry in the area of advanced materials.

The forum agenda (Appendix A) was structured to allow for both formal and informal opportunities to exchange information. The topics of discussion included use of advanced materials such as high-temperature alloys, advanced ceramics, and refractories and insulation in process heating equipment. Representatives from DOE-EERE and IHEA, as well as members of industry and scientists from the national laboratories, made presentations on various areas of materials technology and their application to process heating systems. The agenda included a tour of the Materials Research Laboratories at ORNL.

Three round table discussions involving representatives from industry, materials suppliers, and the national laboratories addressed the future needs of the industry and possible areas of research and developments. The three areas of focus were (1) High-Temperature Alloys; (2) Insulation and Refractories, and (3) Advanced Ceramics. These sessions identified the following research needs that could help U.S. industries make significant improvements in energy efficiency and related areas such as productivity, waste reduction, emission reduction, safety, and production cost reduction.

The recommendations and research needs identified in the round table discussions for the three areas follow:

1. High-Temperature Alloys

- Creep rupture property improvements.
- Extension of temperature limits to 2300°F+
- Better life prediction/monitoring
- Enhance resistance to aggressive environments

2. Refractories and Insulation

- Modeling of phases and reactions and corrosion modeling
- New refractory application and mounting methods
- Advanced coatings for current refractories
- The use of bonded-spinel refractories, or very pure silica refractories coated with spinel or mullite for use in furnace crowns
- Development and application of preformed refractory shapes
- Utilization of low-thermal-conductivity materials

3. Advanced Ceramics

- Advanced ceramics to eliminate or reduce erosion of material used in handling of liquid or solid fuels.
- Oxidation and coking resistance ceramics or coatings on alloys for burner parts (i.e., flame stabilizers)
- Special coatings with customize spectral characteristics to enhance radiation heat transfer in high-temperature furnaces using rare earth oxides or other ceramic coatings for refractories.
- Advanced ceramic materials for tubular (or other shapes) heat exchangers and associated joining technologies to recover heat from high-temperature corrosive stack gases.
- Ceramic materials for catalyst base to avoid poisoning of catalyst.
- New ceramic materials for sensors and probes that can survive in stack gases containing high-temperature, highly corrosive gases.

Details for each of the round table sessions are given in this report.

The information obtained from this forum will be discussed by the advanced materials subcommittee and would be used for defining potential R&D and other activities that could meet he industry requirements.

Introduction

Almost every product that we purchase, use, and consume in daily life requires process heating. Process heating accounts for nearly 17% of all U.S. industrial energy use. Improving the efficient operation of process heating systems through use of advanced materials such as high-temperature alloys, ceramics and composites, and refractories and insulation will contribute to greater energy efficiency. It should also help lower operating costs, increase reliability and productivity, and improve safety. For these reasons, DOE-EERE and IHEA jointly sponsored the Process Heating Advanced Materials Forum held at ORNL February 5–6, 2003.

The forum was attended by 56 representative end users from Industries of the Future, equipment suppliers, and research scientists and engineers from DOE national laboratories. The purpose of the forum was to provide an environment in which representatives from the process heating industry, the associated user community, and scientists and researchers from our national laboratories and elsewhere can share information on recent R&D and discuss the future research needs of the process heating industry in the area of advanced materials. The forum provided an opportunity for the attendees to visit R&D facilities at ORNL and to discuss various means available to pursue collaborative R&D and other activities at ORNL.

The forum agenda (Appendix A) was structured to allow for both formal and informal opportunities to exchange information.

Prior to this meeting, a white paper (matrix) was prepared to describe materials needs for process heating equipment and components. This information was sent to DOE national laboratories to help them identify research areas that could serve needs of the industry and could be presented at the forum.

In response to this request, several national laboratories submitted abstracts to the Process Heating Advanced Materials Subcommittee. The subcommittee selected five of these proposed papers for presentation at the forum.

The forum included presentations on the current status of the process heating industry, status of the technology for three major areas (high-temperature alloys, refractories and insulation, and advanced ceramics) of materials used in process heating, new developments in materials at the national laboratories, and the industry-government collaboration opportunities. The attendees visited various laboratories performing research and application-related activities at ORNL.

Following the presentations and laboratory visit, forum participants broke out into three separate sessions, one for each of the topics of interest mentioned above, to discuss the industry needs and future R&D activities that could meet the industry needs.

The following sections provide summaries of the presentations, details of discussions at each of the three round table meetings, and additional remarks on methods of collaborative activities between industry and DOE national laboratories. Additional information on the forum is provided in the end of the report: Appendix B: Speaker/Presenter Information, Appendix C: List of Forum Attendees, Appendix D: Research Briefs, and Appendex E: Forum Presentations.

The forum arrangements were made by ORNL with help from Mr. Peter Angelini and Ms. Gwen Sims. The Process Heating Advanced Materials Subcommittee would like to express their sincere thanks for their efforts.

Materials Requirements for Process Heating Industry

Prior to the forum the subcommittee compiled a list of materials needs for the industrial heating systems. The process included three steps: (1) defining material selection criteria, (2) identifying areas for improvement, and (3) identifying components or subsystems that require one or more of the considerations identified in step 1.

Define Material Selection Criteria

The first step was to define specific considerations that are used in selection of materials used in furnaces. The material selection criteria that were identified are numbered in the following list. Numbers associated with the criteria are also used under the heading "Major criteria for material section" in Table 1.

Material selection criteria

1. Strength at operating temperature – tensile, compressive, and shear
2. Creep at operating temperature
3. Thermal fatigue – cycling
4. Thermal fatigue – cycling
5. Oxidation resistance
6. Corrosion resistance – halogens (cholorine, fluorine, etc.), sulfur and acidic environment
7. Reducing atmosphere resistance
8. Liquid metal – steam resistance
9. Solid-metal reactions
10. Other – specify

Identify Specific Areas For Improvement

The second step was to identify specific areas for improvement that would improve performance of the process heating equipment and components. The areas identified follow:

Areas for improvement

- Longer life for heating elements, radiant tubes, etc.
- Weight reduction for trays, fixtures, baskets, etc.
- Increased life of insulation and refractory for combustion chamber, furnace walls, and burner blocks.
- High-strength, high-temperature materials for recuperators, regenerators, heat exchangers, etc.
- Reduction or elimination of water – air cooling through use of improved material for load support, rails, rollers, etc. (nonmetallic – ceramics)
- Materials for high-temperature fans (metallic, ceramics or composite material)
- Long-life sensor and protection materials
- Increased life of heater tubes, heat exchanger elements (matrix), etc., for high- and low-temperature heat recovery systems.

Identify Components or Subsystems Requiring Considerations in Step 1.

The third step involved identifying components or subsystems such as burners, fans, and material-handling systems that require one or more of the considerations identified in step 1. The list is provided in Table 1. The table divides the materials in three general categories: high-temperature alloys, refractories and insulation, and advanced ceramics including composite materials.

This information was sent to the DOE national laboratories with active programs in materials area through the Laboratory Coordination Council. Laboratories includes ORNL, Lawrence Berkley National Laboratory (LBNL), Argon National Laboratory (ANL), Albany Research Center (ARC), and Sandia National Laboratory.

Twelve abstracts, listed in Appendix D, were received. They were reviewed by the subcommittee consisting of the following seven members:

1. Mario Ciampini, President, IHEA.
2. Jason Wilson, Technical Marketing Manager, Rolled Alloys, Inc.
3. Robert Licht, Manager Government Programs Group, Saint-Gobain Ceramics & Plastics, Inc., and Chairman, USACA
4. Gary Deren, Unifrax Corporation
5. Peter Angelini, ORNL
6. Arvind Thekdi. President, E3M, Inc.
7. Russ Mosher, President, Mosher and Associates

Five abstracts were selected for presentation at the forum. The selection was made based on the research topic and its match with the industry requirements, it potential for commercial application, and the timeframe for availability of the technology. A list of the selected papers is provided in the next section.

Table 1. Advanced materials requirement in process heating systems

Application area	Criteria for material selection[a]	Metals/high-temperature alloys	Engineered materials		Composites
			Refractories/ insulation	Ceramics/ nonmetallic	
Heat generation					
Burners/combustors - normal	1,2,3,4,5,6,7	Nozzles	Blocks	Nozzles	Nozzles
Burners – IR and panel	1,2,3,4,5	Matrix for IR burners	Matrix for IR burners	Matrix for IR burners	Matrix for IR burners
Radiant tubes	1,2,3,4,5,7,9	Tube		Tube	Tube
Immersion tubes	1,2,3,4,5,8	Tube		Tube	Tube
Combustion chamber	1,3,4,5,6,9		Exposed surfaces		
Heat transfer surfaces	1,2,3,4,5,6,7,8,9	Surface coating		Surface coatings	
Electrical heating elements	1,2,3,4,5,6,7	Elements		Elements	Elements
Mounting system	1,2,3,4,5,7		Mounting panel (MP)	Elements and MP	

Table 1. Advanced materials requirement in process heating systems (cont.)

Application area	Criteria for material selection[a]	Metals/high-temperature alloys	Engineered materials: Refractories/ insulation	Engineered materials: Ceramics/ nonmetallic	Composites
Heat transfer					
Furnaces, heaters, etc.	1,2,3,4,5,6, 13	Nozzles Fans Radiation schields Baffles Retorts		Nozzles Fans Radiation schields Baffles	Nozzles Fans Radiation schields Baffles
Heat containment					
Furnances, heaters, etc.			Furnace walls, crowns	Furnace walls, crowns	Nozzles
Water/air cooling		Matrix for IR burners	Matrix for IR burners	Matrix for IR burners	Matrix for IR burners
Waste heat recovery					
Recuperators		Tubes / separators Fins / extended surfaces		Tubes / separators Fins / extended surfaces	Tubes / separators Fins / extended surfaces
Regenerators		Heat transfer (HT) matrix	HT matrix	HT matrix	HT matrix
Heat transfer surfaces		Surface coatings		Surface coatings	
Emission control					
Scrubbers		Corrosion resistant packing, etc.		Corrosion resistant packing, etc.	Corrosion resistant packing, etc.
SCRs for NO_x control		Substrate Coatings		Substrate Coatings	
			Refractories/ insulation	**Ceramics/ nonmetallic**	
Material handling					
Load support		Trays, fixtures, etc.		Trays, fixtures, etc.	Trays, fixtures, etc.
Transfer		Rails, belts, pushers, flights, etc.		Rails, belts, pushers, flights, etc.	Rails, belts, pushers, flights, etc.
Rolls, rollers, etc.		Rolls, rollers, etc. Coatings		Rolls, rollers, etc. Coatings	

Table 1. Advanced materials requirement in process heating systems (cont.)

Application area	Criteria for material selection[a]	Metals/high-temperature alloys	Engineered materials		Composites
			Refractories/ insulation	Ceramics/ nonmetallic	
Material handling					
Waste containment		Crucibles, holders, etc.	Crucibles, holders, etc.	Crucibles, holders, etc.	
Sensors and controls					
		Protection tubes Probes		Protection tubes Probes	

[a] See the section titled "Define Material Selection Criteria" for a numbered list of criteria.

The Forum Presentations

The forum agenda was structured to allow for both formal and informal opportunities to exchange information. It was intended to give an overview of the materials program supported by the DOE–EERE and the status of the process heating industry and its general needs, followed by a review of the current status of materials used by the industry. The review was divided into the three categories of the materials mentioned earlier.

The speakers and their presentations are listed below.

1. Advanced Materials Programs/DOE/National Labs. – Dr. Sara Dillich, DOE-OIT
2. A Look at the U. S. Process Heating Industry: Today and Tomorrow – Mr. Mario Ciampini, President, IHEA. (presented by Arvind Thekdi, President E3M, Inc.)
3. High-Temperature Alloys – Jason Wilson, Technical Marketing Manager, Rolled Alloys, Inc
4. Advanced Ceramics – Robert Licht, Manager Government Programs Group, Saint-Gobain Ceramics & Plastics, Inc. and Chairman USACA
5. Refractories and Insulation for the Heating Equipment Industry – Gary Deren, Unifrax Corporation

Following papers, selected by the subcommittee, were presented by the DOE national laboratories.

6. High-Temperature Alloys – Vinod Sikka, ORNL
7. Low-Cost Ceramic Composite Fan Materials – Ronald Ott, ORNL
8. Monolithic and Surface Modified Ceramics – Andrew Wereszczak, ORNL
9. Advanced Nonporous Composite Materials for Industrial Heat Applications – Michael Ayers, LBNL
10. Advanced Refractory Materials Research Program – Cindy Dogan, ARC
11. Materials Degradation Processes in Elevated-Temperature Environments Relevant to Process Heating – Peter Tortorelli, ORNL

Additional presentations included:

12. Welcome and Introduction to ORNL - Marilyn Brown, Director, EERE Program, ORNL
13. Working with DOE National Laboratories – Lou Dunlap, Deputy Director Technology Transfer and Economic Development
14. Dinner Presentation: Superconductivity: Evolution of a Research and Development Project – Donald M. Kroeger, ORNL

All of these presentations, with exception of the dinner presentation, are listed in Appendix E. Because of their large size, the actual presentations are provided on the CD-ROM.

Round Table Break-Out Sessions Reports

Three breakout sessions were held during the forum. The three topics were (1) High-Temperature Alloys, (2) Insulation and Refractories, and (3) Advanced Ceramics.

The following reports prepared by the session chairpersons describe the summary of discussion and R&D program recommendations suggested by the session attendees.

High-Temperature Alloys

Session Chair: Jason Wilson - Rolled Alloys

Participants

Jason Wilson	Rolled Alloys
Ahmed Abada	Steel Tech Ltd.
Russ Mosher	R.N. Mosher & Associates
Bill Scott	ASM International
Malcomb Gordge	Spirax Sarco, Inc.
Vinod Sikka	ORNL
David Collier	Eclipse Combustion
Dennis Bickford	Westinghouse Savannah River
Rick Sisson	Worcester Polytechnic Institute
Don Voke	Duraloy Technologies
Bruce Kelly	Sandia National Laboratory
Richard Alstott	Bloom Engineering
Jim McLaughlin	ExxonMobil Research & Engineering
Phil Anderson	ExxonMobil Research & Engineering

Stated meeting objectives

- Provide interaction between the user of heat-resistant metals (i.e., the Process Heating Industry) and the R&D community (i.e., ceramic suppliers, national laboratories, and universities).
- Identify future materials needs to improve performance of process heating equipment systems.

Overview and approach

The group was composed of a good cross section of heat-resistant alloy suppliers: Wrought & Castings (3), national laboratories (2), universities (1), trade associations (1), equipment suppliers [burners, boilers) (3)], end use industries [(refining, nuclear (2)], and consulting (1).

Each participant was asked to volunteer two life-limiting issues related to heat-resistant metallics.

Heat-Resistant Metallic Areas for Improvement

- Creep rupture properties
- Toughness properties (long-term aging)
- Scaling resistance/oxidation resistance
- Resistance to halogens/salts

- Extension of temperature limits from 2200°F by 100-200°F
- Thermal shock resistance
- Improved tools for materials selection
- Ductility – castings
- Life prediction/assessment tools or software
- Sulfidation resistance

A discussion ensued to determine which areas were felt to be of greatest importance. Four items were agreed upon.

I. Creep rupture property improvements
II. Extension of temperature limits beyond 2200°F by 100 to 200°F.
III. Life prediction/assessment tools or software
IV. Aggressive environment resistance (sulfidation)

Potential areas of study for these four items were then discussed.

I. Creep rupture property improvements

    A. Nanophase strengthening
        1. Inexpensive means of strength improvement capable of use in traditionally melted alloys if better understood.

    B. Greater data generation
        1. More accurate design capabilities for long-term service.
        2. Computational software for greater long term modeling of high-temperature alloys.

II. Extension of temperature limits to 2300°F+
    A. Improved intermetallics usability
        1. Joining methods
        2. Wrought products
    B. Oxide dispersion alloys
        1. Fe-Cr-Al type offer high melting points up to 2600°F
            a. Lack ability for joining by conventional arc welding
            b. Need production improvements to reduce costs

III. Better Life Prediction/Monitoring

    A. Collaboration with sensors group to apply newer inspection technologies to high-temperature components to assess the materials condition and predict remaining life.
    B. Better data collection for specific types of units (boilers, ethylene furnaces, crude heaters, recuperators)
    C. Better modeling tools
    D. Integrate the above 3 items to create a better overall picture of what is occurring in these units.

IV. Enhance resistance to Aggressive Environments
    A. Surface treatments or Coatings suitable for high temperatures

Summary

A recurring theme in the discussion was the need for better data collection and compilation of this information for engineers to use for better design and, once in service, greater life prediction. The ability to better use existing information to select the proper alloy initially and then to design with these alloys more accurately seems to be a first step while newer alloy technologies are maturing.

Insulation and Refractories

Session Chairs: Peter Angelini and James Hemrick, ORNL

Participants

Peter Angelini, ORNL (angelinip@ornl.gov)
Michael Ayers, Lawrence Berkeley National Laboratory (LBNL) (mrayers@inreach.com)
Michael Binni, Bloom Engineering (mbinni@bloomeng.com)
Gary Deren, Unifrax Corporation (gderen@unifrax.com)
Sara Dillich, U.S. DOE (sara.dillich@ee.doe.gov)
Cynthia Dogan, Argonne National Laboratory (dogan@alrc.doe.gov)
Donald Foster, LBNL (DGFoster@lbl.gov)
Wayne Hayden, MMPaCT (HWHayden@cs.com)
James Hemrick, ORNL (hemrickjg@ornl.gov)
Edward Kubel, Industrial Heating Magazine (edkubel@industrialheating.com)
Anthony Martocci, Bethlehem Steel Corporation (martocci@bethsteel.com)
Jim Shell, Shell Glass Consulting, Inc. (jshell@columbus.rr.com)
Carsten Weinhold, Schott Glass Technologies (carsten.weinhold@us.schott.com)

Current Areas and Issues of Refractory Use

Several industries where identified where improved refractories can result in improved processing and energy efficiencies. These are highlighted below.

Steel

About 20–40% of the refractories found in the steel industry are used in ladles for both integrated mills and minimills. This use accounts for the single largest application of refractories in the steel industry. Large amounts of energy are required to preheat ladles prior to their being filled with molten metal; otherwise, the refractories may fracture from mechanical and thermal shock and separate from their anchoring systems. Currently, the heating times for ladles are high, and heating efficiency is low. Additionally, ladles are often held at operating temperature for long periods of time (8–12 hours) before use to avoid reheating. Energy is required to hold the ladles at temperature, and heat losses from the refractory during this time can be substantial. Preformed refractory systems may reduce the heating time and improve thermal efficiency substantially, which could also lead to lower hold times and losses for heated ladles.

Another area where refractories are used in the steel industry is as protective coverings on metallic skids. These refractories must provide both mechanical and thermal protection to the metallic skid material beneath it. Currently, most skids are water-cooled, a process that leads to substantial energy losses. Additionally, up to 30% breakage of the refractory due to abrasion, and erosion occurs in less than 2 years of service life.

Also, blast furnaces use large amounts of refractories. The refractories in this case are generally bricks. These furnaces can cost up to $100 million and require extensive repairs every 10 to 12 years to extend the operational lifetime of the units. Additionally, maintenance issues must be addressed during the operational period. Some of the current major refractory issues include (1) use of gunnable or castable refractories in place of bricks, (2) mounting designs for the refractories used, (2) requirements for improved thermal insulation, (4) lack of understanding of the corrosion and chemical reactions of the refractories in that environment, (5) lack of sensors for determining the thickness and recession of the refractories during service, and (6) energy losses associated with the thinning of refractories.

Glass

Crown materials for glass melting furnaces are also an area of great interest. Improvements in these materials could lead to higher operating temperatures (through conversion to oxy-fuel firing), better thermal efficiency, and longer refractory service lives in these types of furnaces. Improved insulation aspects of crowns are especially needed with respect to the use of higher conductivity fused cast refractories versus the use of traditional lower conductivity pressed silica based refractories. In some cases water-cooling is needed on the cold face of the refractories to cool them as they are corroded, in order to maintain integrity of furnaces. This can lead to substantial energy losses. Mounting designs of refractories are also critical to successful longevity of the refractories.

Molten metal line corrosion in sidewall refractories is another area of concern. Such corrosion can lead to inclusions in the glass due to particles of refractories in the bath and can severely impact overall productivity and yield. For example, the current yield of some types of glass is only 25%. Therefore, improved yield could result in direct energy savings. Additionally, metal line corrosion can lead to reduced thermal efficiency due to the refractory recession. There is interest in addressing these issues by applying hot gunning techniques for the repair and maintenance of furnaces during service.

Aluminum

In the aluminum industry there are also various areas where improved refractories lead to significant energy and production benefits. One of these is in the Hall-Heroult process where cells are designed with a steel shell lined with castable refractory, porous insulating refractory, less-porous semi-insulating refractory, and finally firebrick. The sides of the cell are designed with less insulation to promote heat loss through the walls resulting in a lower wall temperature that causes electrolyte in contact with the wall to solidify forming a “frozen ledge” which protects the walls of the cell from the corrosive molten cryolite. Yet, it is thought that cell efficiency could be increased by developing a sidewall that would allow direct contact with the molten cryolite bath eliminating the “frozen ledge.” This development could result in less heat loss from the cells along with reduced corrosion of the refractories.

A second area of interest is in the use of fibrous or foam linings in areas such as doors and linings in aluminum reheat furnaces. These materials provide excellent thermal insulation but do not resist erosion and corrosion well. They are also currently limited in their use by an upper service temperature of 980–1090^{o}C.

Identified Research and Development Topics

Basically, the discussion identified two primary areas for refractory research and development: (1) preformed shapes and (2) low-thermal-conductivity materials.

Development and Application of Preformed Shapes

Currently refractory preformed shapes, procured from the refractory manufacturers, are finding limited application in areas of the steel industry as protective coverings on skid rails, pipes, and risers. Some preformed shapes are also used in high-wear regions on the bottom of ladles. However, various issues can arise relative to the premanufactured nature of these materials when they are implemented in process heating systems. In addition to the research and development of preformed shaped refractories, it is imperative to address various approaches on how to implement these new types of refractories in industrial systems.

Use of preform shapes, compared to the use of castable or gunnable materials, can lead to the following improvements:

1. Less downtime as compared to castables when used in furnaces and easier installation. Additionally refractory dry out cycle is not needed.

2. Improved corrosion resistance and mechanical performance (i.e., coverage is maintained for a longer period of time).
3. Decreased breakage of the refractory due to improved thermal shock and system design.
4. Improved productivity from their being easier to utilize in a larger number of applications.
5. Enables the use of insulating refractories to back up the preformed refractory, thus leading to improved energy efficiencies.
6. Improved energy efficiency due to shorter preheat times and lower energy used to maintain them at temperature due to improved thermal resistance.
7. Improved quality control of the refractory.
8. Improved damage control of refractory components.

Utilization of Low-Thermal-Conductivity Materials

These materials include fibers and porous materials, along with low-density materials coupled with higher density refractory materials on their exposed surface.

As highlighted above, one of the major issues with these types of materials is chemical attack. In reheat burners for example, the fibers are not stable near the flame environment, thus leading to high corrosion rates. Similarly when the fibers corrode, the burner can also be compromised, leading to unexpected shutdowns. One of the great advantages of fibrous materials, however, is their inherently low thermal conductivity. This property leads to shorter heat up times to furnace operating temperatures and, due to superior thermal efficiency, to less energy use once at operating temperature. For example, the use of fibrous insulation can decrease the heat up schedule of a steel reheat furnace by nearly 6 hours. The major issue, however, is that the fibers have a service temperature of less than ~1900^{o}C and a service life of only about 5 days under the specific temperature and operating environment in the furnaces.

Therefore, a refractory systems approach is needed where a fibrous or porous refractory material is teamed with a dense surface refractory layer on its exposed surface. At the present time, efforts related to increasing the upper use temperature of fibrous or low-thermal-conductivity materials are required. Through this approach, the insulating properties of the fibrous (or porous) materials are exploited while the dense surface layer can provide chemical, thermal, and mechanical protection from the detrimental furnace environment. These systems could then be applied to many of the industries and problems highlighted above. Implementation of these types of systems is expected to lead to increased furnace efficiency and productivity that could result in better thermal efficiency and the use of fewer furnaces.

Future Needs

1. Modeling of phases and reactions and corrosion modeling, as well as sensors for monitoring of refractory wall condition and thickness and recession.
2. New refractory application and mounting methods, including the preformed shape approach, to enable easier installation, greater wear resistance, and longer refractory life.
3. Advanced coatings for current refractories. These may be possible through new corrosion resistant material coatings, surface modified refractories incorporating the properties of fiberous/foam materials with those of dense corrosion resistant materials, or glass-coated refractories for use in metal line applications. The use of bonded composites or refractory systems will have significant benefits because these types of materials could have lower thermal conductivity, higher corrosion resistance, and similar thermal insulating properties relative to monolithic silica refractories. Another area which needs further investigation is in situ reaction processed refractories-.
4. The use of bonded spinel refractories, or very pure silica refractories coated with spinel or mullite for use in furnace crowns. This could especially have significant benefits in flat glass manufacturing. These types of materials may also have a cost benefit over fused cast refractories such as alumina and spinel.

5. Focused efforts are needed in the areas of
    a. Development and Application of Preformed Refractory Shapes
    b. Utilization of Low Thermal Conductivity Materials

Advanced Ceramics

Session Chair: Bob Licht, - Saint-Gobain Ceramics & Plastics, Inc.

Participants

Bob Licht, Meeting Chairman	Saint-Gobain Ceramics & Plastics, Inc.
Arvind Thekdi, Co-Chair	E3M, Inc.
Beth Armstrong	ORNL
Andy Wereszczak	ORNL
Roberto Ruiz	John Zink Co.
Ramesh Jain	DOE
Sam Arcara	Honeywell
Ronald Ott	ORNL
Andy MacQueen	Ceradyne, Inc.
Biljana Mikijelj	Ceradyne, Inc.

Stated Meeting Objectives

The objectives of this meeting were (1) to provide interaction between the users of advanced ceramics (i.e., the process heating industry) and the R&D community (i.e., ceramic suppliers, national laboratories, and universities) and (2) to identify future materials needs to improve performance of process heating equipment systems.

Overview and Approach

As shown by the list of attendees, there was a good mix of representatives: three from ceramic suppliers, three from the process heating industry and four from government/national labs. The group

- Reviewed the nine major **Segments of the Process Heating Industry**. The three representatives from the process heating industry were in agreement as to the top three priority segments to address in the time allowed: fluid heating; melting; and heat treating.
- Listed the six **Process Heating Elements** common to all segments, with the 7^{th}, Materials, common to all the other elements.
- Reviewed **Critical Materials Problems and Potential Advanced Ceramics Solutions** in the highest priority segment (fluid heating) by the major process elements.
- Developed a **Summary and Next Steps**.

Notes and Results

Segments of the Process Heating Industry

A.	Fluid Heating (g, v, l) (chemical and petroleum)	Priority #1
B.	Melting	Priority #2
C.	Sintering	
D.	Heat Treating	Priority #3
E.	Preheating (e.g., for metal forging)	
F.	Calcining	
G.	Boiling/Evaporating (phase change, e.g. boilers)	
H.	Drying	
I.	Curing	

Process Heating Elements, (common to all Segments)

1. Heat Generation
2. Heat Transfer
3. Heat Containment
4. Heat Recovery
5. Environmental
6. Sensors and Control

} 7. Materials (common to all)

Critical Materials Problems and Potential Advanced Ceramics Solutions

Segment A: Fluid Heating
Process Element 1. Heat Generation

Need: a. Flame stabilizer for burner; need oxidation resistance and longer life.
Current material: high-temperature alloy, large part 18–20 in. (Roberto Ruiz drew a schematic of this part.)
Possible solutions: ceramic, CMC, ceramic coating on alloy. First step is to analyze properties and failure probability to determine materials solution. The advanced ceramic part could be made in segments to reduce cost, but this approach requires design collaboration.

Need: b. Nozzle–coking resistance, high-temperature oxidation, ceramic – metal fastening.
Current material: high-temperature alloy

Need: c. Erosion of material when liquid or solid fuel.
Possible solution: advanced ceramics.

Process Element 2. Heat Transfer

Need: a. Enhanced heat transfer, prevent heat escape, increase reflection.
Current materials: refractories.
Possible solutions: rare earth oxides, coatings on refractories, tailor spectral characteristics.

Process Element 3. Heat Containment
Current materials: refractories (no advanced ceramic solutions discussed).

Process Element 4. Heat Recovery (e.g. heat exchangers)

Need: a. High-temperature corrosion of alloys, industry specific.
Possible solution: advanced ceramics.

Need: b. Higher temperature capability
Possible solution: advanced ceramic tubes. Requires sealing technology.
Unknown variable for ceramics in heat recovery: Viability (cost-effectiveness dependent on energy cost.

Process Element 5. Environmental Problems

Need: a. Solve problem of the poisoning of catalyst.
Current material is not a ceramic.

Need: b. Reduce high-temperature corrosion of construction materials.
Current materials: metal, very large components.
Possible solutions: ceramics or refractories. Size limitations.

Need: c. High-temperature sensors for NOx. Improved corrosion/high-temperature capability.
Possible solutions: New ceramic materials to survive in stack.

Summary and Next Steps

The brainstorming was very effective, but we could have used more time. We covered only one of the nine process heating segments, fluid heating, which was the highest priority. It was believed that other segments would have similar material needs (e.g., high-temperature capability and corrosion resistance) and similar advanced ceramics solutions.

There is a benefit to teaming among the process heating industry, material suppliers and R&D support groups such as national laboratories, to find solutions to high-value problems. The DOE Industry of the Future programs could provide the structure for this teaming.

It was agreed that the approach to a specific materials substitution program should occur in two phases. Phase 1 would evaluate currently available advanced ceramic materials, which had not been tried in the program application. Laboratory and field testing would be needed and would include failure analysis. Phase 2 would be the improvement of these materials or development of new advanced ceramics to meet the requirements determined from Phase 1.

Appendix A: The Forum Agenda

DOE/IHEA
Materials Forum

Oak Ridge National Laboratory
Oak Ridge, Tennessee

AGENDA

Wednesday February 5, 2003

11:00 AM	Bus Pick-up	Garden Plaza Hotel (Front Entrance)
11:45 AM	Call to Order	Jason Wilson, Sub-Committee Chair Building 4515, Conference Room 240
	Welcome & Introductions	DOE–ITP Sara Dillich, Lead Technical Manager, MMP ORNL Marilyn Brown, Director, EERE Program, ORNL IHEA Mario Ciampini, President, IHEA
12:15 PM	Lunch	
1:00 PM	Keynote Presentation:	Advanced Materials Programs/DOE/National Labs. Sara Dillich, DOE-OIT
1:20 PM	Industry Presentations	A Look at the U. S. Process Heating Industry: Today and Tomorrow – Mario Ciampini, President, IHEA High-Temperature Alloys – Jason Wilson, Technical Marketing Manager Rolled Alloys, Inc Advanced Ceramics –Robert Licht, Manager Government Programs Group, Saint-Gobain Ceramics & Plastics, Inc. and Chairman USACA Refractories and Insulation for the Heating Equipment Industry – Gary Deren, Unifrax Corporation
3:00 PM	Break	
3:15 PM	DOE National Laboratory Presentations	High-Temperature Alloys – Vinod Sikka, ORNL Low Cost Ceramic Composite Fan Materials – Ronald Ott, ORNL Monolithic and Surface Modified Ceramics – Andrew Wereszczak, ORNL Advanced Nonporous Composite Materials for Industrial Heat Applications –Michael Ayers, LBNL Advanced Refractory Materials Research Program – Cindy Dogan, ARC Materials Degradation Processes in Elevated-Temperature

		Environments Relevant to Process Heating – Peter Tortorelli, ORNL
5:15 PM	General Discussion	Jason Wilson, Discussion Leader
5:45 PM	Session Adjournment	
6:00 PM	Bus Returns	to Garden Plaza Hotel
7:00 PM	Reception	Museum of Science and Energy, Oak Ridge, TN Near the Garden Plaza Hotel
8:00 PM	Dinner	Museum of Science and Energy, Oak Ridge, TN Near the Garden Plaza Hotel Speaker and Presentation: Donald M. Kroeger, ORNL – Superconductivity: Evolution of a Research and Development Project

Thursday February 6, 2003

7:30 AM	Bus pick-up	Garden Plaza Hotel (Front Entrance)
8:15 AM	Tour of Oak Ridge National Laboratories	(Meet in Lobby of Bldg. 4515)
10:40 AM	Presentation:	Working with DOE National Laboratories – Lou Dunlap, Deputy Director Technology Transfer and Economic Development Building 4515, Conference Room 240
11:00 AM	Lunch	
12:00 PM	Breakout Sessions	An opportunity for interaction between industry, DOE and national laboratory representatives to discuss R& D needs and future actions and activities. Session 1 – High-Temperature Alloys Building 4515, Conference Room 240 Session 2 – Advanced Ceramics Building 4500S, Conference Room Z62 Session 3 – Insulation and Refractories Building 4515, Conference Room 114
1:45 PM	Summary Session	Summary by leader from each breakout session Building 4515, Conference Room 240
2:15 PM	Summary Session	Jason Wilson – Discussion Leader Building 4515, Conference Room 240
2:45 PM	Conference Adjourns	
3:00 PM	Bus Returns	to Garden Plaza Hotel

Appendix B: Speaker /Presenter Information

Michael Ayers received his Ph.D. in inorganic chemistry from the University of Massachusetts-Amherst. His research focuses on the synthesis, characterization, and applications of nano-porous materials, especially aerogels. Recent projects have included aerogel nanocomposites, aerogel-based gas sensors, laser speckle characterization of gels, microgravity effects, and thin porous films for semiconductor applications. Current projects involve the synthesis of porous refractory oxides from low-cost raw materials for high-temperature insulations.

Marilyn Brown is the director of Oak Ridge National Laboratory's (ORNL's) Energy Efficiency and Renewable Energy Program. During her 18 years at ORNL, she has researched the design and impacts of policies and programs aimed at accelerating the development and deployment of sustainable energy technologies. She currently manages a $125 million/year program of research to develop and assess advanced energy efficiency and renewable energy technologies. Before coming to ORNL in 1984, she was a tenured associate professor in the Department of Geography at the University of Illinois at Urbana-Champaign. She has a Ph.D. in geography from the Ohio State University where she was a University Fellow, a master's degree in resource planning from the University of Massachusetts, and a bachelor's degree in political science (with a minor in mathematics) from Rutgers University. She has authored more than 140 publications and has received awards for her research from the American Council for an Energy-Efficient Economy, the Association of American Geographers, the Technology Transfer Society, and the Association of Women in Science. Dr. Brown sits on the boards of several energy and environmental organizations and serves on the editorial boards of several journals.

Mario Ciampini is president and C.E.O. of Ipsen International, Inc., Rockford, Illinois. In addition, he is president of LINAC Holdings, Inc., a member of the board of directors for LOI, Inc., and chairman of Hauck Manufacturing Company. Mr. Ciampini has a degree in business management and majored in finance from Ryerson University of Toronto, Canada. He is a certified management accountant in the Province of Ontario, Canada.

Gary Deren is the manager of marketing operations for the Unifrax Corporation in Niagara Falls, New York. After graduating from the State University College at Buffalo, Mr. Deren taught public school for the first five years of his career. He joined the Carborundum Company (currently Unifrax Corporation) in 1979. In his current position he manages a staff responsible for identifying and commercializing new products, as well as developing new business opportunities. Mr. Deren has published several articles addressing furnace-lining issues.

Sara Dillich is the lead technology manager for Materials and Materials Processes in the DOE-EERE Office of Industrial Technologies (OIT). Previous responsibilities within OIT have included leading the Aluminum Industry of the Future program and initiating the Supporting Industries program in OIT. Her prior work experience includes Materials Research program management with the U.S. Bureau of Mines, teaching materials engineering at the undergraduate and graduate level, and a National Research Council–sponsored postdoctoral appointment at the Naval Research Laboratory. She received her Ph.D. in Materials Science from the University of Virginia and has performed research in the areas of electrical contacts, surface modification and tribology.

Cynthia Powell Dogan is a materials research engineer and the project leader for the Advanced Refractories for Gasification project at the U.S. Department of Energy's Albany Research Center. She has more than a decade of research experience in the areas of high-temperature phase and microstructural development in ceramic materials and the effect of these phase changes on the bulk mechanical properties of the material. She received her Ph.D. in materials science from Case Western Reserve University in 1989, preceded by an M.S. and B.S. in ceramic engineering from Clemson University in 1985 and 1983, respectively. Her research has also addressed microstructure/property and microstructure/processing relationships in a wide range of intermetallic, metallic, and composite materials, and the influence of microstructure on the tribological performance of ceramics and ceramic-based composites. She currently has more than 40 publications in these areas, including the paper "Improving Refractory Service Life in Slagging Coal Gasifiers," which was recognized for technical merit at the 2001 International Pittsburgh Coal Conference in Newcastle, Australia.

Louise Dunlap is associate director of Technology Transfer and Economic Development at Oak Ridge National Laboratory. This organization is responsible for a wide range of technology transfer and industrial outreach activities. Her previous assignments include serving as director of the Office of Science and Technology Partnerships, where she was responsible for the guest research and user programs, and as business manager for the High Temperature Superconductivity Pilot Center Program, where she assisted in establishing the first industrial partnership program at the Laboratory. Ms. Dunlap has a B.S. Degree in Chemistry from the University of Tennessee and has completed numerous management courses. She is immediate past president of the Technology Partnerships Working Group, a national organization of technology transfer professionals in the DOE laboratory system. In addition to her professional activities, she is involved with many community groups including the Oak Ridge City Council, Pellissippi State Community College Foundation, Rotary Club, and the Methodist Medical Center Foundation.

Donald Kroeger received his B.A. in physics from Washington University and his Ph.D in physics from Vanderbilt University. He is a distinguished research staff member and leader of the Superconducting Materials Group in the Metals and Ceramics Division at Oak Ridge National Laboratory (ORNL). He is responsible for coordination of the conductor development activities within the Superconducting Technology Program. He is principal investigator for, or has supervision over, ORNL's collaborative projects with industry on conductor development.

During 35 years as a member of the research staff at ORNL, Dr. Kroeger has conducted research and development programs on superconducting materials and related technology, atomic transport in solids, rapid solidification processing and metallic glasses. He has published about 100 papers on superconducting materials and related technology and has made numerous invited presentations at conferences, universities, and research laboratories in the United States and abroad, and has participated in the organization of several symposia and workshops on superconductivity. He is a member of the Materials Research Society and the Minerals, Metals and Materials Society. Dr. Kroeger is the holder of one U.S. patent and has received ORNL awards for inventions and publications.

Robert Licht has been with Saint-Gobain and Norton Company (acquired by Saint-Gobain in 1990) for over 20 years. His primary responsibilities lie in research and development management in advanced materials, ceramic processing, machining and abrasive products. Mr. Licht holds two patents and is the author or co-author of several technical papers. He has an M.S. in Ceramic Science from Penn State University and a B.S. in Ceramic Engineering from Rutgers University.

Ronald Ott graduated from the University of Alabama at Birmingham (UAB) with an undergraduate degree in mechanical engineering in 1991, with emphasis on mechanical systems. At UAB he also earned a master's degree in materials engineering in 1994 and a Ph.D. in 1997. Ron conducted his dissertation research at the High Temperature Materials Laboratory (HTML) at Oak Ridge National Laboratory (ORNL) under the HTML graduate fellowship program (1994–1997). Following graduation, he held a postdoctoral research fellowship at the Materials for Information Technology (MINT) Center at the University of Alabama where he conducted nano-tribology research associated with the computer hard disk industry. After completion of the postdoctoral work, Ron began work at Oak Ridge National Laboratory in Surface Processing and Mechanics (SPM) group in 1999, performing research in the area of tribology. He transferred to the Materials Processing Group in 2002 and is currently involved with research associated with the Infrared Processing Center.

Vinod K. Sikka received a Ph.D. in metallurgical engineering from the University of Cincinnati. He is a Fellow of ASM International; has received six R&D 100 Awards, and the Federal Laboratory Consortium Award of Excellence in Technology Transfer award; and is a Corporate Fellow, leader of the Materials Processing Group, Oak Ridge National Laboratory. He has worked in developing metallic and intermetallic alloys for high-temperature applications and developed materials processes including Exo-Melt and infrared processing for manufacturing of advanced materials. He has 33 patents and over 200 publications and has extensive experience in working with industry and the transfer and implementation of materials technologies.

Arvind Thekdi has over 30 years of experience in design and development of process heating equipment such as high-temperature furnaces used by all major industries. His areas of expertise include design and application of combustion and heating systems, waste heat recovery systems for high-temperature furnaces and heaters, emission (NOx) reduction systems, and use of combined heat and power systems. He has worked on a number of programs related to development and commercialization of innovative furnace designs for the metals industry to improve energy efficiency and reduce emissions. During the past five years, he has prepared tools and training courses that offer instructions on practical and cost-effective methods to reduce energy use in process heating equipment. He holds 25 U.S. and foreign patents related to high-temperature processes and equipment. Dr. Thekdi has conducted several technology related studies, published more than 50 technical papers, and contributed to two books in the area of combustion, process heating, and application of improved technologies in industries.

Peter Tortorelli has a Ph.D. in metallurgy from the University of Illinois at Urbana-Champaign. He has extensive research experience in the areas of high-temperature oxidation and corrosion of alloys, metal matrix composites, ceramics and ceramic composites, the mechanical behavior of oxide scales, and liquid metal corrosion in support of energy efficiency in key industrial applications and enabling technologies for advanced fossil-fuel-based power plants and other energy systems. He is employed in the Metals and Ceramics Division of Oak Ridge National Laboratory, where he has research responsibilities as a principal investigator and serves as the manager of the Corrosion Science and Technology Group. He is a Fellow of ASM International and is also a member of TMS, the American Ceramic Society, and the Materials Research Society. He has published more than 130 scientific or technical papers and made more than 140 presentations at conferences or workshops.

Andrew Wereszczak is a senior research and development staff scientist in the Structural Ceramics Group at Oak Ridge National Laboratory (ORNL). He rejoined ORNL in September 2002 and is presently performing research on structural ceramics for heat engine applications and materials for power electronic devices. From 2000 to 2002, Andy worked at the U.S. Army Research Laboratory, Aberdeen Proving Ground, Maryland, and researched ceramic gun barrel technology and the microstructure - mechanical performance relationship in armor ceramics. From 1991 to 2000, Andy was a staff ceramic scientist in ORNL's Mechanical Characterization and Analysis Group and researched mechanical performance and reliability issues associated with monolithic structural ceramics under consideration for components in (primarily) diesel and gas turbine engines, mechanical reliability of ceramics used in electronic components, and high-temperature performance of refractories used in glass melting furnaces. He received a PhD in materials science and engineering from the University of Delaware and a BS in ceramic engineering from Alfred University. Andy has authored or co-authored more than 90 publications and given over 60 presentations on his work and is a member of the American Ceramic Society (Engineering Ceramics Division, Committee Member) and ASTM C28 (Advanced Ceramics).

Jason Wilson received his BSME from the University of Toledo. He began his career with Rolled Alloys in Temperance, Minnesota, as a materials engineer in 1991. He is currently the Technical Marketing Manager at Rolled Alloys. Mr. Wilson has published four papers on heat resistant alloys and their use in heating equipment.

Appendix C: List of Forum Attendees

DOE/IHEA
Materials Forum

Oak Ridge National Laboratory
Building 4515, Room 240
Oak Ridge, Tennessee
February 5-6, 2003

Ahmed Abada
Steeltech Ltd.
1251 Phillips Avenue, SW
Grand Rapids, MI 49507-1589
Phone: 616-243-7920
Fax: 616-243-0091
Email: alloys@steeltechltd.com

Richard H. Alstadt
Bloom Engineering Company, Inc.
5460 Horning Road
Pittsburgh, PA 15236
Phone: 412-653-3500, Ext. 3222
Fax: 412-653-2253
Email: ralstadt@bloomeng.com

G. Phillip Anderson
ExxonMobil Research and Engineering Company
3225 Gallows Road
Fairfax, VA 22037
Phone: 703-846-2229
Fax: 703-846-2389
Email: g.phillip.anderson@exxonmobil.com

Peter Angelini
Oak Ridge National Laboratory
P. O. Box 2008, Bldg. 4515, MS-6065
1 Bethel Valley Road
Oak Ridge, TN 37830-6065
Phone: 865-574-4565
Fax: 865-576-4963
Email: angelinip@ornl.gov

Samuel A. Arcava
Honeywell
1100 Virginia Drive
Fort Washington, PA
Phone: 215-641-3614
Fax: 215-641-3300
Email: sam.arcara@honeywell.com

Jerry L. Arnold
AK Steel Corporation
705 Curtis Street
Middletown, OH 45043-0001
Phone: 513-727-5719
Fax: 513-727-5872
Email: jerry.arnold@AKSteel.com

Michael Ayers
70-108
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
Phone: 510-486-4292
Fax: 510-486-7303
Email: mrayers@inreach.com

John J. Barnes
DuPont Company
1007 Market Street
Wilmington, DE 19898
Phone: 302-695-3259
Fax: 302-695-8347
Email: J-J-Sean.Barnes@usa.dupont.com

Robert D. Bessette
Council of Industrial Boiler Owners (CIBO)
6035 Burke Centre Pkwy, Suite 360
Burke, VA 22015-3757
Phone: 703-250-9042
Fax: 703-239-9042
Email: bessette@cibo.org

Michael J. Binni
Bloom Engineering Company
5460 Horning Road
Pittsburgh, PA 15236
Phone: 215-938-7748
Fax: 215-938-7727
Email: mbinni@bloomeng.com

Marilyn A. Brown
Oak Ridge National Laboratory
P. O. Box 2008, Bldg. 4500N, MS-6186
1 Bethel Valley Road
Oak Ridge, TN 37830-6186
Phone: 865-576-8152
Fax: 865-576-7572
Email: brownma@ornl.gov

Mario Ciampini
Ipsen International, Inc.
P. O. Box 6266
Rockford, IL 61125
Phone: 815-332-2577
Fax: 815-332-2058
Email: cia@abaripsen.com

David W. Collier
Eclipse Inc.
1665 Elmwood Road
Rockford, IL 61103
Phone: 815-637-7216
Fax: 815-637-7091
Email: dcollier@eclipsenet.com

Subodh K. Das
Secat. Inc.
533 South Limestone Street
Lexington, KY 40508
Phone: 859-514-4958,Ext. 300
Fax: 859-514-4988
Email: skdas@engr.uky.edu

Gary W. Deren
Unifrax Corporation
2351 Whirlpool Street
Niagara Falls, NY 14305
Phone:
Fax:
Email: gderen@unifrax.com

Robert DeSaro
Energy Research Company
2571-A Arthur Kill Road
Staten Island, NY 10309
Phone: 718-608-8788
Fax: 718-608-0933
Email: rdesaro@er-co.com

Sara A. Dillich
Industrial Technologies Program
U.S. Department of Energy/EE-2F
1000 Independence Avenue. SW
Washington, DC 20585
Phone: 202-586-7925
Fax: 202-586-7114
Email: sara.dillich@ee.doe.gov

Ralph B. Dinwiddie
Oak Ridge National Laboratory
P. O. Box 2008, Bldg. 4515, MS-6064
1 Bethel Valley Road
Oak Ridge, TN 37830-6064
Phone: 865-574-7599
Fax: 865-574-3940
Email: dinwiddierb@ornl.gov

Cynthia P. Dogan
U.S. Department of Energy Albany Research Center
1450 Queen Avenue, SW
Albany, OR 97321
Phone: 541-967-5803
Fax: 541-967-5845
Email: dogan@alrc.doe.gov

Lou Dunlap
Oak Ridge National Laboratory
P. O. Box 2008,
Bldg. 111UNV, MS-6499
Oak Ridge, TN 37831-6499
Phone: 865-576-4221
Fax: 865-241-4265
Email: dunlaplb@ornl.gov

Malcolm P. Gordge
Spirax Sarco, Inc
1150 Northpoint Blvd.
Blythewood, SC 29016
Phone: 803-714-2172
Fax: 803-714-2202
Email: malcolmgordge@spirax.com

Jeffrey B. Gorss
Alcoa, Inc.
900 S. Gay Street
Knoxville, TN 37902
Phone: 865-594-4802
Fax: 865-594-4890
Email: jeff.gorss@alcoa.com

Carlos F. Hernandez
E.I. DuPont De Nemours & Co., Inc.
1007 Market Street
Wilmington, DE 19898
Phone: 615-847-6876
Fax: 615-847-6897
Email: carlos.f.hernandez-1@usa.dupont.com

Max Hoetzl
Surface Combustion, Inc.
1700 Indian Wood Circle
P. O. Box 428
Maumee, OH 43537
Phone: 419-891-7182
Fax: 419-891-7151
Email: mhoetzl@surfacecombustion.com

Margaret W. Hunt
ASM International
9639 Kinsman Road
Materials Park, OH 44073-0002
Phone: 440-338-5151, Ext. 5635
Fax: 440-338-8542
Email: mwhunt@asminternational.org

Robert J. Jacenko
Spirax Sarco Inc.
1150 Northpoint Blvd.
Blythewood, SC 29016
Phone:
Fax:
Email: rjacenko@spirax.com

Ramesh C. Jain
Industrial Technologies Program
U.S. Department of Energy/EE-2F
1000 Independence Avenue, SW
Washington, DC 20585
Phone: 202-586-2381
Fax: 202-586-1658
Email: ramesh.jain@ee.doe.gov

J. Bruce Kelley
Sandia National Laboratories
P. O. Box 5800, MS-0753
Albuquerque, NM 87185-0753
Phone: 505-845-3384
Fax: 505-844-6541
Email: jbkelle@sandia.gov

Moe Khaleel
Pacific Northwest National Laboratory
902 Battelle Blvd.
Richland, WA 99352
Phone: 509-375-2438
Fax: 509-375-6605
Email: moe.khaleel@pnl.gov

Edward J. Kubel, Jr.
Business News Publishing
Industrial Heating Magazine
Manor Oak One #450
1910 Cochran Road
Pittsburgh, PA 15220
Phone: 440-543-8277
Fax: 440-543-2622
Email: edkubel@industrialheating.com

Robert H. Licht
Saint-Gobain Ceramics and Plastics, Inc.
9 Goddard Road
Northboro, MA 01532
Phone: 508-351-7815
Fax: 508-351-7760
Email: robert.h.licht@saint-gobain.com

Andrew James MacQueen
Ceradyne, Inc.
3169 Redhill Avenue
Costa Meas, CA 92626
Phone: 714-356-0042
Fax: 714-549-5787
Email: amacqueen@ceradyne.com

Anthony P. Martocci
Bethlehem Steel Corporation
1170 Eight Avenue, Martin Tower
Bethlehem, PA 18016-7699
Phone: 610-694-6657
Fax: 610-694-1523
Email: martocci@bethsteel.com

James E. McLaughlin
Exxon Mobil Research and Engineering
Company
3225 Gallows Road
Fairfax, VA 22037-0001
Phone: 703-846-2693
Fax: 703-846-2389
Email: james.e.mclaughlin@exxonmobil.com

Biljana Mikijelj
Ceradyne, Inc.
3169 Redhill Avenue
Costa Meas, CA 92626
Phone: 714-549-0421, Ext 401
Fax: 714-549-5787
Email: bmikijelj@ceradyne.com

Russell N. Mosher
R.N. Mosher and Associates, LLC
3997 Gumwood Court
Chantilly, VA 20151-2601
Phone: 703-802-0137
Fax: 703-378-5642
Email: rmosher1@doronet.com

Ron Ott
Oak Ridge National Laboratory
P. O. Box 2008
1 Bethel Valley Road
Oak Ridge, TN 37831-6083
Phone: 865-574-5172
Fax: 865-574-4357
Email: ottr@ornl.gov

Roman I. Pankiw
Duraloy Technologies, Inc.
120 Bridge Street
Scottdale, PA 15683
Phone: 724-887-5100
Fax: 724-887-5224
Email: techmgr@duraloy.com

Ray D. Peterson
IMCO Recycling, Inc.
397 Black Hollow Road
Rockwood, TN 37854
Phone: 865-354-6375
Fax: 865-354-9983
Email: rpeterson@imcorecycling.com

William R. Rawson
American Boiler Manufacturers Association
4001 No. 9th Street, Suite 226
Arlington, VA 22203-1900
Phone: 703-522-7350
Fax: 703-522-2665
Email: randy@abma.com

Roberto Ruiz
John Zink Company
11920 East Apache
Tulsa, OK 74116-1300
Phone: 918-234-2720
Fax: 918-234-1827
Email: ruizr@kochind.com

William W. Scott, Jr.
ASM International
9639 Kinsman Road
Materials Park, OH 44073
Phone: 440-338-5151, ext. 5516
Fax: 440-338-4634
Email: wwscott@asminternational.org

James Allen Shell
Shell Glass Consulting, Inc.
77 Saint Martin Court
Gahanna, Ohio 43230-3122
Phone: 614-471-7539
Fax:
Email: jshell@columbus.rr.com

Vinod K. Sikka
Oak Ridge National Laboratory
P. O. Box 2008
1 Bethel Valley Road
Oak Ridge, TN 37831-6083
Phone: 865-574-5112
Fax: 865-574-4357
Email: sikkavk@ornl.gov

Gwen Sims
Oak Ridge National Laboratory
P. O. Box 2008, Bldg. 4515, MS-6065
1 Bethel Valley Road
Oak Ridge, TN 37831-6065
Phone: 865-576-8069
Fax: 865-576-4963
Email: simsgm@ornl.gov

Robert J. Sinko
Eastman Chemical Company
P. O. Box 511, Bldg. 54D
Kingsport, TN 37662
Phone: 423-224-0504
Fax: 423-229-6099
Email: sinkorj@eastman.com

Richard D. Sisson, Jr.
Worcester Polytechnic Institute
100 Institute Road
Worcester, MA 01609-2280
Phone: 508-831-5335
Fax: 508-831-5178
Email: sisson@wpi.edu

Alan J. Smetana
Feco and Park Ohio Company
1441 Chardon Road, North
Cleveland, OH 44117
Phone: 216-531-1599
Fax: 216-441-6529
Email: asmetana@park-ohio.com

Arvind Thekdi
E3M, Inc.
15216 Gravenstein Way
North Potomac, MD 20878
Phone: 240-715-4333
Fax: 301-840-2919
Email: athekdi@e3minc.com

Peter F. Tortorelli
Oak Ridge National Laboratory
P. O. Box 2008, Bldg. 4500S, MS-6156
1 Bethel Valley Road
Phone: 865-574-5119
Fax: 865-241-0215
Email: tortorellipf@ornl.gov

Don Voke
Duraloy Technologies, Inc.
120 Bridge Street
Scottdale, PA 15683
Phone: 724-887-5100, Ext. 155
Fax: 724-887-5224
Email: dvoke@duraloy.com

Robert H. Wehrenberg II
ASM International
9639 Kinsman Road
Materials Park, OH 44073-0002
Phone: 440-338-5151, Ext. 5638
Fax: 440-338-8542
Email: rwehren@asminternational.org

Carsten Weinhold
Schott Glass Technologies
400 York Avenue
Duryea, PA 18642-2036
Phone: 570-457-7485, Ext. 350
Fax: 570-457-3438
Email: carsten.weinhold@us.schott.com

Andrew Wereszczak
Oak Ridge National Laboratory
P. O. Box 2008
1 Bethel Valley Road
Oak Ridge, TN 37831-6068
Phone: 865-576-1169
Fax: 865-574-8445
Email: wereszczakaa@ornl.gov

Jason D. Wilson
Rolled Alloys
125 West Sterns Road
Temperance, MI 48182
Phone: 734-847-0561
Fax: 734-847-3915
Email: jwilson@rolledalloys.com

Angela M. Withers
IMCO Recycling, Inc.
P. O. Box 28
397 Black Hollow Road
Rockwood, TN 37854
Phone: 865-354-5484
Fax: 865-354-9983
Email: awithers@imcorecycling.

Appendix D: List of Research Briefs

The following research briefs were received from various DOE national Laboratories. Note that the presentations and research briefs are included on the CD-ROM rather than in this printed version of the report.

Advanced Nonporous Composite Materials for Industrial Heat Applications
Michael Ayers and Arlon Hunt (Lawrence Berkeley National Laboratory)

Advanced Refractory Materials Research Program, DOE Albany Research Center
Cynthia Powell Dogan (Albany Research Center)

Advanced Wrought Alloys with Improved High-Temperature Performance for Waste Heat Recovery Systems
Philip J. Maziasz (Oak Ridge National Laboratory)

High-Temperature Alloys
Vinod K. Sikka (Oak Ridge National Laboratory)

Low-Cost Ceramic Composite Fan Materials
Ron Ott (Oak Ridge National Laboratory)

Materials Degradation Processes in Elevated-Temperature Environments Relevant to Process Heating
Peter F. Tortorelli (Oak Ridge National Laboratory)

Materials for Low-Cost Sensor Array System for High-Temperature Gas Measurement
Tim R. Armstrong and James E. Hardy (Oak Ridge National Laboratory)

Materials Test Methods, Alloy and Ceramic Selection and Development for Elevated Temperature and Aggressive Environments
Dennis Bickford (Savannah River Site)

Modeling of Thermo-Chemical-Kinetic Reactions Between Gas – Liquid – Glass – Metal in Industrial Process Heating Environment
Theodore M. Besmann and Sudarsanam S. Babu (Oak Ridge National Laboratory)

Monolithic and Surface Modified Ceramics
Andrew A. Wereszczak (Oak Ridge National Laboratory)

PNNL High-Temperature Materials Capabilities
Charles H. Henager, Jr. and Russell H. Jones (Pacific Northwest National Laboratory)

Surface Modification and Thermomechanical Properties of Refractory and Insulation Materials
Terry Tiegs (Oak Ridge National Laboratory)

Appendix E: List of Forum Presentations

Industry Presentations

A Look at the U. S. Process Heating Industry: Today and Tomorrow – Mario Ciampini, President, IHEA

High-Temperature Alloys – Jason Wilson, Technical Marketing Manager, Rolled Alloys, Inc.

Advanced Ceramics – Robert Licht, Manager , Government Programs Group, Saint-Gobain Ceramics & Plastics, Inc. and Chairman USACA

Refractories and Insulation for the Heating Equipment Industry – Gary Deren, Unifrax Corporation

DOE National Laboratory Presentations

High-Temperature Alloys – Vinod Sikka, ORNL

Low Cost Ceramic Composite Fan Materials – Ronald Ott, ORNL

Monolithic and Surface Modified Ceramics – Andrew Wereszczak, ORNL

Advanced Nonporous Composite Materials for Industrial Heat Applications –Michael Ayers, LBNL

Advanced Refractory Materials Research Program – Cindy Dogan, ARC

Materials Degradation Processes in Elevated-Temperature Environments Relevant to Process Heating – Peter Tortorelli, ORNL

Other Presentations

Introduction to Oak Ridge National Laboratory - Marilyn Brown