DRIVING FUNCTIONAL GLASS MANUFACTURING INNOVATION:

A TECHNOLOGY ROADMAP TO 2025

March 2017

The American Ceramic Society
www.ceramics.org

Supported by NIST Cooperative Agreement number: 70NANB15H073

ACKNOWLEDGMENTS

This roadmap was developed through a public-private partnership under the direction of Charlie Spahr, Executive Director of The American Ceramic Society (ACerS); Eileen De Guire, Director of Communications and Marketing at ACerS; and the Functional Glass Manufacturing Innovation Consortium (FGMIC) Leadership Team, with direct input from industry, academia, and government agencies. Nexight Group supported the overall roadmapping process and prepared this roadmap; Sarah Lichtner, Ross Brindle, Annie Best, and Changwon Suh are the primary contributors, and Greg Hildeman and Warren Hunt provided strategic support and materials science expertise. The functional glass manufacturing industry experts who made vital contributions through workshop participation, phone interviews, and roadmap reviews are identified in Appendix A.

This work was supported by the NIST Advanced Manufacturing Program by NIST Cooperative Agreement 70NANB15H073 under the guidance of federal program officer Jean-Louis Staudenmann and grant specialists Dean Iwasaki and Elaine Nghiem.

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ABOUT THIS ROADMAP

Functional glasses are glasses with tailored compositions or engineered structures that enable advanced technologies with enhanced performance.

These glasses help define the capabilities of many products and devices that impact our daily lives, including the smartphones and fiber optic cables that allow our society to be so highly connected and the vehicle windshields and vaccine vials that ensure our health and safety. In the next few decades, key downstream industries—including energy, information technology and communications, defense, consumer electronics, transportation, and medicine—will increasingly rely on high-quality glass manufactured to exacting specifications. Functional glasses will offer solutions to society's grand challenges and transform our way of life.

FGMIC VISION

Coordinate a national initiative to develop and deploy advanced manufacturing technologies across the broad functional glass manufacturing community, driven by the needs of high-performance functional glasses, which will significantly increase sustainability and U.S. global competitiveness.

To meet the growing national need for high-performing glasses, The American Ceramic Society (ACerS) led activities to plan for the launch of the Functional Glass Manufacturing Innovation Consortium (FGMIC) and the development of this roadmap, with funding from the National Institute of Standards and Technology (NIST) Advanced Manufacturing Technology (AMTech) program. This roadmap identifies challenges that currently constrain functional glass manufacturing and provides pathways for developing, improving, and implementing advanced technologies over the next 10 years that are critical to industry innovation.

The development of this roadmap was informed by a variety of stakeholder inputs, built around two highly interactive roadmapping workshops. More than 50 glass manufacturing experts came together from more than 40 organizations—including glass manufacturers, equipment manufacturers, raw material suppliers, end-use industries, academic institutions, national laboratories, government agencies, and professional associations. During these workshops, participants envisioned the future of functional glass manufacturing, identified technical gaps and barriers that currently constrain the industry, identified and prioritized research and development activities that address these gaps and barriers, and defined the vision and mission of FGMIC. To solicit input from key stakeholders who were unable to attend the in-person workshops, ACerS conducted a series of phone interviews. The roadmapping team also reviewed key roadmaps, journal articles, and industry resources on glass manufacturing to ensure the FGMIC effort continued to build on previous work (See Appendix B for a comprehensive list of industry sources reviewed).

The priority activities outlined in this roadmap will inform the initiatives of FGMIC, as well as the entire glass manufacturing industry, academic researchers, public and private funding agencies, and standards organizations. The ultimate vision of FGMIC is to develop and deploy advanced manufacturing technologies across the broad functional glass manufacturing community, driven by the needs of high-performance functional glasses. By facilitating technology implementation, FGMIC aims to significantly increase the sustainability and U.S. global competitiveness of glass manufacturing. To achieve this vision, FGMIC will focus on characterizing glass structures and properties, advancing modeling and simulation, optimizing manufacturing processes, establishing data infrastructure and best practices, and improving workforce development and coordination.

FUNCTIONAL GLASS: A WINDOW TO THE FUTURE

Smartphones, solar panels, fiber optic cables, lasers, and many other technologies that have changed the way we live would not exist without high-performing functional glasses. The unique properties of glass make it an ideal choice for a range of applications, and make glass manufacturing an essential part of the U.S. economy. The industry impacts about 1.83 million people in the United States who are employed at more than 57,100 businesses. Together, these companies generate more than $1 trillion in economic activity each year (see Figure 2 for more detail).[1] Pursuing further improvements in functional glass manufacturing can position U.S. manufacturers for global leadership and create and sustain high-paying U.S. manufacturing jobs.

Innovative breakthroughs in functional glasses can enable new solutions to some of society's grand challenges. For example, research and development of functional glass has already led to improved functional glasses that promise to increase energy efficiency and environmental sustainability, improve health and welfare, enhance national security and workforce safety, enrich information sharing, and advance mobility. With increased investment over the next 10 years, further innovations in functional glass manufacturing could deliver new solutions to these critical challenges and further transform our way of life.

Grand Challenge	Functional Glass Opportunities
 Increased Energy Efficiency and Environmental Sustainability	▶ **INCREASE THE SUSTAINABILITY OF END-USE PRODUCTS –** Lighter-weight, higher-strength, and lower-density glass can improve the energy efficiency of end-use products, while glass coatings could significantly extend product life or enhance functionality. ▶ **FACILITATE INCREASED PENETRATION OF RENEWABLE ENERGY SOURCES –** More efficient solar cells and smaller, lighter-weight wind turbines could increase the efficiency and lower the cost of renewable power generation technologies. ▶ **REDUCE BUILDING ENERGY CONSUMPTION –** Advanced windows could lower heating and cooling energy costs substantially, and the use of advanced lighting could significantly decrease lighting energy consumption. ▶ **MINIMIZE ENERGY CONSUMPTION OF MANUFACTURING PROCESSES –** Advanced manufacturing processes and improved plant design can reduce the overall energy needs and emissions of glass manufacturing.
 Improved Health and Welfare	▶ **ENABLE NEXT-GENERATION MEDICAL DIAGNOSTICS AND TREATMENTS –** Functional glass applications include the use of bioglass to repair soft tissue, new materials and structures for dental materials and other structural medical applications, substrates for genetic and other biomedical sensors, and the use of glass fibers in conjunction with lasers to assist with advanced surgical procedures. ▶ **ENHANCE THE EFFICACY AND RELIABILITY OF DRUG DELIVERY SYSTEMS –** Stronger glass storage containers, including syringes, cartridges, and vials, will ensure the safe storage of medicines and increase the likelihood that products will work as expected during life-saving situations. ▶ **IMPROVE WATER QUALITY AND SANITATION –** Glass could be used in everyday applications that improve overall health, including filtering technologies that facilitate the availability of potable water and anti-bacterial glass to improve sanitation.

1. 2012 Economic Census of the United States; Annual Survey of Manufactures 2014.

Grand Challenge — Functional Glass Opportunities

Enhanced National Security and Worker Safety

- **MODERNIZE INFRASTRUCTURE AND IMPROVE PRODUCT SAFETY –** Glass fiber sensors could be embedded in infrastructure and products to monitor materials reliability (e.g., for concrete used in civil engineering) and could be used to non-destructively evaluate products.
- **ENSURE WORKPLACE SAFETY –** Advanced glass-based sensing technologies can be used to detect dangerous concentrations of chemicals in the air, to conduct agricultural silo inspections, and to read chemical tank levels, ultimately reducing the risk of human harm.
- **INCREASE MILITARY EFFECTIVENESS –** Glasses can be used in a number of military applications—including light-weight, solid-state batteries; portable solar applications; and advanced sensors and lasers—to protect the modern soldier.

Enriched Information Sharing

- **INCREASE THE RATE AND ACCURACY OF INFORMATION TRANSFER –** Improved and more prevalent glass fiber systems can revolutionize the speed of information transfer and the accuracy and capacity of information storage.
- **ENHANCE THE USER EXPERIENCE –** Glasses with improved tactics could provide feedback from the device to the user, and the increased use of smart, connected products could enable entirely new industries, including electronic medical records.
- **INCREASE THE ACCESSIBILITY OF CONSUMER ELECTRONICS –** Functional glasses can enable virtual reality displays for training, medical treatment, and entertainment and can facilitate the increased prevalence of active displays in cars, buses, doctors' offices, hospitals, and other common locations.
- **AMPLIFY COMPUTING POWER –** Next-generation optical glasses could facilitate optical computing—the use of photons produced by lasers or diodes rather than electric pulses to perform digital computations—which could significantly increase future computing power.

Advanced Mobility

- **REDUCE VEHICLE EMISSIONS –** Lighter-weight, stronger glasses—including glass fiber composites and laminates—can be used in automotive windshields, windows, and sunroofs and interior aircraft and train components to reduce overall vehicle weight, increasing fuel efficiency and reducing resulting emissions.
- **ENHANCE VEHICLE SAFETY –** Strong functional glasses integrated in vehicle windshields, cabins, and other components could improve a vehicle's ability to withstand a crash.
- **IMPROVE VEHICLE COMFORT –** Electrochromic glass windows could darken at the touch of a button, and optical glasses could provide acoustic barriers while enabling the increased prevalence of touchscreen devices.

Societal challenges will continue to demand advanced materials and technologies. Functional glasses can offer innovative solutions. New research, for example, could facilitate the development of new types of glass, including glasses that are porous, foam-like, sprayable, and flexible—materials with properties and functionality that previously did not exist. To realize this potential of functional glasses, researchers must learn to better control glass composition, structure, and processing. Through a coordinated, targeted approach to functional glass research and development, the glass industry can enhance the properties of existing glasses and develop new compositions that can revolutionize technology.

Driving Functional Glass Manufacturing Innovation: A Strategy to 2025

This roadmap outlines a strategy for guiding the functional glass manufacturing industry's efforts over the next 10 years, helping the industry offer and capitalize on solutions to many of society's grand challenges. The roadmap strategy combines focused research and development activities with initiatives designed to sustain and support the functional glass manufacturing industry. Through increased industry coordination made possible through the Functional Glass Manufacturing Innovation Consortium (FGMIC), higher-performing functional glasses could penetrate new markets and be increasingly viewed as a trusted, high-performing material. These innovations in functional glass manufacturing could ultimately grow the number of U.S. jobs in this field, improve our economy, and enhance the overall global competitiveness of U.S. manufacturing.

The way in which glass is formed and finished is critically important to its properties, necessitating more reliable characterization technologies, more accurate predictive modeling and simulation tools, and optimized manufacturing technologies and processes. To cost effectively and efficiently develop high-quality glasses for use in a range of demanding applications, the functional glass industry must focus on research and development activities aimed at increasing understanding of glass process-composition-structure-property relationships and more precisely controlling these interactions. To ensure availability of the reliable data on which these advances depend, the glass industry must establish a robust infrastructure with industry best practices for data curation, management, and accessibility.

Increased collaboration and education across stakeholders—including researchers, industry, equipment manufacturers, and end-product industries—will also be critical to the development and deployment of highly engineered products that capitalize on the unique performance capabilities of functional glasses. To accelerate progress, the glass industry must leverage existing knowledge, technologies, and processes throughout the functional glass industry; broaden the interdisciplinary nature of the industry's approach; and closely collaborate with end-use industries. Through these efforts, the functional glass community can ensure the widespread adoption of advanced manufacturing technologies and processes across the functional glass industry, as well as the increased adoption and demand for functional glasses in key end-use industries, including energy, information technology and communications, defense, transportation, medicine, and consumer electronics.

The roadmapping process identified five strategic pathways, which are depicted in Figure 1. Each of the five roadmap pathways—Characterizing Materials Structures and Properties, Modeling and Simulating Performance, Optimizing Manufacturing Processes, Data Infrastructure and Best Practices, and Workforce Development and Coordination—includes key initiatives with focused activities. Figure 1 summarizes the high-priority activities that, if addressed through collaborative research and development, will accelerate progress toward the functional glass manufacturing industry's vision. A more comprehensive action plan for each of the pathways is outlined in subsequent roadmap sections. While many of the roadmap activities could be started immediately depending on resource availability, some activities must be done in sequence or will take longer periods of time to yield meaningful results.

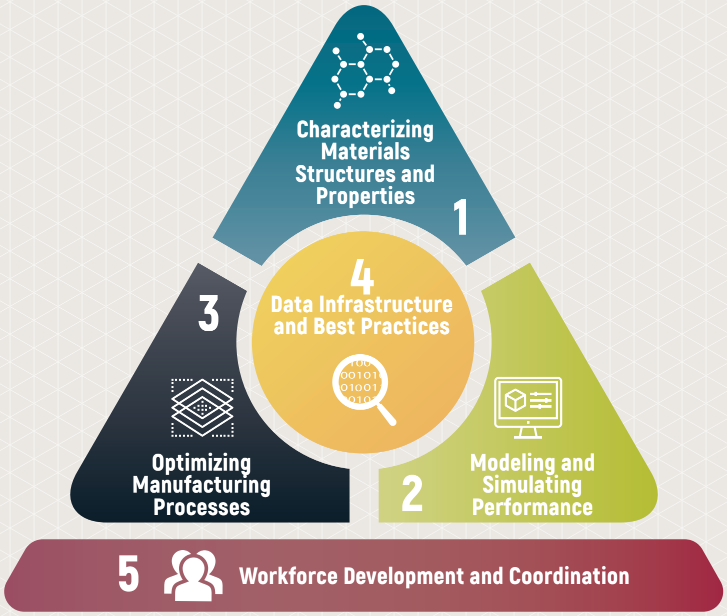
By implementing the roadmap activities, the glass manufacturing industry can facilitate development of innovative technologies that can address some of society's most critical challenges and improve our everyday lives. Through an increased focus on functional glass manufacturing, the United States can not only secure its global lead in this field, but also revitalize the U.S. glass industry, grow the U.S. economy, and create high-paying manufacturing jobs.

FIGURE 1

Functional Glass Manufacturing Innovation Strategy

This figure summarizes the high-priority activities that, if addressed through collaborative research and development, will accelerate progress toward the functional glass manufacturing industry's vision. While many of the roadmap activities could be started immediately depending on resource availability, some activities must be done in sequence or will take longer periods of time to yield meaningful results.

Roadmap Pathways and Associated Initiatives



1. Characterizing Materials Structures and Properties

A greater understanding of glass process-composition-structure-property relationships will enable the glass industry to tailor glasses to achieve desired performance capabilities.

- **1A** Raw Material Supplies and Recycling
- **1B** Batch-to-Glass Reactions
- **1C** Glass Structure-Property Data

2. Modeling and Simulating Performance

Advanced modeling and simulation tools can help glass manufacturers to more cost effectively improve the precision of manufacturing processes, explore the capabilities of new compositions, and predict long-term materials performance.

- **2A** Glass Composition Models
- **2B** Process Models
- **2C** Glass Modeling Infrastructure

3. Optimizing Manufacturing Processes

Optimized manufacturing processes can reduce manufacturing costs and energy consumption and enable the development of functional glasses with more reliable and consistent properties and performance.

- **3A** Advanced Process Monitoring and Controls
- **3B** Advanced Equipment
- **3C** Intermediate-Scale Manufacturing
- **3D** Innovative Processes and Techniques

4. Data Infrastructure and Best Practices

Access to more robust and reliable data is critical for effectively characterizing materials, modeling their performance, and optimizing manufacturing processes.

- **4A** Data Generation and Reliability
- **4B** Database Development and Management
- **4C** Data Dissemination and Accessibility

5. Workforce Development and Coordination

Building a skilled workforce and improving coordination across the glass manufacturing community will be critical for the effective and efficient execution of targeted research, development, and technology implementation activities.

- **5A** Research Community and Industry Coordination
- **5B** Education and Training

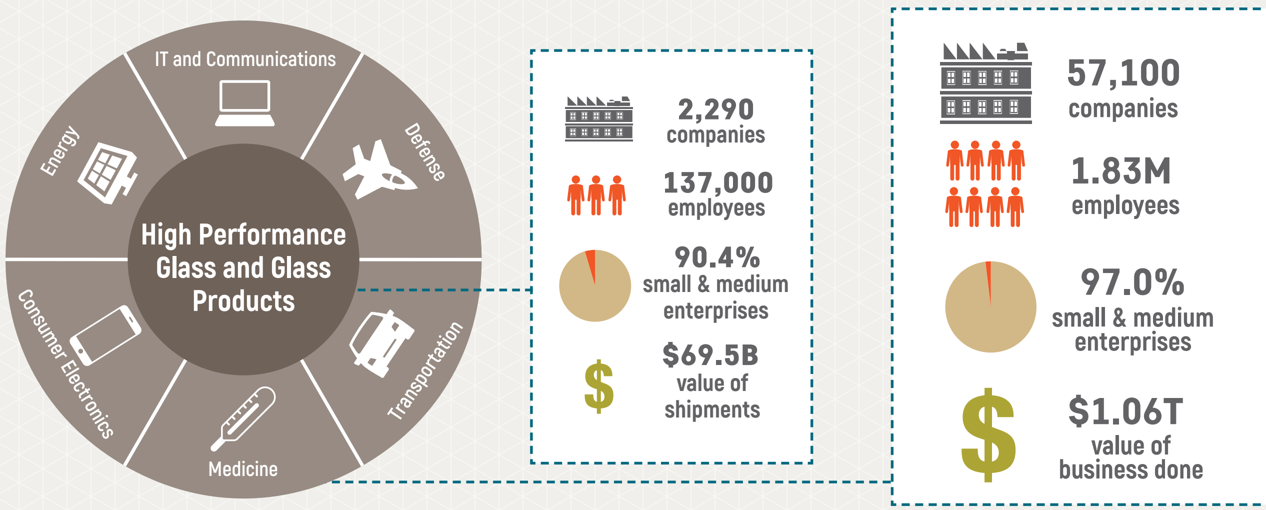
Timeline of High-Priority Activities

2017	1C	Define base composition categories (i.e., standard samples)
	2A	Work with DOE and NSF to establish a consortium of universities, national laboratories, and funding agencies to develop atomistic/molecular models for glass systems of interest
	3A	Solicit industry interest to define key systems that require online, 3D sensor development
	3B	Increase availability of refractories (i.e., reduce current long lead times)
	3D	Develop a glass process (e.g., coating) with the ability to improve a final product's mechanical and thermal strength and chemical durability
	4A	Define minimum data reporting standards—including accompanying metadata (e.g., tolerances and uncertainties) and data schema
	4B	Revive or reinvent the SciGlass or INTERGLAD database systems, and develop new tools or processes to increase their usability
	5A	Establish a needs capture program in the functional glass manufacturing industry at the plant level
2019	1A	Improve infrastructure for glass collection and processing to efficiently and economically increase the quantity and quality of recycled glass
	1B	Advance understanding of the kinetics of batch-to-glass reactions, including the effects of raw materials chemistry, grain size, and temperature
	1B	Designate or develop specialized facilities available to manufacturers for characterizing melts, batch reactions, and fining processes
	1B	Develop more or better sensors to measure data in-situ in tanks
	1C	Identify currently available expressed or accelerated testing methods for screening large sets of glass quickly
	1C	Characterize melt structure, thermophysical properties, and functionality-specific properties
	1C	Develop techniques with high chemical or topographical sensitivity for characterizing the large-scale homogeneity of surfaces and coatings
	2A	Fit interatomic potentials to glass and melt data, not just to crystals
	2B	Develop standardized in-situ measurement techniques
	3C	Design and construct an industry-university-government intermediate-size melt and forming facility
	3C	Develop more energy-efficient melting processes
	3D	Explore green manufacturing processes for waste reduction and environmental remediation
	5A	Increase industry engagement of faculty and students in fundamental and applied research, while also re-engaging funding agencies by articulating the importance of glass research
	5A	Launch industry-funded, interdisciplinary Ph.D. programs on materials development for materials for in-situ sensors and other topics with substantial industry interest
	5A	Establish industrial chair positions for glass professors
	5B	Increase university and industry involvement with high school and middle school teachers
2021	1A	Incentivize glass recycling through increased legislation to enable materials of acceptable quality to be recovered and processed into a usable form for glass manufacturers
	2B	Incorporate batch-to-glass thermodynamics and kinetics into an overall furnace model
	4A	Develop infrastructure for assessing metadata, including measurement techniques and the degree to which the data has been vetted or modeled
	4B	Develop integrated databases that contain data on properties, structure, and processing history to increase their usability
2023	1A	Work with suppliers to identify other possible materials reserves and potential opportunities for new deposits
	1C	Establish a high-temperature measurement facility to develop awareness of instruments and methodology for measuring industrially important high-temperature properties and to provide industry with opportunities to measure and test physical properties of molten glass
	3A	Develop "smart" refractories with in situ sensors
	3D	Advance robotics for glass manufacturing
	5A	Launch pre-competitive research consortia to promote collaborations between companies and universities
2025+	4A	Develop a secure industry standard database to standardize and streamline collection of materials testing data from all industrial raw materials suppliers
	4C	Establish robust infrastructure for secure data access that allows manufacturers to quickly and easily access the data from their suppliers

FIGURE 2

The Current Reach of Functional Glass Manufacturing

Currently, functional glass manufacturing is estimated to directly and indirectly impact the employment of an estimated 1.83 million people in the United States at more than 57,100 businesses. These companies—which in the functional glass manufacturing industry are 90.4% small and medium enterprises—ship $69.5 billion in high-performance glass to downstream markets, which themselves go on to generate $1.06 trillion in economic activity each year. The figure below details the broad reach of applications that functional glasses make possible. With further development, functional glasses will be well positioned to solve a variety of key technical and manufacturing challenges across this diverse range of industries, increasing the market share of glass in these industries as well as the jobs and revenue functional glass manufacturing can contribute to the U.S. economy.



2012 Economic Census of the United States; Annual Survey of Manufactures 2014

Energy

The use of specialized, engineered glasses is critical to many aspects of energy production. For example, glass optics are used in both photovoltaic and solar thermal applications to concentrate sunlight by 2–2,000 times normal solar power,[2] and glass layers are also used to protect and support photovoltaic materials. As a result, glasses currently account for up to 25 percent of solar module cost.[3] In wind-based electricity generation, glass fiber-reinforced composite materials enable lightweight turbine blades, which allows for power generation at lower wind speeds. Other key applications for glass in the energy sector include, but are not limited to:

- **Energy storage**—High-performance glasses are used as solid electrolyte layers in fuel cells and lithium-ion batteries.
- **Coal power**—Glassy coatings help increase corrosion resistance of power plant equipment.
- **Oil and gas mining**—Fiber-optic sensors provide real-time feedback on well environments.
- **Nuclear**—The chemical durability, mechanical properties, and radiation and thermal stability of glass make it well suited for nuclear waste storage.

Information Technology and Communications

Modern information technology and communications infrastructure relies heavily on engineered optical glasses—such as optical fibers, lenses, and optical windows—manufactured to rigorous standards. Advanced optical fibers have enabled the use of longer wavelengths (0.85μm to 1.5μm), minimizing losses of information during transmission,[4] as well as the use of 100 different wavelengths of light within a single fiber, which has increased network capacities by more than 100 times in just the past decade.[5]

Defense

Specialized glasses enable modern soldiers to carry out their mission safely and effectively. Many military technologies—including night-vision goggles, sensing systems, and laser technologies—depend on advanced optics and photonics technologies. These technologies offer smaller, lightweight, long-range alternatives to legacy sensing systems. Advanced sensors and high-energy lasers provide high levels of confidence for potential threat detection and ultra-precise target acquisition and tracking.

Transportation

The automotive industry uses 5.5 billion square feet of glass yearly—glass components made using 1950s technology.[6] Lightweight, thin, strong functional glasses are already helping to increase fuel efficiency, reduce emissions, and maximize electric vehicle cruising range. Functional glasses also enhance automobile comfort and safety by reducing sun glare, noise, and crash impact, as well as through the increased integration of touchscreen devices in cabin control systems.

Medicine

Functional glass can be used in the medical industry for a variety of applications, including restoring the functionality of bones and teeth, accelerating wound recovery, improving diagnostics, and increasing the safety of pharmaceutical packaging. Medical scopes and laser-based surgical tools depend on specialized optics, and non-orally administered drugs are often packaged in glass containers that must reduce the chances of container breakage and minimize the likelihood of glass particles becoming suspended in the medicine.

Consumer Electronics

Functional glasses have facilitated the availability and widespread use of touch-enabled devices. The touchscreens of display devices such as smartphones are made with highly engineered glass compositions and are manufactured using an advanced fusion draw process followed by ion-exchange strengthening. Other functional glasses encapsulate and hermetically seal interior device electronics, and a glass backplane supports thousands of miniaturized electronic components.

2. Committee on Harnessing Light: Capitalizing on Optical Science Trends and Challenges for Future Research, *Optics and Photonics: Essential Technologies for Our Nation* (Washington, DC: The National Academies Press, 2012), 5-107.
3. Klaus Bange, Himanshu Jain, and Carlo Pantano, *Functional Glasses: Properties and Applications for Energy and Information*, ed. Klaus Bange, Alicia Durán, and John Parker (Madrid: Cyan, Proyectos Editoriales, S.A., 2015), 19.
4. Ibid.
5. Committee on Harnessing Light, *Optics and Photonics*, 3-52.
6. Trefis Team, "Automotive Applications New Revenue Potential for Corning's Gorilla Glass," *Forbes*, June 30, 2014.

Courtesy of Corning Incorporated

PATHWAY 1

CHARACTERIZING MATERIALS STRUCTURES AND PROPERTIES

KEY INITIATIVES

- **1A** Raw Material Supplies and Recycling
- **1B** Batch-to-Glass Reactions
- **1C** Glass Structure-Property Data

Glass properties—including optical, mechanical, electrical, chemical, and thermodynamic properties—are defined by glass composition and structure, along with processing parameters during manufacturing. The glass manufacturing industry, however, does not currently have a strong understanding of the process-composition-structure-property relationships of functional glasses due to the essentially infinite number of possible glass compositions and the complex interdependencies between processing parameters. The ability to cost effectively and accurately generate data about functional glasses from state-of-the-art characterizations (e.g., at high temperature) is key to deciphering process-composition-structure-property relationships. An improved understanding of these relationships is critical to enabling the glass industry to accelerate the development of glasses with improved functionality, more consistent and reliable performance, and reduced costs.

Current Challenges

To enable functional glass manufacturing innovation, the glass community must work to overcome the materials structure and properties characterization challenges that follow.

Fluctuations in raw materials consistency, availability, and cost

Due to the globalization and consolidation of raw materials suppliers, as well as high raw materials demand and competition from energy markets, the glass industry sometimes struggles to secure high-quality materials. The industry is often forced to purchase silicate materials that are left over from mining operations—materials that are often higher in impurities or have smaller particle sizes than are ideal for existing glass manufacturing equipment and processes.

In addition to these difficulties securing silicate materials, supplies of rare earth materials are limited and costly, which can lead to potential supply disruptions.

Insufficient fundamental physical and chemical understanding of glass processes

Glass researchers and manufacturers currently lack a holistic understanding of the link between glass chemistry (e.g., glass composition and formation) and glass physics (e.g., glass state—transition or relaxation), making it difficult to understand the long-term performance and durability of glass materials and to tailor manufacturing processes to optimize materials properties. It is a complex undertaking to consider process parameters—including reaction chemistry, heat transfer, rheology, and fusion—

from the microscopic to macroscopic scale. For example, the industry currently has insufficient knowledge of melting (e.g., batch melting) and fining of complex glass compositions, particularly the viscoelastic behavior and gas solubility of glass and the impact of these properties on forming.

Lack of measurement and description of process variables and conditions

There is a critical need to accurately measure and describe process conditions (e.g., batch size) and various phenomena in glass melting. Such information is invaluable to correlating and manipulating parameters for precise process control. While thermodynamic parameters can be calculated as inputs for glass batch modeling, accurate input parameters from experiments—including process descriptions of glass melt—are equally important for robust predictive modeling, which can provide insight into glass melting mechanisms.

Inability to efficiently process recycled glass and manufacturing byproducts into high-quality products

U.S. manufacturing industries are increasingly pressured to improve the sustainability of manufacturing processes but must do so efficiently and economically to maintain profitability. Within current recycling programs in the United States—many of which focus on single-stream collection—the value of glass to waste management companies is relatively low. As a result, current processes for recovering and processing recycled glass have insufficient capacity and infrastructure, which limits the quantity and quality of glass recovered that can be returned to manufacturers and processed into high-quality products. Additionally, glass manufacturers need to proactively address technical barriers and policy issues associated with recycling waste glass for use in non-container glass products.

Key Initiatives for Advancing Functional Glass Manufacturing

Addressing these challenges will require coordinated efforts across the glass manufacturing community to develop, optimize, and implement advanced characterization technologies. To realize the potential of functional glasses, the glass community must collaborate on the following key characterization initiatives: Raw Material Supplies and Recycling, Batch-to-Glass Reactions, and Glass Structure-Property Data. Specific activities for each of these initiatives are included in the Action Plan on pages 20-21; high-priority activities are designated with bold, colored text.

Raw Material Supplies and Recycling

Glass is produced by melting raw materials, including acidic or basic oxides (e.g., silica/industrial sand [SiO_2], lime [$CaCO_3$], and soda ash [Na_2CO_3]), cullet (i.e., crushed waste glass from manufacturing), and coloring agents. The quality of raw materials determines the chemical and physical properties of the glass products, necessitating tight supply chain control of raw materials requirements such as chemical composition (e.g., iron content), grain size, or initial color. To enable mass production of functional glasses, it will be critical to ensure the reliability and consistency of raw materials and to reduce overall materials costs. Additionally, with the growing emphasis on manufacturing sustainability, the glass industry must work to incentivize glass recycling and advance glass recycling infrastructure to grow the quantity and improve the quality of recycled glass.

Batch-to-Glass Reactions

Deep insight of batch-to-glass conversion provides useful routes to optimize the mechanical, chemical, and physical properties of end products by tailoring glass compositions and processing techniques. However, glass manufacturers do not currently have an adequate understanding of glass reactions from batch processing of raw materials to the development of the final product. This is mainly because a study of batch melting reactions should take into account all aspects of the melting processes on a wide range of scales, from microscopic (e.g., particle dissolution) to macroscopic (e.g., glass melting in a furnace). A more robust understanding of batch-to-glass reactions will be critical for reducing the need for trial-and-error materials development and accelerating the development and availability of high-performing functional glasses in both existing and new applications.

Glass Structure-Property Data

The properties and performance of functional glasses are intimately connected with the structure of glasses both in the bulk and on the surface. By generating structure-property data from characterizations coupled with modeling and existing glass databases, manufacturers will gain an increased understanding of the structural characteristics of glasses, enabling them to more accurately develop materials with desirable performance characteristics for a given application.

Courtesy of Mo-Sci Corporation

FUNCTIONAL GLASS CASE STUDY

HEALING SKIN WOUNDS IN DIABETIC PATIENTS WITH BIOACTIVE GLASS FIBERS

CHALLENGE

Due to the weakened immune systems of people with diabetes, any wounds they develop will heal more slowly than wounds in nondiabetic people, increasing the risk of repeated wound reopening and infection. Persistent wounds often require the use of large, expensive vacuum-assisted healing equipment.

Alternative methods for wound healing have leveraged bioglass, which is designed to react with human tissue to encourage cell growth. To date, most bioglasses are silica-based and have been used primarily to regrow bone and other hard tissue. These silica-based compositions regrow soft tissue at a rate comparable to that of traditional wound care protocol.

INNOVATION

Based on previous studies that demonstrated antibacterial properties of boron-based bioglass, glass scientists from Mo-Sci Corporation investigated the potential for a borate glass composition to encourage tissue growth at wound sites while fighting off further infection. This microfiber composition—13-93B3 glass, or "Mirragen"—mimics the structure of fibrin that facilitates blood clots[7] and resembles a cotton fiber pad or cotton candy (see image on page 18) that can be molded into any shape to cover wounds of varying sizes. Wound treatment with borate glass compositions like Mirragen could provide a lower-cost and more effective way to heal tissue wounds.

RESULT

Mirragen was tested in 12 diabetic patients suffering from severe extremity wounds, including one patient who had dealt with the same wound for three years. Mirragen quickly healed the various wounds, promoting new skin growth while preventing infection. After a few months, the wounds of eight patients were repaired entirely, and the remaining four patients were expected to heal soon afterwards. A subsequent trial with 50 patients yielded similar results.[8]

Most of the Mirragen treatments to date have resulted in minimal scarring, which suggests that Mirragen actually heals skin more efficiently than the body's natural methods. Due to these promising results, Mo-Sci is expanding use of the treatment to additional applications, including for healing large burn wounds.

7. Peter Wray, "'Cotton candy' that heals?: Borate glass nanofibers look promising," *American Ceramic Society Bulletin* 90, no. 4 (2011): 25-29, http://americanceramicsociety.org/bulletin/2011_pdf_files/may_11/#/27/

8. ———. "Wound healing: An update on Mo-Sci's novel borate glass fibers," *American Ceramic Society Bulletin* 92, no. 4 (2013): 30-35, http://americanceramicsociety.org/bulletin/2013_pdf_files/may_13/index.html#/32/

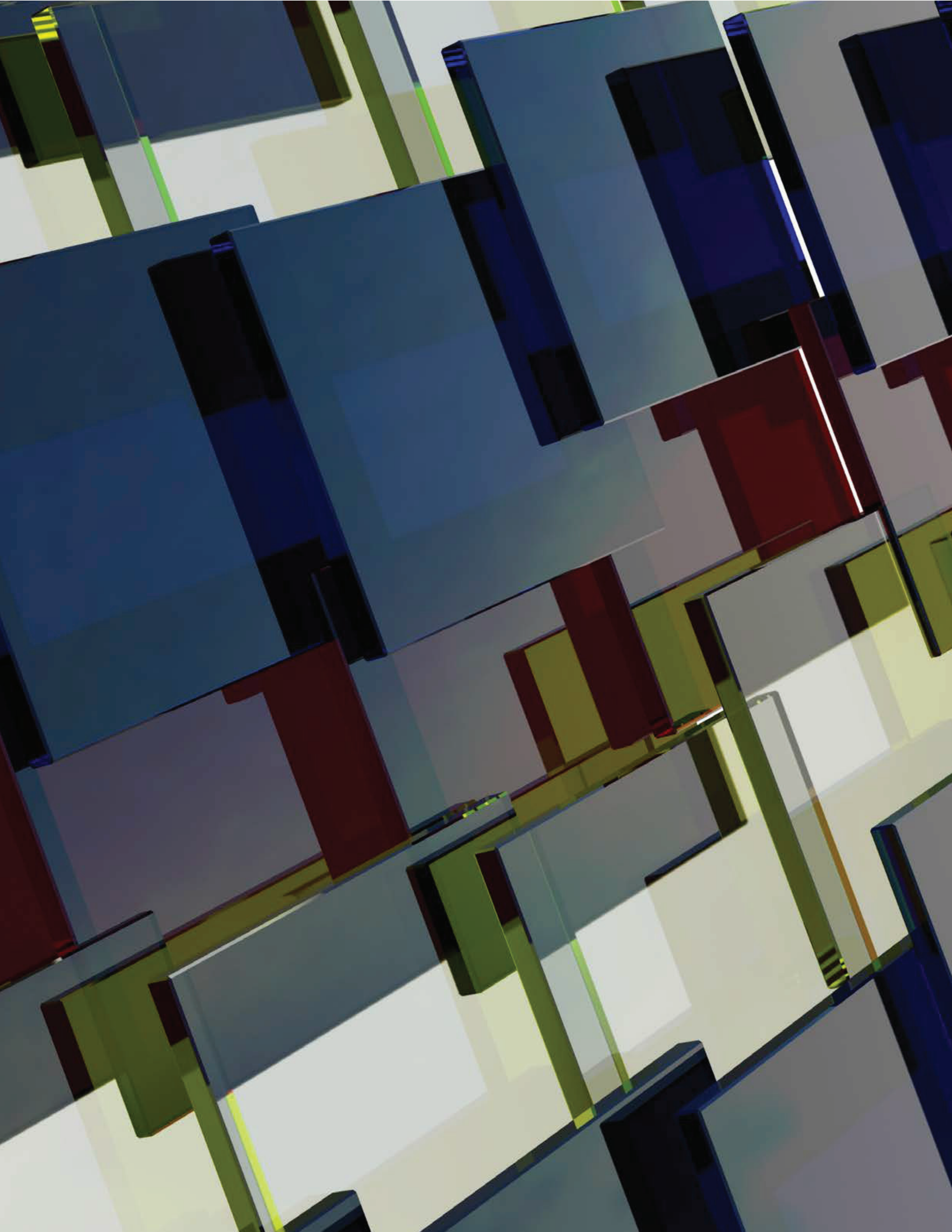
ACTION PLAN → PATHWAY 1

Arrows signify sequential or iterative activities.
Colored text indicates activities that were identified as priorities.

	2017	2019
RAW MATERIAL SUPPLIES AND RECYCLING	▶ Support and expand on the recycling efforts of the Glass Packaging Institute to increase the quantity of recycled glass ▶ Define the motivation for pursuing non-silicate glasses based on their specific properties	▶ **Improve infrastructure for glass collection and processing—separated by color, viscosity, and other key properties—to efficiently and economically increase the quantity and quality of recycled glass** ▶ Conduct studies to compare the results of using high-purity materials with industrial raw materials, contact materials, etc. ▶ Develop a low-cost and highly accurate high-throughput chemical analysis "qualification standard" to ensure the reliability and stability of raw materials ▶ Encourage additional North American rare earth materials mining to increase the availability and affordability of these materials
BATCH-TO-GLASS REACTIONS	▶ Define parameters to measure, as well as scaling impacts of measurement	▶ **Advance understanding of the kinetics of batch-to-glass reactions, including the effects of raw materials chemistry, grain size, and temperature** ▶ **Designate or develop specialized facilities available to manufacturers for characterizing melts, batch reactions, and fining processes** ▶ **Develop more or better sensors to measure data in-situ in tanks (redox measurements)**
GLASS STRUCTURE-PROPERTY DATA	▶ **Define base composition categories (i.e., standard samples)** ▶ Define the key structural aspects for increased understanding of more complex glasses (driven by industrial problems) ▶ Assess available property measurement technologies and identify gaps in current techniques and procedures ▶ Identify existing characterization tools to increase understanding of complex glass structures (in the bulk)	▶ **Identify currently available accelerated testing methods for screening large sets of glass quickly** ▶ **Develop techniques with high chemical or topographical sensitivity for characterizing the large-scale (i.e., mm to a few cm) homogeneity of surfaces and coatings** ▶ **Characterize melt structure, thermophysical properties (e.g., glass transition temperature, heat capacity, melt viscosity, and melt and glass density), and functionality-specific properties (e.g., conductivity, fracture toughness, and glass hardness)** ▶ Conduct levitation studies (i.e., melts in a containerless environment) to increase understanding of melt structure (leverage Advanced Photon Source [APS] at Argonne National Laboratory (ANL), Spallation Neutron Source [SNS] at Oak Ridge National Laboratory [ORNL]), properties (NASA), and high-temperature crystalline refractories

CHARACTERIZING MATERIALS STRUCTURES AND PROPERTIES

2021	2023	2025+
▶ **Incentivize glass recycling through increased legislation (e.g., recovery of glass from waste streams, bottle bills) to enable materials of acceptable quality to be recovered and processed into a usable form for glass manufacturers** ▶ Develop novel processes to produce very fine (e.g., <0.5 μm aluminas) raw materials at much lower cost and at industrial scale ▶ Identify practical glass process techniques for use of very fine sand supplies	▶ **Work with suppliers to identify other possible materials reserves (silica, limestone, non-dolomitic materials [e.g., magnesium]) and potential opportunities for new deposits to be available to the glass industry** ▶ Leverage existing processes (e.g., from General Electric and Heraeus Group) to establish the infrastructure needed to economically reduce iron levels in raw materials, especially sand and dolomite, at large scale	▶ Develop new glass chemistries that move beyond silicates
▶ Generate thermodynamics (e.g., solubility, activity) and kinetics (e.g., diffusion coefficient) data relevant to fining for functional glasses ▶ Partner with universities and manufacturers to investigate gas solubility in non-soda-lime silicate commercial glasses	▶ Develop a virtual measurement laboratory that leverages well-known and existing instrumentation centers	▶ Identify a robust universal method to visualize and simultaneously measure batch-to-glass reactions in real time
▶ Advance surface characterization techniques to interrogate the structure of glass surfaces (e.g., chemical erosion resistance, surface of melt) ▶ Develop new characterization tools to increase understanding of complex glass structures (in the bulk)	▶ **Establish a high-temperature measurement facility to develop awareness of instruments and methodology for measuring industrially important high-temperature properties and to provide industry with opportunities to measure and test physical properties of molten glass (some exist at NASA, APS at Argonne, and SNS at ORNL)** ▶ Conduct mass balance, including surface and bulk properties, and solution analysis to produce robust data ▶ Develop high-temperature phase diagrams (e.g., multicomponent models)	



PATHWAY 2

MODELING AND SIMULATING PERFORMANCE

KEY INITIATIVES

- **2A** Glass Composition Models
- **2B** Process Models
- **2C** Glass Modeling Infrastructure

Modeling and simulation can help glass scientists increase their understanding of glass physics and chemistry to better control processes such as melting, predict the performance of new furnace designs and glass compositions, and enable advanced monitoring and control during processing. Existing models, however, are not adequately sophisticated to effectively and accurately predict all relevant properties of glass materials with respect to manufacturing conditions and history, including high-temperature and dynamic processes such as batch charging and refractory corrosion. Advancing glass manufacturing modeling and simulation tools and increasing access to precise data (e.g., diffusion coefficients, gas solubility) could help the glass manufacturing community improve understanding of long-term materials performance (i.e., collective behaviors) in response to manufacturing parameters, reducing the need for time-intensive and costly trial-and-error approaches to materials and process design, and ultimately increasing the quality of products delivered to consumers. By predicting experimentally measurable/non-measurable process parameters, the glass community can also eliminate the complex design requirements and high cost of installing and maintaining various in-line metrology and characterization tools.

Current Challenges

To enable functional glass manufacturing innovation, the glass community must work to overcome the modeling and simulation challenges that follow.

Limited access to glass-specific models

The glass manufacturing industry's modeling capabilities and computational techniques, particularly first principles modeling, are currently insufficient for specifying the compositions and processing routes needed to design glasses with specific properties and functionality. Some models that do exist are not accessible to small and medium glass manufacturing companies due to their proprietary nature, while others must be operated by a modeling expert, a resource many small and medium businesses lack.

Lack of multiscale models

The glass field currently lacks multiscale models for composition-property relationships at both low (200°C–600°C) and high temperatures. Without these models, it is difficult to tailor glass properties and process parameters and predict long-term glass performance. A combination of various models at different scales—from atomistic to empirical modeling—would be useful for designing optimized glass compositions at the industrial manufacturing level. The glass community could collaborate with other materials communities (e.g., metals) to help develop and benchmark these necessary tools.

Inability to prove the long-term performance of glass materials

Many end-use market segments, particularly within the medical industry, have stringent requirements (i.e., FDA approval) for product materials. Proving the long-term performance and durability of new materials requires significant amounts of time to assure that glasses will not fail in service. The need to re-qualify materials after any iterative improvements prevents the implementation of higher-performing glasses in these market segments. Advanced physics-based modeling and simulation capabilities, coupled with statistical modeling such as accelerated lifetime testing, could help shorten materials qualification processes while increasing the reliability of functional glass materials for market segments with such stringent requirements.

Key Initiatives for Advancing Functional Glass Manufacturing

Addressing these challenges will require coordinated efforts across the glass manufacturing community to develop, optimize, and implement advanced modeling and simulation tools. To realize the potential of functional glasses, the glass community must collaborate on the following key modeling and simulation initiatives: Glass Composition Models, Process Models, and Glass Modeling Infrastructure. Specific activities for each of these initiatives are included in the Action Plan on pages 28-29; high-priority activities are designated in bold, colored text.

Glass Composition Models

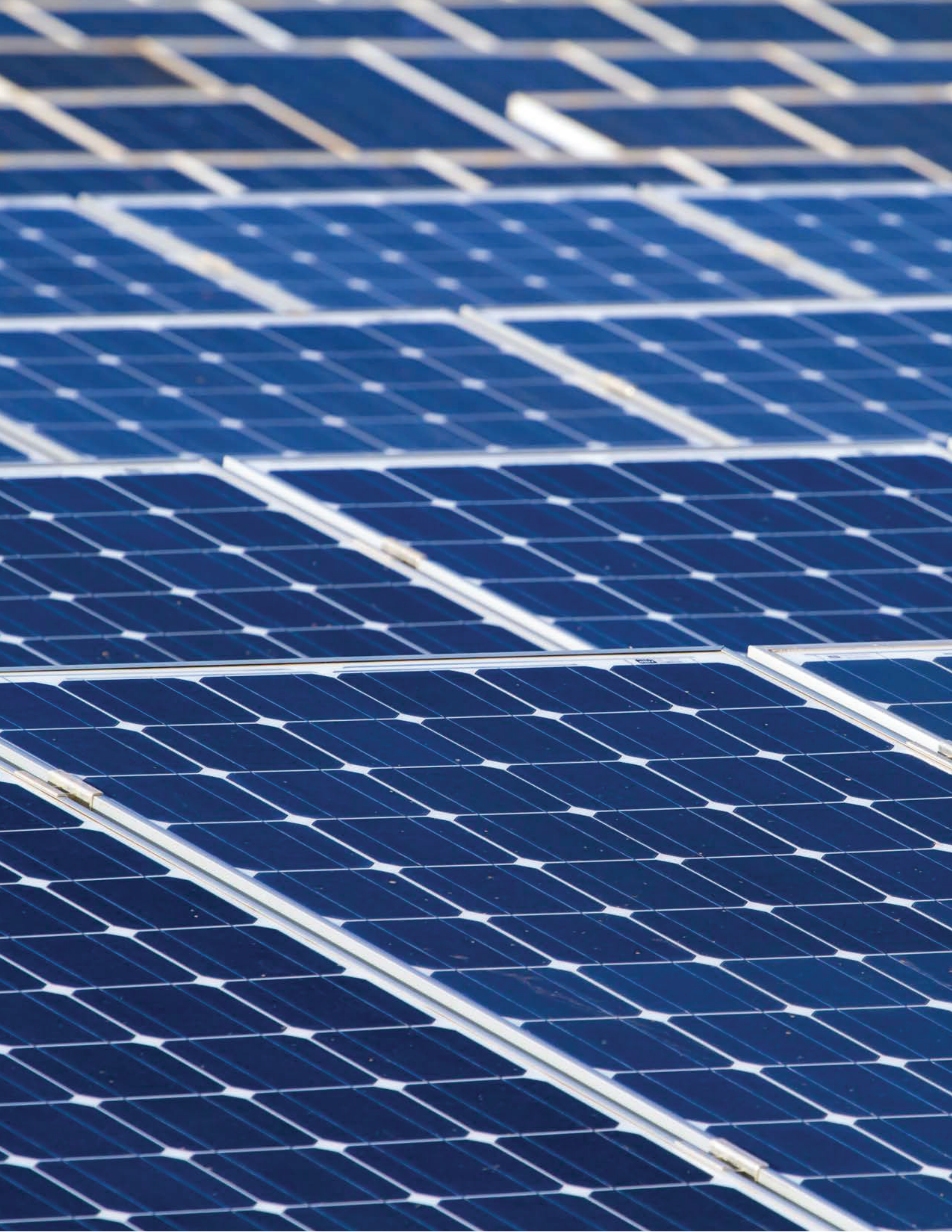
Most current functional glasses are based on well-established compositions that have been tweaked incrementally over time to achieve desired properties and performance. To develop more specialized glasses with increasingly tailored functions, the glass manufacturing industry must explore and optimize new compositions. The number of potential glass compositions, however, is essentially infinite, necessitating the need for researchers and manufacturers to use modeling and simulation to focus their time and attention on compositions that promise the most desirable results, rather than relying on trial-and-error approaches to materials and process design. Using well established glass theory and simulation, coupled with data-driven glass informatics for information sifting or screening (i.e., the driving concept of the Materials Genome Initiative), can help narrow down the vast composition space.

Process Models

The major goal of process modeling is to optimize ad-hoc manufacturing processes to enable the low-cost, high-rate processing of functional glasses. Advanced process modeling and simulation tools can inform process improvements and accelerate integration of alternative chemical fining techniques and non-traditional glass manufacturing processes such as physical fining. For process modeling and simulation tools to be most effective, they must account for as many process parameters as possible that could impact the properties and performance of an end product. To do so, the glass community needs to develop a sophisticated way of fusing heterogeneous data from varied theoretical calculations, empirical modeling, and processing characterizations. Combining this information with process conditions will help companies pinpoint opportunities for maximizing process efficiency, which can reduce product development time and minimize manufacturing costs.

Glass Modeling Infrastructure

To maximize the benefits of more advanced modeling tools, the functional glass manufacturing community must work together to make these tools easier for non-modeling specialists to use. While most small and medium enterprises do not have the resources to employ the help of a modeling expert, these companies could realize the benefits of modeling and simulation tools if these tools were more accessible, user friendly, and affordable. Modeling and simulation tools must also be validated with actual operating data to ensure the accuracy and reliability of their predictions.



FUNCTIONAL GLASS CASE STUDY

IMPROVING SOLAR PANEL PERFORMANCE WITH ANTI-SOILING COATINGS

CHALLENGE

The accumulation of dust and sand on the surface of solar panels can reduce solar panel efficiency by about 5 percent over the course of a year, decreasing the amount of energy that panels can absorb and convert to electricity.[9] Currently, panels must be manually cleaned to maintain efficiency, which increases the cost of electricity from solar sources.

INNOVATION

Researchers at the National Renewable Energy Laboratory (NREL) and Oak Ridge National Laboratory (ORNL) are working to better understand soiling mechanisms and to develop and test more durable and cost-effective anti-soiling coatings.

To analyze soiling mechanisms and patterns, NREL researchers are developing and validating a predictive soiling model. This model includes data from more than 200 sites, including data related to solar panel system specifications and layout; maintenance routines; site precipitation, temperature, and humidity; and potential nearby debris sources (e.g., highways, railways, industrial sites). The model leverages data from U.S. Environmental Protection Agency (EPA) particulate maps, rainfall maps, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS) to predict the effects of soiling in different geographic locations over the course of a season or entire year.[10] An ORNL research team developed and tested new anti-soiling nanoporous silica coatings that can be applied using low-cost conventional painting and spraying methods. Mimicking the superhydrophobic (i.e., the superior ability to repel water) characteristics of certain plant leaves, the ORNL solar panel coating was designed to repel most liquids and solid particles.[11] To rigorously test the coating's ability to withstand soiling from contaminants that would be present at actual solar sites, the research team compared the results of field tests and laboratory testing.

RESULT

By presenting site-specific soiling data, NREL's soiling model will help the solar industry to improve operations and maintenance procedures at individual sites, develop more effective anti-soiling coatings for specific regions and conditions, and drive the establishment of comprehensive durability standards for solar panel coatings.

In ORNL field and laboratory tests, panels with the anti-soiling coating did not experience degradation and exhibited only a minimal decrease in solar absorption capabilities.[12] When subjected to a wind tunnel blowing dust and sand, the coating successfully prevented the particles from adhering to the solar panel glass, demonstrating the potential for the coating to effectively maintain solar panel performance and energy absorption efficiency, even in extreme environmental conditions.

9. National Renewable Energy Laboratory, System Advisor Model (SAM), https://sam.nrel.gov/.

10. Lin Simpson, Matthew Muller, et al, NREL, "The Modeling of the Effects of Soiling, Its Mechanisms, and the Corresponding Abrasion," PV Module Reliability Workshop: Lakewood, Colorado, February 2016.

11. US Department of Energy, "Low-Cost Self-Cleaning Reflector Coatings for CSP Collectors," Energy.gov, accessed October 27, 2016, http://energy.gov/eere/sunshot/project-profile-low-cost-self-cleaning-reflector-coatings-csp-collectors.

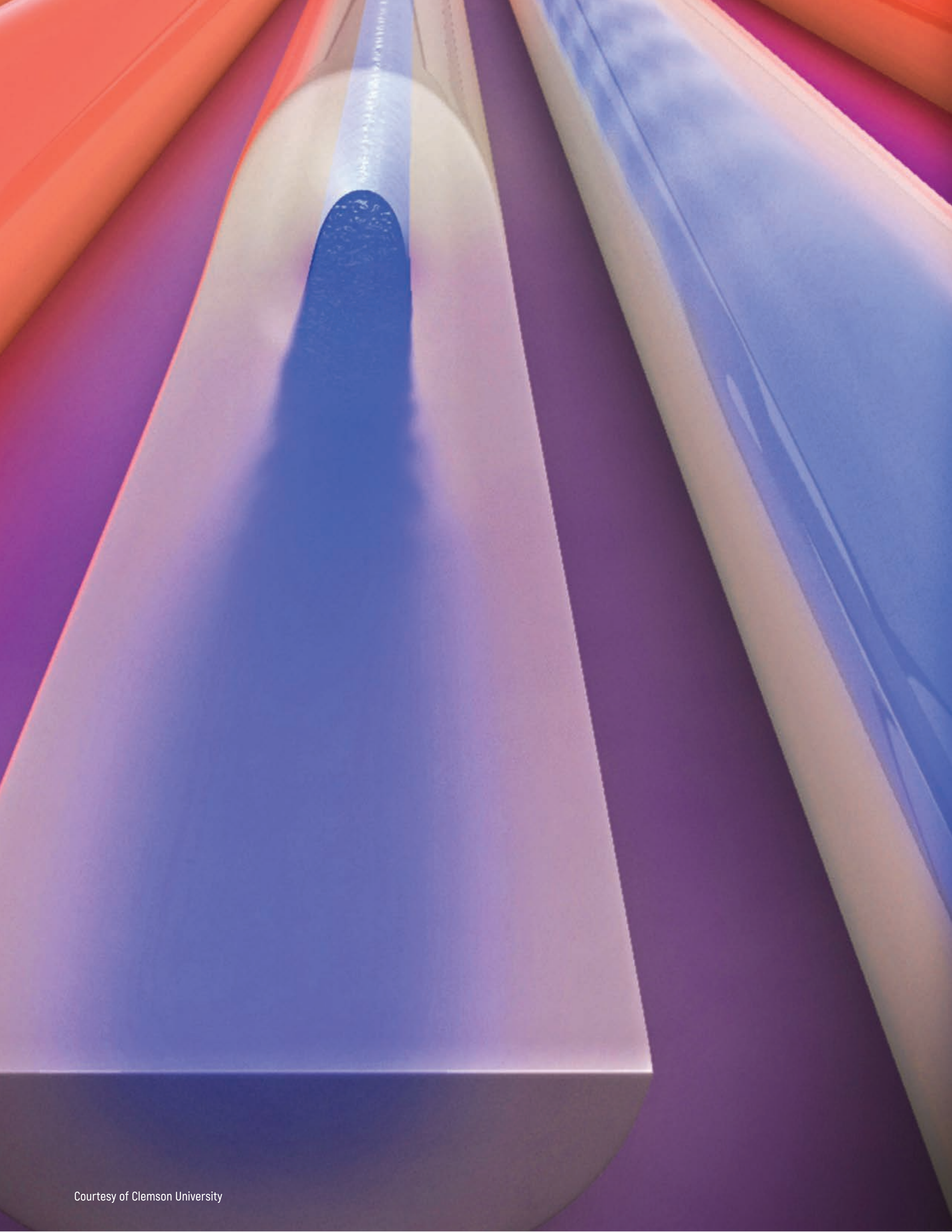
12. Oak Ridge National Laboratory, "Anti-soiling coating keeps solar reflectors clean and efficient," *ScienceDaily*, www.sciencedaily.com/releases/2014/01/140129164644.htm (accessed October 27, 2016).

Arrows signify sequential or iterative activities.
Colored text indicates activities that were identified as priorities.

	2017	2019
GLASS COMPOSITION MODELS	▶ Work with the Department of Energy (DOE) and the National Science Foundation (NSF) to establish a consortium of universities, national laboratories, and funding agencies—partnering with global research and development groups—to develop atomistic/molecular models for glass systems of interest ▶ Conduct round-robin calculation to standardize atomic potentials	▶ Fit interatomic potentials to glass and melt data, not just to crystals ▶ Increase understanding of the physics of glass compositions and develop accelerated measurement tools and techniques ▶ Perform literature search of existing glass models ▶ Pursue a genomic approach to advance properties prediction (relies on database of measurements)
PROCESS MODELS	▶ Connect modeling experts with experimentalists to validate models and make them more useful	▶ Develop standardized in-situ measurement techniques ▶ Identify promising composition regions and build corresponding data sets
GLASS MODELING INFRASTRUCTURE	▶ Connect with federal funding agencies to establish programs focused on building predictive capabilities, leveraging ongoing Integrated Computational Materials Engineering (ICME) and Materials Genome Initiative (MGI) efforts ▶ Increase the availability of high-performance computers for modeling, both at the generic and product-specific level	

MODELING AND SIMULATING PERFORMANCE

2021	2023	2025+
▶ Develop a customizable predictive database of glass properties (e.g., physical, chemical, mechanical, thermal, and radiational) ▶ Assess customer issues with final product stability issues and model stability to reduce the need for costly stability testing		▶ Create linking tools that bridge fast molecular dynamics timescales and slower, macro-scale phenomena ▶ Develop atomistic models that can use realistic temperatures and temperature differences, rather than the unphysical timescales used in models
▶ Incorporate batch-to-glass thermodynamics and kinetics into an overall furnace model ▶ Connect model data on simple compositions to commercial compositions ▶ Develop a model for fining in a multi-component system ▶ Develop forming models for generic forming processes and make them available to U.S. glass companies ▶ Produce liquidus temperature and viscosity curve models based on first principles rather than empirical data ▶ Provide more detailed data (e.g., chemistry, particle-size distribution) for raw materials to assess and ultimately predict the impact of raw materials properties on glass properties and composition	▶ Build environmental impact (e.g., gases, heat) modeling capability to assess impact of glass compositions	
▶ Continue taking advantage of GPU processing and parallel computing approaches to conduct ab initio calculations at meaningful scales without high-performance computing; need advances in parallel algorithms to take advantage of this approach		▶ Develop modeling tools accessible to the non-specialist ▶ Ensure models allow easy input of data, including from open sources ▶ Make process models available for glass companies on-line or off-line



Courtesy of Clemson University

FUNCTIONAL GLASS CASE STUDY

ENHANCING THE FUNCTIONALITY OF NEXT-GENERATION OPTICAL FIBER

CHALLENGE

Much of today's data-sharing, communication, and entertainment technologies depend on optical fibers—hair-thin strands of glass that carry information at nearly instantaneous speeds around the world. Over the past 40 years, the glass from which optical fibers are made has been engineered to its fundamental performance limits. To push this technology further and expand its uses, the glass industry must also pursue approaches beyond glass science that will enable the development of higher-performing optical fiber systems that can also be cost effectively manufactured at commercial scale.

INNOVATION

The glass industry is collaborating with the broader materials science industry as well as physics, chemistry, and engineering experts to take a multidisciplinary approach to realizing the next-generation capabilities of optical fibers. By incorporating multiple inorganic and organic (polymeric) glasses—as well as semiconductors and metals—and advanced electronics, materials scientists are developing a new class of multimaterial[13] and hybrid[14] optical fibers with enhanced functionality and efficiency.[15]

Other researchers are working to design fibers that improve signal fidelity, reducing interaction between the light that carries data and the fiber glass. This improved signal fidelity enables greater bandwidths (i.e., increased information capacity), lower latency (i.e., faster data transmission), and potentially lower data loss.[16] Advanced manufacturing techniques are also being explored to reduce overall manufacturing energy consumption and the amount of material used.

RESULT

With these advances and other optical fiber technology research and development currently under way, materials scientists can develop smart optical fiber systems that not only transmit and amplify signals, but that also have multifunctional sensing capabilities. A multidisciplinary approach to optimizing glass fiber technology will continue to improve data transfer rates and accuracy in coming years, ultimately facilitating the growing "Internet of Things"—the embedding of Internet-connected technology and data sharing into everyday objects to make them smarter and more efficient. In addition to improving data transfer, new optical fibers are demonstrating their potential to improve the functionality of a variety of technologies across different sectors, including the conversion efficiency of solar cells.[17]

13. G. Tao, A. Stolyarov, and A. Abouraddy, "Multimaterial fibers," *Inter. J. Appl. Glass*. Sci. 3, 349 – 368 (2012).

14. M. Schmidt, A. Argyros and F. Sorin, "Hybrid Optical Fibers – An Innovative Platform for In-Fiber Photonic Devices," *Adv. Opt. Mater*. 4, 13 – 36 (2016).

15. A. Peacock, U. Gibson, and J. Ballato, "Silicon Optical Fiber – Past, Present, and Future," *Adv. Phys*. X 1, 114 – 127 (2016).

16. Y. Chen et al, "Demonstration of an 11km Hollow Core Photonic Bandgap Fiber for Broadband Low-latency Data Transmission," *Optical Fiber Communication Conference Post Deadline Papers*, OSA Technical Digest (online) (Optical Society of America, 2015), paper Th5A.1.

17. A. Abouraddy et al, "Towards multimaterial multifunctional fibres that see, hear, sense and communicate," *Nat. Mater. 6*, 336 – 347 (2007).


RB1
RB2

PATHWAY 3

OPTIMIZING MANUFACTURING PROCESSES

KEY INITIATIVES

- **3A** Advanced Process Monitoring and Controls
- **3B** Advanced Equipment
- **3C** Intermediate-Scale Manufacturing
- **3D** Innovative Processes and Techniques

The ability to accurately and precisely control functional glass manufacturing is critical to ensure the robustness and repeatability of processes and to facilitate the consistent quality and reliability of functional glass products. To optimize functional glass manufacturing processes, the glass manufacturing community must advance tools such as sensors and automation technologies for measuring, monitoring, and controlling manufacturing processes and conditions; improve the scalability of glass manufacturing processes; and develop next-generation manufacturing equipment and processes that can more efficiently and reliably produce high-performing functional glasses. More robust, accurate, and efficient processes can reduce manufacturing costs and energy consumption while enabling the development of new functional glasses with properties and performance more closely tailored to specific applications.

Current Challenges

To enable functional glass manufacturing innovation, the glass community must work to overcome the functional glass manufacturing process challenges that follow.

Inadequate technologies for real-time in-situ monitoring and material characterization

The glass manufacturing community currently lacks robust measurement technologies such as sensors that can accurately measure glass properties and processing conditions—including viscosity, temperature, pressure, and melt properties—in real time in the high-temperature and corrosive environments of functional glass manufacturing. Such monitoring technologies combined with measurement data analysis will be critical for high-throughput characterization of glass surfaces to standardize glass quality, homogeneity, and reproducibility in an online industrial setting. These sensors, which would ideally be embedded in the volume rather than at the surface of a melting tank for more accurate measurements, must also be able to interface with automated control systems to improve process stability and reduce cycle time.

Difficulty scaling glass production from laboratory to commercial scale

Glasses are traditionally processed at laboratory scale and at industrial scale, but glass behavior can vary significantly across these scales, particularly during the melting process. The glass manufacturing community currently lacks adequate tools and processes (e.g., additive manufacturing) to enable rapid prototyping of new functional glasses, to manufacture glasses at smaller scales for high-value applications with lower market demand, and to cost effectively test materials performance before transitioning to full-scale production.

Inadequate stability and durability of glass manufacturing equipment materials

Current refractory materials used in glass furnaces and other glass-processing equipment are unable to adequately sustain the significant thermal cycling requirements of functional glass manufacturing processes. Current materials start to react with the glass melt at around 1,650°C, which is below the expected manufacturing temperatures of advanced functional glasses. While materials such as platinum are more stable, durable, and non-reactive at high operating temperatures, these materials are prohibitively expensive for use in commercial production.

Insufficient large-scale melting and fining technologies for functional glass manufacturing

Functional glasses require higher-temperature manufacturing environments than conventional glasses to achieve their exacting specifications. The glass community, however, currently lacks high-temperature melting technologies for efficient large-scale production of functional glasses (i.e., greater than 5 metric tons per day). The glass manufacturing community also lacks methods for fining that can reliably and cost effectively introduce uniformity into the melt without the use of toxic elements like arsenic and antimony.

Key Initiatives for Advancing Functional Glass Manufacturing

Addressing these challenges will require coordinated efforts across the glass manufacturing community to develop, optimize, and implement advanced process technologies and techniques. To realize the potential of functional glasses, the glass community must collaborate on the following key manufacturing process initiatives: Advanced Process Monitoring and Controls, Advanced Equipment, Intermediate-Scale Manufacturing, and Innovative Processes and Techniques. Specific activities for each of these initiatives are included in the Action Plan on pages 38-39; high-priority activities are designated with bold, colored text.

Advanced Process Monitoring and Controls

Improved sensing technologies can enable more accurate measurement, monitoring, and control of the high-temperature and corrosive operating environments of glass manufacturing. While there are currently a number of sensors available that can measure glass properties—including temperature, batch blanket thickness, glass defects, composition, redox state, oxygen partial pressure, and combustion parameters—these sensors are not widely used in the glass industry because they have short lifetimes and are difficult to calibrate to functional glass processing conditions. Advanced ad-hoc sensing technologies that can measure glass processing conditions more reliably and accurately could enable the development of real-time glass measurement systems that can detect product quality problems or inconsistencies in process conditions and automatically adjust process variables. The ability to control processes with such accuracy is critical to ensure the robustness and repeatability of glass manufacturing processes needed to facilitate the development of higher-quality products.

Advanced Equipment

As glass manufacturing conditions change (e.g., higher temperatures, different atmospheres) to facilitate development of higher-performing products, the materials currently used in conventional silicate glass manufacturing equipment will approach their operational limits. To develop more robust processing equipment, the functional glass manufacturing industry needs to identify materials that can withstand higher-temperature operation and serve as more sustainable and cost-effective alternatives to materials such as platinum and platinum-rhodium alloys that are currently cost-prohibitive for commercial use.

Intermediate-Scale Manufacturing

Though millions of potential glass compositions exist that could be tailored to new technology requirements, glass manufacturing at small, exploratory scales is often not representative of glass behavior at industrial scales. Intermediate-scale manufacturing processes can bridge the gap, helping glass scientists to increase their understanding of glass behavior while reducing the cost and time of trial-and-error approaches as new products scale to industrial levels. Intermediate-scale manufacturing capabilities can also enable the production of high-performing glasses for niche, high-value applications that require quantities greater than the capabilities of current laboratory techniques but that do not warrant full-scale commercial production.

Innovative Processes and Techniques

Due to the inherent complexity of glass manufacturing, there is a continuous need for innovative processes and techniques that can facilitate more efficient and cost-effective manufacturing of higher-performing functional glasses. New approaches to glass manufacturing could enable new glass structures or multimaterials with enhanced properties or functionality. Additive manufacturing of glass, for example, will allow manufacturers to conduct rapid prototyping of new forms and compositions much faster than current processes allow. Alternate processing methods—including processes that capture waste heat, reduce materials waste, and optimize energy use at every manufacturing step—also have the potential to improve the cost effectiveness, efficiency, and sustainability of functional glass manufacturing.

Courtesy of Corning Incorporated

FUNCTIONAL GLASS CASE STUDY

REDUCING VEHICLE WEIGHT USING LIGHTER, STRONGER WINDOW GLASS

CHALLENGE

The North American automotive industry is faced with increasingly stringent standards for miles-per-gallon (mpg) and emissions in vehicles. By 2025, passenger cars and light truck models must achieve more than 50 mpg,[18] but the average fuel economy of most current models is only about half of this requirement. Though glass can have a substantial role in reducing vehicle weight—and subsequently improving vehicle fuel economy—it has not been a significant focus in vehicle lightweighting designs.

INNOVATION

Vehicle manufacturers are now considering advanced glasses for a variety of vehicle components, including to develop lighter, stronger vehicle body panels and windows.

Continental Structural Plastics Inc. developed TCA Ultra Lite™, a composition with light, silane-coated glass microspheres that was designed to replace some of the sheet molding used in vehicle body panels. TCA Ultra Lite™ was used in 21 body panels of the 2016 Chevrolet C7 Corvette Stingray coupe, including the doors, trunk lid, and fenders. The microspheres reduce the weight of these vehicle components, while also making them stronger.

To improve vehicle windshields and windows, researchers at Corning Incorporated reworked their patented Gorilla© Glass known for its use in cell phones and tablet PCs. In December 2015, the Ford GT supercar was the first vehicle to be produced with Gorilla© Glass as the interior layer of its windshield, rear window, and rear separation wall. By using the new Gorilla© Glass design, the Ford GT's windows are thinner, lighter, and stronger than standard vehicle windows.

RESULT

TCA Ultra Lite™ reduces body panel weight by up to 40 percent, decreasing the total weight of the C7 Corvette Stingray by 20 pounds.[19] This new composition also resists more damage and costs about the same as conventional body panel materials.[20] Vehicle window glass containing the Gorilla© Glass is five times stronger, 25 to 50 percent thinner, and about 30 percent lighter than a standard vehicle window, reducing the weight of the Ford GT by 12 pounds.[21] Though the use of functional glass in vehicle components cannot address the need for improved fuel economy alone, it can get the automotive industry one step closer to meeting the new industry standards within the mandated timeframe.

18. Environmental Protection Agency and Department of Transportation, 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards; *Final Rule, 77 Fed. Reg.* 62623 (Oct. 15, 2012).

19. Michael Lauzon, "Glass Microspheres Lighten up the 2016 Corvette," *Plastics News*, last modified August 21, 2015, http://www.plasticsnews.com/article/20150728/NEWS/150729896/glass-microspheres-lighten-up-the-2016-corvette.

20. "Continental Structural Plastics' TCA Ultra Lite™ Recognized with Unsurpassed Innovation Award," Continental Structural Plastics, last modified October 28, 2015, http://www.cspplastics.com/continental-structural-plastics-tca-ultra-lite-recognized-with-unsurpassed-innovation-award/.

21. April Gocha, "Gorilla Glass Goes Fast: Automotive Version of Corning's Strengthened Glass Goes in New Ford GT," The American Ceramic Society, January 7, 2016, http://ceramics.org/ceramic-tech-today/gorilla-glass-goes-fast-automotive-version-of-cornings-strengthened-glass-goes-in-new-ford-gt.

ACTION PLAN → PATHWAY 3

Arrows signify sequential or iterative activities.
Bold colored text indicates activities that were identified as priorities.

	2017	2019
ADVANCED PROCESS MONITORING AND CONTROLS	▶ **Solicit industry interest to define key systems that require online, 3D sensor development (e.g., 3D flow, online defect measurement), assessing the needed parameters and data, the applicable furnaces or processes, and the limitations of current industry practices, while identifying existing sensors that could be adapted and sensor manufacturers and experts** ▶ Ensure technology transfer of national laboratory sensor technology to industry ▶ Identify sensor needs similar with those of other industries (e.g., steel, gasification) and engage federal funding agencies, particularly through seed funding for start-up companies, to help fund the development of sensors that are in high demand	▶ Work with standards bodies (e.g., NIST, ASTM) to develop additional glass properties standards ▶ Develop in-line methods for non-destructive sensing of the glass surface state (e.g., moisture, contamination, or microcracks)
ADVANCED EQUIPMENT	▶ **Increase availability of refractories (i.e., reduce current long lead times)**	▶ Develop low-cost, next-generation refractories (e.g., castable, oxide) that can withstand thermal cycling and corrosion and that have advanced physical and mechanical properties ▶ Identify materials for use in temperature- and corrosion-resistant in situ sensors ▶ Develop the ability to adjust machine automation to conform to glass variability ▶ Refine equipment and processes to more efficiently and economically use materials with finer particle sizes, enabling the glass industry to leverage a greater portion of current raw materials supplies, manufacturing byproducts, and recycled materials
INTERMEDIATE-SCALE MANUFACTURING	▶ Conduct a thorough assessment of needed capabilities and testing equipment, and develop protocols and a financial model for an intermediate-scale manufacturing facility	▶ **Design and construct an industry-university-government intermediate- size melt and forming facility where industry can manufacture glasses between current laboratory and production furnace scales (i.e., 200 kg-1,000 kg per day)** ▶ **Develop more energy efficient melting processes**
INNOVATIVE PROCESS AND TECHNIQUE	▶ **Develop a glass process (e.g., coating) with the ability to improve a final product's mechanical and thermal strength and chemical durability** ▶ Evaluate existing functional glass manufacturing processes at TRLs 1–3 and select the most promising ones for further development ▶ Develop a centrifugal plasma melter with one component (e.g., SiO_2) ▶ Evaluate the energy use of rapid-melt batch processes (i.e., pelletized, preheated) and the current commercial melting techniques for large tonnage applications	▶ **Explore green manufacturing processes (e.g., preheating glass batch with waste heat) for waste reduction and environmental remediation**

OPTIMIZING MANUFACTURING PROCESSES

2021	2023	2025+
▶ Advance real-time glass measurement science, leveraging existing femtosecond light/XRD (beamline) diagnostics and attosecond science	▶ **Develop "smart" refractories with in-situ sensors** ▶ Use sensors in conjunction with process control systems to improve the quality of produced glass and to reduce the energy consumed per ton of manufactured glass	
▶ Develop advanced stirring concepts/tools for direct, continuous melting of high-temperature glass ▶ Develop advanced sensors, including ones to monitor viscosity, chemistry, defects, temperature, and reactions	▶ Develop advanced optical sensors that leverage radar, millimeter waves, and ultrafast lasers to improve sensing capabilities	
▶ Develop a fast melt process with low raw material volume requirements to enable 1–200 ton-per-day production volumes through fast changeover, multiple process feeds, and quick on/off capabilities		▶ Develop novel forming techniques such as roll-to-roll processing to develop thin and flexible glasses
▶ Identify process that applies novel physics for non-contact shaping of glass ▶ Develop innovative secondary glass manufacturing processes—including new approaches for coating, laser processing, glass strengthening, and nanostructuring—or novel combinations of processes to optimize glass characteristics and enable multimaterials that include functional glasses ▶ Establish processes for manufacturing complex structures (e.g., microfluidics)	▶ **Advance robotics for glass manufacturing** ▶ Explore the possibility of spray glasses ▶ Identify and assess scalable approaches for containerless or near-containerless melting ▶ Establish tools and facilities for manufacturing and demonstrating 3D-printing of glass	

PATHWAY 4

DATA INFRASTRUCTURE AND BEST PRACTICES

KEY INITIATIVES

- **4A** Data Generation and Reliability
- **4B** Database Development and Management
- **4C** Data Dissemination and Accessibility

The future of functional glass manufacturing will be increasingly dependent on the industry's ability to effectively generate, manage, and share glass data from experiments, theory, and simulation. Researchers and manufacturers from across the functional glass community must be able to readily access more reliable data—including data about diffusion coefficients, thermodynamics of chemical or redox reactions, and chemical and physical solubility—to understand the complex relationships between glass properties, composition, structure, and processing history. Establishing standards and best practices for data measurement, maintenance, storage, and sharing will be critical for improving data quality and access. The resulting ability to make critical connections about process-composition-structure-property relationships—through advanced modeling and simulation and through next-generation data analysis—will enable the functional glass manufacturing community to accelerate selection of new functional glass compositions, develop and implement higher-performing functional glasses into end-use products, and optimize manufacturing precision and efficiency.

Current Challenges

To enable functional glass manufacturing innovation, the glass community must work to overcome the data challenges that follow.

Insufficient uncertainty quantification and data reliability

Ensuring the robustness of glass data depends on an understanding of uncertainty, which is particularly difficult to characterize in functional glass materials given their complex chemistries and higher processing temperatures. Inconsistent measurement techniques and other influences such as inadequate descriptions (e.g., tolerance) of process conditions can increase uncertainty of glass data by an order of magnitude, elevating the need to capture or reduce this variability. The glass industry, however, does not have publicly available reference standards for instrumentation calibration to ensure measurement consistency, lacks standard compositions for more complex functional glass chemistries, and has insufficient data validation and reproduction procedures (e.g., automatic outlier detection, peer review processes). As a result, data uncertainty is not adequately captured in existing databases, leaving it up to the individual user to assess data reliability.

Difficulty organizing and managing complex functional glass data for a range of data needs

It is difficult and costly to build, grow, and maintain infrastructure for data management and to ensure that databases are populated with the data that is most relevant to glass manufacturers. In the functional glass industry, these common data management difficulties are compounded by the complexity of glass data and the varying needs of both researchers and manufacturers, making it difficult for the glass industry to develop a logical and comprehensive data framework (i.e., database schema, metadata documentation, and/or data curation) that satisfies all needs. As a result, existing functional glass data is currently dispersed across a large number of databases—all with unique frameworks for organizing different data sets. With a limited number of established glass-specific databases (i.e., INTERGLAD and SciGlass), researchers must decide where to find and publish data and must sort through different databases to access the data they need.

Inadequate incentives to share data

Increased access to accurate and reliable data could improve understanding of glass process-composition-structure-property relationships, enabling accelerated development of functional glasses with advanced properties. Generating this data, however, can be costly and time consuming. Due to the tendency for many individual companies to keep data proprietary, much of the existing glass data is not publicly available. In the case of government-funded projects that are required to make their data publicly available, there is currently no standardized requirement or audit process to ensure that this data is readily available in a prominent industry database, rather than simply provided upon request.

Insufficient communication and transparency across the supply chain

Glass manufacturers rely on suppliers to regularly analyze raw materials and provide properties data for shipments, particularly with regard to chemical composition (e.g., impurities) and particle size. Changes at supplier companies—including to personnel, equipment, mining processes, and shipment protocols—that can impact materials quality and availability are not always adequately communicated to manufacturers. While many larger suppliers have more established quality-assurance programs, keeping track of these day-to-day changes can be challenging when working with a large number of suppliers, small raw materials supply companies, or suppliers located outside of the United States. Manufacturers must improve mechanisms for information sharing to receive timely, secure notifications from suppliers about changes that could lead to manufacturing disruptions or require adjustments to manufacturing processes to maintain product quality and reliability.

Key Initiatives for Advancing Functional Glass Manufacturing

Addressing these challenges will require coordinated efforts across the glass manufacturing community to develop, optimize, and implement next-generation data infrastructure and best practices. To realize the potential of functional glasses, the glass community must collaborate on the following key data initiatives: Data Generation and Reliability, Database Development and Management, and Data Dissemination and Accessibility. Specific activities for each of these initiatives are included in the Action Plan on pages 44-45; high-priority activities are designated with bold, colored text.

Data Generation and Reliability

To ensure the availability of robust, reliable data needed to accelerate advances in functional glass materials and processes, the functional glass manufacturing industry must incentivize and standardize data generation and curation across the community. Experimental and operational data must be obtained through consistent measurement techniques (i.e., metrology) from calibrated equipment and must capture process parameters, including the thermal history of a material throughout the supply chain. By encoding and publishing data in a repeatable fashion, data users can better account for data uncertainty and assess data reliability and quality. The functional glass manufacturing industry could leverage the use of high-throughput combinatorial experimentation coupled with integrated computational materials engineering (ICME) to generate large amounts of data. This data should include multivariate (i.e., multiple variables) and multiscale data—from sub-nanometers to meters (i.e., different length scales)—to simulate materials behavior in different time scales—from picoseconds to seconds, or even days. Generating robust, reliable data is critical for helping glass scientists validate modeling tools and more accurately link materials process, structure, property, and performance information.

Database Development and Management

Researchers and manufacturers rely on materials databases to interpret and model experimental data, design experiments, validate computational models, and define input for theoretical calculations. Existing functional glass data, however, is currently dispersed across literature and a variety of industry databases, each with unique frameworks for organizing different sets of data. For heterogeneous glass properties, structure, and processing history data from modeling, simulations, and experiments to be more usable, it must be consistently organized in existing databases or integrated in a single comprehensive, user-friendly data repository. These glass databases must be flexible and scalable, and include reliable systems for handling complex, dynamic queries and massive amount of data. To increase data consistency across the functional glass community, the industry must work with standards organizations (e.g., National Institute of Standards and Technology and ASTM International) to establish standard techniques for organizing and storing data, including database schema, metadata documentation, and data management plans. Establishing these data management standards—along with other widely available next-generation materials data infrastructure tools and codes—will be critical to improving data reliability and robustness.

Data Dissemination and Accessibility

The functional glass industry must stress the critical importance of data sharing and consistent data generation, storage, and maintenance to facilitate collaboration. For small and medium enterprises to benefit from available data and willingly share additional data, they must be able to easily and affordably access and navigate glass databases. Systems for data storage will also need to allow varying levels of access to data, including data from raw materials suppliers and across manufacturers, maintaining the proprietary nature of data. To incentivize database use and increased data sharing, the functional glass manufacturing industry must emphasize data science in undergraduate- and graduate-level curricula, increase data-related workforce training, and share data best practices and case studies through industry publications and events. Sustained data sharing will be critical for the industry to uncover hidden data trends through advanced data analysis (e.g., data mining and machine learning) and ultimately improve the U.S. glass manufacturing industry's ability to ensure product quality and reliability.

Arrows signify sequential or iterative activities.
Colored text indicates activities that were identified as priorities.

	2017	2019
DATA GENERATION AND RELIABILITY	▶ Establish minimum data reporting standards—including accompanying metadata (e.g., tolerances and uncertainties) and data schema—leveraging work being done through the Materials Genome Initiative ▶ Define standard materials compositions that reflect industry needs and account for thermal history, helping to increase the reliability and consistency of equipment calibration and measurement ▶ Identify and prioritize the types of data that need to be curated to satisfy the needs of different data users ▶ Identify and select metrics for evaluating glass data quality ▶ Improve mechanisms for transferring data (i.e., an alternative to emails and certificates of analysis [COA]) from suppliers to manufacturers that will minimize errors, enhance supply chain security, and reduce the labor requirements of manufacturing companies	▶ Establish data workflows that streamline and increase the consistency and frequency of glass data collection and submission
DATABASE DEVELOPMENT AND MANAGEMENT	▶ Revive or reinvent the SciGlass or INTERGLAD database systems, and develop new tools or processes (e.g., curating) to increase their usability	▶ Establish a database framework (e.g., database schema design) and reliable querying systems to enable high-throughput screening of glasses
DATA DISSEMINATION AND ACCESSIBILITY	▶ Publish case studies and best practices from both within and outside of the glass industry that demonstrate the need for and benefits of standardized data sharing ▶ Increase programming and data science education in the materials field, including through hands-on meetings, workshops, and symposia ▶ Develop interdisciplinary undergraduate- and graduate-level curricula with an increased focus on data science education	

DATA INFRASTRUCTURE AND BEST PRACTICES

2021	2023	2025+
▶ Develop infrastructure for assessing metadata, including measurement techniques and the degree to which the data has been vetted (e.g., reproduced, peer reviewed) or modeled ▶ Establish mechanisms to incentivize data sharing and publication, including a website or journal that streamlines data submission	▶ Run data mining processes to validate glass data in databases, identify hidden relationships, increase the robustness of databases, and improve the prediction accuracy of properties and structures ▶ Develop a communication mechanism for contacting researchers to collect additional or missing metadata	▶ Designate a group (e.g., NIST) with the responsibility to regularly assess and update standards for data curation and management
▶ Develop integrated databases that contain data on properties, structure, and processing history		▶ Develop a secure industry standard database (maintained by a third-party entity) to standardize and streamline collection of materials testing data (e.g., particle size and chemistry) from all industrial raw materials suppliers
▶ Incentivize the increased use of glass databases to develop new properties models and inform predictive modeling		▶ Establish robust infrastructure for secure data access that allows manufacturers to quickly and easily access the data from their suppliers

PATHWAY 5

WORKFORCE DEVELOPMENT AND COORDINATION

KEY INITIATIVES

5A Research Community and Industry Coordination

5B Education and Training

Increased collaboration and information sharing across the glass manufacturing community is essential to address the common technical barriers, workforce development needs, and operational constraints that must be overcome to advance functional glass manufacturing. Improved collaboration throughout the glass manufacturing community will help build stronger partnerships across companies and organizations with complementary expertise, which will be critical for effective and efficient execution of targeted research and development activities. These partnerships can also facilitate the increased sharing and distribution of non-proprietary information to build a knowledgebase that will help educate the current and next-generation workforce and support the business case for increased implementation of advanced technologies throughout the glass manufacturing community.

Current Challenges

To enable functional glass manufacturing innovation, the glass community must work to overcome the workforce development and coordination challenges that follow.

Limited pipeline of qualified students

The prospective glass manufacturing workforce comprises university students who do not receive sufficient training in glass science or an interdisciplinary (e.g., physics, data science) education needed to maximize their contributions to advancing the glass industry. The lack of exposure to industry-relevant problems and a shortage of professors who can adequately train the next generation of researchers has led to a deficiency in highly skilled undergraduates and graduate students ready to join the functional glass manufacturing workforce. Those most qualified for careers as glass scientists and engineers can be difficult to attract to the industry, as they are often drawn to fields that receive more funding or that are viewed more commonly as cutting edge.

Inadequate workforce training

The glass manufacturing community currently lacks a common platform for workforce education, particularly about new glass manufacturing tools and processes as well as advanced data infrastructure and best practices. The existing workforce's insufficient knowledge of advanced manufacturing technologies and next-generation data practices is limiting the widespread adoption and optimized operation of tools and processes with the potential to enable development of higher-performing functional glasses.

Insufficient industry and university coordination

Glass science and functional glass manufacturing combines many expertise areas, including materials engineering, physics, chemistry, geology, and computer and data science. Insufficient coordination between university researchers across these disciplines and with the glass manufacturing industry currently limits the efficient development of advanced manufacturing technologies that meet critical industry needs. Increased coordination between researchers and manufacturing companies is needed to ensure that university research addresses interdisciplinary industry challenges and to effectively facilitate the transition of basic research into advanced manufacturing technology that can be widely implemented.

Lack of engagement with relevant manufacturing industries

The glass manufacturing community does not engage substantially with other relevant manufacturing industries despite the potential to leverage the expertise and lessons learned of industries that have experienced similar challenges, especially related to scale-up and high-temperature operation. The glass manufacturing industry has the opportunity to adapt advanced manufacturing technologies (e.g., additive manufacturing) from these other industries, but lacks the established relationships needed to facilitate this technology transfer.

Key Initiatives for Advancing Functional Glass Manufacturing

Addressing these challenges will require structured platforms for collaboration and consistent and robust workforce education and training. To realize the potential of functional glasses, the glass community must collaborate on the following workforce development and coordination initiatives: Research Community and Industry Coordination and Education and Training. Specific activities for each of these initiatives are included in the Action Plan on pages 52-53; high-priority activities are designated with bold, colored text.

Research Community and Industry Coordination

Increased collaboration and information sharing across stakeholders—including researchers in complementary disciplines, glass manufacturers, equipment manufacturers, and end-use industries—can facilitate the accelerated development and implementation of advanced technologies throughout the glass manufacturing community. Developing a structured framework for collaboration across companies and industry segments will reduce instances of unproductive duplication of efforts and ensure that the research and development community develops and improves the technologies that industry needs most. A comprehensive and easy-to-access knowledge base can also provide the functional glass industry with opportunities to learn about the benefits of new and existing glass manufacturing equipment, advanced manufacturing technologies, next-generation data infrastructure and best practices, and innovative materials—all of which can improve the efficiency and productivity of functional glass manufacturing operations.

Education and Training

The future of functional glass manufacturing depends on a highly skilled and forward-looking workforce with sufficient knowledge to consider and implement innovative technologies and processes that can facilitate the development and implementation of high-performing functional glasses. The glass manufacturing community must launch technical college, undergraduate, and graduate programs that emphasize technology demonstrations, apprenticeships, internships, study abroad programs, hands-on design projects, and glass technology certifications to encourage students to study disciplines and pursue careers related to glass manufacturing. To ensure that students obtain an interdisciplinary education, curricula should emphasize integrated laboratory-scale experiments, multiscale modeling and simulation, industry-level manufacturing processes, and data analytics (e.g., statistics, machine learning, databases, and data mining). Robust continuing education programs are also critical to ensure the current workforce has the knowledge needed to implement and operate emerging advanced manufacturing technologies.

FUNCTIONAL GLASS CASE STUDY

SUPPORTING INDUSTRY-RELEVANT RESEARCH AND BUILDING WORKFORCE CAPACITY FOR INNOVATION

CHALLENGE

With the glass and ceramics industry poised for substantial growth, there is a need to accelerate the translation of basic and applied research to practical glass industry applications. Current academic research, however, is not always technically relevant and commercially valuable to the glass industry. Future functional glass research and development also significantly depends on attracting new talent to the field to build a stronger, more innovative, and multidisciplinary workforce. However, due to the underrepresentation of industry-relevant glass science topics in university research and current STEM curricula, many graduates lack the specialized functional glass and ceramics knowledge that the industry needs. As a result, many recent graduates are not adequately qualified for or not focused on finding employment in the glass industry.

INNOVATION

New initiatives are being launched to improve collaboration between researchers and manufacturing companies and to provide students with the experience necessary to excel as part of the next-generation glass manufacturing workforce.

The Ceramic and Glass Industry Foundation (CGIF) initiated the University-Industry Network, a program that provides resources for professors to connect with glass industry members and supports undergraduate students in the study of glass- and ceramic-related topics. Some companies are also leading their own initiatives, including Corning Incorporated's Gordon S. Fulcher sabbatical program. As part of Corning's strategy to increase collaboration between industry and academia, the Fulcher sabbatical program selects professors to study a topic of mutual interest for up to one year at Corning's Sullivan Park Research and Development Center.

In addition to ensuring professors have the experience needed to teach students industry-relevant glass science, The American Ceramic Society and CGIF collaborated on an online job postings board that connects students with potential employers. Through the Ceramic and Glass Career Center, students can search and apply for glass industry jobs and internships, and employers can post positions and internships and search through the posted resumes for prospective employees.

RESULT

Together, these three programs are working to accelerate fundamental understanding of glass science with practical value to industry, provide professors with industry-relevant experience to inform their research and curricula, and prepare students for and attract them to a career in glass manufacturing. Five universities have signed on to the University-Industry Network program, including Alfred University, Clemson University, the Colorado School of Mines, Missouri University of Science and Technology, and Pennsylvania State University; and two associate professors of materials science and engineering (Liping Huang and Yunfeng Shi) from Rensslaer Polytechnic Institute have already completed six-month research sabbaticals through Corning's Gordon S. Fulcher program. Additionally, the Ceramic and Glass Career Center website—careers.ceramics.org—went live at the end of 2015, with companies such as Darmann Abrasive Products, Inc., Eli Lilly and Company, and CoorsTek, Inc. posting job opportunities.

ACTION PLAN — PATHWAY 5

Arrows signify sequential or iterative activities.

Colored text indicates activities that were identified as priorities.

	2017	2019
RESEARCH COMMUNITY AND INDUSTRY COORDINATION	▶ Establish a needs capture program in the functional glass manufacturing industry at the plant level (e.g., need for sensors that do XYZ) ▶ Find mechanisms to connect to end-use industries (e.g., automotive medical) with functional glass needs ▶ Develop glass industry fellowships, matched by government funding, that allow graduate students to complete their thesis at a company or industry engineers to spend a year at a university at reduced overhead costs ▶ Develop a database of experts and corresponding skillsets relevant to functional glass manufacturing ▶ Hold topical workshops that convene experts and target research institutes to discuss research results or commercial applications for new melting and fining technologies	▶ Increase industry engagement of faculty and students in fundamental and applied research, while also re-engaging funding agencies by articulating the importance of glass research ▶ Launch industry-funded, interdisciplinary Ph.D. programs on materials development for materials for in situ sensors and other topics with substantial industry interest ▶ Establish industrial chair positions for glass professors ▶ Transfer knowledge and testing methods for batch-to-glass reactions from companies to testing laboratories and universities
EDUCATION AND TRAINING	▶ Develop new special topics glass courses ▶ Increase sharing of online glass courses among universities and professional societies through interactive online sites ▶ Increase collaboration among existing, independent glass science courses ▶ Encourage universities to hire faculty in materials science departments ▶ Provide internships/co-ops/ and special opportunities for undergraduates ▶ Hold yearly recruitment event ▶ Establish interview-in-the-USA "travel" program	▶ Increase university and industry involvement with high school and middle school teachers ▶ Develop a tiered continuing education online course module that starts with courses on basic science (e.g., glass chemistry) and builds to courses focused on more advanced technology and processes, culminating with the opportunity for functional glass manufacturing certification ▶ Increase the number of co-op / internships for large and (eventually) smaller companies and establish longer internships or apprenticeship programs to provide more in-depth, hands-on training opportunities

WORKFORCE DEVELOPMENT AND COORDINATION

2021	2023	2025+
▶ Communicate the expertise needs of industry to drive hiring	▶ Launch pre-competitive research consortia to promote collaborations between companies and universities ▶ Pursue an Industry-University Cooperative Research Center (IUCRC) through the National Science Foundation to fund student research	
▶ Leverage government and state partnerships (look at models used in other countries) to fund technical college education in targeted and underserved communities ▶ Ensure that education and training reaches small and medium-sized institutions, where resources could result in the "capture" of many students for glass	▶ Create a manufacturing training program and potentially a curating role, perhaps at a prominent undergraduate institution	▶ Create career pathways for glass technologists, engineers, and researchers

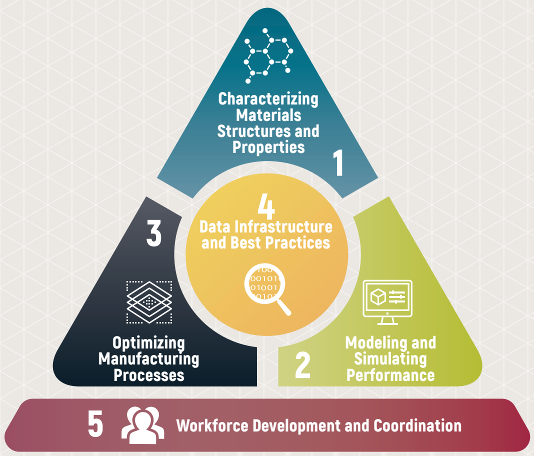
FIGURE 3

FGMIC Roadmap Implementation

FGMIC VISION

Coordinate a national initiative to develop and deploy advanced manufacturing technologies across the broad functional glass manufacturing community, driven by the needs of high-performance functional glasses, which will significantly increase sustainability and U.S. global competitiveness

WHAT: Roadmap Strategy



WHO: Functional Glass Stakeholders

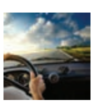
- Academia
- National Laboratories
- Glass Manufacturers
- Raw Materials Suppliers
- Equipment Manufacturers
- Industry Associations
- Standards Organizations

WHY:

Offer Solutions to Society's Grand Challenges


Enhanced national security and worker safety


Increased energy efficiency and environmental sustainability


Advanced mobility


Improved health and welfare


Enriched information sharing

Increase Global Competitiveness of U.S. Glass Manufacturing

- Increased understanding of glass science and the ability to more precisely control glass properties
- Improved collaboration and knowledge sharing across glass manufacturing stakeholders
- A highly skilled and innovative glass manufacturing workforce
- Increased adoption and demand for functional glasses as a trusted, high-performing material
- High-paying jobs and sustained economic growth

THE PATH FORWARD

This roadmap is designed to guide the functional glass manufacturing industry's efforts over the next 10 years, accelerating the development and implementation of high-performing functional glasses and facilitating the long-term growth and global competitiveness of the U.S glass industry. The roadmap's research and development activities will help advance understanding of glass process-composition-structure-property relationships and drive development of innovative manufacturing technologies and processes. Initiatives designed to support research and development and sustain industry growth will help facilitate the widespread adoption of next-generation data infrastructure and best practices and build a skilled U.S. glass manufacturing workforce that can accelerate development and market penetration of innovative materials, technologies, and processes.

This strategy will make the functional glass industry well positioned to offer solutions to some of society's grand challenges, including the need for increased energy efficiency and environmental sustainability, improved health and welfare, enhanced national security and workforce safety, enriched information sharing, and advanced mobility. With increased investment over the next 10 years, innovations in functional glass manufacturing could further the opportunities for functional glass to deliver new solutions to these critical challenges.

Execution of the priority activities within this roadmap will be led by the Functional Glass Manufacturing Innovation Consortium (FGMIC), an industry-driven effort aimed at establishing a collaborative public-private partnership between glass manufacturing companies of all sizes, researchers at universities and national laboratories, raw materials suppliers, equipment manufacturers, industry associations, standards organizations, and other relevant stakeholders. By leveraging knowledge, data, innovative technologies and processes, and specialized skills from across these stakeholders, this community will accelerate growth of U.S. functional glass manufacturing at a speed and magnitude far greater than individuals or small groups could accomplish working independently.

By implementing the priority activities outlined in this roadmap, FGMIC can fulfill its vision to coordinate a national initiative to develop and deploy advanced manufacturing technologies across the broad functional glass manufacturing community, driven by the needs of high-performance functional glasses, which will significantly increase sustainability and U.S. global competitiveness. With an increased focus on functional glass manufacturing, the United States could not only lead global innovation in this field, but could also create U.S. manufacturing jobs and companies and improve our nation's economy.

APPENDIX A: ROADMAP CONTRIBUTORS

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APPENDIX B: INDUSTRY SOURCES

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