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Advanced Ceramics in Glass Production:

Needs and Opportunities

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Executive Summary

Advanced ceramics offer significant advantages over conventional materials currently used in glass manufacturing. These lightweight, durable ceramics resist corrosion, abrasion, and thermal shock and perform well at high temperatures–key properties for harsh glass production environments. Additionally, advanced ceramics come in three different forms– monoliths, coatings, and composites–to meet requirements for a variety of applications. Use of advanced ceramics, although generally higher in cost, can often be justified by the materials' superior performance.

Glass producers, however, do not currently use advanced ceramics in their manufacturing processes. While this practice may be attributed to concerns with the material's high cost, survivability, predicted durability, design issues, and lack of extensive, real-world operating experience, it is more likely due to glass producers' unfamiliarity with the capabilities, characteristics, and production benefits of advanced ceramics. Similarly, advanced ceramic manufacturers may be unaware of the material properties required for various glass environments.

This report summarizes the results of a workshop that examined how advanced ceramics can be adapted and applied to meet the needs of glass production. Participants included representatives from the advanced ceramics industry, the glass industry, and government. The workshop helped to match advanced ceramic compositions to specific glass industry applications and identified the research and development needed to encourage commercial use and acceptance of advanced ceramics in the glass industry.

Key Findings

- Advanced ceramics show promise for several applications in glass furnace and downstream fabrication operations. Potential advantages over existing materials include longer life, higher quality glass, faster production, and environmental improvements.
- Since little data exists on the performance of advanced ceramics in glass production environments, a better understanding of the chemical compatibility of these materials with various glass compositions is needed.
- The high cost of advanced ceramics may be the biggest barrier to acceptance within the glass industry unless sufficient productivity and quality benefits can be clearly demonstrated.
- Initial opportunities for advanced ceramics will likely be in high value or niche applications. In particular, glass producers place high priority on opportunities to substitute ceramics for precious metals such as platinum.
- To take full advantage of the unique characteristics of advanced ceramics, new designs and applications should be examined rather than limiting the scope to simple one-for-one material replacements.
- Glass companies are often resistant to changes that could adversely affect manufacturing operations. However, when benefits are clear and significant, the industry can quickly embrace new technology, as was the case with oxy-fuel firing.
- Key opportunities to substitute advanced ceramics for materials currently used in glass production are shown below.

Opportunities for Advanced Ceramics

- Corrosion-resistant refractories that can operate in an oxy-fuel environment without affecting glass quality
- Sheathing material for thermocouples that can survive the furnace campaign without affecting glass quality
- Mold materials with high thermal conductivity that require no lubrication
- Combustion exhaust fans and duct work
- Low-cost bubblers, lances, and stirrers
- Longer-life forming lip and tweel for float glass
- Burners for gas-fired heaters used in the float zone
- Low-cost, high-tolerance materials for use around holes in fiberglass production
- Lehr rolls and conveying equipment that do not affect glass quality

Research and Development Needs

Before advanced ceramics can be applied in commercial glass manufacturing, additional research and development must be conducted. Selected R & D needs–which can be classified as general, specific, and related analysis–are shown in Exhibit 1.

The most important R&D initiative is to explore how specific ceramic formulations will perform with various glass chemistries. This will require examining existing material test data, conducting additional material corrosion tests, and characterizing the performance of precious metals for comparison. The results of these activities should be collected in a comprehensive database containing the effects of glass composition on corrosion of advanced ceramic materials. The database should be made available to ceramic producers and glass manufacturers as an aid for future development work.

Exhibit 1. Selected R&D for Advanced Ceramics

General	• Glass and vapor corrosion testing • Database of glass/advanced ceramic compatibility • Characterization of currently used materials and precious metals • Examination of advanced ceramics manufacturing and design issues
Specific	• Improved refractory compositions • Coatings for molds • Thermocouple sheathing material • Coatings for forming lip and tweel • Ceramic burners for gas-fired heaters • Alternative heating methods, such as ceramic heat pipes
Related	• Case studies of the use of advanced ceramics in glass operations • Economic studies and modeling • Energy modeling

Future collaboration between the advanced ceramics industry and the glass industry may be best coordinated through the newly formed Glass Manufacturing Industry Council (GMIC). The Council represents the technical interests of all four glass sectors and coordinates with other glass organizations and research institutions such as the Center for Glass Research and national laboratories.

CHAPTER 1

Introduction

Advanced ceramic materials have several characteristics that can be quite beneficial to glass manufacturing. These materials, which include monolithic ceramics, ceramic coatings, and ceramic composites, are light weight, corrosion resistant, durable, resistant to thermal shocks, and perform well in high temperature environments. These are the very characteristics that are required for glass production environments.

Glass producers have not incorporated many advanced ceramic materials into their manufacturing processes. Producers may have concern about the material's high cost, survivability, predicted durability, design issues, and lack of real-world operating experience. But probably the biggest issue is that most glass technologists are unfamiliar with advanced ceramic materials and their material properties, applications, and recent technology advances. Likewise, producers of these materials may be unfamiliar with the specific operating conditions and associated materials needs of glass operations. This report summarizes a workshop that sought to improve understanding between these two industries and identify high-priority research activities that could lead to wider adoption of advanced ceramics by the glass industry.

Background

In December 1996, the advanced ceramic industry, represented by the United States Advanced Ceramics Association (USACA) with sponsorship by the U.S. Department of Energy's Office of Industrial Technologies, undertook a study to assess the opportunities for advanced ceramics to meet key materials needs of major energy-intensive industries. Seven industries were examined including aluminum, chemicals, forest products, glass, metal casting, steel, and petroleum refining. The study focused on manufacturing environments which exhibit high temperatures, corrosion, and abrasion.

In September 1997, USACA and the U.S. Department of Energy Office of Industrial Technologies (DOE/OIT), sponsored a conference to share the initial results of this study with representatives of these seven *Industries of the Future*. The conference provided valuable feedback on how advanced ceramics could benefit these industries. Identified benefits included increased energy efficiency, reduced maintenance costs, improved environmental performance, and higher quality products. Barriers to implementation include a bias toward metals, lack of field

test and evaluation data, and general lack of awareness about advanced ceramics properties and cost performance.

One conclusion of the study and the conference was that advanced ceramics appear well-suited for many of the material needs in glass production environments. One glass manufacturer has already demonstrated a ceramic radiant screen burner for a glass plant and has plans to install this technology in its facility. Leaders in the ceramics community felt that advanced ceramics could potentially offer superior performance in a variety of glass processes, provided they are designed to meet the specific needs of glass producers. The "Opportunities for Advanced Ceramics to Meet the Needs of the Industries of the Future" was published by USACA and the U.S. Department of Energy in January 1999.[1]

Advanced Ceramics for the Glass Industry

To better understand the material requirements of glass producers, USACA and DOE/OIT sponsored a collaborative workshop on September 22-23, 1998. The workshop brought together members of the ceramics industry and the glass industry to examine specific opportunities to apply advanced ceramics in glass production. The workshop sought to identify promising opportunities, understand technical barriers, and outline additional research and development needed to bring advanced ceramics into practical application. Participants represented a cross-section of companies that produce flat, fiber, and specialty glass; ceramic manufacturers; researchers; and government programs (see Appendix A).

This document summarizes the findings and recommendations that resulted from the workshop and represents the collective views and thoughts of its participants. While the workshop design did not permit participation by all ceramic and glass companies, the views of the participants are believed to reflect many of those held by their colleagues and competitors.

The workshop consisted of a plenary session, breakout sessions, and a summary session (see Appendix B). Presentations given during the plenary sessions are provided in Appendix C and are summarized in the remainder of this chapter. Two breakout groups were conducted on glass melting and glass forming and fabrication processes that are summarized in chapters 2 and 3. The summary session identified common research themes that emerged from each breakout group.

Glass Industry Technology Roadmap

The glass industry has undertaken an immense effort to create a vision and a draft technology roadmap that outlines technology and research priorities.[1] Any effort to match advanced materials with glass industry needs should respond to the targets, barriers, and research priorities contained in the draft technology roadmap. The glass industry has set some ambitious targets that place new demands on the materials used inside and outside of the glass furnace. The strategic

[1]Copies of these reports can be obtained by contacting the OIT Resource Room at (202) 586-2090 or fax (202) 586-1658. These reports are also available on the U.S. Department of Energy's OIT web site at www.OIT.doe.gov

goals of the glass industry are shown in Exhibit 2. It is critical that the suppliers who wish to meet the needs of the glass industry really focus on these goals. Glass companies have uncovered a winning formula: set bold industry targets and work with suppliers, customers, and technologists in a coordinated fashion to achieve them.

Exhibit 2. Glass Industry Goals

- Reduce production costs by at least 20%
- Recycle 100% of all glass products within manufacturing
- Reduce process energy use by 50% toward theoretical limits
- Recycle 100% of post-consumer glass (where consumption >5 lb/capita)
- Achieve 6 sigma quality control
- Create innovative products that broaden the marketplace
- Increase supplier and customer partnerships in raw materials, equipment, and energy improvements

Coordination of research efforts among private companies within the glass industry represents only one kind of successful collaboration. Public-private R&D partnerships have also proven to be very beneficial to companies and the government. In 1997, DOE/OIT conducted a study of federal research activities that might be relevant to the major energy-intensive industries. The study identified 28 federal programs representing a combined budget of $3 billion that was in some way related to the needs of the glass industry. Even if only part of this budget is focused on the specific goals and targets of the glass vision, the vision and roadmap should be used to guide these investments toward the needs of the glass industry.

Role of Advanced Ceramics in Industry

Advanced ceramics encompass a set of materials that offer many of the desirable characteristics of conventional ceramics without many of the flaws (see box). They are best suited for high temperature applications in power generation, transportation, aerospace, and manufacturing where their generally higher cost can be justified by their superior performance. For most purposes, advanced ceramic materials can be classified as monolithics, coatings, or composites.

What Are Advanced Ceramics?

Advanced ceramics are distinguished by their purity and performance. They include both oxides and nonoxides and various particulate, whisker and continuous fiber reinforced ceramic composites. High purity ceramic coatings are also part of the advanced ceramics family.

Monolithic Ceramics

There have been major developments in monolithic ceramics over the past 10-15 years. In the refractory industry, monolithics refer to aggregate or cement type ceramics. In advanced ceramics terminology, monolithic ceramics generally refer to oxide and non-oxide ceramics that are essentially made up of a single material. There is also a grey area of what is a ceramic composite and what is a monolith. Advanced monolithic ceramics include oxides, (e.g., aluminum oxides, alumina-zirconia-silica (AZS), which are also used by the glass industry for refractories, and transformation-toughened zirconia); carbides (e.g., silicon carbide and boron carbide); and nitrides (e.g., reaction bonded, sintered and pressure densified silicon nitride).

Monolithic ceramics can have complex microstructures and are produced using many different processes. There are also many suppliers of monoliths, coatings, and components so customers

are not reliant on any one supplier. However, monoliths all share some common properties that are attractive to manufacturing customers:

- high temperature resistance (operates at temperatures that will melt many metals),
- corrosion resistance,
- thermal shock resistance,
- abrasion and wear resistance,
- oxidation resistance,
- light weight,
- high stiffness.

Over the years there have been improvements in the toughness and strength of ceramics. The industry is increasing the toughness of silicon nitride, transformation-toughened zirconia, and composites to be more competitive with other materials. There have been industry successes replacing tungsten-carbide cobalt with transformation toughened zirconia because the toughnesses are comparable but wear resistance of the latter is superior. In-situ toughened silicon nitride is meeting the strength requirements to replace metal structural components while demonstrating superior use temperature, and wear and corrosion resistance.

Although there has been significant materials development over the past 20-25 years, there are two key barriers to commercialization: reliability (monolithic ceramics are still considered brittle), and cost-effectiveness (advanced ceramics are still expensive to manufacture). If a monolithic ceramic costs 10 times that of an alternative metallic part, then it must show greater than 10 times the benefit.

The U.S. DOE Office of Transportation Technologies Ceramic Technology Project has had an objective for the past 15 years to improve both reliability and cost-effectiveness of advanced ceramics. Some of the compositions the industry has today, such as zirconia, silicon carbide, and silicon nitride, came out of basic science conducted in the early and mid 1980's. Improved reliability will be achieved through improved ceramic processing. Cost issues are overcome by improving ceramic manufacturing. Today, monolithic ceramics are being commercialized in applications as far ranging as cam roller followers in diesel engines, igniters, for gas appliances, nozzles in turbine engines for auxiliary power generation in airplanes, and seals for water pumps in automobiles.

Ceramic engineers are learning how to design with what is essentially a brittle material. Their strategy is to use compositional and processing improvements to improve strength and toughness. This improves component reliability by raising and narrowing the distribution of component failure stress. This will result in a much lower probability of failure. However, materials improvements alone may not be enough to reduced failure probability to acceptable levels for some systems. New developments in NDE (nondestructive evaluation) and proof testing can exclude parts that could fail in service. Additionally, finite element analysis can be used to redesign components to reduce mechanical and thermal stresses. All of the above can reduce the probability of failure of ceramic components to a more acceptable or zero probability of failure.

Typical ceramic processing includes six steps:

1) powder processing,
2) forming,
3) green machining,
4) firing,
5) finish machining,
6) inspection.

The highest cost operations in processing advanced ceramics are typically finish machining and inspection. Powder processing may involve milling, blending, slurry prep, spray drying, and fusion. Examples of forming include pressing, cold isostatic pressing, dry bag/isostatic pressing, injection molding, slip casting, gel casting, extrusion, and tape casting. There is no one process that is clearly superior; it's basically what is economical to produce a given shape and what will provide the required performance and materials properties. To a greater extent, ceramic engineers are today utilizing in-process control throughout all the ceramic processing unit operations, which encompasses full characterization during powder processing, NDE, statistical process control and intelligent processing.

A new advanced ceramic forming technology that is being studied is solid freeform fabrication, also know as layer processing or rapid prototyping. While not currently developed for advanced ceramics, it is now used commercially for making plastic molds, polyester molds, and some porous ceramic molds. The basic premise of the process involves converting a computer design of a complex part and making that part without molds by cutting, solidifying or forming precise shapes in thin layers and stacking them into multiple layer structures that are solidified into a final part. The main advantages of this fabrication process is the ability to greatly reduce the time and steps needed to go from design to a finished prototype product, and the possibility of producing parts with functionally gradient materials with a different composition and property for each layer.

Cost effectiveness of advanced ceramics versus metals is a key issue. Market penetration of ceramics will increase as the price premium that a customer must pay comes down. Accordingly, several commercial and government programs have objectives to reduce material costs by a factor of ten. One example is a DOE program that seeks to reduce the cost of silicon nitride valves for diesel engines while meeting all material performance requirements.

Ceramic Coatings

Ceramic coatings offer a different approach for meeting demanding material needs. The concept is to allow the substrate material to provide structural strength while the ceramic coating provides a protection layer against the environment. The objective of this concept, however, is the same: high reliability for the life of the part. Some standard ceramic coating technologies that are used today include plasma spray, high-velocity oxy fuel (HVOC), flame spray ceramic coating, electron beam physical vapor deposition (EBPVD) and chemical vapor deposition (CVD).

Advanced ceramic coatings are now at the point where the reliability and cost effectiveness have been demonstrated. For example, thermal barrier coatings are routinely used in gas turbine

engines. The industry is on the verge of other significant commercial breakthroughs for producing advanced ceramic-coated components for a variety of applications.

Ceramic Composites

Ceramic composites, which include ceramic matrix composites and continuous fiber ceramic composites (CFCCs), attempt to overcome the catastrophic failure mode that occurs in some monolithic ceramics. Composites are designed to produce a "graceful" failure by using ceramic fibers to carry the load across a developing crack. The ceramic fiber can be oxide or nonoxide in a continuous phase of oxide or nonoxide ceramics.

CFCC's are extremely tolerant materials. Not only do they perform well at standard baseline conditions, they also perform acceptably in extreme conditions that are well outside normal operating conditions. For example, during a burst strength test of a 2-inch CFCC tube at 1200°C, seals started to leak at 700 psi but the tube did not burst until the pressure exceeded well over 2000 psi. When damage does occur to ceramic composite components it is predictable, making it easier to incorporate these materials into designs and use graceful failure as an advantage. Furthermore, ceramic composites are custom materials that can be tailored to meet operating conditions of various process environments.

Industry groups that represent existing or future customers have raised issues concerning the use of advanced ceramics. Major issues include risk, exposure performance, lifetime prediction, and design (codes and standards).

Risk. Companies are typically risk adverse when choosing materials that could potentially harm their operations. Ceramic manufacturers have worked to mitigate concerns about risk by conducting material tests in actual operating environments and presenting the successful results to potential customers. In 1998, turbine engines containing ceramic components ran successfully in commercial electric service for 2400 hours in California. This will be followed by 3000- and 4000-hour tests in 1999. Engines with ceramic components are planned to go into commercial service next year.

Exposure Performance. Tests have also been conducted in harsh environments to demonstrate successful exposure performance. Ceramic composite heat exchangers are being designed for use in very alkaline environments. In field testing of the CFCC materials in a TVA power plant, there was no strength loss after 8000 hours at 1680°F to 1850°F (915°C to 1010°C). There has also been lab testing for 1500 hours at 2100°F (1149°C) with alkaline ash that resulted in 90%+ strength retention. Other conditions have also been tested with the same materials and a database had been developed that can be used to predict performance under various conditions and environments.

Life Prediction. Life prediction is very hard to do and continues to be an issue. Researchers at Virginia Tech are working on a true, non-linear, damage accumulation model and associated database to predict damage and lifetime based on stress-strain, environmental damage, and corrosion correlations.

Design. Although these are new materials, there are valid codes that allow customers to compare data across companies and products. This includes testing standards to develop tensile data, compressive data, and shear data. There is a ceramic composite database that is being put together, primarily for aerospace applications, to examine reliability and there is a special section being written specifically for ceramics in the ASME pressure vessel and boiler code.

Two good examples of successful activities that may be applicable to the needs of the glass industry include radiant burner screens and furnace fans. The radiant burner has been examined by an autoglass company that has proven it for paint drying on the trim of the glass and in glass formation to bend flat glass for the back and rear car windows. It handles thermal shocks quite well, having been tested for over 15,000 on-off cycles with a hot surface temperature of 2000°F (1093°C). Scale-up work to build a furnace to go into an operating plant is in progress.

Furnace fans are considered basic equipment but they can cause problems if they do not circulate air uniformly. Metal fans can droop and lose efficiency. The SiC CFCC ceramic fans are very creep resistant, and they are lighter weight. This saves energy and reduces maintenance problems for the hot bearing housings that need to be water-jacketed and cooled.

Overview of the U.S. Glass Industry

There are many commonalities in the processes that transform raw materials into molten glass. However, the chemistries of the glass can be very different as well as the fabrication methods to make glass products. The chemistries impart different physical properties for different applications. Understanding the various glass chemistries is important in designing materials to perform well in glass operating environments.

There are four major segments to the glass manufacturing industry: container, flat, fiber, and specialty (pressed and blown). The container industry produces the most glass with roughly 9 million tons of production per year. It is a significant energy user that produces bottles, jars, and other containers that compete with plastic, aluminum, steel, and paper. Four main companies dominate this sector as a result of past mergers and consolidation. This segment includes 128 furnaces with a typical output of 250 tons of product per day. Most furnaces are regenerative furnaces (102 furnaces), 24 furnaces are oxy fuel fired, and 2 are all-electric.

The flat glass industry is dominated by five major firms that produce nearly 5 million tons of glass per year. Products are used mainly for windows in buildings and automobiles and for architectural features. This segment consists of 38 regenerative furnaces with a typical output of 600 tons/day. The first oxy fuel furnace went into operation in April 1998.

The fiber glass sector produces about 3 million tons of product per year and is dominated by five large manufacturers. Products include a variety of insulation materials and textile products. Of the furnace population that is 75-100 tons/day, about half are unit melters and about one-quarter are oxy fuel. Of the furnaces with output of 100-150 tons/day, about half are oxy fuel and about half are unit melters.

The specialty (pressed and blown) segment encompasses a broad variety of products ranging from tableware, cookware, lighting, scientific products, and television tubes. This segment produces about 2 million tons of glass products per year worth roughly $1.7 billion. Typical furnace size is 75 tons/day. Oxy fuel furnaces represent roughly 35 percent of the furnaces in this segment.

The glass industry has laid out its main technology and research agenda in their vision and draft technology roadmap. This agenda responds to the industry's ambitious 25-year goals that cover energy use, environmental performance, productivity, quality, and markets. A subsequent technology roadmap workshop, which had broad participation from the glass industry, helped to identify the comprehensive research agenda that will be needed to achieve the vision goals.

The proposed research needs are organized into production efficiency, energy efficiency, environmental protection and recycling, and innovative uses. Exhibit 3 shows some of the key technology barriers for each of these areas. Material issues in which advanced ceramics may have an impact include refractories, high-temperature sensors, and longer lasting materials (non-refractory).

To implement the glass research agenda, the industry has formed a new organization, the Glass Manufacturing Industry Council (GMIC), consisting of U.S. glass producers and suppliers. The diversity of the industry and the lack of coordinated research were key motivators for creating the GMIC. Its primary mission is to facilitate, organize, and promote the technical interests of the glass industry. As the advanced ceramics industry begins to collaborate with the glass industry, the GMIC will be the logical organization to help facilitate and promote this process.

Exhibit 3. Technology Barriers from the Draft Glass Technology Roadmap

Production Efficiency	• Inadequate in-process sensors and control systems • Inadequate refractory materials • Materials performance limitations • Getting energy into the glass effectively • Scale-up of fundamental knowledge
Energy Efficiency	• High cost to develop and implement process technology • Lack of adequate refractories • Inadequate and unvalidated models • Poor heat recovery • Industry characteristics
Environmental Protection	• Lack of process control and instrumentation • Lack of understanding of process mechanisms influencing particulates • High cost of oxygen • Economics of beneficiation • The effect of glass composition on emissions • Technologies for separation and sorting of wastes

Although the glass industry is sometimes viewed as resisting new technologies, they have shown an ability to quickly change if a technology addresses important needs of the industry. Oxy fuel firing of furnaces is a case-in-point. The technology for oxy fuel was first introduced around 1990 and in a span of eight years, 24 percent of the glass industry has converted over to this new technology. The industry's experience with oxy fuel is an important lesson for ceramic companies as they introduce new technologies that outperform conventional alternatives.

CHAPTER 2

Glass Melting: Opportunities for Advanced Ceramics

Glass Melting

Glass melting encompasses the portion of the glassmaking process up to the point that the glass melt exits the furnace. It includes batch preparation, melting, and refining, and is centered primarily on the glass furnace and its components. A typical operating period, or "campaign", for a large glass furnace is about eight to ten years depending on the type of glass production. At the end of the campaign the furnace is shut down and rebuilt. Some high-value specialty glass furnaces may have much shorter campaigns. Rebuild costs for large furnaces often run into the tens of millions of dollars, partly because glass manufacturers also make other capital and operational improvements during the rebuild, such as resizing the furnace and adding or changing downstream forming operations.

The limiting factor that forces the furnace rebuild varies. One factor is failure or excessive corrosion of some portion of the refractories in the furnace, such as the crown or sidewalls. Failure may be accelerated by poor construction, a bad heat up, or high maintenance activity. Opportunities for fixing operational problems during a campaign are limited, especially for refractories, although replacing expendable parts may be less problematic. At some point the cost of constant repairs and increased defect rates makes it uneconomical to continue operating.

Extending the campaign life is a critical goal of glass manufacturers due to the high costs of shut down and rebuild. Glass manufacturers would like campaigns of ten years or more, as the daily value of lost product can be in the vicinity of $250,000 a day for large furnaces or for very high value specialty glass furnaces.

Most furnaces are combustion heated, with natural gas in an air or oxygen environment. Often, combustion heating is supplemented by an electric boost to improve heating uniformity. About 65% of glass furnaces are natural gas-fired regenerative furnaces, and about 25% are oxy fuel-fired furnaces that combust natural gas in an oxygen-enriched environment. There were no oxy

fuel-fired furnaces in operation ten years ago. However, the glass industry has rapidly adopted oxygen-firing due to environmental and productivity benefits. The remaining glass furnaces are electric.

Critical Material and Technology Needs in Glass Melting

Glass furnaces operate at very high temperatures. The temperature of molten glass is usually 1350°C to 1400°C, and the atmosphere within the furnace can reach or exceed 1600°C. In addition, the raw materials used in making glass, along with the fuel, cause chemical reactions in the furnace that emit corrosive gases. This creates a hostile environment that requires special materials that can endure these conditions.

The critical material and technology needs in glass melting can be organized into seven main categories:

- Furnace Components
- Refractories
- Expendable Parts
- Burners
- Sensors
- Batch/Cullet Preparation
- Fabrication and Processing

Exhibit 4 shows a summary of key materials needs organized into these categories.

Materials are important for several glass ***furnace components*** to improve furnace performance. Glass companies need materials that last longer than currently used materials, many of which include precious metals, particularly platinum. Precious metals, which perform fairly effectively in the glass furnace, are expensive and create environmental hazards during production or recovery in a machine shop. One specific area where the glass industry is looking to replace precious metals is in bubblers and lances. Another area is in the exhaust system where material corrosion is a problem in flue glass ducts. Lighter materials in exhaust fans can also improve efficiency.

Refractories, in the form of blocks, are used extensively in the glass furnace as the sidewalls, shell, and crown of the furnace. They also provide insulation and thermal radiation to the melt. Some refractory materials are in contact with the melt, while others are in contact with the atmosphere in the combustion space above. The major property requirements for refractory materials are that they resist high temperature, corrosion, erosion, and do not affect glass quality. Corrosive elements in the high temperature furnace atmosphere include carbon dioxide, water, and alkali vapors such as potassium and sodium hydroxides. Rat holes, which can develop at the joints between blocks, can also cause contamination.

Silica refractory blocks have been used extensively with natural gas-fired furnaces. While silica blocks will slowly erode over time and pieces can fall into the melt, they are relatively inexpensive and do not affect the quality of the melt. Oxygen-fired furnaces, which dramatically reduce NO_x emissions, have changed the chemical composition of the combustion space atmosphere. In addition, the volume of gases present is much less than with gas-fired furnaces, and the dynamics of heating have also changed. These changes have resulted in accelerated decay of refractories in oxygen-fired furnaces.

Exhibit 4. Critical Material and Technology Needs in Glass Melting Priority

(Priorities of Participants: ✪ = Glass Industry; ♦ = Ceramics Industry)

Furnace Components	Refractories	Expendable Parts	Burners	Sensors	Batch/Cullet Preparation	Fabrication and Processing
General - materials to replace precious metals ✪♦♦♦ General - longer lasting non-refractory materials Gobber Stirring (Needle) High-temperature, long-life, uncooled heat exchangers Low cost, uncooled bubblers/lances - water-cooled or precious metal ✪✪♦♦ Corrosion-resistant, high-temperature flue gas ducts ♦ Fans for combustion exhaust ✪✪♦♦♦♦♦ Better electrode materials for melters - Electrode supports - Mo-metal or tin oxide	Refractory materials that resist high temperature, corrosion, erosion, and don't affect quality - Oxy fuel has increased problem - Rat holes that cause contamination - Fused-cast AZS is potential solution - Graded structures? ✪✪♦♦♦♦♦ Monolithic crowns Corrosive elements - High temperature, CO2, water, alkali vapor	Orifice rings Low-cost, uncooled stirrers - Platinum or fused silica ✪♦♦♦ Tube and needle - Smooth surface vs. thermal shock Low-cost, uncooled plungers - Thermal shock problem - Bonded AZS ♦♦♦	Longer life higher temperature burner nozzle	Thermocouple that lasts for furnace life (for 24% lead glass) - Sheathing material currently aluminum oxides - Platinum ✪✪ Sensor materials that won't affect glass quality ♦ Longer life, uncooled thermocouple and camera shields ✪✪♦♦♦♦♦♦	Ceramic rollers vs. rubber rollers Abrasion resistant materials ♦♦ Automated systems (sluice delivery)	Low cost, high temperature robots Long-life glass stop insulation (tweel?) ♦ Shearing - Non-lubricated ✪✪ Non-contact level for glass forming Pressing and extrusion Grinding and polishing (TV glass) Rollers with low thermal shock and conductivity ✪♦ Mold materials (higher temperature) - Net finished product - Eliminate renite use ✪✪♦♦♦♦♦♦

Expendable parts include those parts that can be replaced without interfering much with furnace operations during the campaign. One particular part of interest is stirrers, which are used to improve homogeneity in the melt. Further downstream, orifice rings and plungers are used to control the volume and shape of molten glass. These expendable parts could also be improved. As with furnace components, replacement of precious metals is desired. Other concerns include thermal shock properties during hot installation, surface smoothness, and cost. Normally, the smoother the material surface, the less resistance to thermal shock.

In ***burners***, the major concern is for long-life, high-temperature burner nozzles. Although current materials are viewed as operating satisfactorily, further improvement would have economic benefits.

Because of the high temperature, corrosive environment inside the glass furnace, current ***sensors*** have problems surviving the desired lifetime. The major needs are for thermocouples and camera shields that have a longer life and do not require cooling. In most instances, glass manufacturers place numerous thermocouples in a furnace, assuming some will fail during the campaign. In addition, sensor materials should not affect glass quality if they fall into the melt.

A key material issue in ***batch/cullet preparation*** is abrasion and corrosion of equipment such as rollers and other devices used to transport the raw materials to the furnace. Materials for batch/cullet preheaters are not an issue currently, as there are no operating preheaters in the United States. Preheaters are now used in parts of Europe where higher energy costs allow profitable operation.

Fabrication and processing includes several parts that are outside the furnace, but are deemed critical for overall glass processing. The major need is for mold materials that can withstand higher temperatures and have better wear characteristics. In addition, molds that provide a net finished product without the need for grinding and polishing are also desired. Additional needs are rollers with improved thermal shock and conductivity properties, and blades that can be used in shearing operations without the need for lubrication.

Opportunities for Advanced Ceramics

There are six priority areas where advanced ceramics have good potential to solve critical material needs in the glass industry. The best matches are: (1) corrosion-resistant refractory materials that can operate in an oxy fuel environment and will not affect glass quality; (2) sheathing material for thermocouples that last for the furnace campaign and will not affect glass quality; (3) mold materials that can operate at higher temperature and do not require lubrication; (4) materials for combustion exhaust fans and duct work; (5) materials for low cost bubblers and lances; and (6) materials for low cost stirrers. These areas, which are summarized in Exhibit 5, are discussed below.

Materials for Bubblers and Lances

Bubblers and lances are used to improve homogeneity of the glass melt. Bubblers normally introduce a gas in the form of bubbles, such as oxygen, through many holes in an approximately one-inch diameter tube structure such as a manifold to help mix the melt. Occasionally, other gases, such as chlorine, may be used in certain specialty glass applications. Bubblers and lances operate in the glass melt at about 1350-1400°C, and bubbler tubes are usually made from platinum or a water cooled stainless steel. Bubblers enter the melt through the bottom of the furnace. If the bubbler fails, leakage through holes in the bottom of the furnace can cause problems. Special refractory blocks are used around the bubbler, because local corrosion is greater due to the additional convection in the melt.

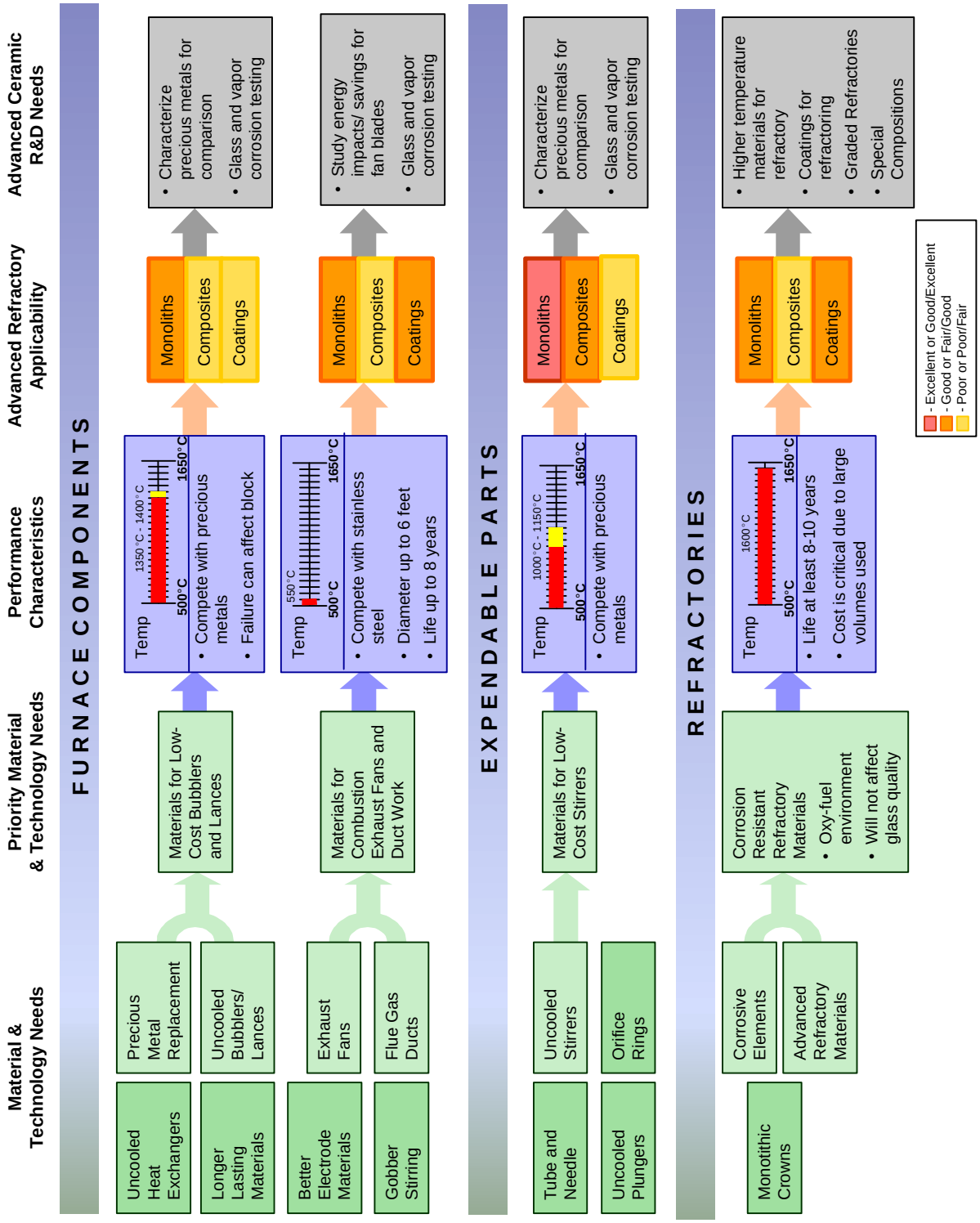

Exhibit 5. Opportunities for Advanced Ceramics in Glass Melting

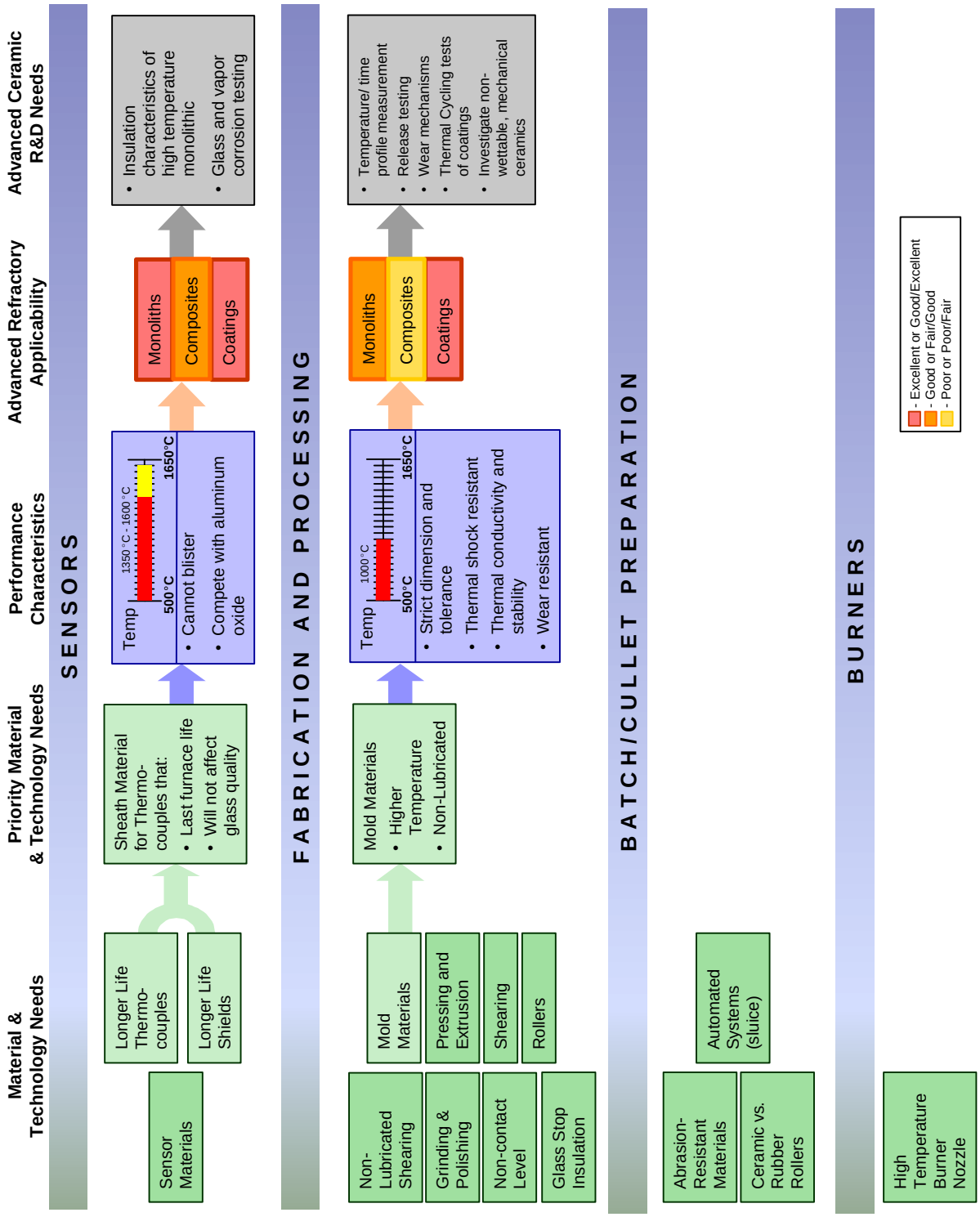

Exhibit 5. Opportunities for Advanced Ceramics in Glass Melting (cont.)

Advanced monolithic ceramics are believed to be best suited to replace current materials, as coating tubes with small holes could be problematic and there would be little value added by utilizing higher cost composites. Specific R&D needs include characterizing precious metals used for comparison and testing replacement ceramic materials for corrosion in various glass melt compositions.

Materials for Combustion Exhaust Fans and Duct Work

Variable speed furnace exhaust fans and associated duct work help regulate hot gas flow and are also used for environmental control. In many instances there are two fans, one outside the furnace before an environmental control device such as an electrostatic precipitator, and one between the control device and the exhaust stack. By the time the exhaust gas reaches the first fan, it usually has cooled to about 550°C. Duct work, especially close to the furnace, is typically ceramic-lined and may extend 100 feet from the furnace. Fan blades, which rotate at speeds up to roughly 1000 rpm, are primarily made of stainless steel and may be as large as six feet in diameter. While exhaust fans generally last the life of the campaign, premature failure can be caused by corrosion, particularly for lead glasses. Particle impingement can also be a problem. Although exhaust fans could be replaced during the campaign, glass manufacturers would prefer to avoid it.

Lightweight ceramics may be able to replace the heavier stainless steel fan blades currently used. Monoliths have potential, although further analysis of stresses in the fan blades would be needed considering the operating speed. Composites are a good candidate material, assuming the energy savings are sufficient to justify the cost of the composites. In addition, composites would not fail castastrophically. Coatings would be the least likely replacement material since the energy savings in the lightweight ceramics would not be present. There is also some uncertainty whether coatings would last in the operating conditions, but coatings could help reduce particle impingement. The main R&D need is to study energy savings and impacts for fan blades. Corrosion testing of glass vapor compositions is also required. Ceramic manufacturers would need to work with fan manufacturers to downsize the entire fan system, including the motor, to operate with lighter ceramic blades. Finally, fabrication of ceramic monolith blades at the sizes necessary may require additional research.

Materials for Low Cost Stirrers

Stirrers are used to improve homogeneity in the glass melt and increase the time the melt is in the melter. Stirrers are typically near the end of the furnace, where the melt temperature is around 1000-1150°C. Stirrers are paddles usually made of either platinum or water-cooled stainless steel, but could be made of fused silica or bonded alumina-zirconia-silica (AZS) for furnaces with short campaigns or lower value markets where production cost is more important. Stirrers only operate at 20 rpm or lower, since higher speeds will increase shear forces enough to cause blisters in the glass. Accordingly, brittle failure of ceramics should not be a problem once installed. Stirrer materials are exposed to both the glass melt and the atmosphere; if the material were to fail it will end up in the melt. Therefore, substitute materials must not adversely affect glass quality. Platinum stirrers are made at considerable expense, and environmental hazards are associated with platinum part manufacture and recovery.

Monoliths appear to be the most likely replacement material, whereas composites would be less desirable since there is little value added by using the higher cost composites. Coatings would be the least appropriate due to concerns of wearing of the coatings in the melt. As with bubblers and lances, the main R&D need is to characterize precious metals for comparison and corrosion testing of advanced ceramics in several glass compositions.

Corrosion Resistant Refractory Materials

Refractories encase the melt at about 1350°C and the atmosphere above the melt at about 1600°C. Refractory life and cost are major issues, since the volume of refractories needed is quite large and the refractories can be the time limiting factor in the campaign. The weight and creep characteristics of refractories are also important, and the thickness required may change depending on the type of material used. As crowns corrode, pieces of the refractory may fall into the melt. This requires that refractory materials do not corrode during the campaign or if they do, glass quality will not be affected. In large glass furnaces, a 1% glass loss could translate into about $1 million a year. The current cost of fused silica refractories to glass manufacturers is about $1000 for a block 42" x 18" x 12". Vendors provide refractories to various industries at $5-50 per pound depending on their complexity and the industry served.

Monoliths may be a potential replacement material, but composites are an unlikely replacement because little value is gained for the higher cost. Coatings, including the development of graded refractory structures, may also be a good replacement material. Refractory R&D needs include development of higher temperature materials, coatings, graded refractories, and special refractory compositions for specialty glasses.

Sheath Materials for Thermocouples

The glass industry has identified improved process control as a key for productivity improvement and one of its highest priorities. At the heart of process control are sensors, including thermocouples that provide temperature data and help operators control the process. Other measurement systems are available and used, but do not give enough information for effective process control. Glass manufacturers often use many thermocouples with the understanding that some will likely fail during the campaign. (Thermocouples are usually not replaced during the campaign.) Failure is mainly caused by corrosion, although erosion is also a concern. Thermocouples operate both in the melt and above the melt at 1350-1600°C. As with refractories, interaction with the melt is also an issue since the material could fall into the melt and adversely affect glass quality. Glass manufacturers would like thermocouples to last for the entire campaign, and are looking for better materials for thermocouple sheaths. Currently, sheathing is commonly aluminum oxides. Because the volume of material is quite low, cost is not a major concern.

Monoliths, composites, and coatings are all likely replacement materials. The main R&D need is for corrosion testing of advanced ceramics in various glass compositions. Some experts believe that the development of innovative high-temperature measurement systems may eventually replace thermocouples in glass furnaces.

Mold Materials

Molds generally receive molten glass at about 1000°C, where the glass is cooled to about 500-600°C and then released. Molds are generally complex shapes that are machined to size. Molds have strict dimensional tolerances and need to display good thermal shock resistance, thermal conductivity, stability, and wear resistance. Cast nickel, cast iron, tool steel, and graphite are common mold materials. Normally, molds are cooled to help thermal stability of the mold. In many cases, the molds are lubricated with lubricants such as renite, which causes smoke and requires fans to keep the plant environment clean.

Monoliths are a promising replacement material, but probably only for smaller molds where the fabrication cost of the monolith would be economical. Composites are not a likely replacement material, as little value is added by using the high cost composites. Coatings appear to be an excellent replacement material, and would likely be applied by a wash or spray coat. However, coatings may be a good match only for certain glass compositions. Mold coatings have not been explored much by glass manufacturers. R&D needs include measuring the temperature/time profile of molds, release testing, understanding of wear mechanisms, thermal cycling tests of coatings, and developing non-wettable, machinable ceramics.

R&D Priorities

The application of advanced ceramics in the glass industry may have the best initial opportunity in niche specialty glass applications where performance is critical and product value is high. In addition, campaigns in these applications are often significantly shorter. Because these operations can have special compositions, it is difficult to generalize about their effectiveness in the large variety of glass compositions used by the industry.

R&D priorities for applying advanced ceramics in glass production may be grouped into seven categories:

- Refractory Materials,
- Materials Characterization and Data Development,
- Studies, Modeling, and Analysis,
- Fabrication Approaches,
- Mold Material Needs,
- Alternative Heating Methods, and
- Other.

Exhibit 6 presents specific R&D needs for each of these categories and are described below.

Materials characterization and data development underlies nearly all research needed to make advanced ceramics commercially viable in glass manufacturing environments and is by far the highest priority R&D area. Ceramic manufacturers need to know how a certain type of advanced ceramic will perform in a given glass environment. This requires testing in a variety of glass environments. One roadblock to using new materials in glass industry applications is the resistance to innovation in the glass industry. Glass manufacturers are much more likely to use a material once it is successfully tested and used by someone else. Corrosion testing of ceramics, in

both the glass melt and combustion space atmosphere, is the most critical need. Options meeting this need include using experimental facilities such as those at the Center for Glass Research and Oak Ridge National Laboratory to test five base glasses and perform blister tests. Supporting these tests is the development of a database containing information on how glass composition affects corrosiveness, temperature limitations and stability of ceramics, and prototype demonstration and testing. A potential sequence of these and other crosscutting needs is shown in Exhibit 7.

Exhibit 6. Research Needed to Foster Use in Glass Melting

(✪ = Top; **F** = Other)

Materials Characterization and Data Development	Refractory Materials	Studies, Modeling, and Analysis	Fabrication Approaches	Mold Material Needs	Alternative Heating Methods	Other
Develop baseline on various glass types Glass and vapor corrosion testing - 5 base glasses - CGR R&D - Blister test - Above and below melt ✪✪✪✪✪✪✪✪✪✪ ✪✪✪✪✪ **F** Database on how glass composition affects corrosiveness **F F F F F F F F F F** Insulation characteristics of high temperature monoliths **F** Quantify emissions and environmental factors Data on temperature limitations and stability of ceramics **F F F F** Characterize precious metals for comparison **F F** Prototype demonstration and testing **F F F F F F**	R&D on higher temperature materials for refractories ✪✪ **F** Coatings on refractories **F F** Feasibility of graded refractories **F F F F F** Develop special refractory compositions **F F F F F**	Energy modeling **F F F F** Economic modeling **F** Characterize life expectancy modeling Energy modeling of innovative designs (Backward engineering to materials) **F** Study energy savings for fan blades **F**	Coatings for ceramics and composites **F F F** Examine solid freeform fabrication (bubbler) Investigate non-wettable, machinable ceramics **F**	Accurate measurement of temperature-time profile for mold Test for mold release characteristics Wear mechanisms on molds Coatings on molds - Thermal cycling tests ✪ **F F F F F F F** **F**	Submerged burner **F** Microwave Examine advanced ceramics for heat pipes **F F F F F F** Ultrasonic Vacuum **F** Ceramics for catalytic combustion **F F F F** Waste heat recovery (study feasibility)	High temperature filter **F** Durable high-termperature measurement systems for process control - new methods of temperature measurement **F** Better terminology between advanced ceramics suppliers and glass industry - Avoid over-engineering

There are four important R&D needs for ***refractory materials***. In general, R&D is needed on refractory materials that can operate at higher temperatures. Additional R&D is needed to examine coatings on refractories, the feasibility of graded refractories, and the development of special refractory compositions.

In the area of ***studies, modeling, and analysis***, energy modeling is a priority. Ceramic manufacturers would like to see a generic energy model of a glass furnace. While data on a specific furnace may be collected, it is not generally shared with the glass community due to proprietary concerns. Ceramic manufacturers would also like a more thorough analysis of where energy is used in glass plants to determine where ceramics may be applied to reduce energy use. One possible approach may be to study European glass plants.

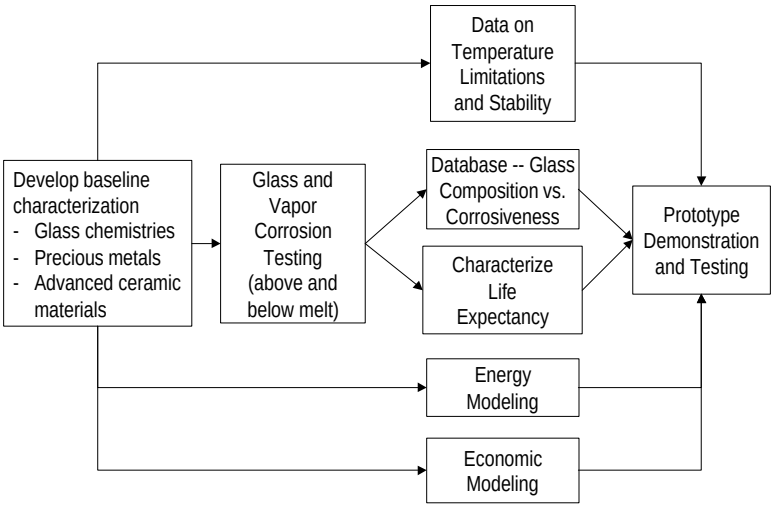

Exhibit 7. Materials Characterization R&D Activities

Research is needed on ***fabrication approaches*** for coatings for ceramics and composites, along with non-wettable, machinable ceramics. The major ***mold material*** need (coatings are considered the most likely candidate for mold materials) is R&D on coatings, particularly testing the performance of coatings under thermal cycling.

Alternative heating methods include the use of advanced ceramics to enable radical changes in furnace design. These include examining advanced ceramics for heat pipes, ceramics for catalytic combustion, submerged burners, and vacuum melting.

Finally, ***other*** needs that have potential for glass industry application include research on high temperature filters for screening glass seeds and durable high-temperature measurement systems for process control, including the development of new methods for temperature measurement.

CHAPTER 3

Glass Fabrication: Opportunities for Advanced Ceramics

Glass Fabrication

Glass fabrication – defined here as the processing, forming, and finishing that takes place after the molten glass leaves the furnace – is a capital-intensive, energy-demanding process in the flat glass, container glass, fiber glass, and specialty glass industries. Many of the critical material and technology needs in glass fabrication could be met by advanced ceramics, provided they are developed for specific applications. However, advanced ceramics need to be evaluated in extreme glass processing environments before they are accepted for commercial application.

There are three major objectives in glass fabrication: lower manufacturing costs, faster production lines, and higher glass quality. Reducing the cost of materials is important, especially in applications using precious metals. Increasing the life of a material enhances productivity by postponing the need for material replacement and by decreasing defects imparted to the glass. Thus, higher cost materials can be justified by increasing material cost-effectiveness. The life of a component has to be balanced with the life of the system in terms of costly shut downs for change-outs. If a new material can make a contribution to the life of the system, not just the life of a component, even greater value is added to the process. New materials with superior properties can enhance productivity by reducing glass defects and rejects, and by enabling the production line to produce more pieces per minute.

Glass fabrication presents a variety of material and technology challenges (Exhibit 8). In general, most glass contact refractories – the specialized heat-tolerant materials used – are made with oxides; lower temperature applications use metals or metal alloys. Improved wear resistance, corrosion resistance, and thermal conductivity are among the beneficial characteristics that advanced ceramics can bring to glass production.

A primary goal in glass fabrication is to control the reduction in temperature as glass moves from a fluid to a rigid state. Material in contact with the glass must impart the proper heat transfer properties to avoid the creation of defects. Different cooling rates are needed in different parts of a glass product, and inconsistency in temperature changes during glass forming and fabrication can lead to product loss. High heat transfer rates are needed in the case of molds, and low heat transfer rates are needed in the case of forming and conveying devices. Thinner glass lends itself to faster heat transfer, allowing processing to operate faster. Thicker glass takes longer to become rigid and, therefore, is more sensitive to surface defects and quality variability.

Exhibit 8.
Technology Considerations in Glass Fabrication

Glass Composition and Atmosphere Issues
Glass Chemistry and Variability
High and Fluxuating Temperature
Controlled Nitrogen/Hydrogen Atmosphere

Material Life and Performance Issues
Reactivity with Glass or Atmosphere
Wear Resistance
Thermal Conductivity
Thermal Shock
Corrosion Resistance
Diffusivity, Porosity and Solubility

New materials are needed to increase glass quality and to reduce production losses from glass defects and breakage. A major concern in glass processing is the environmental and material effects on the surface of the glass produced. The strength of glass is determined by the glass surface, and any contact with glass surfaces can cause defects, especially while solidifying. Defects can cause rejection of the glass or a jam in the system that causes the system to shut down. These continuous, highly mechanized, and synchronized systems operate at high temperature in dirty, smoky ambient conditions with flying glass from problem machines.

Flexible processing capability is required to convert the system to the needs of a specific product line and to adapt to new production needs. New, higher-value glass with stricter processing requirements is becoming a larger part of the product mix. For example, today there is a broader family of glass types that require a broad range of operating conditions and process needs, such as privacy and low-e glass.

Critical Material and Technology Needs in Glass Fabrication

While there are many common material needs in glass melting, the differences inherent in the forming and finishing of plate glass, auto glass, fiber glass, bottles, televisions, tableware, and other glass products result in many diverse material needs. The critical needs in each of the four main glass sectors are presented below along with a summary of key process requirements.

Flat Glass Fabrication

Products of flat glass include windows, windshields, and mirrors. Key process steps include the float zone furnace, annealing, tempering, and reforming.

Float Zone Furnace

In flat glass processing, the float zone furnace regulates the flow of molten glass onto a tin bath. The glass is transferred through the process in the Lehr and becomes rigid in 10 to 15 minutes.

The molten glass ribbon changes widths and thickness to meet product requirements through a day's operation. Materials in contact with the glass and the atmosphere must withstand high temperatures while maintaining their strength and coatings, and while meeting the glass requirements for high optical quality and no defects. A typical lifetime for float zone furnaces is 10 or more years.

Exhibit 9. Critical Needs in Float Furnace

✪ = Highest Priority; ✦ = Greatest Opportunity

- Longer life tweel refractory ✪
- Improved forming lip ✪
- Longer life bath roof which is hung on a metal structure that is 1400°F to1500°F (760°C to 815°C)
- New materials for tightly sealed and flexible tin bath (no O_2) (avoid water cooled wheels) ✪
- Methods and materials to prevent tin from picking up compounds from glass and reacting with the refractories
- High temperature non-contact sensors for ongoing oxygen analysis in tin
- Replace refractory-lined bath ✪
- Thermocouple in tin under glass ribbon that will not float up
- Materials that survive corrosive tin-atmosphere interface (coolers, thermocouples) ✦
- Heat exchangers above the glass for waste heat recovery ✦
- Gas-fired radiant burners without O_2 that are muffled in a radiant tube, with low operating cost and turndown capability ✪
- High-temperature fans
- Longer life heating elements that do not form compounds with atmosphere ✪
- Uncooled sensors
- Improved materials for edge stretching drives that are flexible and sealed

Critical needs in the float zone furnace are shown in Exhibit 9. The float zone furnace atmosphere is nitrogen with five percent hydrogen. The hydrogen scavenges oxygen which otherwise cause platinum used in the process to become brittle. Any material in contact with the glass can alter the glass chemistry and change its gas solubility. Electric heaters made of silicon carbide are currently used above the glass to control temperature and to put heat into the bath. Replacing the electrical heating system with a gas system could reduce operating costs, but such a system would need to be enclosed and muffled to avoid oxygen or fcombustion gas contamination of the glass and to maintain the controlled nitrogen atmosphere.

The tweel, located at the top of the forming lip, is the refractory dam that controls the amount of glass flowing into the tin bath at 2050°F (1121°C). Currently, the fused silica tweel refractory is replaced every 6 to12 months due to wear, corrosion, and thermal degradation. During replacement, the ribbon of glass is diverted to another tweel further down in the process. Sealants are needed to prevent tin vapors (tin sulfide and tin oxide) from leaking and creating defects.

The stationary forming lip is the refractory that delivers up to 600 pounds of glass per day from the elevation of the furnace to the elevation of the tin bath. Currently, the fused cast alumina lips (40" wide) typically last one to four years due to cracking, wear, and corrosion which contaminates the glass. Replacing the lip takes one to five days and requires a costly hot shut down. The higher the temperature, the more wear on the forming lip. Glass that comes in contact with the lip is trimmed off to avoid glass defects, causing significant melt loss.

The refractory lining of the tin bath – the actual tub the tin bath sets in – is a problem because the fire clay material that is used, peels and shells when it comes in contact with the ribbon of glass. Corrosion, usually due to wear, occurs at both the glass-atmosphere and the refractory-glass interfaces. Half of the 200-foot refractory is replaced every 10 years which requires a cold shut

down. Steel bolts that are corroded by the tin are used to bolt blocks (18" x 36" x 12") to the bottom of the bath and prevent them from floating.

Annealing, Tempering, and Reforming

In the annealing process, hot glass undergoes controlled cooling to reduce thermal residual stress. The annealing process is typically 450 feet long (twice as long as the bath). Most Lehr rolls are electrically-driven, 12" in diameter, 18" apart, operate at 1100°F (593°C), and fail due to bearing wear. The water-cooled annealing rolls are 300°F to 400°F (149°C to 204°C) and are outside the annealing layer. The Lehr rolls along the float line pick up tin, which imparts defects to the glass and is difficult to locate. When the Lehr rolls lift the glass off the tin, the glass and atmosphere are sealed using fiberglass curtains. The curtains maintain the desired nitrogen atmosphere but they can mark the glass. Critical needs in annealing are summarized in Exhibit 10.

Exhibit 10. Critical Needs in Annealing
✪ = Highest Priority; ✦ = Greatest Opportunity

- Better seal at beginning of Lehr between glass and atmosphere
- Better materials for longer life transport rolls that do not impart defects to glass or pick up tin ✪
- Replace asbestos transport rolls ✦
- An atmosphere that creates glass layer to keep glass from getting marked by rolls (avoid sulfate modules)
- Lehr roll materials that are self-lubricating and do not stain the glass, attract tin, or cause defects ✦
- High-temperature non-contact sensors including sensors for temperature, oxygen content in tin, and composition
- Low maintenance radiant heaters ✦✪
- Scoring tools for running and snapping

In the tempering and reforming process, the glass is cooled, re-heated, and re-cooled without imparting defects to the glass. In this flexible operating environment, many tools are used including wheels to grind the edges of glass. Critical needs in tempering and reforming are shown in Exhibit 11.

Exhibit 11. Critical Needs in Tempering and Reforming
✪ = Highest Priority; ✦ = Greatest Opportunity

- Improved hot handling materials ✦✪
- Rolls that withstand high temperature and do not damage glass strength or coatings ✦
- Adequate grinding wheels
- Burner nozzle material that cost less and impart fewer defects
- Process controls to speed up the process including temperature gradient controls and sensors
- Improved rolls for SO_2 heat transfer, temperature measurement, heating elements
- [Reforming needs are similar to Tempering needs]
- Improved mold materials and manufacturing methods ✪
  - Better mold materials for automobiles
  - Improved mold release coatings or film barriers ✦
- High temperature non-contact sensors

Container Glass Fabrication

Products of the container glass sector include bottles, jars, and other glass containers. Major process concerns include the gob feeder, sensors, molds, and conveying.

Gob Feeder

The melting process in container glass is similar to flat glass although the optical quality requirements are not as high. In container glass, the molten glass is channeled into multiple production lines in order to make different sizes and types of containers simultaneously. Streams of glass are cut by shears that form gobs up to 60 pounds. The gobs are dropped onto the individual section machine which receives one to four gobs at a time; 6 to 20 individual section machines are in continuous operation. Gobs at 2210°F (1210°C) are reduced to 900°F (482°C) in the container mold in ten seconds, with 600 containers per minute produced from a typical machine. The process is designed to control the glass temperature as the glass goes from a liquid to a rigid product in the mold.

Exhibit 12. Critical Needs in Gob Feeders
✪ = Highest Priority; ✦ = Greatest Opportunity

- Longer life materials where gob is formed
- Longer life of refractories (now 6 weeks to 1 year) ✦
- Non-expendable, lower-cost orifice through which glass gobs flow that stay the same size for weeks (avoid precious metals on sharp edges that wear) ✦
- In-glass temperature measurement device to replace precious metals (before gob is formed) ✦
- Lower cost glass-contact sensors – a sheath to protect thermocouple (2000°F to 2200°F [1093°C to 1204°C]) ✪
- Longer life stirring devices to maintain uniform temperature where glass flows into feeder ✦
- Lower cost stirrer materials (to reduce erosion), plunger materials, and un-cooled cutter materials ✪
- Eliminate water cooling of metallic shears that use oil for lubricity (water and lubricants lead to defects) ✦
- Lower maintenance-requiring mechanical devices (bearings, lubricants) ✦

During glass delivery into the fabrication machine, the glass, over time, erodes or corrodes the traditional refractories and the refractories that are coated with precious metals (used to minimize the rate of deterioration). Materials are needed to improve the refractory life without the capital investment required for precious metals. Exhibit 13 presents a summary of the critical needs of gob feeders.

Sensors

Thermocouples are in contact with the atmosphere above the glass and in the glass melt itself. The materials are often unsatisfactory and are often coated with costly precious metals to decrease the rate of deterioration. Efficiencies could be gained from better temperature measurement of the float bath. Long-life alternative materials are needed to improve thermocouple life, which currently is three to four years. Exhibit 13 presents the critical needs in sensors.

Exhibit 13. Critical Needs in Sensors
✪ = Highest Priority; ✦ = Greatest Opportunity

- An automated individual section (IS) machine to meter heat flux in the highly mechanical system ✪
- Longer life thermocouple shields✦

Molds

Exhibit 14 presents the critical needs in molds. Molds require a high capital investment because each glass article is made with a different shaped mold. Molds are usually made of metal and require surface coatings to aid release of the glass product. The molds are preheated in gas ovens to 400°F to 500°F (204°C to 260°C); they are further heated by the molten glass to 700°F to 800°F (371°C to 427°C) once in the system. Currently, there is no automatic way to control mold temperature. Molds are changed for each category of container one to two times per day which interrupts the glass flow and production, and causes temperature cycles for the refractories.

Exhibit 14. Critical Needs in Molds
✪ = Highest Priority; ✦ = Greatest Opportunity

- Better mold materials ✦✪
- Alternative materials in cast iron molds
- Higher toughness materials with improved oxidation resistance ✪

The individual section machine manages the gobs, the opening and closing of the molds, and the transfer of the solidified glass. Molds can be damaged if glass flow is altered and becomes brittle. The costly molds suffer from damage and wear that can lead to glass breakage and production disruption. Up to 10 percent of the individual section output is lost due to wreckage. The entire individual section has to be shut down to clean up the breakage and repair molds, creating heat loss from the mold and glass. Metallic flakes from the cast iron molds can also create glass defects. Molds for wide automobile windshields are currently covered with a high temperature fiberglass that wears out and requires replacing.

The individual section machine is currently limited in the amount of energy that it can extract from the glass per second. If the heat could be extracted faster with proper control, the equipment could operate more rapidly and the entire mold process could be improved. Different areas of the molds, such as the thread, have different heat transfer properties. Alternative materials to the traditional metallic molds are needed that have heat transfer capabilities that allow higher heat transfer rates, higher processing rates, more durability to minimize maintenance problems, greater toughness, and are designed to avoid oxidation (metal molds are near temperatures where oxidation occurs rapidly).

Conveying

In conveying, the production goal is to control the movement of glass and avoid the generation of defects. Conveyers 10 to 16 feet wide move the glass to the annealing process where the glass is re-heated then cooled in the Lehr. The metallic conveyers need to be heated to a compatible temperature, otherwise they become a heat sink and cause localized cooling on the glass article surface which can result in cracking and defects. In the forming process (including bending, tempering, and fire polishing), various materials used come in contact with the glass. Currently used materials exhibit unsatisfactory wear rates, thermal properties, or structural properties that can lead to production inefficiencies. Hot end coatings (tin oxide or

Exhibit 15. Critical Needs in Conveying
✪ = Highest Priority; ✦ = Greatest Opportunity

titanium oxide), polyethylene coatings, or water soluble coatings are placed on glass bottles during the finishing process. Bottles are inspected for defects by devices that squeeze or by lasers, and then they are placed into boxes for shipping. Exhibit 15 presents the critical needs in conveying.

Fiber Glass Fabrication

Products of fiber glass include building insulation and textile fibers used in reinforcing plastic composite car bumpers. Typical fabrication processes include melting, wool forming, and textile forming.

Melting

Exhibit 16 presents the critical needs in melting. The melting process is similar to flat glass and container glass except that borates tend to foul the exhaust systems. Molten glass from the furnace in moved into four or more channels to fiberizing stations where the temperature drops from 2000°F to 500°F (1093°C to 260°C) in one second.

Exhibit 16. Critical Needs in Melting
✪ = Highest Priority; ✦ = Greatest Opportunity

- Eliminate borates problem that limits refractory life and furnace life -- this causes localized high-wear at neck and raw materials feed point (fluxes) ✪
- Non-recuperative furnaces that last longer especially at curves and wells (if furnace has not been switched to oxy fuel)
- Methods to manage high-alkaline water vapor when using oxy fuel furnaces and capture heat in exhaust ✪
- Non-deteriorating radiant burner tips
- Temperature-resistant materials for radiant burners in oxy fuel furnaces ✦

Wool Forming

Exhibit 17 presents the critical needs in wool forming. In wool forming, glass falls into a rapidly spinning container with steam or compressed air much like a cotton-candy machine. Very thin fibers (20 to 30 microns in diameter) are removed from the process and are ready for use.

Exhibit 17. Critical Needs in Wool Forming
✪ = Highest Priority; ✦ = Greatest Opportunity

- Low-cost centrifuge material✪
- Precious metal replacement for sieves and bushings ✪
- Better materials for handling glass going into the fiberizing machine (very corrosive environment)
- Avoid costly platinum use in maintaining orifice size ✦
- Replace precious metals in high-wear areas with low cost materials ✦

Textile Forming

Exhibit 18 presents the critical needs in textile forming. In textile forming, molten glass is fed into channels that flow onto platinum plates with many tiny orifices that are selectively heated. The glass is pushed, pulled, or thrown through the orifices to attenuate the glass into thin strands.

Exhibit 18. Critical Needs in Textile Forming
✪ = Highest Priority; ✦ = Greatest Opportunity

- Precious metal replacement for bushings ✦✪
- Improved fiber handling materials

The orifices can be fouled from glass-metal reactions and from silicon gas volatilization which causes crystalline defects in the glass. The orifice size changes overtime from wear and thermal

shock, and the platinum plates have to be replaced and recycled. Fibers are formed from several strands that are spun together and coated at high speeds. Continuous fibers over a mile long are bundled together and are formed into products.

Specialty Glass Fabrication

Exhibit 19. Critical Needs in Specialty Glass
✪ = Highest Priority; ✦ = Greatest Opportunity

Specialty glass products encompass a wide variety of products we encounter in our daily routines. Examples include light bulbs, tableware, cookware, televisions, and fiber optics. The specialty glass sector produces thousands of different products, many in small volumes. It includes all glass products that are not produced by the flat glass, container glass or fiber glass sectors. The molten glass typically has different compositions and the system operates at higher temperatures. Operating conditions both above and below the molten glass are much harsher. Exhibit 19 presents the critical needs in specialty glass.

R&D Priorities

Many of the material and technology needs of glass fabrication can be met by advanced ceramics, provided that a focused research and development effort is pursued. R&D needs of advanced ceramics include both overarching R&D requirements and specific requirements. Each are described below.

Overarching R&D Needs Related to Glass Fabrication

Exhibit 20. Overarching R&D Needs in Advanced Ceramics for Glass Fabrication

- Collect information about ceramic use in glass processing (include successes and failures)
- Develop a ceramic and glass compatibility database
- Conduct research to test ceramic and glass compatibility
- Conduct economic analysis comparing ceramics to the currently used material
- Develop ceramics with the greatest potential to increase glass processing productivity
- Demonstrate ceramics with the greatest glass productivity payoffs
- Develop new lubrication systems for ceramics
- Investigate glass processing issues that result from replacing metal parts with ceramics
- Develop design methods to investigate process changes that might be required to take advantage of ceramics and enhance the process

Exhibit 20 presents the overarching R&D needs to promote the use of advanced ceramics for glass fabrication. These overarching R&D needs encompass a systematic approach to R&D that could focus research efforts and optimize the investment of research dollars.

The chemical compatibility of advanced ceramics in a glass processing environment is not well understood. Therefore, research to investigate the material and chemical compatibility of advanced ceramics is a priority. Many ceramics have been tested in the past; the results of these tests should be surveyed and

summarized. From this, candidate ceramic materials can be defined, and an efficient test plan can be developed to screen key ceramics for specific applications in glass processing. A single test could screen ceramics for several glass applications. For candidate materials with the greatest performance potential and with widespread application in glass processing, further specialized tests can be conducted.

A major concern in glass processing is the effect a material has when it comes in contact with molten and rigid glass. Any contact with glass surfaces can cause defects, especially while solidifying. An important initial R&D step is to investigate the types and causes of defects and how ceramics could prevent them. Once this relationship is understood, candidate ceramic materials that may eliminate the causes of defects can be evaluated.

The application of an advanced ceramic in glass processing will usually not entail a one-to-one replacement with the currently used material. Process changes might be required to take advantage of the ceramics and enhance the process and will need to be investigated.

Specific R&D Needs in Advanced Ceramics

Exhibit 20 identifies the specific R&D needed to enable advanced ceramics to meet the critical material and technology needs in glass fabrication. The highest priority needs in glass fabrication are organized into six major categories: Refractories, Precious Metal Replacement, Sensors, Temperature Controls, Handling/Finishing, and Molds. These categories characterize processing similarities among the four glass sectors. *Performance Characteristics* describe how materials must perform in the glass fabrication environment. It includes temperature, material used currently in the process, and the "Achilles Heel" – the component in the system with the shortest life. *Advanced Ceramics to Consider* lists the type of advanced ceramic that researchers will want to evaluate for use in glass fabrication. *Specific R&D Needs* lists research objectives for advanced ceramics to meet the top priority material and technology needs in glass fabrication.

The diverse R&D needs for advanced ceramics focus on extending material life and developing new ceramics with new capabilities to reduce glass production costs, increase production output, and improve glass quality. The overarching and specific R&D needs present opportunities for advanced ceramics to make a contribution to glass processing and play a key role in the growth of the glass industry.

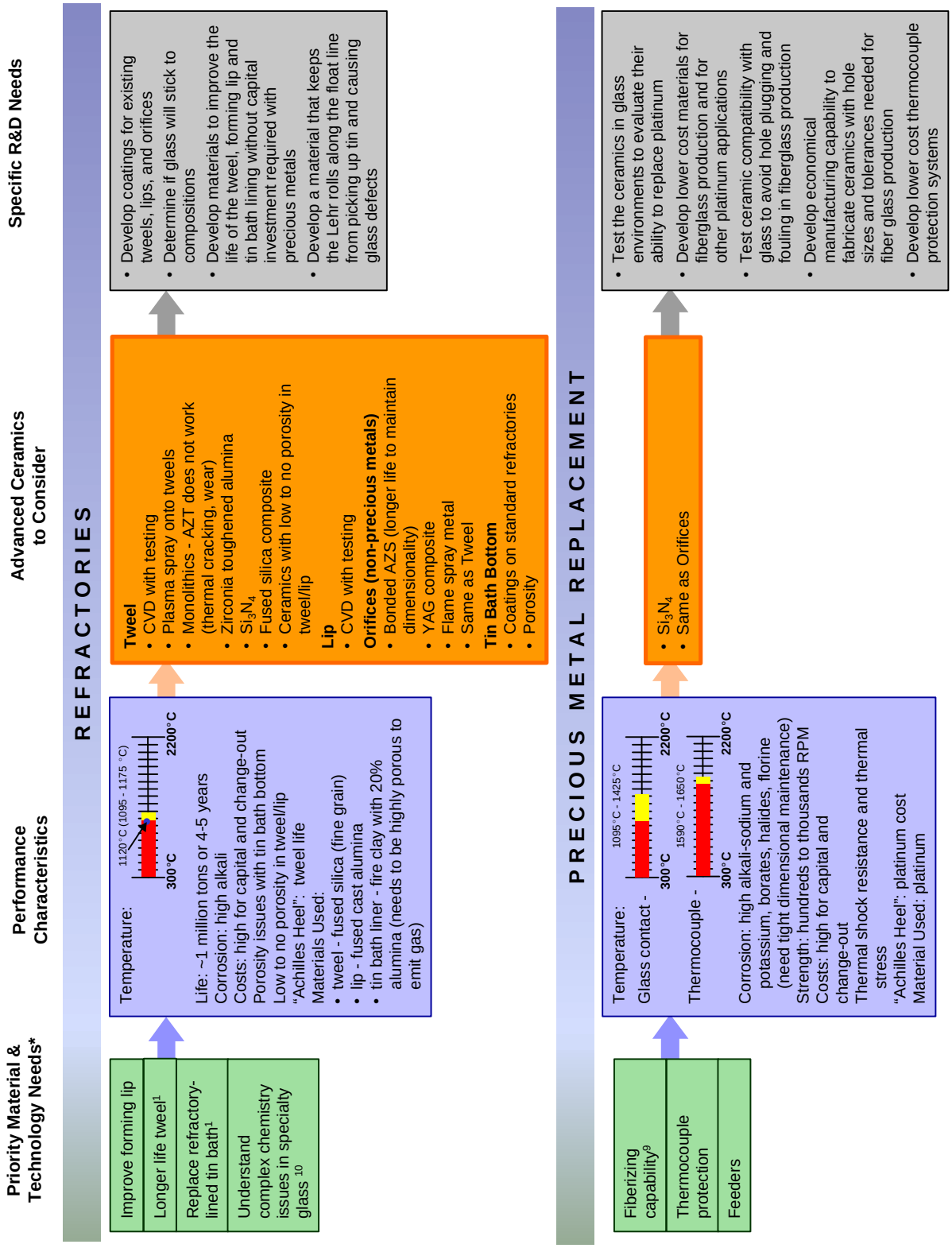

Exhibit 21. Opportunities for Advanced Ceramics in Glass Fabrication

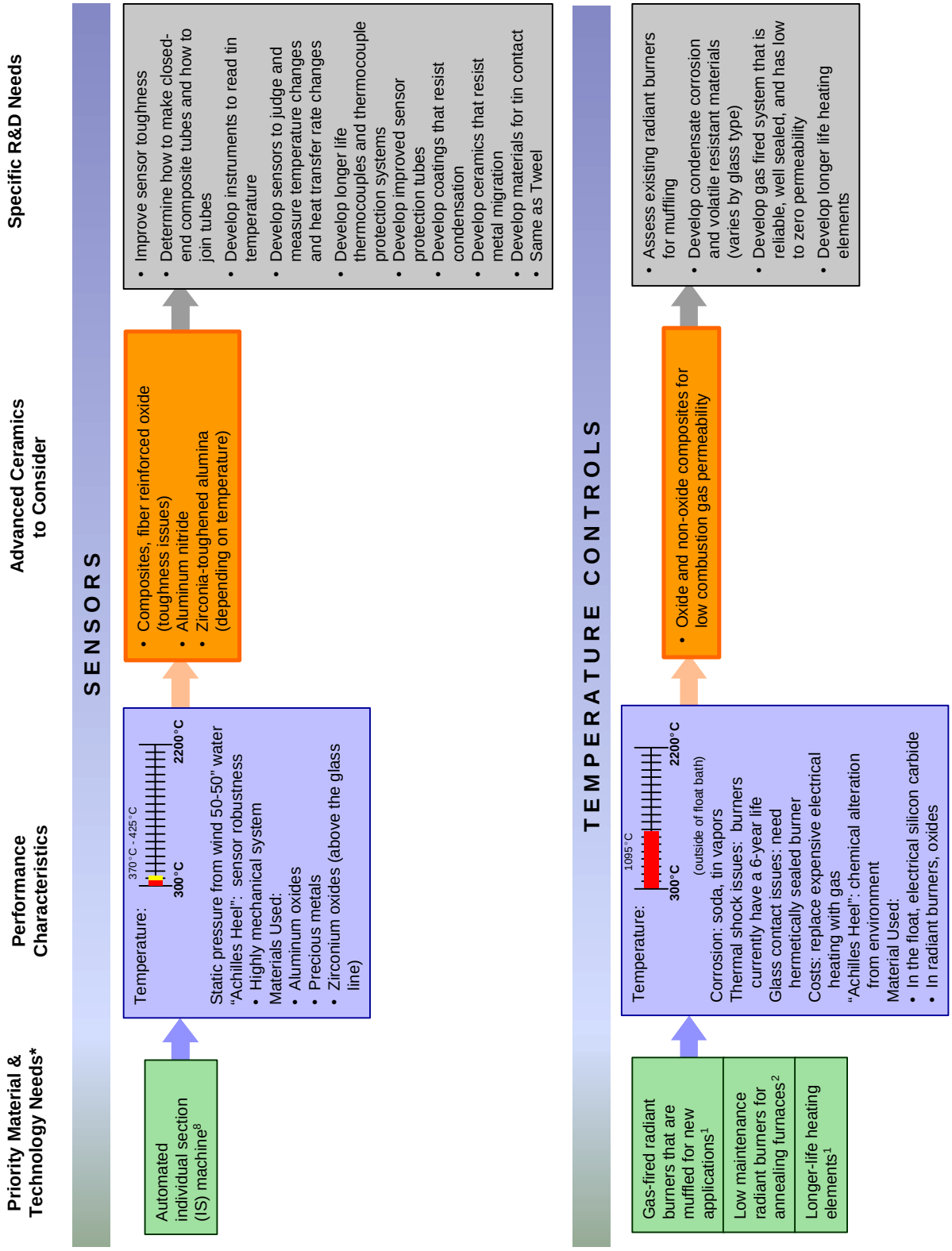

Exhibit 21. Opportunities for Advanced Ceramics in Glass Fabrication (cont.)

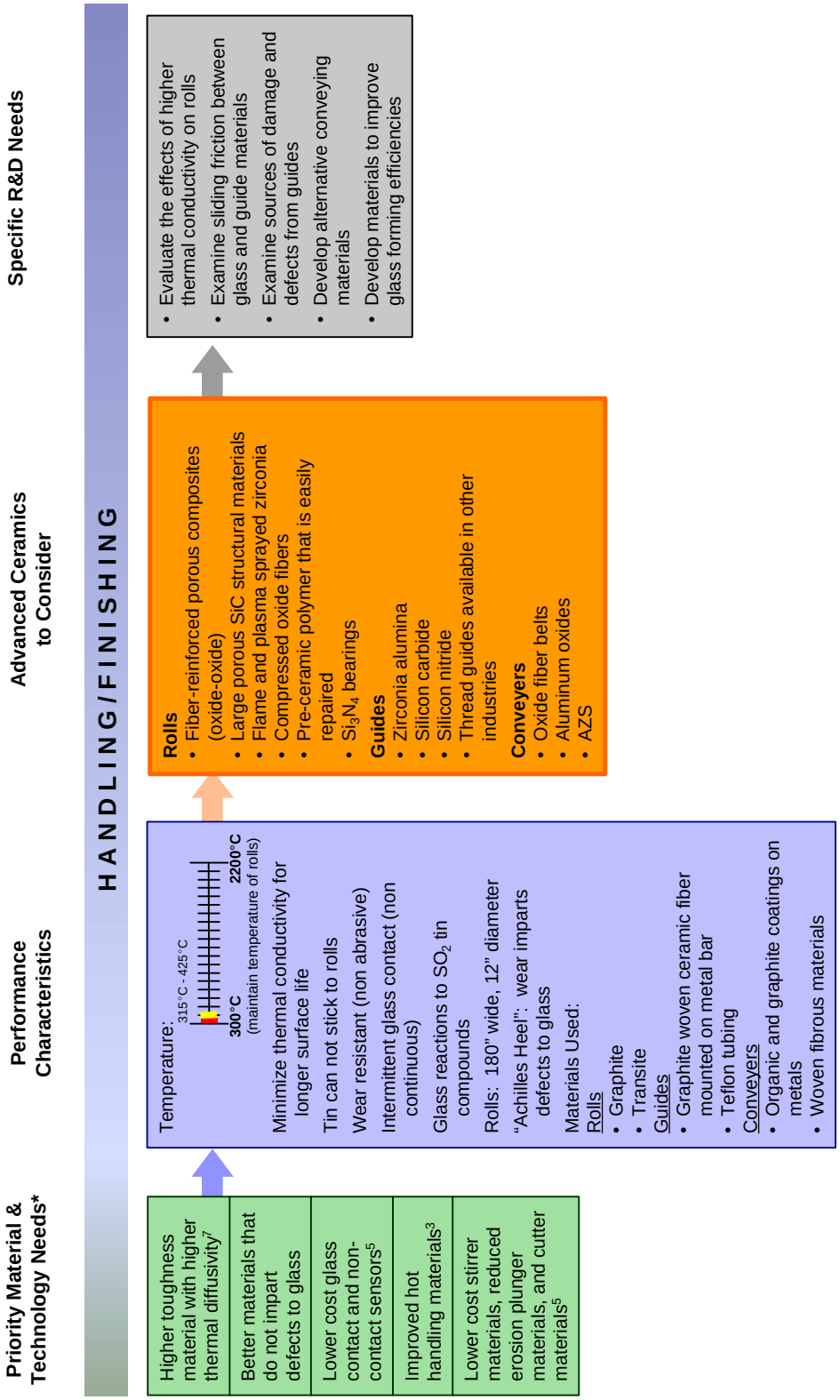

Exhibit 21. Opportunities for Advanced Ceramics in Glass Fabrication (cont.)

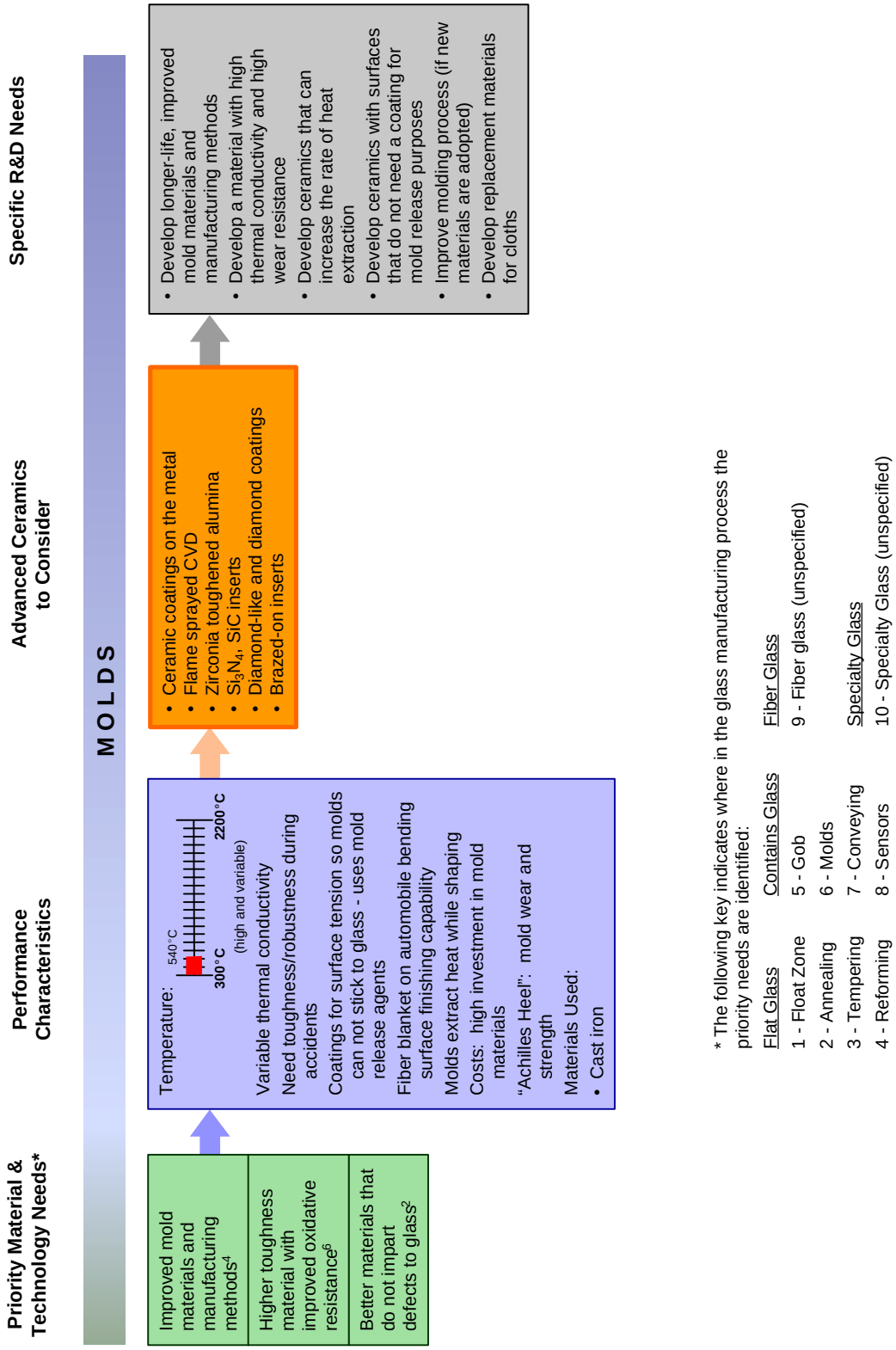

Exhibit 21. Opportunities for Advanced Ceramics in Glass Fabrication (cont.)

APPENDIX A

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APPENDIX B

Agenda

Time	*Session*	*Location*
	Tuesday, September 22	
9:30 - 10:30	Registration and Coffee	Foyer
10:30 - 12:30	**Plenary Session** Welcome – Bruce Boardman, President, USACA Industries of the Future -- Denise Swink, DOE New Developments in Advanced Ceramics Monoliths & Coatings – Bob Licht, St. Gobain Industrial Ceramics Composites – Phil Craig, Dupont Lanxide Overview of U.S. Glass Production and Processes – Philip Ross, Glass Industry Consulting Preliminary Opportunities for Advanced Ceramics – Doug Freitag Introductions and Instructions – Jack Eisenhauer, Energetics	Francis Scott Key Room
12:30 - 1:30	LUNCH	Potomac Salon B (Lobby Level)
1:30 - 5:00	**Breakout Sessions** – *Material and Technology Needs in Glass Processes* 1) **Glass Melting** 2) **Glass Fabrication** (Fluid Glass Handling and Fluid Flow, Production and Fabrication, Low-Temperature Operations)	Georgetown A & B and Francis Scott Key Room
6:00 - 7:00	Reception	"The View"
7:00 - 10:00	Dinner	"The View"

Wednesday, September 23		
7:30 - 8:00	Continental Breakfast	Foyer
8:00 - 8:15	Instructions and Questions – Jack Eisenhauer, Energetics	Francis Scott Key Room
8:15 - 10:30	**Breakout Sessions** – *Research Priorities for the Application of Advanced Ceramics in Glass Production* 1) **Glass Melting** 2) **Glass Fabrication** (Fluid Glass Handling and Fluid Flow, Production and Fabrication, Low-Temperature Operations)	Georgetown A & B and Francis Scott Key Room
10:30 - 10:45	BREAK	
10:45 - 12:00	**Breakout Sessions** (Cont.)	Georgetown A & B and Francis Scott Key Room
12:00 - 1:00	LUNCH	"The View"
1:00 - 3:00	**Summary Session** *Findings of Breakout Sessions* *Closing Comments*	Francis Scott Key Room
3:00	Adjourn	

APPENDIX C

Presentations

Presenters	Presentation Names
Robert H. Licht	Applications for Advanced Ceramics in Glass Production: New Developments in Advanced Ceramics Monoliths and Coatings
Phillip A. Craig	Ceramics Composite Materials for Industrial Applications
Philip Ross	The Glass Industry Past and Present
Doug Freitag	Preliminary Opportunities for Advanced Ceramics