



Glass

Industry Technology Roadmap



April 2002

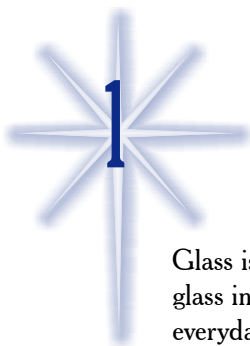
ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

Glass is a unique material that has been produced for thousands of years. The glass industry's products are an integral part of the American economy and everyday life. Glass products are used in food and beverage packaging, lighting, communications, transportation, and building construction. However, the glass industry needs to increase its productivity, reduce its energy use, and lessen its environmental impact.

At a workshop in 1997, members of the U.S. glass industry came together to address these issues. During this workshop, participants identified the most critical technology developments needed to improve glassmaking operations and develop new product classes. Subsequent to this workshop, the Glass Manufacturing Industry Council (GMIC) was established in late 1998, under the auspices of the American Ceramic Society, to promote the interests of the U.S. glass industry in the areas of technology, productivity, and the environment. The GMIC held follow-up workshops in 1999 and 2000 to update and refine the output of the earlier workshop to obtain wider input and develop a more coherent roadmap. The input of these workshops has resulted in the publication of this document.

It is hoped that this technology roadmap will provide guidance to the glass industry as it pursues research and development over the next twenty years. This document defines technical challenges confronting the industry, and outlines a cohesive strategy to ensure future success in this endeavor. By establishing a dialogue among senior technical and business leaders, the roadmap aligns the technical and business capabilities of the glass industry.

STRATEGY

The glass technology strategy is defined in four technical elements:

- ★ **Production Efficiency** - undertake research and development that will help the industry become more efficient, productive, and competitive.
- ★ **Energy Efficiency** - identify and pursue technology that can reduce the gap between current process energy use and the theoretical minimum.
- ★ **Environmental Performance** - achieve cleaner operations with lower environmental control costs and increase glass recycling.
- ★ **Innovative Uses** - develop new applications for glass that reflect a higher technical content and create a positive impact on the industry.

These four elements define the central themes that will guide future research and development investments in order to directly address key challenges that could hinder the industry's future. The U.S. glass industry is committed to pursuing a research and development agenda that recognizes the need for both near-term and long-term research, as well as a clear distinction between pre-competitive process development and proprietary product development. The glass industry intends to ensure that while developing new technology, it will incorporate issues relating to deployment, training, and educa-

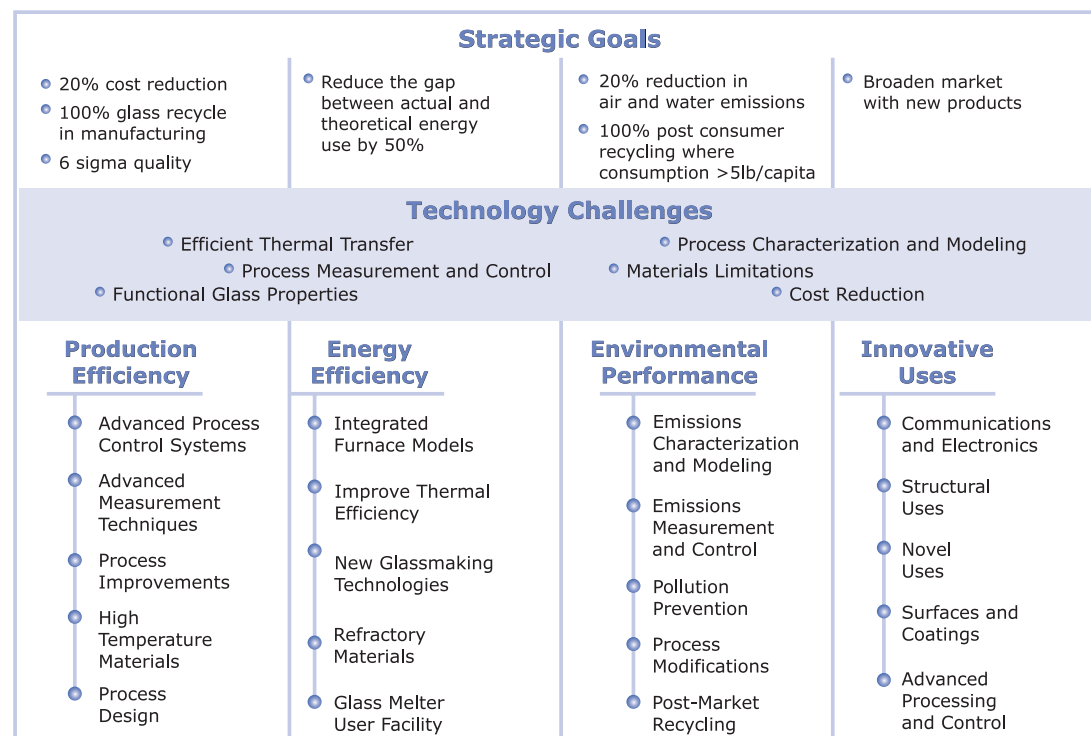
tion. The specific research and development needs for each of the above technology elements are presented in separate sections of this roadmap. A strategic map of key technology priorities and challenges is presented below. Following these sections, interrelationships of the four elements are presented.

IMPLEMENTATION

The glass industry has learned that successful technology development benefits from a coordinated strategy that engages key suppliers, manufacturers, and customers in accomplishing mutual technology goals. The financial and technical resources needed to accomplish this roadmap are beyond the practical reach of individual glass companies. Universities and government laboratories also bring valuable scientific capabilities to overcome current limitations. Government agencies also can significantly contribute to collaborative efforts, provided there are clear public benefits and the activities are appropriate to their missions. Roles for various stakeholders are presented in a later section of this roadmap.

The glass industry looks optimistically towards a bright future. The industry will supply its customers with products that exceed the performance of existing products and do so at lower cost, and will also introduce new classes of products - thereby providing exceptional value and service to its customers. The industry must be aggressive in its commitment to invest in technology, create innovative products, and collaborate where needed. By moving decisively to improve its future, the glass industry intends to survive and prosper in the intensely competitive and challenging global marketplace.

EXHIBIT 1-1. INDUSTRY CHALLENGES AND PRIORITIES



OVERVIEW OF THE U.S. GLASS INDUSTRY

Glass is an integral part of the American economy and everyday life. It is essential for food and beverage packaging, for lighting homes and businesses, for communicating sounds and visual signals, and for commercial and residential construction. The four sectors of the glass industry – container, flat, specialty, and fiberglass – produce over 20 million tons of glass annually, which is used for myriad consumer products ranging from ordinary tableware to televisions to automotive glass.

The unique attributes of glass -- transparency, chemical durability, optical properties, low cost, recyclability -- and the abundance of the raw materials from which it is made account for the ubiquity of glass products in our society and ensure its continued success. But while opportunities are expanding, in many markets glass must increasingly compete with other materials such as plastics and aluminum that may offer lighter weight, higher strength, lower cost, or other competitive advantages.

The 1970s and 1980s brought significant restructuring to the glass industry in response to changes in the global business climate. During this period, sectors such as container and flat glass pared excess capacity to maximize productivity, while others, such as specialty glass, expanded to keep pace with increased demand for new products that were the result of pioneering research. Indeed, many glass products that now are considered commonplace, such as fiber optics, were only developed within the last two decades.

Today, the glass industry ships nearly \$30 billion of products annually, and employs nearly 150,000 employees (Exhibit 2-1). The U.S. glass industry is now more streamlined, efficient, and closely aligned to its customers' needs. It is also an industry increasingly dependent on new or improved products, and as the industry enters the 21st century international and intermaterial competition for many market segments continues to increase. Manufacturers are confronted with ever increasing environmental regulations and pollution control expenditures. And each sector faces its own challenges in addition to those of the collective industry.

EXHIBIT 2-1. GLASS INDUSTRY STATISTICS

Employment	148,500
Shipments	\$29.2 billion
Capital Expenditures	\$2.0 billion
Average Hourly Wages	\$16.43
Energy Use (estimated)	250 trillion Btu
Energy Expenditures	\$1.7 billion

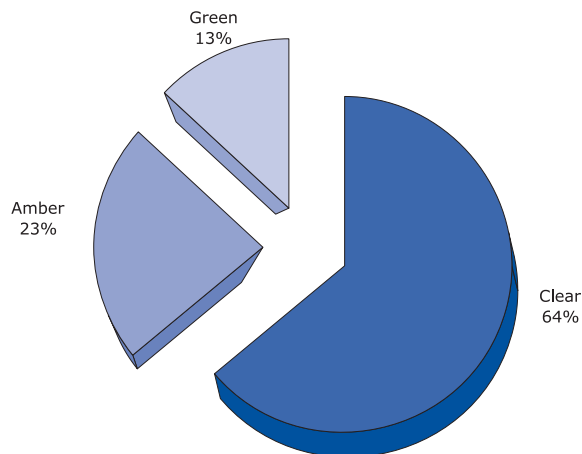
Sources: U.S. Department of Commerce
U.S. Energy Information Administration

PRODUCTS AND MARKETS

CONTAINER GLASS

The container glass sector is the industry's largest producer, manufacturing roughly ten million tons of product per year. The sector uses a significant amount of energy to produce bottles, jars, and other containers that compete with alternative materials such as plastic, aluminum, steel, and paper.

EXHIBIT 2-2. GLASS CONTAINER PRODUCTS



The majority of the industry's container products are made of clear glass.

Prior to 1970, many glass furnaces were fueled by oil, thus the oil crisis of the 1970s had a significant impact on the glass industry. Higher oil prices, combined with high capital costs necessary to convert plants to an alternative fuel -- natural gas -- resulted in the closure of 15 container glass plants between 1979 and 1983. Further economic pressures in the form of increased competition, environmental compliance, and labor costs contributed to the closing of an additional 33 plants from 1983 to 1992. Currently, there are about 55 plants operating in the United States producing around 36 billion glass containers per year.

As a result of past mergers and consolidation to maintain competitiveness, the make-up of the container glass sector has changed dramatically. Three manufacturers now account for about 95 percent of the domestic container glass market. Although container glass sales have currently stabilized, the

sector remains under intense pressure from other materials. Distribution also remains a limiting factor for container glass; the weight and volume of empty containers prohibits transportation over long distances thus limiting international trade. Often, plants are strategically located close to the facilities that process the products for which the containers will be used.

Competition for container glass comes primarily from alternative materials, particularly plastic and aluminum. Plastic and aluminum have made substantial inroads into the container market, especially for food and soft drinks, which once were stalwarts of the glass container industry. Beverage and food products account for the largest portion of U.S. glass container production.

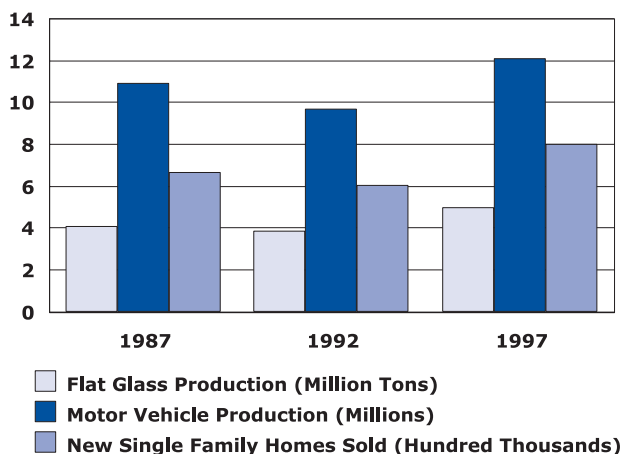
In the future, the gains made by plastic in the past two decades may be offset somewhat by growing concerns about wastes and toxic emissions associated with plastics manufacturing and recycling. Glass manufacturing, on the whole, has fewer environmental hazards. In addition, recycling efforts within the container glass sector continue to increase. In 1998, 35% of all glass containers were recycled for the manufacture of new glass products.

FLAT GLASS

The flat glass sector (also commonly referred to as the float glass sector, based on the name of the manufacturing process involved in making flat glass) produces about five million tons of glass per year, with residential and commercial construction and automotive industries comprising about 80 percent of the market. Other products from this sector include mirrors, instrumentation gauges, and architectural items such as table tops and cabinet doors.

There are currently six raw flat glass manufacturers in the United States operating around 30 plants. The industry has become increasingly global, with a rise in foreign ownership of U.S. facilities as well as increased U.S. participation in overseas plants.

EXHIBIT 2-3. FLAT GLASS COMPARISON



Flat glass production is highly dependent on the fluctuating economic cycles of its primary market industries, as depicted in Exhibit 2-3. In addition, international trade has become an important component of the U.S. flat glass market. Exports accounted for about 23% of glass shipments in 1998 while imports accounted for about 12% of apparent consumption. Both import and export levels have risen over the past decade.

Few alternative materials currently exist for flat glass, securing its dominant position in its primary markets. However, because this sector is subject to the economic cycles of other industries its growth patterns are somewhat difficult to predict.

Flat glass manufacturers recycle 15 to 30 percent of their own cullet. Because of extremely high quality requirements, scrap glass from post-consumer sources such as building sites or household uses is currently incompatible with flat glass manufacturing.

The flat glass industry sector is facing several issues as it looks toward the future. Regulations affecting the construction and automotive industries will present additional challenges by imposing new energy efficiency and safety requirements on glass used in buildings and vehicles, as will the desire for improved product characteristics by customers. Consolidation in the global automotive industry will also affect this sector.

FIBERGLASS

Fiberglass is composed of two distinct subindustries: insulation, which is often referred to as glass wool, and textile/reinforcement fibers, which are continuous fiber strands used to reinforce plastics and other materials important to the transportation, marine, and construction industries. These two subindustries together manufacture about 3 million tons of product annually. Similar to flat glass, fiberglass production is greatly affected by the economic cycles of its primary markets: the construction, automotive, and marine industries. Currently, there are about ten major fiberglass producers in the United States operating around 40 plants.

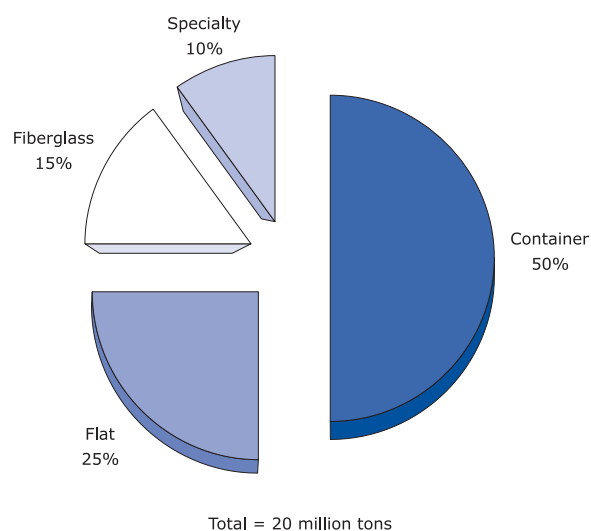
Since the binders used to hold insulating fibers together can fail when greatly compressed, transporting fiberglass insulation is expensive and limits international trade. Fiberglass insulation currently dominates the U.S. insulation market, however, alterna-

tive materials such as foam and cellulose are beginning to make market inroads. The development of new binders that allow more intense compression during packaging could reduce shipping costs and make exports more feasible.

Recycled glass plays a prominent role in fiberglass insulation production. The fiberglass sector is the largest secondary market for post-consumer and industrial waste glass, reusing around one billion pounds of post-consumer and waste glass annually. Although fiberglass insulation companies now utilize 10 to 40 percent recycled glass in their manufacturing process, research is needed to facilitate recycling of the fiberglass itself.

Textile, or composite, fiberglass faces little competition from alternative materials. This sector is expected to grow with the increased use of fiberglass-reinforced composites in automobiles and watercraft. Textile fiberglass is still an emerging market with strong domestic and international potential. Fiberglass-reinforced polymer composites are an alternative replacement material for many traditional wood and metal applications.

EXHIBIT 2-4. ESTIMATED ANNUAL GLASS PRODUCTION



SPECIALTY GLASS

The specialty glass sector is very diverse, and consists of traditional products, such as lighting, cookware, and television glass components along with newer products such as fiber optics, photonics, flat screen displays, and LCD panels. The sector produces roughly two million tons of glass products annually, and has traditionally relied on research to develop new products. New and highly successful products such as fiber optics and photonics now routinely outperform traditional specialty glass segments such as lighting and cookware. Specialty glass is evolving so rapidly that many of today's most profitable products did not even exist a decade ago, particularly for glass used in electric and electronic applications.

Specialty glass is also unlike the other glass industry sectors in that it is comprised of many small, specialized manufacturers in addition to a few large, multinational corporations. This make-up is due to the

diversity of the markets and the costs necessary to compete in high-tech markets. Finding capital to fund research into advanced technologies remains a concern; the best performing specialty glass products are also normally those with the highest capital investment costs. Another limitation is the diverse equipment required to produce different forms of specialty glass, such as the precision mirrors of the Hubble and Subaru space telescopes.

Specialty glass producers face varying degrees of competition. Although there are few alternative materials for such products as television tubes and LCD displays, the electronic glass segment faces strong challenges from foreign producers, particularly in Europe and Asia. The technological race among the United States, Europe, and Asia has become increasingly overt in this sector as key alliances between manufacturers and materials suppliers can determine the viability of key industrial segments. Lower environmental compliance, labor costs, and tax policies in the third world are additional

complications facing U.S. producers. Joint ventures between American and foreign-owned companies may partially compensate for this phenomenon, as well as help U.S. manufacturers enter some overseas markets. Although a low tonnage product in terms of production, the high-tech products have high market value and profit margins, in addition to their state-of-the-art appeal. This is particularly evident in the rapidly changing telecommunications industry where demand for data transmission is surging exponentially.

The traditional consumer specialty glass products such as kitchenware, tableware, and fine crystal are challenged by numerous alternative materials -- such as ceramics, stainless steel, and enamel -- and are impacted greatly by imports. The few remaining American manufacturers of these products are surviving in the global market, but the absence of long-term capital investment and research funding remains a concern.

Recycling is also an issue for this segment. By their very nature, certain specialty products do not justify recycling due to insufficient volume and glass being an inherently environmentally friendly material. However, waste reduction goals and mandates may make recycling justifiable when volume makes it practical. For example, the television glass industry is undertaking efforts to recycle glass from used television sets and computer monitors.

TRENDS AND DRIVERS

Given the challenges posed by international competition and alternative materials, the U.S. glass industry must be able to provide superior products with unique properties that make them more desirable than the products made from other materials and other countries. These new glass products and formulations will require the development of novel process technologies that reduce production costs and enhance desirable characteristics. Innovations in glass composition and glass properties will be needed to support the expansion of glass into completely new markets.

In general, glass company funds are very limited for researching improvements in mature glass processing technology such as the glass furnace, even as a significant portion of the industry is changing from an air/natural gas combustion process to an oxygen/natural gas combustion process for the glass furnace which reduces emissions and energy use while increasing productivity.

To help address these needs and challenges of the future, the glass industry vision identified four broad areas in which the industry must focus its technological efforts. Improvements in these areas will help address the critical energy, environmental, and economic concerns of all four sectors of the glass industry.

PRODUCTION EFFICIENCY

The industry will explore opportunities to improve the efficiency of glass production, including improved manufacturing processes and new techniques that maximize glass strength and quality. In particular, production efficiency gains are expected to result from improved melting, refining and forming processes that will increase product yield while lowering energy and other production costs. A constant driver is the desire to increase the life of a furnace campaign, at the end of which the furnace is essentially rebuilt.



ENERGY EFFICIENCY

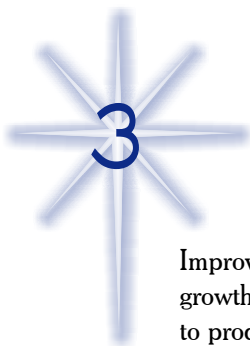
Development of more energy-efficient manufacturing processes and technologies will help the industry achieve significant energy savings while strengthening the competitiveness of glass products. Since the majority of energy consumption in the glass industry occurs in the melting and refining process, it offers the largest opportunity for improvements. The availability and price of natural gas, oxygen, and electricity are also a constant concern.

ENVIRONMENTAL PERFORMANCE

Efforts in the environmental area focus on challenges and opportunities to reduce emissions and waste in the glass industry through leaner and cleaner processing. Increased emphasis on wise use of natural resources and solid waste reductions will also help increase recycling within the industry as a whole. Emission regulations are expected to continually become more stringent, with increasing concern for greenhouse gas emissions, which will likely result in increasing pollution control costs for glass manufacturers.

INNOVATIVE USES OF GLASS

To meet the challenges of the future, the U.S. glass industry must broaden the use of glass in existing markets and support research to create completely new and innovative uses for glass by investigating new glass compositions, developing a better understanding of glass properties and interactions, and modifying and improving essential glassmaking processes. The industry needs to be able to respond to rapidly changing market needs at volume. In many markets, customers demand for lighter, stronger glass products is increasing rapidly.



PRODUCTION EFFICIENCY

Improving the productivity of the glassmaking process is critical to the future growth and profitability of the U.S. glass industry. It ensures that all inputs to production – capital, labor, raw materials, energy, and knowledge — are used as efficiently as possible to maximize quality and minimize costs. Because energy can represent as much as one-fifth of glass production costs, energy efficiency and production efficiency go hand-in-hand. However, efficient production is a broader concept, encompassing all aspects of the manufacturing process and their impact on energy use, glass quality, product yield, waste generation, and production costs. Important production gains are expected to result from improvements in melting and refining processes that are common to all types of glass production. Therefore, the focus of this chapter is precompetitive technology advancement that will increase product yield while lowering production costs.

PRODUCTION EFFICIENCY GOALS

Production efficiency improvements contribute to all eight goals contained in the glass industry vision. However, the greatest and most direct contributions will be made to two goals:

Reduce production costs by at least 20 percent below 1995 levels. Reduce the real (inflation-adjusted) costs of production by 20 percent or more by 2020 as compared to 1995. This equates to an annual cost reduction of about 0.7 percent per year.

Achieve 6 sigma quality control in the overall production process. Adhere to the 6 sigma quality standard which seeks no more than 3.4 defects per million units.

The objective of production efficiency is to improve process yield and quality while lowering production costs and environmental impacts. To achieve this, the industry must better understand the composition of its production costs and the factors that influence them. Process optimization will require a better understanding of underlying chemical and physical phenomena involved in melting, refining and forming. Once understood, the industry should establish a goal for “lowest process loss”.

To achieve its cost and quality goals, the industry has outlined seven recommended production targets in Exhibit 3-1. These targets are representative of the steps glass manufacturers should take and are not all-inclusive.

EXHIBIT 3-1. EXAMPLE PRODUCTION EFFICIENCY TARGETS

- ★ Reduce capital costs by 25 to 50%.
- ★ Improve operating efficiency by 25% (yield x cycle time x up time).
- ★ Double sales per capital investment (\$ per \$ basis).
- ★ Improve optical quality by 50% while maintaining yield.
- ★ Eliminate all sources of surface damage.
- ★ Extend furnace life by 5 years or 30%.
- ★ Reduce capital investment or increase capacity by 35% through process and equipment innovations.

TECHNOLOGY CHALLENGES AND BARRIERS

The glass industry faces significant technical challenges and opportunities as it seeks to attain its goals. Glass production is a mature process that has achieved significant improvements in cost, efficiency, and quality over the past 50 years and future incremental benefits will be harder and more costly to achieve. However, advances in materials, process measurement, automation, and scientific understanding have created new opportunities to improve the production process. The major technical barriers to better production efficiency are shown in Exhibit 3-2.

- ★ **Intelligent process control** – Process control enables manufacturers to optimize and automate glass production and fabrication. It involves measuring and monitoring actual process conditions throughout glass melting and forming, analyzing real-time process data to identify potential problems, and automatically adjusting process variables toward optimal conditions. Upsets to the production process can affect product quality for several days.
- ★ **Advanced sensors** – Sensors and other detection tools that measure and report manufacturing conditions are the building blocks of process control systems. They enable operators to improve efficiency and optimize performance by providing real-time data on conditions in the glass melt and the combustion atmosphere in the furnace and allow them to make appropriate adjustments. Current sensors and related process controls cannot accurately and cost-effectively measure and control melting, refining and forming processes in real time.
- ★ **Process improvements** – Improvements encompass a variety of enhancements to equipment, raw materials, operating procedures, and production systems. The objective is to increase throughput, lower costs, improve quality, and enable new finishing techniques.
- ★ **High temperature materials** – Durable and inexpensive materials continue to be one of the most important needs in glass production. In addition to refractories (discussed in the next chapter), a variety of other materials are in constant contact with molten glass, combustion gases, and hot glass products. Glass furnaces operate continuously at temperatures reaching 1400°C in the molten bath and 1600°C in the combustion atmosphere for an entire operating “campaign”, often eight to ten years in length. Opportunities to replace parts and equipment that fail during the campaign are limited. Limitations on material performance can limit energy efficiency and degrade glass quality, particularly in oxy-fuel environments.
- ★ **Process design** – Tools that enable scientists and engineers to optimize existing equipment and modify processes to take advantage of technology advancements are needed. For example, conversion to oxy-fuel combustion changes the temperature and combustion atmosphere within furnaces and creates new operating conditions.

INTELLIGENT PROCESS CONTROL

★ **Inability to accurately measure and control the production process**

- Controls for product and process are not well integrated
- Processes are complex and highly interactive
- Control variables and their interrelationships are not completely understood

★ **Current process data and models are limited**

- Accurate high temperature physical properties don't exist
- Models are not vectorized
- High quality laboratory data sets don't exist
- Current models not integrated with quality control programs

ADVANCED SENSORS

★ **Reliability and durability**

- Longer-lasting, more reliable sensors needed

PROCESS IMPROVEMENTS

★ **Input materials are too expensive or poor quality**

- Better quality raw materials needed
- Lower cost oxygen needed for oxy-fuel combustion

★ **Heat transfer is too slow and inefficient**

- Need to get more energy into the glass and remove it faster
- Need better understanding of heat transfer limits, both in the furnace and in forming

HIGH TEMPERATURE MATERIALS

★ **Refractory materials erode and corrode, thereby degrading the quality of the glass**

- Current materials performance limits furnace temperatures and efficiency
- Limited investment by refractory and equipment producers
- Better materials property data and understanding of corrosion mechanisms needed

★ **Performance of glass contact materials is limited**

- Material surfaces are needed that withstand high surface temperature and do not react with glass volatiles
- Contact materials often mar glass surface

PROCESS DESIGN

★ **Current understanding of the fundamental physics of glassmaking is limited**

- Scale up of fundamental knowledge is difficult
- Need to understand alternative ways to melt and process glass

★ **Poor dissemination of technical information**

- Lack forum for exchange of pre-competitive technical information

★ **No long-term commitment to fund glass process R&D**

- R&D viewed as an expendable investment

RESEARCH AND DEVELOPMENT NEEDS

The most costly and energy-intensive step in glass production is the melting and refining of raw materials to produce a homogenous, contaminant-free molten bath that is the basis of all glass products. Precompetitive R&D focused on production efficiency will improve the design and operation of the glass furnace and the forehearth. Although alternative glassmaking concepts (discussed in the next chapter) have important long-term potential, they will require enormous capital investments and several decades to develop. Over the next 20 years, most glass producers will work to improve the efficiency and reduce the operating cost of their existing physical infrastructure of furnaces, processing equipment, and facilities. New capacity expansion and furnace rebuilds will take advantage of the latest technology but it is unlikely to include radical new melting concepts and equipment.

Production improvements are centered on five key strategies to improve yield and quality while minimizing costs and pollutants. They are:

- ★ Intelligent Process Control
- ★ Advanced Sensors
- ★ Process Improvements
- ★ High Temperature Materials
- ★ Process Design

Research that is required in the near (0-3 years), mid (3-10 years), and long terms (>10 years) within each of these areas is outlined in Exhibit 3-3.

INTELLIGENT PROCESS CONTROL

Such systems will be developed in stages: 1) modeling of process parameters for quick results, 2) stand-alone advisory systems to enable manual adjustments by furnace operators, and 3) neural network systems that gather and analyze numerous process conditions and automatically adjust parameters toward optimal conditions. Maximum benefits will be obtained with rapid implementation of process control systems as advances are developed. Key R&D needs include:

- ★ ***Integrated Control Systems*** – Integration of sensors and controls for glass preforming in the furnace and forehearth
- ★ ***Product Fabrication Control Process*** – Systems to control the forming process and fabrication, including off-line control (not hot glass)
- ★ ***Diagnostic, Prognostic, and Condition-Based Maintenance*** – Smart systems that can detect and diagnose product quality problems, predict process requirements and changes, and signal maintenance activities based on operating conditions

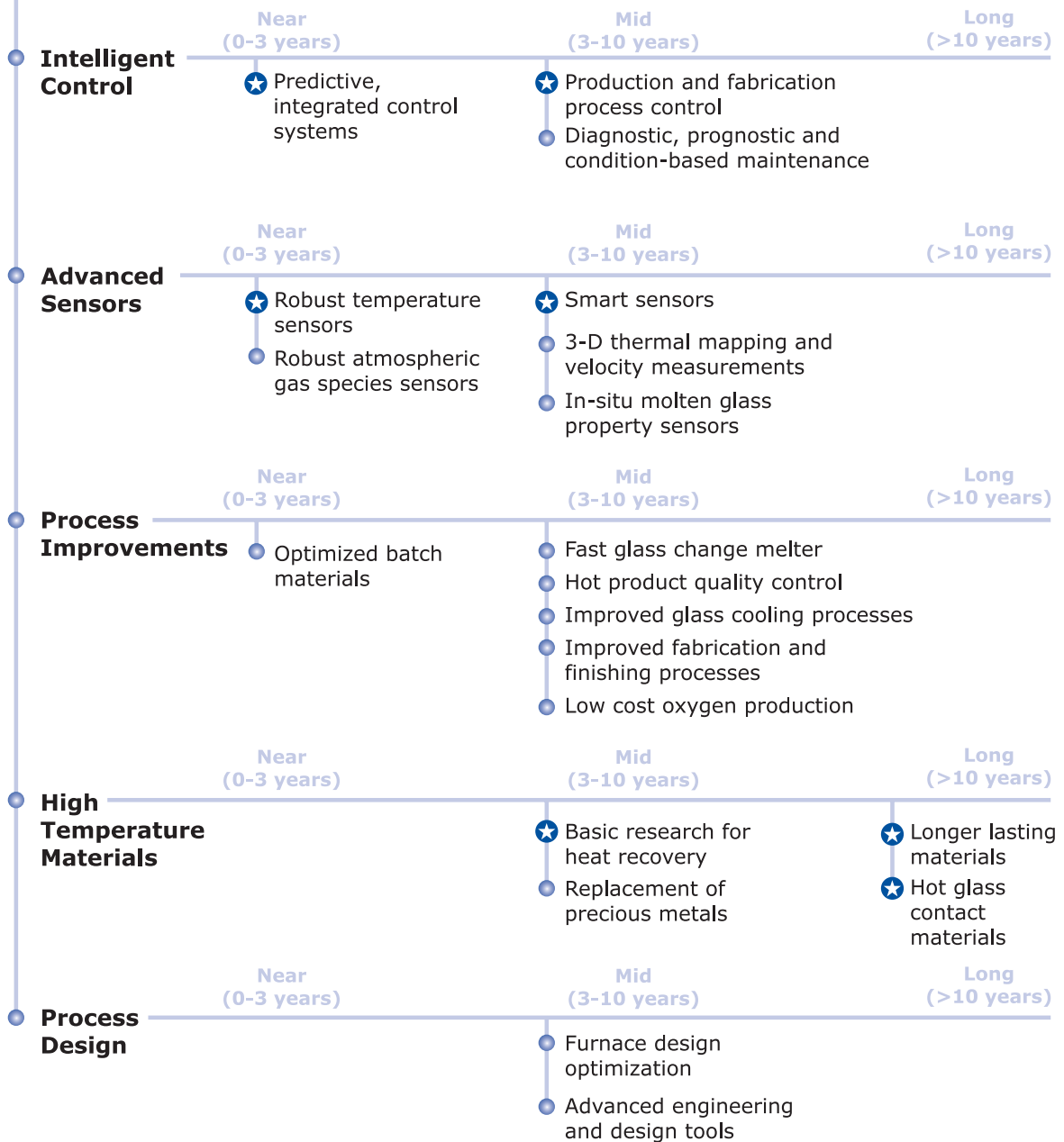
Production Efficiency

Goals

- Reduce production costs By 20% or more
- Achieve six sigma quality Control in some processes

Key Challenges

- Measuring and controlling processes
- Limitation of process data and models
- Material performance in hostile environments
- Thermal performance
- Understanding the fundamental science of glassmaking



★ High Priority

ADVANCED SENSORS

Advanced sensing devices must be reliable, durable, accurate, and inexpensive to allow operators to quickly gather detailed process information that can be integrated with data from currently available process sensors. Key R&D needs include:

- ★ **Smart Sensors** – Sophisticated sensors that indicate when they are drifting or failing and have the ability to self calibrate
- ★ **Robust Temperature Sensors** – Durable, long-life sensors that can accurately measure temperature in extremely hot and corrosive atmospheres
- ★ **Robust Atmospheric Gas Species Sensors** – Durable, long-life sensors that can detect and analyze species in the combustion gases above the glass bath
- ★ **3-D Thermal Mapping and Velocity Vector Measurements** – Measurement devices that can provide a 3-D thermal profile of the combustion space as well as the thermal velocity
- ★ **In-Situ Molten Glass Property Sensors** – Sensors and other measurement devices that detect glass properties within the molten glass

PROCESS IMPROVEMENTS

Improvements are available throughout the glass production process including batch preparation, melting, forming, fabrication, annealing, and finishing. Key R&D needs include:

- ★ **Hot Product Quality Control** – Technologies that improve the homogeneity and consistency of the molten glass as it exits the furnace, such as improved stirrers and bubblers
- ★ **Fast Glass Change Melter** – Technologies that enable furnaces to rapidly shift production over to different glass compositions and products
- ★ **Optimized Batch Materials** – Tools to determine and produce raw materials with an optimal grain size, in addition to batch pelletization and prevention of batch segregation
- ★ **Low-Cost Oxygen Production** – Technologies to reduce the cost and improve the purity of on-site oxygen production for oxy-fuel firing, including cogeneration
- ★ **Improved Glass Cooling Processes** – Technologies to improve the understanding, efficiency, and consistency of thermal quenching of hot glass products
- ★ **Improved Fabrication and Finishing Processes** – Technologies that add value and quality to finished glass products such as polishing, grinding, joining, and coatings and other surface treatment

HIGH TEMPERATURE MATERIALS

A long furnace campaign is a critical objective in lowering overall production costs; high performance materials are needed to extend furnace life. Key R&D needs include:

- ★ **Longer Lasting Materials** – Materials that can withstand the high temperature and corrosive production environment for over ten years without failure, including stirrers and sheathing materials for sensors and camera shields located within the furnace
- ★ **Hot Glass Contact Materials** – Improved materials for equipment that is contact with glass products after it leaves the furnace such as improved mold materials for container manufacturing, improvedlehr roll materials that are self-lubricating and do not stain the glass surface, and blades used in shearing operations that do not require lubrication
- ★ **Replacement of Precious Metals** – Innovative materials that can replace expensive precious metals such as platinum used for lances, bubblers, and stirrers
- ★ **Basic Materials Research for Heat Recovery Applications** – Materials that can aid heat recovery in glass processes. High-temperature, corrosion-resistant materials are needed for regenerative recuperators and other heat recovery systems to increase system efficiency

PROCESS DESIGN

Advancements in process design will reduce operating and capital costs for glass facilities. Key R&D needs include:

- ★ **Furnace Design Optimization** – Optimizing the size, shape, and design of glass furnaces for maximum throughput and heat transfer
- ★ **Advanced Engineering and Design Tools** – Development and application of computer-aided engineering tool for glass melting, refining and forming

PRIORITIES

The preceding R&D needs comprise an integrated technology portfolio that will be required to achieve the glass industry goals for 2020. The portfolio includes many interdependent research activities that must proceed together. Within this portfolio are several high priority activities that are considered critical for improving production efficiency.

INTELLIGENT PROCESS CONTROLS

- ★ Integrated Control Systems
- ★ Product Fabrication Control Process

ADVANCED SENSORS

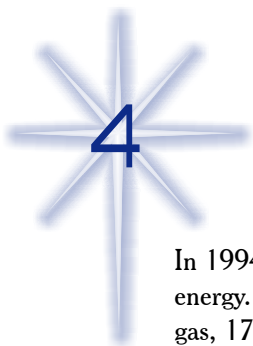
- ★ Robust Temperature Sensors
- ★ Smart Sensors



HIGH TEMPERATURE MATERIALS

- ★ Longer Lasting Materials
- ★ Hot Glass Contact Materials
- ★ Basic Materials Research for Heat Recovery Applications

These priorities address the two most important barriers to improved production efficiency: limited ability to measure and control process parameters, and limitations of materials used in glass production.



ENERGY EFFICIENCY

In 1994, the U.S. glass industry consumed over 249 trillion Btu of process energy. Approximately 80 percent of this energy was in the form of natural gas, 17 percent in the form of electricity, and the remaining 3 percent in the form of fuel oil and other fuels. Purchased energy represented a cost of nearly \$1.7 billion to the industry in 2000 and, on average, accounted for about 14% of direct glass production costs. The melting/refining process is by far the most energy intensive of the primary glassmaking processes and is responsible for the majority of energy consumption.

In the face of growing challenges from foreign manufacturers and other materials, the glass industry seeks to reduce energy use as part of its broader effort to lower glass production costs. Fluctuations in energy prices, particularly natural gas, greatly impact glassmaking margins and profitability. The industry believes the development of more energy-efficient manufacturing technologies will achieve significant energy savings and help to strengthen the competitiveness of glass products both internationally and with other materials. In today's competitive climate, the industry realizes the need for total energy management of the glass plant.

ENERGY EFFICIENCY GOAL

Energy efficiency improvements will contribute to other glass industry goals, however, the most direct contribution will be made to one goal:

- ★ **Reduce the gap between actual and theoretical melting energy use by 50% by the year 2020 from 1995 levels.** Whereas melting one ton of glass should theoretically require only about 2.2 million Btu, in practice it requires a minimum of twice that much because of a variety of losses and inefficiencies and the high quality of glass that is often required.

TECHNOLOGY CHALLENGES AND BARRIERS

Technological advances in glass making over the last 25 years have helped reduce the energy per pound of glass being “pulled” through the furnace along with improving glass quality and reducing cost. More recent advances have slightly impacted the energy requirements for glass production but at a premium cost. Still, present glass manufacturing facilities offer a large opportunity for energy savings. In the future, advances need to give greater returns at a reduced cost. Critical energy efficiency challenges, highlighted in Exhibit 4-1, are characterized by five key issues:

- ★ **Furnace Modeling** - A limited understanding of some aspects of the glassmaking process is a key barrier to improved energy efficiency. This lack of understanding hampers efforts to improve existing models and develop new ones for optimizing glassmaking processes and maximize output for a given size furnace. Insufficient knowledge of the physical processes in glassmaking prevents the development of techniques for optimizing the use of raw materials.

- ★ **Improve Thermal Efficiency** - Advances in other areas such as burners, heat transfer mediums and material preheaters have generated much enthusiasm, although further advancements are needed. The rate at which energy enters and exits the glass needs to be increased. The problem of maintaining peak efficiency throughout the entire life of a furnace campaign still exists (e.g., the presence of hotspots and thermal leaks reduce efficiency). Advances in the types and qualities of raw materials, both natural and synthetic, are needed to reduce energy requirements in the melting process and/or less flue gas energy leaving the furnace.
- ★ **New Glassmaking Technologies** - Some characteristics of the glass industry create barriers such as prevailing corporate investment philosophies. Conservative business approaches in the glass industry constitute a key barrier to technology advancement. As a whole, the industry shies away from radical approaches to research and exhibits an aversion to high risk, regardless of potential payoff. Funding constraints within glass companies can be traced to the practice of spending a relatively small portion of funds on process research. The high cost and lack of capital to develop and implement technologies is a significant constraint on investments in energy efficiency.
- ★ **Refractory Materials** - Another important concern is the performance and quality of existing refractory materials, which have a relatively short production life and are expensive to replace. Further reduction of energy requirements is attained due to advances in refractory quality allowing the use of more insulation which reduces the heat loss through the walls leaving more for the glass melt. Better methods are needed to evaluate and repair refractories in service.
- ★ **Glass Melting Research Facility** - The glass industry has historically lacked a common facility for testing new production technologies and products, as capital costs in the industry are very high. In particular, this is important for improved combustion and furnace efficiency. Applications that may be tested if a facility was available include sensors, instrumentation, refractories, and burners.

RESEARCH AND DEVELOPMENT NEEDS

The glass industry will pursue a range of R&D activities aimed at developing enabling technologies and practices. These activities include:

- ★ Integrated Furnace Models
- ★ Improve Thermal Efficiency
- ★ New Glassmaking Technologies
- ★ Refractory Materials
- ★ Glass Melting Research Facility

A more detailed explanation of each area is described below and summarized in Exhibit 4-2.

EXHIBIT 4-1 - TECHNOLOGY CHALLENGES AND BARRIERS

FURNACE MODELING

★ **Limited understanding of glassmaking process**

- Current models require improvement and validation
- Dichotomy between insulation, convection, and refractory wear in glassmaking reactions
- Learning curve involved when converting to a new technology

THERMAL EFFICIENCY

★ **Limited rate of heat transfer into/out of the glass**

- Raw materials are not optimized and higher quality raw materials are needed
- Glass compositions may not be optimal
- Combustion is not optimized
- Better material data is required

★ **Waste heat not fully utilized**

- Heat recovery systems require improvement
- Preheating systems require improvement

★ **Limited use of cullet**

- Cullet requires about 30% less energy to melt than raw materials and also reduces volatilization

GLASSMAKING TECHNOLOGY DEVELOPMENT

★ **Glass manufacturers conservative mentality**

- Lack of industry cooperation and too much proprietary thinking
- Lack of interest in future technologies, radical approaches and cooperative research
- Risk aversion and restrictive management criteria

★ **High capital equipment and technology development cost**

- Capital intensive, competitive industry with low margins
- Assets are large and long-lived
- Lack of capital to implement known technology
- Lack of funds for process R&D
- Non-existent enabling technologies

★ **Poor perception of industry by students**

- Limited amount of students entering ceramic and glass engineering

REFRACTORY MATERIALS

★ **Limitations of current refractories**

- Need improvements in refractories to better withstand high temperature, erosion, corrosion, and not affect glass quality

GLASS MELTING RESEARCH FACILITY

★ **Lack of melting research facilities**

- Available facilities are insufficient to provide accurate results to use in commercial scale units

INTEGRATED FURNACE MODELS

The use of computer modeling has spurred the design of more efficient, longer lasting and better quality glass furnaces. But the total design package capabilities of modeling is still in its infancy with the true impact years away. Modeling could identify process designs that would not depend upon thermal gradients to drive glass making reactions. Key R&D needs include:

- ★ **Validated Coupled Melter/Combustion Space Models** - Validation of models is needed to ensure model results are accurate
- ★ **Realtime Dynamic Modeling for Process Control** - Development of realtime models are needed for improved process control

IMPROVE THERMAL EFFICIENCY

Improved thermal efficiency will lower the amount of energy required to melt glass. However, most current activities in this area will likely only lead to incremental improvements. The glass industry could also better utilize waste heat with appropriate technology development. Key R&D needs include:

- ★ **Breakthrough Glass Compositions** - Development of these compositions would allow much lower energy requirements for melting glass
- ★ **Batch and Cullet Preheating** - Technologies would preheat raw materials to reduce the energy required for melting in the furnace
- ★ **Utilize Waste Heat** - Waste heat could be better utilized, either through technologies to preheat raw materials or convert to other forms of energy, including recuperation of forehearth exhaust gases
- ★ **Combustion Optimization** - Technologies to improve combustion in the furnace would include burners
- ★ **Raw Materials Optimization** - Optimization would improve glass quality and reduce energy requirements

NEW GLASSMAKING TECHNOLOGIES

New glassmaking technologies are critical to significantly reduce energy use. Radical “leap-frog” developments could significantly improve the glass business model. Key R&D needs include:

- ★ **Non-Traditional Melting** - Technologies would offer a significant improvement from current operations
- ★ **Non-Traditional Refining** - Technologies would reduce the time required to ensure uniformity in the glass melt
- ★ **Systematic Look at Oxy-Fuel Firing** - By looking at oxy-fuel firing systematically, significant operational improvements may be identified

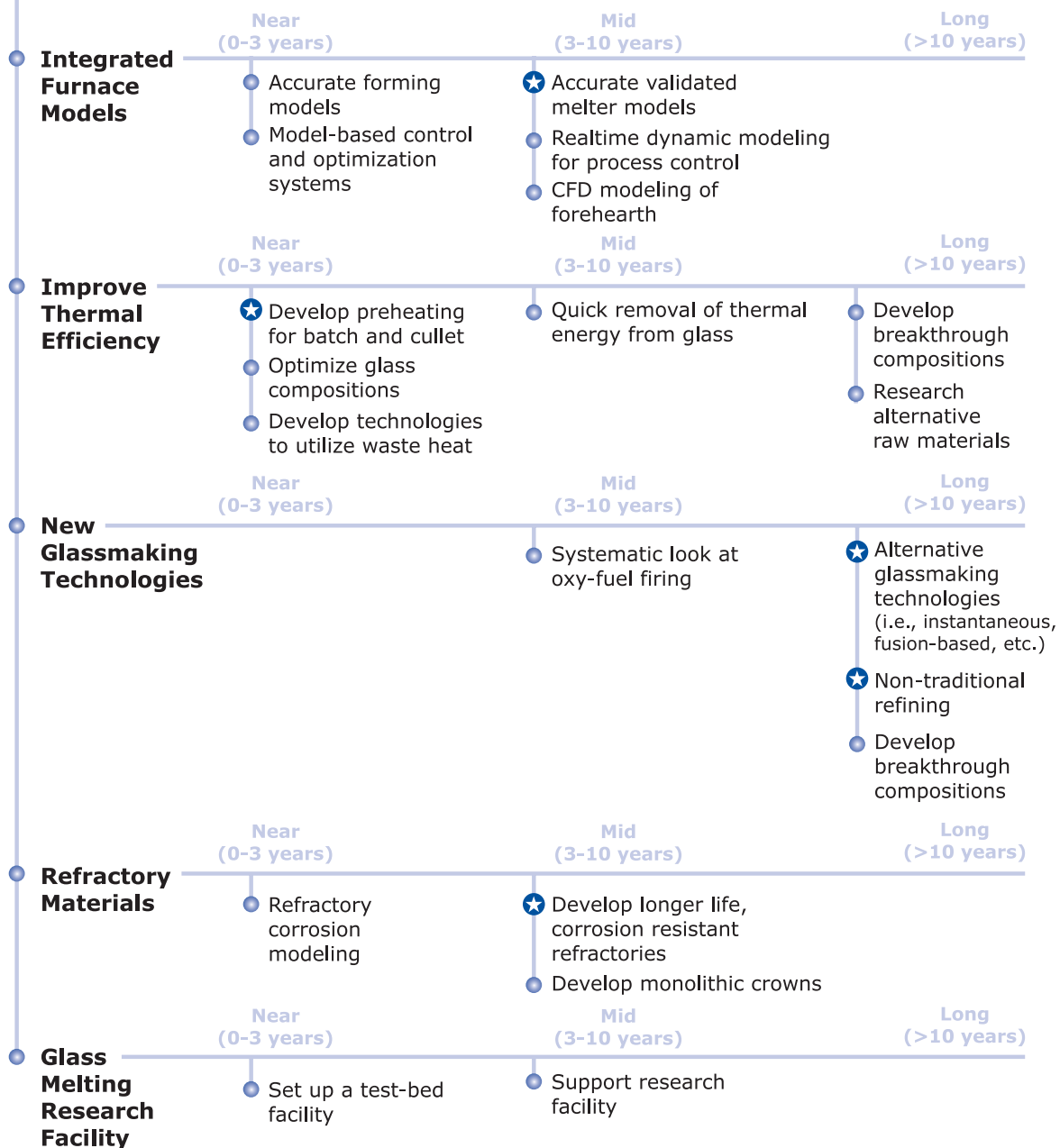
Energy Efficiency

Goals

- Reduce gap between actual and theoretical energy use by 50%

Key Challenges

- Improve understanding of glassmaking
- Increase heat utilization and transfer rates
- Reduce equipment and development costs
- Change current mentality and perception



★ High Priority

REFRACTORY MATERIALS

Refractory materials are often the limiting factor in the furnace campaign life. Improved refractories are needed that can last longer and withstand the glassmaking environment. Key R&D needs include:

- ★ **Corrosion Mechanisms Modeling** - Corrosion mechanism modeling will help determine solutions for reducing corrosion in refractories
- ★ **Longer Life, Corrosion-Resistant Materials** - Improved refractories will extend furnace campaigns, thereby reducing capital costs

GLASS MELTING RESEARCH FACILITY

A glass melting research facility will allow glass manufacturers and suppliers to test technologies that meet common needs of the glass industry. Key R&D needs include:

- ★ **Melting Facility** - A melting facility is needed to evaluate new pre-competitive glass technologies

PRIORITIES

The preceding R&D needs comprise an integrated technology portfolio that will be required to achieve the glass industry goals for 2020. The portfolio includes many interdependent research activities that must proceed together. Within this portfolio are several high priority activities that are considered critical for improving energy efficiency.

Integrated Furnace Models

- ★ Validated coupled melter models

Improve Thermal Efficiency

- ★ Preheating of batch and cullet

New Glassmaking Technologies

- ★ Alternative glassmaking technologies
- ★ Non-traditional refining

Refractory Materials

- ★ Longer life, corrosion resistant refractories

These priorities address the most important barriers to improved energy efficiency.



ENVIRONMENTAL PERFORMANCE

The glass industry is focusing on challenges and opportunities to reduce emissions and waste through leaner and cleaner production and processing as well as increased recycling. While in many regards the glass industry is relatively gentle on the environment relative to other industries, glass manufacturing processes are also fairly benign with the exception of NO_x emissions. Nevertheless, environmental issues are of growing concern to the industry. The reduction of undesirable wastes and emissions is a central component of the glass industry vision.

The glass industry expects a continuation of current trends toward more stringent pollution control regulations and higher waste disposal costs. Regulations may force the industry to control additional types of emissions or provide for the recycling or reuse of all products.

ENVIRONMENTAL GOALS

Improvements in environmental performance and recycling contribute primarily to three goals in the glass industry vision:

Recycle 100% of glass production wastes back into the manufacturing process. While many in-process wastes are recovered, opportunities are available to increase in-process waste utilization.

Reduce air and water emissions by at least 20% through environmentally sound practices. Reduce emissions on a per ton of glass produced basis by 20% by 2020 compared to 1995 levels.

Recover, recycle, and minimize 100% of available post consumer glass where consumption is greater than 5 lb/capita. Economics are more favorable where population density is greater.

TECHNOLOGY CHALLENGES AND BARRIERS

Over the past several decades, the industry has had to modify its processes and add equipment to comply with increased government restrictions on the emissions of NO_x , SO_x , and particulates. While improvements have been made over the past 25 years to reduce environmental impacts from glassmaking, significant challenges remain to further reduce environmental impacts. To achieve environmental goals, the industry must overcome significant barriers associated with the glass melting process, the fundamental understanding of emissions, and regulations. Environmental components are depicted in Exhibit 5-1. The most critical environmental challenges, highlighted in Exhibit 5-2, are characterized by five key issues:

Emissions Characterization and Modeling - The industry lacks a strong understanding of the formation and fate of emissions in current melting, refining and forming technologies, particularly as they relate to hazardous materials, process mechanisms influencing the formation of particulates, and glass composition-dependence. Other aspects include the lack of predictive emissions modeling tools and existing technology-based restrictions on the types of fuels that can be used for processing.

Emissions Measurement and Control - One area of primary environmental interest is the minimization of volatile process emissions. The glass melting furnace is the principal source of such pollutants that include: volatile non-condensable gases, such as nitrogen oxides, condensable gases, such as alkali metal salts, and particulates or small particles entrained in the gas effluent stream. In today's glass industry, emission control technology has developed to meet emission regulations, but at high cost; however, more R&D will be needed to reduce costs and to meet anticipated future regulations and permitting requirements.

Pollution Prevention - Environmental concerns encompass volatile furnace emissions and waste prevention -- the redesign of processes and products to minimize volatile emissions and the generation of wastes -- as well as health, safety, and ecology. Glass industry spending on environmental projects continues to be driven by reaction to state and federal regulations. Another area of environmental concern is waste material generated in the glass making process.

Process Modifications - Regulations often set forth inflexible emissions standards at levels that may be technically feasible but not economically feasible. Expenditures used to meet these regulations inhibit industry's ability to invest in the development of new

EXHIBIT 5-1. COMPONENTS OF ENVIRONMENTAL PROTECTION AND RECYCLING

Environmental Protection

Air

- Nitrogen Oxides (NO_x)
- Sulfur Oxides (SO_x)
- Carbon Monoxide (CO)
- Carbon Dioxide (CO₂)
- Volatile Organic Compounds (VOCs)
- Particulate Matter (PM)
- Hazardous Air Pollutants (HAPs)

Water

- Suspended Solids
- Dissolved Solids
- Thermal

Solid

- Hazardous
- Non-Hazardous

Work Environment and Occupational Health Concerns

- In-Plant Temperature
- Noise
- Exposure to Substances

Recycling

Product

- Pre-Consumer
- Post-Consumer

Manufacturing Waste

- Raw Materials
- Packaging
- Lubrication
- Paint & Decoration
- Cleaning
- Pollution Control Wastes
- Spent Finishing Wastes

Future Concerns

- PM < 2.5 microns

EMISSIONS CHARACTERIZATION AND MODELING

- ★ **Lack of understanding of process mechanisms influencing particulates**
- ★ **Lack of understanding of volatilization (e.g., temperature, combustion space velocities, raw material particle size, batch moisture content and composition)**
- ★ **Lack of predictive emissions modeling tools**

EMISSIONS MEASUREMENT AND CONTROL

- ★ **Lack cost-effective technologies to capture CO₂ emissions**
- ★ **Lack of low-cost emission measurement technology**
- ★ **Current technology produces emissions**
- ★ **Lack of complete understanding of melting and refining technology**

POLLUTION PREVENTION

- ★ **Lack of cost-effective water treatment technology**

PROCESS MODIFICATIONS

- ★ **Nature of hazardous materials (e.g., carcinogenic, fibrous, air, etc.)**
- ★ **Lack of understanding of mold release chemistry/emissions**
- ★ **Production of by-products and contamination**
- ★ **Government regulations**
 - Inhibit some technologies
 - Varying standards (state, federal, minimum) and enforcement
 - Moving regulatory drivers (sometimes can be misguided)

POST-MARKET RECYCLING

- ★ **Composition-dependence of glass**
- ★ **Separation and sorting of mixed post-consumer waste**
 - Implications for both glass and other industries (e.g., aluminum)
- ★ **Economics of recycle and beneficiation**
- ★ **Reverse distribution system—collection of post consumer waste**
- ★ **Lack of tracking technology for recovery**

technologies or processes that may be more effective or cost-efficient in controlling emissions in the long run. A further problem is the lack of uniformity among state and federal regulations, especially as more and more states set their own standards -- Making it difficult for manufacturers to develop cohesive pollution prevention and control strategies.

Post-Market Recycling - Post-consumer disposal of glass products is an area of great concern. While current regulations do not focus on recycling of glass products, this may change if landfill costs rise significantly or if regulatory agencies increase their attention to product stewardship issues. Some recycled glass is now commonly used in the glass industry, although the majority is landfilled or stockpiled. There is a lack of economical technologies that can reliably identify and eliminate non-glass materials from the stream and efficiently sort glass by color. Other important barriers to increased recycling are economic: the industry needs to improve the cost-effectiveness of beneficiation and otherwise strengthen economic incentives for collecting and reusing post-consumer glass.

RESEARCH AND DEVELOPMENT NEEDS

The glass industry will pursue a wide range of R&D activities aimed at developing enabling technologies and practices. These activities include:

- ★ Emissions Characterization and Modeling
- ★ Emissions Measurement and Control
- ★ Pollution Prevention
- ★ Process Modifications
- ★ Post-Market Recycling

A more detailed explanation of each area is described below and summarized in Exhibit 5-3.

EMISSIONS CHARACTERIZATION AND MODELING

An effective approach is to prevent formation of volatile pollutants through an understanding of the mechanisms responsible for their creation. Accurate predictive emissions modeling tools are considered to be the most important research need. Although some predictive models exist, they require further refinement and validation as well as calibration for use with glass furnaces. More reliable modeling tools are a necessary prerequisite for another high-priority research need—the development of integrated control systems to link production with emissions. Key R&D needs include:

- ★ **Identify Emission Mechanisms** - Fundamental understanding of the mechanisms involved in the formation of emissions from glass and raw materials
- ★ **Predictive Emission Modeling Tools** - Reliable modeling tools for predicting emissions

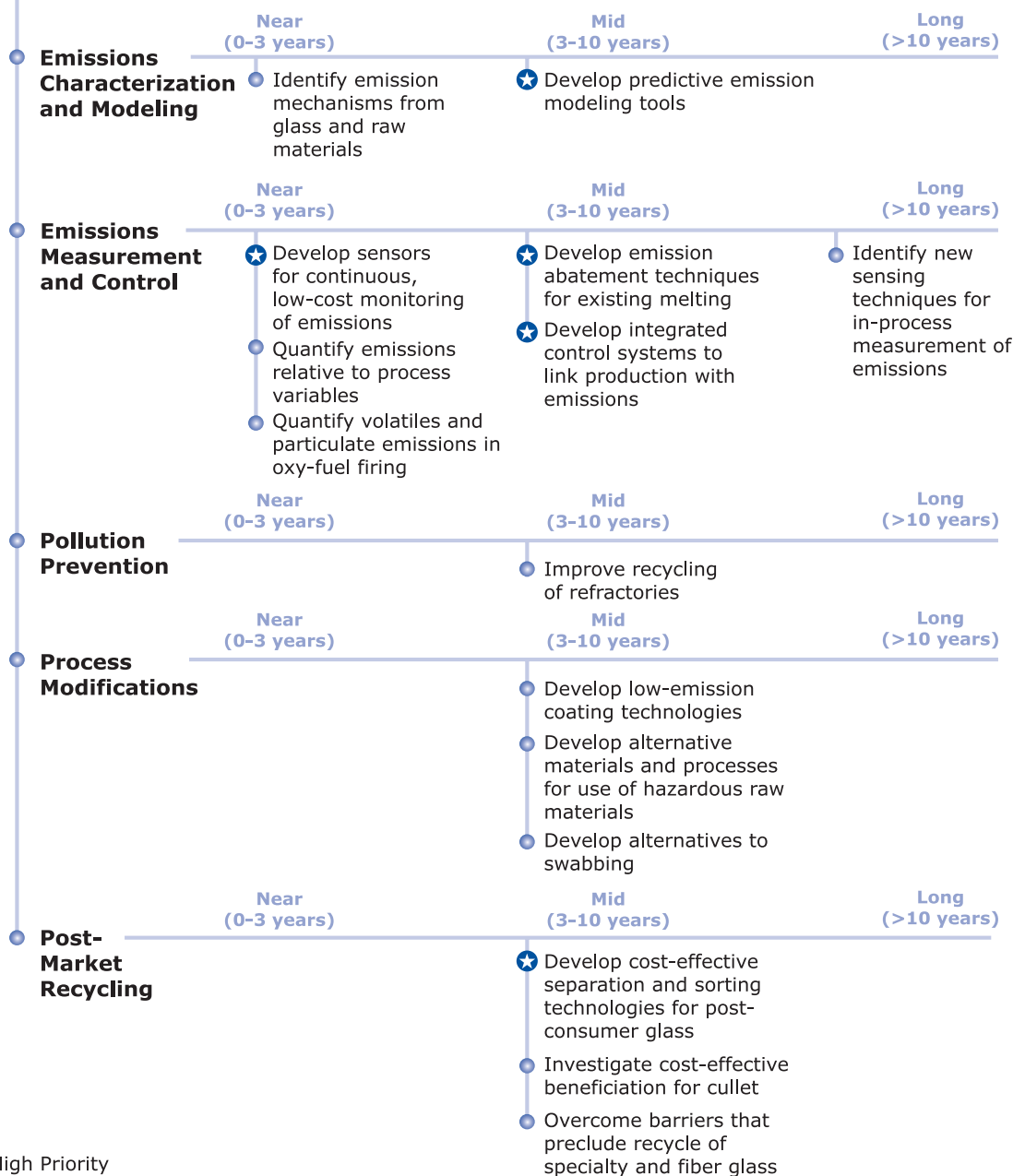
Environmental Performance

Goals

- Recycle in-process waste
- Reduce air/water emissions by at least 20%
- Recycle available post-consumer glass

Key Challenges

- Predictive modeling tools
- Understanding mechanisms of pollutant formation
- Economics of recycling and separating post-consumer waste
- Government regulations



EMISSIONS MEASUREMENT AND CONTROL

A predictive emission model can be developed and integrated with a process control model to allow both process optimization and emission minimization. Advanced, low-cost sensors are needed to continuously monitor in-process and post-process emissions. Key R&D needs include:

- ★ **Develop Abatement Techniques for Existing Melting** - Improved emission abatement technologies are needed to effectively control the release of emissions from existing melting furnaces at a reasonable cost
- ★ **Link Emissions to Production via Control Systems** - Systems would enable plant operators to adjust production parameters in response to real-time analysis of emissions, including data development to support process modeling and control, especially quantitative data on emissions (e.g., volatiles and particulates) relative to process variables
- ★ **Measure and Reduce VOC in Total Process** - New low-cost sensing techniques and processes to reduce volatile organic compounds

POLLUTION PREVENTION

Pollution prevention encompasses practices that reduce or eliminate the creation of pollutants through increased efficiency in the use of raw materials, energy and water. Key R&D needs include:

- ★ **Solid Waste Minimization** - Techniques to minimize solid waste generation
- ★ **Wastewater Reduction** - Processes to reduce wastewater generation or recycle wastewater
- ★ **In-Process Recycling** - Practices and processes to improve recycling of waste created during production processes, such as separation and grinding techniques

PROCESS MODIFICATIONS

Once researchers understand emissions mechanisms and how they are affected by process variables, it may also be possible to develop alternative materials and processes for the use of hazardous raw materials. The development of longer-life mold coatings are another way to reduce undesirable emissions. Periodically, glass molds must be coated with a release agent. This swabbing process generates large quantities of smoke containing particulate matter and volatile organic compounds. Longer-term, development of emission-free melting technology would be a great benefit. Key R&D needs include:

- ★ **Low Emission Coating Technology** - Process technology for coating glass with fewer emissions, including the development of more durable coatings or mold materials that reduce the frequency of swabbing
- ★ **Alternate Materials and Processes for Hazardous Raw Materials** - New processes and materials that reduce the impact of hazardous materials, such as arsenic, lead, and fluorides

POST-MARKET RECYCLING

The industry's top need is a *cost-effective* technology for sorting and separating post-consumer glass. Given the reverse distribution logistics involved in post-market recycling, the industry could develop this technology in partnership with other industries that have a vested interest in effective post-consumer material recovery processes. This would also reduce the industry's use of raw materials and provide production cost savings. Research on the cost-effective beneficiation of cullet is needed to develop new markets and higher-value uses for cullet. By removing impurities from the glass waste stream, this technology could serve as an intermediary technology until an integrated, inter-industry sorting technology can be developed, or it might be incorporated into the broader technology. Key R&D needs include:

- ★ **Cost-Effective Separation and Sorting Technologies** - Develop technology for sorting and separating post-consumer recycled glass
- ★ **Fiberglass Recovery/Recycling** - Process technology to improve recycling of fiberglass, such as coatings that could be easily removed
- ★ **Specialty Glass Recycling** - Process technology or product changes to improve recycling of high volume, commodity specialty glass products such as computer CRT and television glass

PRIORITIES

The preceding R&D needs comprise an integrated technology portfolio that will be required to achieve the glass industry goals for 2020. The portfolio includes many interdependent research activities that must proceed together. Within this portfolio are several high priority activities that are considered critical for improving environmental performance.

Emissions Characterization and Modeling

- ★ Identifying emission mechanisms
- ★ Developing predictive emission modeling tools

Emissions Measurement and Control

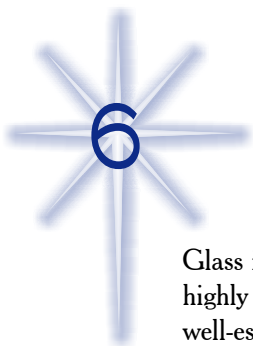
- ★ Linking emissions to production via control systems

Post Market Recycling

- ★ Developing of cost-effective sorting and separation technology

These priorities address the most important barriers to improved environmental performance.





INNOVATIVE USES

Glass is found in a myriad of products ranging from everyday tableware to highly sophisticated fiber-optic communication systems. Glass products are well-established in a number of key markets, including insulation, lighting, windows, composites, containers, and consumer electronics, to name a few. The unique properties of glass such as transparency, chemical durability, optical and electrical qualities, high intrinsic strength and recyclability and the fact that a great many glasses are produced from abundant natural resources such as sand are behind the success which glass products have enjoyed.

All segments of the glass industry, which include container, flat, fiber and specialty glass, have many commodity products found in the lower left quadrant of Exhibit 6-1. The glass industry must broaden the use of existing manufacturing technologies to develop new products in existing and new market areas, develop more cost-effective manufacturing techniques to compete effectively against other materials in new and existing markets and support business and technical research to create completely new, innovative glass-containing products and processes in markets which previously did not use glass products. While there have been dramatic increases in the use of glass products during the past decade in fiber optics, photonics, glass fiber-reinforced composites and the safe storage of radioactive wastes, the unique attributes of glass have not been fully explored in these areas.

INNOVATIVE USES GOAL

The primary goal for innovative uses is to:

Create innovative products which broaden the marketplace. To remain as a viable and vibrant industry there must be support of work aimed at developing new glass compositions and products through increased fundamental understanding of the relationship between glass properties, glass structure and composition, and surface interactions.

TECHNOLOGY CHALLENGES AND BARRIERS

A number of technology barriers inhibit the greater utilization of glass. Some of the barriers are related to the physical, chemical, and aesthetic requirements of the finished product whereas others concern the current limitations of existing glassmaking processes. Opportunities to overcome critical innovative uses challenges, highlighted in Exhibit 6-2, are characterized in five key areas:

Communications and Electronics - Development of passive components and doped optical fibers as light amplifiers although not new, offer potentially new markets in communications for glass fibers.

Structural Uses - Fiberglass can find a significant new market potential if compatibility issues (e.g., alkali resistance) with concrete are resolved. More scratch resistant glass surfaces can resolve some production issues. The major barrier to OEM and architectural uses of flat glass is relatively high heat transfer coefficient and weight.

Novel Uses - Chemical and mechanical durability, and bio-compatibility are significant technological issues. Additional advances in uv-absorption for container glass and solar performance for flat glass are needed and are dependent on new or modified compositions. Weight reduction and high strength are needed for novel container and flat glass applications. Bio-compatible glasses as implant material and bio-active glasses for regenerative applications in orthopedic medicine can initiate high margin new markets.

Surfaces and Coatings - Improved understanding of surfaces is needed. Improvements are needed for glass coatings which covers a broad range of applications including anti-reflective and anti-static coatings for display components, low-emissivity and heat reflecting coatings, solar control coatings, fiberglass reinforcement, and coatings for electromagnetic radiation applications. An example is hydrophobic coatings, which were recently developed, that make it easier to perform the dreaded task of washing windows.

Advanced Processing and Control - The glass industry produces a broad range of products including large volume commodity to specialty application glasses. Advanced processing and control techniques are needed for innovative applications. For example, glass is uniquely suited for the fabrication of flat panel displays. As the processing and performance requirements for these devices become more severe, thermal stability, thermal expansion coefficient, and alkali migration issues become more demanding.

EXHIBIT 6-1. GLASS PRODUCTS

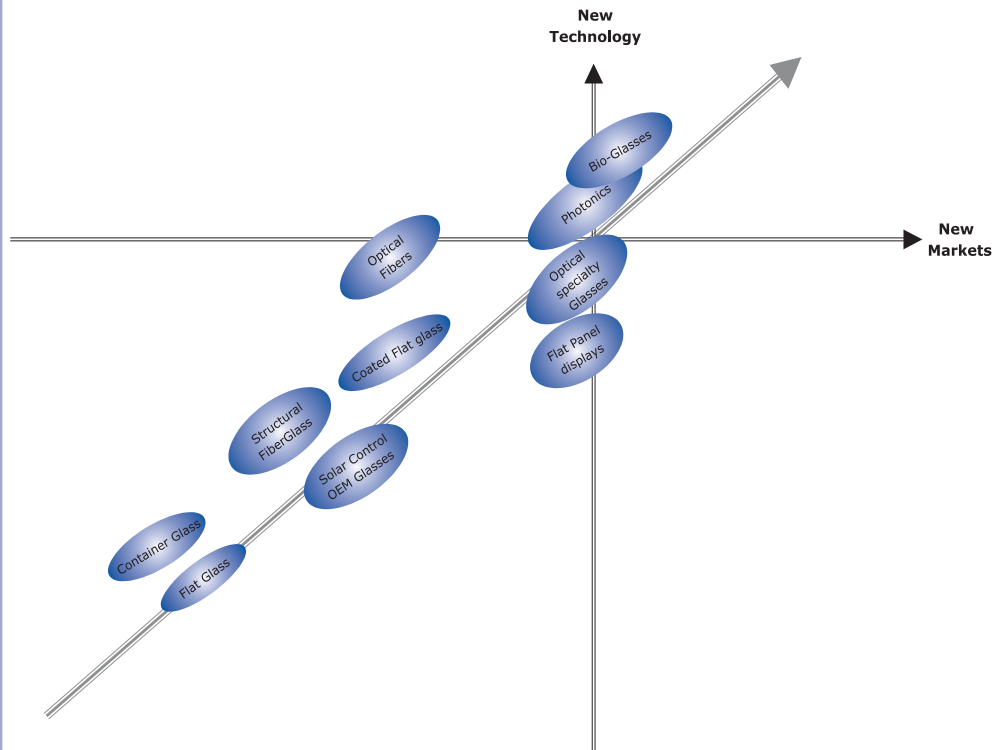


EXHIBIT 6-2. TECHNOLOGY CHALLENGES AND BARRIERS

COMMUNICATIONS AND ELECTRONICS

- ★ **Little or no data on non-linear properties of glasses**

STRUCTURAL USES

- ★ **Lack of adequate protection for large glass surfaces in transport**
- ★ **Limited data for accelerated life time analysis**
- ★ **Potential liability issues**
- ★ **Temperature limitations of glass composites**
- ★ **Limited new inorganic/organic composites**
- ★ **Lack of availability of high strength and high modulus glass products**

NOVEL USES

- ★ **Highly prohibitive and costly regulatory and liability issues**
- ★ **Lack of public knowledge of the benefits of using glass to encapsulate waste**
- ★ **Limited innovative uses for products made from wastes and adverse public perception of waste products**
- ★ **Inadequate or uncertain availability and purity of raw materials**

SURFACES AND COATINGS

- ★ **Lack of understanding of surface structure, surface chemistry, and surface interactions**
- ★ **Less than optimal durability of low-temperature glass**

ADVANCED PROCESSING AND CONTROL

- ★ **Suboptimal measurement and control of processes**
- ★ **Lack of adequate distortion measurement technology**
- ★ **Poor understanding and control of temperature gradients during forming**
- ★ **Lack of a non-intrusive flow characteristic measurement device**
- ★ **Limited processes for on-line coatings**
- ★ **Lack of processes for nitrided/carbided glasses**
- ★ **No cheap way to produce large area-controlled porosity glass**
- ★ **Lack of substitutes for toxic glass components**
- ★ **Need to expand limits of chemical durability**

RESEARCH AND DEVELOPMENT NEEDS

The glass industry will pursue a range of R&D activities aimed at developing enabling technologies and products. These activity areas include:

- * Communications and Electronics
- * Structural Uses
- * Novel Uses
- * Surfaces and Coatings
- * Advanced Processing and Control

A more detailed explanation of each area is described below and summarized in Exhibit 6-3.

COMMUNICATIONS AND ELECTRONICS

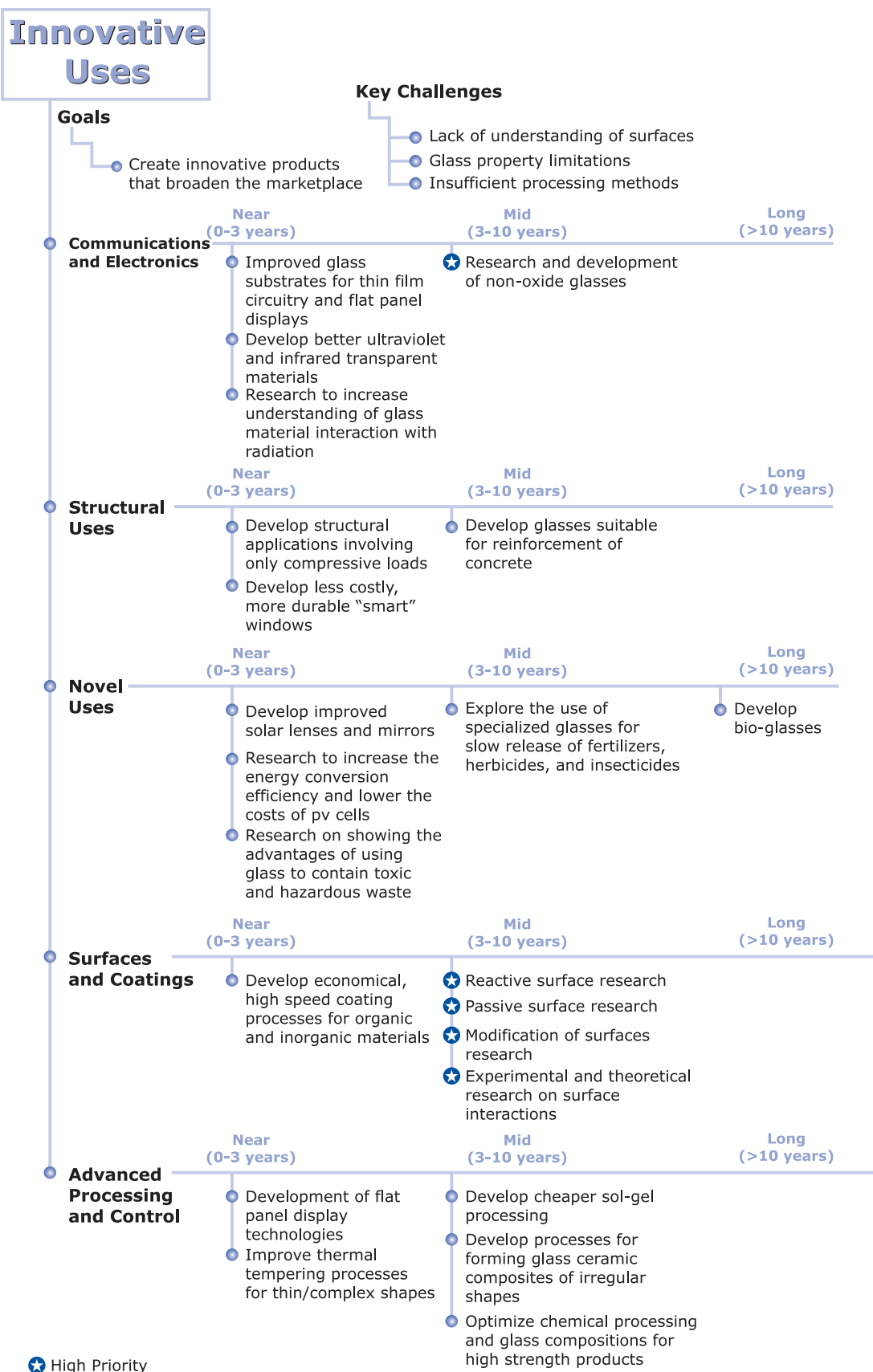
Particular areas of technology development include cost-effective optically non-linear glasses, graded index glasses, non-oxide glasses, and glasses with environmentally sensitive spectral properties for sensor development. Key R&D needs include:

- * **Fiber Optics** - Develop applications and improve performance of optical fibers, semi-conducting materials, optoelectronic circuits, circuit substrates, displays, lasers, fibers and other telecommunications components, optical security devices, and large optical elements
- * **Non-Oxide Glasses** - Develop non-oxide glasses with advanced compositions
- * **Glass Substrate Improvement for Thin Film/Flat Panels** - Develop improved processes for glass substrates used in thin film applications
- * **UV and IR Transparent Materials** - Develop glasses with ultraviolet and infrared transparent characteristics
- * **Understand Interaction with Radiation** - Research to increase understanding of glass interaction with radiation

STRUCTURAL USES

Potential applications exist in a number of markets, including buildings, roads and bridges, and vehicles. Key R&D needs include:

- * **Concrete Reinforcement** - Develop alkali-resistant systems for concrete reinforcement
- * **Load Bearing Applications** - Expand glass application in load bearing applications such as reinforcing fiber, fireproof materials, load bearing floors/supports, composite structures, and ceiling roofs
- * **Durable, Low-Cost Smart Windows** - Develop processes and compositions for smart window products



- ★ **Infrastructure Uses** - Develop glass compositions for reinforcement of roadways and bridges, and alkali-resistant glass fibers or whiskers for providing corrosion and earthquake protection of structural columns

NOVEL USES

Potential novel uses include solar, agricultural, environmental, medical and biomedical applications. As a component of these research efforts, the industry should support university research to acquire fundamental knowledge that would help enable the development of innovative glass products and markets. Key R&D needs include:

- ★ **Improved Solar Lenses and Mirrors** - Develop improved processing methods for solar lenses and mirrors
- ★ **Improved PV Cells** - Develop improved processing methods for photovoltaic cells
- ★ **Agricultural Uses** - Examine use of glass in agricultural applications such as controlled release fertilizers, herbicides, insecticides, and pest control
- ★ **Environmental Uses** - Expand use of glass in environmental applications such as encapsulation of various types of hazardous waste in glass

SURFACES AND COATINGS

Advances in producing harder and less expensive large area coatings or environmentally active coatings to render functional properties to glass surface can enhance or develop new markets for flat, container, fiber, or display glass products. Key R&D needs include:

- ★ **Economical High-Speed Coating Processes** - Develop economical processes for high-speed coating of glass
- ★ **Reactive Surfaces** - Develop glass compositions with reactive surfaces for biotechnology, biomedical, environmental, reinforcement, and sensor applications
- ★ **Passive Surfaces** - Develop glass compositions with passive surfaces that may be used for maintaining glass strength and durability and for spectral modification
- ★ **Modified Surfaces** - Develop improved glass products by modifying surfaces via compositional variations and/or coatings
- ★ **Experimental and Theoretical Surface Research** - Perform experimental and theoretical research focusing on increasing the understanding of glass surface interactions with various environments and materials

ADVANCED PROCESSING AND CONTROL

Development of new technologies and markets in the traditional commodity areas may have a large impact on the financial performance of most existing companies. On the other hand, major new developments in, for example, bio-glasses, can result in new startup companies with limited short term impact but potentially major long term results. Key R&D needs include:

- ★ **Optimized Chemical Processing and Composition for High Strength** - Develop improved processing and compositions for high strength glass products
- ★ **Flat Panel Display Processing** - Develop improved processing technology for flat panel displays
- ★ **Thermal Tempering** - Develop improved processes to reduce time and cost of thermal tempering
- ★ **Sol-Gel Processing** - Improve characteristics of this innovative processing method for glass products
- ★ **Irregular Shapes for Glass Composites** - Develop processing techniques for reinforcing new polymer systems
- ★ **New Concepts to Impart High Strength** - Develop novel processing approaches to create unbreakable glass products

PRIORITIES

The preceding R&D needs comprise a technology portfolio that will need to be undertaken to achieve a broader market for glass products. Within this portfolio are several high priority activities that are considered critical.

Communications and Electronics

- ★ Development of non-oxide glasses

Surfaces and Coatings

- ★ Reactive surfaces
- ★ Passive surfaces
- ★ Modified surfaces
- ★ Experimental and theoretical surface research

These priorities address the most important barriers to innovative uses.





COMMON THEMES AND PRIORITIES

The technology portfolio of the glass industry should be robust to respond to both near and long term changes in markets, technologies, and customer preferences. However, limited resources also require that the portfolio be focused on the most critical technology priorities that will lead to the production of high quality glass products (1) at reduced cost, (2) with increased productivity and (3) in an environmentally friendly manner; as well as the development of innovative product classes that will expand the reach of the glass industry. This chapter identifies the most important research and development priorities and common themes from the four technical elements and indicates how they can be integrated into an overall research portfolio. From the various research needs portrayed in this technology roadmap, the successful development and deployment of many of these technologies will be needed by the glass industry for its long term success.

MANUFACTURING FOCUS ON MELTING AND REFINING

The majority of the technical priorities fall within the melting and refining step of the manufacturing process, which is common to all sectors of the glass industry and provides the greatest opportunity for pre-competitive collaboration. Near and mid term research priorities such as advanced sensors, furnace and emission modeling tools, and batch and cullet preheating will provide valuable knowledge and technological improvements for the industry; however, they are primarily focused on current melting and refining technologies.

In the long term, the glass industry is convinced that a more radical improvement in the melting and refining process will be needed to solidify the competitive position of the industry. As such, a significant commitment from the industry will be needed to undertake such high-risk efforts, and considerable time and research funding will be required to develop and implement such technology. The GMIC has initiated a program to investigate opportunities for developing a Next Generation Melting System (NGMS) to focus that commitment. In accordance with the priorities identified in this Roadmap, this program is launching a process to: establish benchmark standards for today's glass industry technology, develop criteria for a future NGMS, solicit technically innovative ideas from researchers and inventors in the field, collect and analyze current technology levels and past efforts to upgrade glass melting technologies, and, depending on results of the foregoing, formulate proposals for major and systemic improvements to the glass melting process. Such technological advancements are expected to reduce: time requirements for melting and refining, production costs and energy consumption, capital investment, and environmental impacts.



PRODUCT FOCUS ON EXPANDING MARKETS

While the goal of this roadmap is not to advocate the development of specific products, it is instructive to provide guidance to the industry on the array of market opportunities available and fundamental knowledge required to broaden the marketplace for glass products. To complement this information, it is expected that the development of advanced processing techniques will be required to manufacture these novel products in a cost-effective manner. Priority is placed on researching surfaces and their interactions, the development of non-oxide glasses, and processing technologies.

COMMON THEMES

Many of the technology priorities within the four individual technical elements share technological elements with or will affect the research agenda of other technical elements. To illustrate this, relationships between priorities of the four technical elements are depicted in Exhibit 7-1, both in terms of their relative position in the glass manufacturing process and the anticipated timeframe for research results.

Beyond these individual relationships, there are several common themes contained in the research priorities described in the previous chapters. The most important research themes contained in this roadmap and their impact on the four technical elements include:

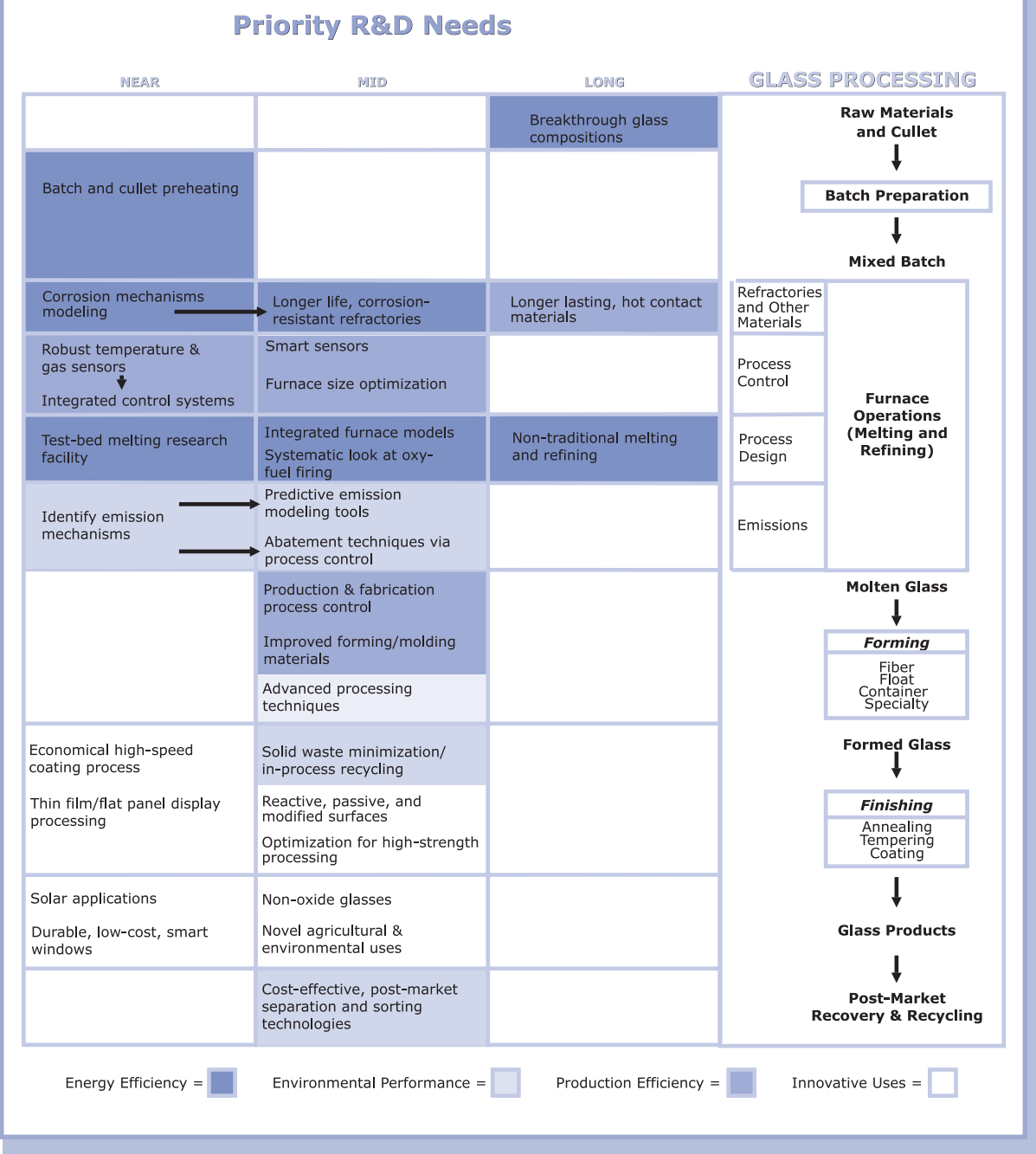
- ★ **Advanced Sensors and Controls** - while sensors and controls exist in current operations, improvements are needed throughout the glassmaking process. These sensors and controls are needed to provide additional information regarding the operating environment to improve control of glassmaking operations and the quality of glass products. Examples include viscosity sensors and robust temperature sensors.

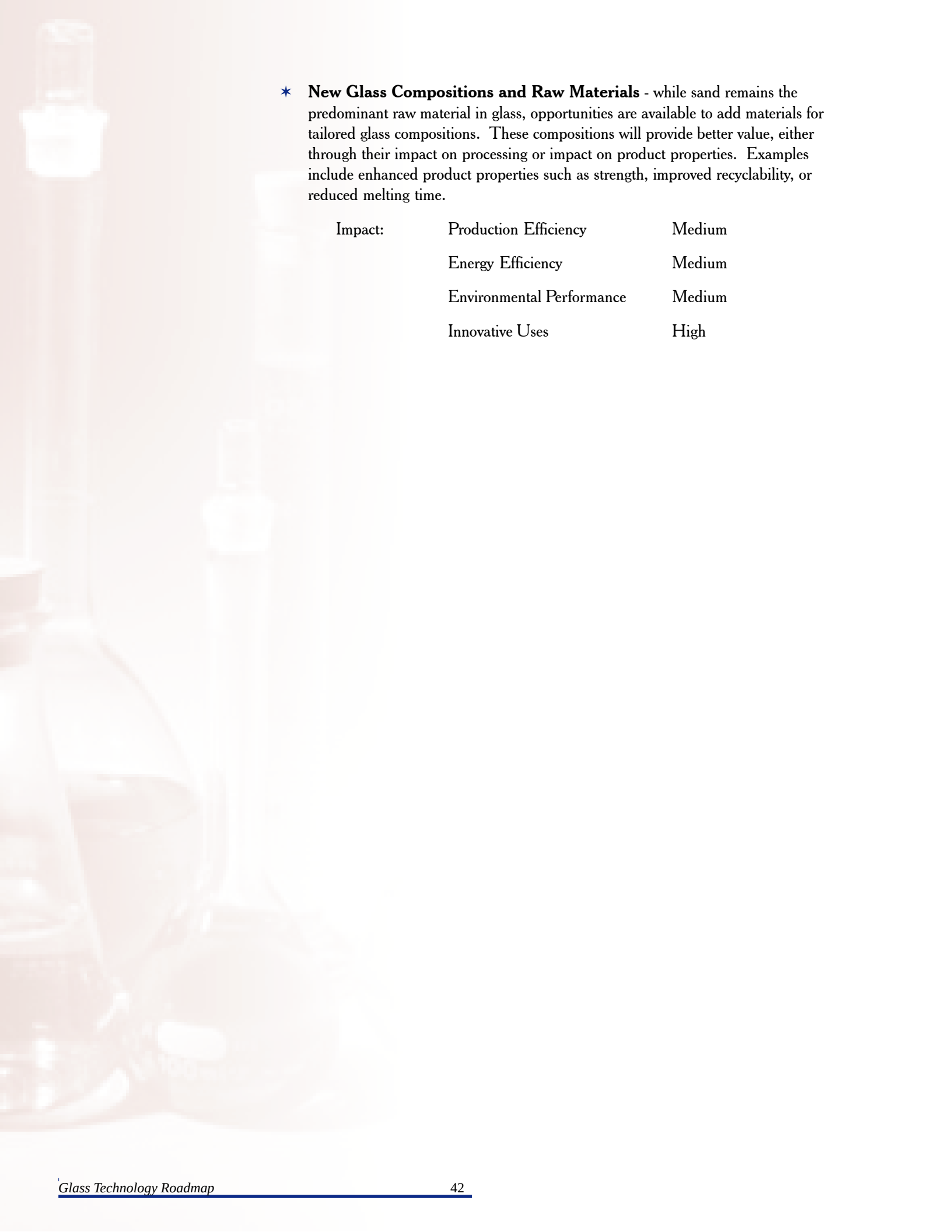
Impact:	Production Efficiency	High
	Energy Efficiency	Medium
	Environmental Performance	Medium
	Innovative Uses	Low

- ★ **Improved Materials for Operations** - opportunities abound to provide better materials for glassmaking operations. These materials are needed to provide better durability and value for service conditions encountered by glass manufacturers. Examples include refractories and hot glass contact materials, along with materials for equipment for alternative processing techniques for innovative uses.

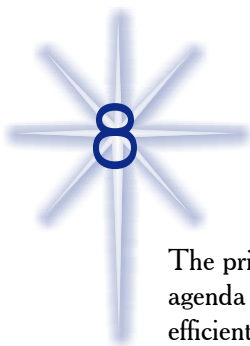
Impact:	Production Efficiency	High
	Energy Efficiency	Medium
	Environmental Performance	Low
	Innovative Uses	Medium

EXHIBIT 7-1. RELATIONSHIPS BETWEEN PRIORITY R&D NEEDS AND GLASS PROCESSING



- 
- ★ **New Glass Compositions and Raw Materials** - while sand remains the predominant raw material in glass, opportunities are available to add materials for tailored glass compositions. These compositions will provide better value, either through their impact on processing or impact on product properties. Examples include enhanced product properties such as strength, improved recyclability, or reduced melting time.

Impact:	Production Efficiency	Medium
	Energy Efficiency	Medium
	Environmental Performance	Medium
	Innovative Uses	High



IMPLEMENTATION

The primary purpose of this roadmap is to provide guidance on the technology agenda of the glass industry, and to ensure that this agenda is executed in an efficient and effective manner by focusing programs on issues which address the industry's most critical technology needs.

To facilitate the implementation of these efforts, a partnership was formed between the glass industry and the federal government, specifically between the Glass Manufacturing Industry Council and the U.S. Department of Energy. The partnership should strive to serve the legitimate needs of both parties, and is meant to serve national needs and industry priorities. However, the glass industry plays the leading role in defining goals, identifying research needs, and making specific recommendations on research projects. Implementation roles of various stakeholders are depicted below.

EXHIBIT 8-1. CURRENT GMIC MEMBERS

Core	Associate
• CertainTeed Corporation • Corning Incorporated • Fire and Light Originals L.P. • Johns Manville • Leone Industries • Owens Corning • Osram Sylvania • PPG Industries (Fiber) • PPG Industries (Flat) • Saint-Gobain Containers • Saint-Gobain Vetrotex America • Schott Glass Technologies Inc. • Society for Glass Science and Practices • Technoglas • Visteon Corporation	• Advanced Manufacturing Center • Air Liquide America • BOC Gases • Center for Glass Research • Eclipse Inc./Combustion Tec • Gas Technology Institute • Glass Service, Ltd. • Mississippi State University (Diagnostic Instrumentation and Analysis Laboratory) • Pacific Northwest National Laboratory • Praxair, Inc. • Siemens • U.S. Borax

GLASS MANUFACTURING INDUSTRY COUNCIL (GMIC)

Founded in 1998, the GMIC is a trade organization of the U.S glass industry that includes members of all four glass sectors: flat, container, fiber, and specialty. The mission of the GMIC is to facilitate, organize, and promote the interests and growth of the U.S. glass industry through cooperation in the areas of technology, productivity, and the environment.

As shown in the accompanying table, the GMIC is composed of both core members - those that create glass products from raw materials; and associate members - those that support the glass industry. The GMIC receives guidance from its board of directors, an executive advisory committee, and technical subcommittees representing the four elements of the roadmap: production efficiency, energy efficiency, environmental performance, and innovative uses. The GMIC will identify technology priorities,

evaluate proposals, attract research funding, provide oversight on research, help determine intellectual property rights, and protect the interests of its members.

The GMIC will also be instrumental in promoting best practices and tools for energy and cost management, in order to maximize the use of existing technologies within glass plants. Efforts may include training sessions, workshops, and information dissemination.

GMIC COMPANY MEMBERS

Each technical subcommittee is composed of individuals from members of the Glass Manufacturing Industry Council. These individuals have been delegated the responsibility for recommending priority research areas, as well as making assessments of proposals that have been submitted. Each subcommittee has a chairperson from a GMIC core member company.

HOST FACILITIES

It is envisioned that as research and development is completed within the partnership, technology demonstrations and showcases will be required as a step to commercial success and industry adoption. Those facilities within the industry that act as host for these demonstrations and showcases will become a valuable and integral element of the partnership.

SUPPLIERS

The glass industry's reliance on its suppliers has increased over the past decade - a trend that is likely to continue as competitive pressures increase. Many of the innovations developed through the partnership can become a reality only if industry suppliers are intimately involved in the planning, execution, and commercialization of process technologies and services. Because of this reliance, suppliers are encouraged to be associate members of the GMIC, as are research institutions engaged in the development of related technology.

DEPARTMENT OF ENERGY (DOE)

Without the stimulus provided by the DOE Office of Industrial Technologies that catalyzed the glass industry, it is unlikely that the current partnership between the glass industry and the federal government would exist. DOE helps industry reach consensus on their technology agenda, forms collaborative partnerships with energy-intensive industries and provides funding for cost-shared projects to address industry priorities that are appropriate with DOE's mission. Projects undertaken by the partnership are depicted in Exhibit 8-2, and a complete list of partners is contained in Exhibit 8-3.

NATIONAL LABORATORIES

The national laboratories of the Department of Energy represent an enormous resource, both in intellectual assets and unique capabilities and facilities. Working with the DOE's Office of Industrial Technologies, the national laboratory system has formed the National Laboratory Coordinating Council (LCC) to better serve the needs of industry. The LCC provides simplified

EXHIBIT 8-2. DOE GLASS PARTNERSHIP R&D PROJECTS (AWARDEE IN PARENTHESES)

Area	1996 and Earlier	1997 - 1999	2000 and Later
Production Efficiency	- Advanced High Temperature Materials for Glass Applications (Los Alamos National Lab) - Advanced Temperature Sensor (Accutru International Corp.) - Auto-Glass Process Control (Pacific Northwest National Lab) - Development of Advanced Refractories for the Glass Manufacturing Industry (Oak Ridge National Lab)	- Advanced Process Control for Glass Fabrication (Pacific Northwest National Lab) - Diagnostics and Modeling of High-Temperature Corrosion of Superstructure Refractories in Oxyfuel Glass Furnaces (PPG Industries) - Dynamic Expert System Controls for Optimal Oxyfuel Melter Performance (Air Products & Chemicals) - Enhanced Cutting and Finishing of Hand Glass Using a CO₂ Laser (Federal Energy Technology Center) - Molybdenum Disilicide Composites for Glass Processing Sensors (Los Alamos National Lab) - Redox State Sensor Technology in Glass Melts (Oak Ridge National Lab)	Measurement and Control of Glass Feedstocks (Energy Research Co.)
Energy Efficiency	- Development, Experimental Validation, and Application of Advanced Space Models (Brigham Young University) - High Luminosity, Low-NOx Burner (Gas Technology Institute) - Integrated Batch & Cullet Preheater System (Corning and Praxair) - Modeling of Glass Making Processes for Improved Efficiency (Center for Glass Research)	- Development and Validation of a Coupled Combustion Space/Glass Bath Furnace Simulation - Phase I (Techneglas) - Glass Furnace Combustion and Melting Research Facility (Sandia National Lab)	- Development and Validation of a Coupled Combustion Space/Glass Bath Furnace Simulation - Phase II (Techneglas) - Demonstration of an Integrated Batch Preheater and Emissions Abatement Device (BOC Gases)
Environmental Performance	Oxygen-Enriched Air Staging Technology for Sideport Furnaces (Gas Technology Institute)		- Monitoring and Control of Alkali Volatilization and Batch Carryover for Minimization of Particulate Emissions and Crown Refractory Corrosion in Glass Melting Furnaces (Gallo Glass) - Development of a Process for the In-House Recovery and Recycling of Glass from Glass-Manufacturing Waste (Argonne National Lab)
Innovative Uses	On-Line Vapor Deposition of Coatings on Float Glass (Sandia National Lab)	- On-Line Sensor System for Monitoring the Cure of Coatings on Glass Optical Fibers and Assemblies (Ames Lab) - Integrated Ion-Exchange Systems for High-Strength Glass (Center for Glass Research)	Development of Process Optimization Strategies, Models, and Chemical Databases for On-Line Coating of Float Glass (PPG Industries)

access to laboratories and facilities, provides technical input to industry in developing research agendas, and stimulates and fosters collaborations with industry and academia.

OTHER GOVERNMENT AGENCIES

Other federal and state government agencies will have a significant role in the implementation of the partnership. Federal agencies that have program missions relating to glass technology, such as the Departments of Commerce and Defense and the National Science Foundation (NSF), are engaged in science and technology as well as the development of specialized products that require new processing methods. State governments, through their state energy offices, economic development offices, and research agencies, also have considerable interest in these partnership efforts.

ACADEMIC INSTITUTIONS

The nation's extensive academic institutions will also provide ideas and knowledge, along with teaching future scientists and engineers that will be employed by the glass industry and its partners. The GMIC is developing the University Research Alliance in Support of the Glass Industry (URASGI) to identify specific skills, capabilities, and research interests of institutions engaged in related research to more effectively utilize available resources. Of particular note is the Center for Glass Research (CGR). Located at Alfred University, with satellite campuses at the University of Missouri-Rolla focusing on refractories and at Pennsylvania State University focusing on glass surfaces and interfaces, the CGR is a NSF Industry-University Center whose purpose is to advance the field of glass science and engineering in basic, pre-competitive glass research.

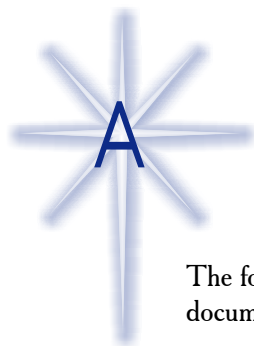
INDUSTRY GROUPS

The GMIC will actively engage other interested parties that share similar interests. These groups mostly fall into two areas: those associated with individual glass sectors, such as the Glass Packaging Institute, North American Insulation Manufacturers Association, Primary Glass Manufacturers Council and the National Glass Association, and those associated with similar missions, such as the American Council for an Energy Efficient Economy and the Alliance to Save Energy.

EXHIBIT 8-3. DOE GLASS R&D PARTNERS TO DATE

Glass Manufacturers	Suppliers	Laboratories	Universities and Research Institutions
• CertainTeed Corp. • Corning, Inc. • Fenton Art Glass Company • Gallo Glass • GE Lighting • Johns Manville • Leone Industries • Libbey, Inc. • Osram Sylvania • Owens Corning • Owens-Brockway • Pilgrim Glass • Pilkington LOF • PPG Industries • Saint-Gobain Vetrotex America • Society for Glass Science and Practices • Techneglas • Thomson Consumer Electronics • Visteon Corporation	• Accutru International Corp. • Advanced Control Solutions • Air Products & Chemicals • American Air Liquide • BOC Gases • Combustion Tec • Corhart Refractories • Emhart • Energy Research Co. • Exotherm Corp. • Harbison-Walker • Monofrax • North American Refractory • Praxair	• Ames Lab • Argonne National Lab • Federal Energy Technology Center • Los Alamos National Lab • Oak Ridge National Lab • Pacific Northwest National Lab • Sandia National Lab	• Brigham Young University • Center for Glass Research • Gas Technology Institute • Mississippi State University • Ohio State University • Purdue University • University of Missouri-Rolla • West Virginia University





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