AMERICAN CERAMIC SOCIETY

bulletin

emerging ceramics & glass technology

MAY 2023

Deep decarbonization of glassmaking

GE Lighting at Nela Park | Ceramics on the ISS | CGIF receives transformational gift

Biomedical Materials at Alfred University

Dr. Tim Keenan

Dr. Tim Keenan is Assistant Professor of Biomaterials Engineering at Alfred University. He has a diverse array of research interests, ranging from the design and fabrication of new/improved materials for both hard and soft tissue replacement, all the way to the design of anti-microbial materials and coatings for residential construction and consumer product applications. Dr. Keenan leads the efforts at AU in 3-D printing of scaffold material and tissue growth. Specific areas of research include composites development for wound healing applications, composites development for internal sealant/adhesive applications, metal coatings development for internal applications, glass microsphere development for 3-D printing, anti-microbial applications, fine-tuning of glasses for dental applications, and emulsion-derived constructs from HA/polymer composites for tissue engineering scaffolds.

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CACT Center for Advanced Ceramic Technology

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As seen on *Ceramic Tech Today*...

Credit: RMIT University

Mopping up microplastics: Nanopillar-stabilized metal-organic framework removes contaminants from water

Adsorption is an effective way to remove microplastics from water by adhering them to an easily removable/retrievable surface. Researchers at RMIT University in Australia developed a nanopillar-stabilized metal-organic framework adsorbent that effectively removes microplastics from water, as well as the toxic pollutant methylene blue.

Read more at www.ceramics.org/mopping-microplastics

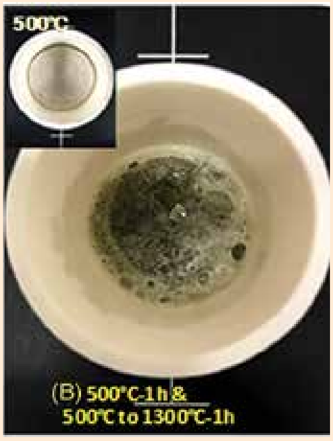
Also see our ACerS journals...

A comprehensive study of the batch-to-melt conversion process of a high-boron alkaline earth aluminosilicate glass
By H. Li, M. Reben, J. Dobyne, et al.
International Journal of Applied Glass Science

Simulation and evaluation of float glass furnace with different electrode positions
By J. Han, L. Li, J. Wang, et al.
Journal of the American Ceramic Society

Microstructural examination of interactions between chromia-based refractory and nuclear glass in a melter
By N. J. Smith-Gray, J. M. Bussey, and J. S. McCloy
Journal of the American Ceramic Society

Investigation of glass sintering to improve strength and interfacial interactions in glass-to-AISI 316L metal joints
By M. C. Özdemir Yanık, O. Demirel, M. Elmadağlı, et al.
International Journal of Applied Glass Science



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Read more at www.ceramics.org/journals

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ACSBA7, Vol. 102, No. 4, pp. 1–40. All feature articles are covered in Current Contents.

news & trends

Low-carbon cement technology heading from lab to market

Credit: Sublime Systems

Carbon-neutral lime created using a new process developed by Massachusetts Institute of Technology researchers. The MIT researchers launched a company called Sublime Systems to commercialize the process.

It has been just over one year since the U.S. National Science Foundation announced the establishment of the Directorate for Technology, Innovation, and Partnerships (TIP).

The TIP directorate embodies the push in recent years for the federal government to take a larger role in supporting use-inspired research and its transition from the lab to the marketplace. It has already started to spin up smaller-scale initiatives alongside its flagship initiative, the Regional Innovation Engines program, and this work is expected to continue based on the recently passed fiscal year 2023 budget.

Green technologies are a main area into which this use-inspired research funding is being channeled. If the U.S. is to uphold its commitment to the Paris Climate Agreement, industrial operations need to be decarbonized, whether through capturing emissions, implementing new processing methods, or using alternative fuels.

Cement manufacturing accounts for a significant portion of industrial emissions. To create ordinary Portland cement, calcium carbonate ($CaCO_3$, generally limestone) is ground and then cooked with sand and clay at high heat, produced by burning coal. The cooking process breaks $CaCO_3$ down into calcium oxide (CaO) and CO_2. The CaO is then reacted with silica (SiO_2) to produce alite, the major mineral phase in Portland cement.

While the coal for heating could be replaced with other fuels, the CO_2 emitted from breaking down $CaCO_3$ cannot be overcome due to the fundamental nature of the material. However, there are different ways for processing $CaCO_3$ that result in purer CO_2, which makes it easier to reuse in other applications.

Researchers at Massachusetts Institute of Technology (MIT), led by ACerS

Fellow and Kyocera Professor of Materials Science and Engineering Yet-Ming Chiang and postdoctoral fellow Leah Ellis, are working on one such process.

The process, which was reported on *Ceramic Tech Today* in 2019, is called ambient temperature electrochemical calcination. It uses electrolysis to reduce the $CaCO_3$.

Not only is the need for fossil fuels removed, as calcium is extracted using low-cost electricity rather than heat, CO_2 is released in a pure stream of O_2/CO_2 gas. The CO_2 can be easily extracted from this stream, in contrast to the impure flue gas from traditional cement kilns that must undergo an expensive amine scrubbing process for usable CO_2 to be secured.

Additionally, the researchers say that the process is naturally purifying, so impure inputs can be used, including low-grade limestones or noncarbonate calcium minerals that do not have embedded CO_2.

"We can separate the calcium from common impurities such as silica, magnesium, iron, and aluminum since these components either don't dissolve in acid or don't precipitate at the same pH as calcium. … [So] Sublime's process of making lime results in a pure lime almost no matter what the starting material, and other higher-value minerals, such as magnesium, can be isolated too," they say in a *Medium* blog post.

In 2020, the MIT researchers established a start-up company called Sublime Systems to commercialize the process. Since then, they made several improvements to the process, including

- More energy efficient,
- Eliminated net production of H_2,
- Allowed separation of CO_2 and O_2 gas streams,
- Enabled continuous extraction of calcium oxide from the reactor, and
- Used commercial off-the-shelf electrolyzer hardware.

In January 2023, Sublime Systems announced that it had closed a $40 million Series A funding round. The funding round was led by climate-tech focused fund Lowercarbon Capital with participation from existing investors, including The Engine, Energy Impact Partners, and others. Siam Cement Group, the largest cement producer in Southeast Asia, also plans to join as a strategic investor.

The new capital will be used to ramp up production at a pilot plant, build the company's team, conduct product testing, and advance offtake commitments from new customers and partners. Beyond that, Sublime Systems plans to construct and operate a commercial demonstration plant by 2025 and then construct a full-scale, million-tonne-per-year cement plant by 2026/2027, with operations by 2028.

If the process is successfully commercialized, Sublime Systems may be able to take advantage of the Biden–Harris Administration's Buy Clean initiative, which prioritizes the federal government's purchase of steel, concrete, asphalt, and glass with lower emissions. On the state level, New Jersey recently signed a bill that incentivizes the implementation of concrete in construction projects with lower carbon emissions than traditional concrete.

With the ramp-up of use-inspired research funding and programs at the TIP directorate, ideally more university researchers will be able to transition their research to market, just as Chiang and Ellis are doing with Sublime Systems. ■

Chicago startup offers 'close-looped' water vending service based on reusable glass bottles

Glass in theory is a perfect container material because it is infinitely recyclable. But for this benefit to be realized, systems must be in place to reuse or recycle the glass. And compared to most European countries, glass recycling rates in the United States are dismal.

There are numerous reasons for these low rates, but part of the reason is that consumers are unsure which materials their city-sponsored recycling collectors accept. Even when glass is ostensibly accepted, high levels of contamination among the collected glass make it more economical for companies to throw it in the dump instead.

Credit: Kadeya

Consumers can receive and deposit glass water bottles from any Kadeya vending machine by scanning a QR code.

Instead of home collection, some local governments rely on glass-only drop-off sites to ensure cleaner glass is collected. But such programs result in much less glass being collected because fewer people are able or willing to drive out of their way to a drop-off center.

In the absence of effective city or county glass recycling programs, numerous private groups are stepping up to expand access and improve the process. Kadeya is one startup offering a unique approach to glass recycling.

Kadeya is a water vending service founded in 2020 in Chicago, Ill. Instead of single-use plastic bottles, water is dispensed in reusable glass bottles that consumers can return at the same machine.

On the Kadeya website, Kadeya founder and CEO Manuela Zoninsein says she became aware of the problem of single-use packaging after working for several years in China. However, the idea for a "closed-loop" vending program came after moving back to the U.S. and seeing Citi Bike stands in New York City.

"Can't we build a bike-sharing network, but for water bottles? Why do we manufacture a new container for every bottle of water someone drinks?" she asks.

The Kadeya system, which comes from the word *cadeia* ("supply chain") in Portuguese, aims to make water vending sustainable on all levels. The water is locally sourced and purified using an advanced filtration process. The purified water is then dispensed in glass bottles when someone scans a QR code on the vending machine.

When a consumer is finished with the bottle, they can scan the QR code again and deposit the bottle. Inside the vending machine, a custom dishwasher cleans and sanitizes the bottle, after which it is refilled and sealed with a new sterile tamper-evident cap.

"It's really just like Citi Bike—we understand when a bottle is undocked from the system, and who got it, but we don't follow them around," Zoninsein says in a *Fast Company* article. "We don't know where they [take] that bottle while they have it. But then we know who it was that returned it, and at what time and what location."

The Kadeya vending machine is now in place at its first pilot location, a sprawling construction site in Indianapolis, Ind.

Industrial sites and factories offer an ideal test environment for Kadeya. OSHA regulations require that water be provided to workers on these sites, but due to the nature of the work, it is often dangerous or impractical for employees to bring water into work areas. The Kadeya system allows construction companies to offer easy access to water without the complicated logistics of having enough bottled water on hand each day for dozens of tradespeople.

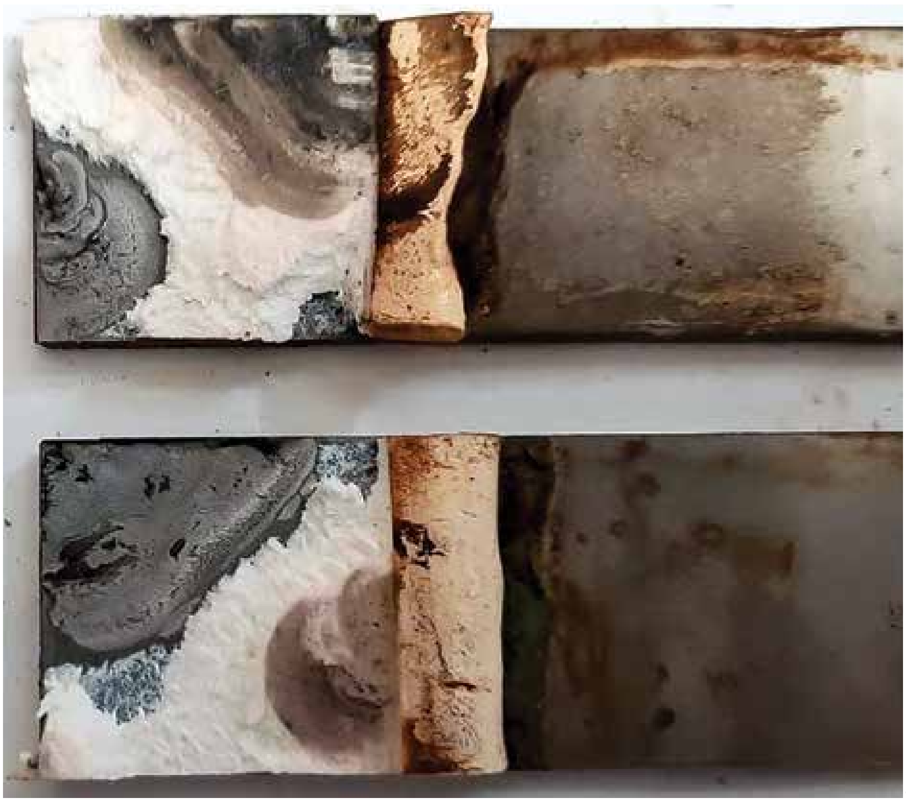
The *Fast Company* article reports that Kadeya is beginning to work with a billion-dollar beverage brand to test placing sparkling water and other flavored beverages in Kadeya's machines.

"We think our platform can enable the entire industry to transition away from single use without sacrificing any of the quality or convenience or profitability that single use provides them today," Zoninsein says. ■

Multiyear study provides vast data on materials wear in marine energy technologies

Though less reported on than wind and solar technologies, marine energy technologies are also making waves in the renewable energy market. Intellectual property firm Marks & Clerk reports that the global ocean energy technology market is worth an estimated 53 billion euros (US$56.6 billion) annually, and it is expected to grow as in-development technologies reach commercialization.

As marine energy technologies mature, there is the risk that companies



Credit: National Renewable Energy Laboratory

Corrosion observed deep in the bondlines of 316 steel metal–metal lap shear specimens conditioned at Pacific Northwest National Laboratory.

will learn the hard way that their devices will not last long in salt water. To help technology developers avoid wasted time and money, a new multiyear study provides much-needed data on the benefits and pitfalls of about 300 different specimens built from materials commonly used in marine energy devices.

The study is a product of the Marine Energy Advanced Materials project, which aims to address barriers and uncertainties facing marine energy developers in adopting advanced materials for structural applications.

A multi-institutional team led by Sandia National Laboratories conducted the multiyear study, which took place from 2019 to 2022. Collaborators on the project include Florida Atlantic University, Montana State University, the National Renewable Energy Laboratory, and Pacific Northwest National Laboratory.

To collect the data, the researchers soaked the specimens for up to 18 months in different types of ocean water baths. The parts were then shipped to the National Renewable Energy Laboratory's Structural Technology Laboratory for stress tests.

The data revealed that each material had its own merits, performing well in some circumstances and poorly in others. For example, composites with embedded steel generally held up well, but one specific fiberglass composite with a certain steel exhibited significant corrosion.

The biggest surprise for the researchers was that some specimens corroded at a shockingly fast rate in Pacific Ocean water versus Atlantic Ocean water. They hypothesize that it may be due to differences in the saltwater chemistry or oxygen concentrations (Pacific Ocean water has higher oxygen concentrations than Atlantic Ocean water).

The multi-institutional group plans to further investigate this strange reaction, in addition to experimenting with other materials, such as recyclable plastic resins, to assess which might be best suited for 3D printing. They also hope to perfect the aging process to make future materials testing a little less cumbersome and more accurate.

Ultimately, "The more understanding you have, the more cost you can save in the long run," says Paul Murdy, mechanical engineer at the National Renewable Energy Laboratory, in a press release.

The report, "Subcomponent validation of composite joints for the Marine Energy Advanced Materials Project," is freely available at https://www.nrel.gov/docs/fy23osti/84487.pdf. ■

DOE charts paths to commercializing emerging energy technology

In March 2023, the Department of Energy launched the "Liftoff Reports" series, which maps pathways to commercialization for emerging clean energy technologies.

The reports in this series provide projections of commercialization timelines and outline the primary challenges various clean energy technologies face. DOE states it intends for the reports to provide "a common fact base and a tool for ongoing dialogue with the private sector," and it plans to update the reports as the commercialization landscape evolves.

The first three reports released in March focus on advanced nuclear, clean hydrogen, and long-duration energy storage technologies. DOE expects to release additional reports over the coming months.

View the reports at https://liftoff.energy.gov. ■

Decarbonization of industry: CCUS and hydrogen technologies

By BCC Publishing Staff

If nations are to uphold their commitments to the Paris Climate Agreement, industrial operations need to be decarbonized.

Two recent BCC Research reports provide a look into the markets of two emerging decarbonization strategies: carbon capture, utilization, and storage (CCUS) and hydrogen fuel.

CCUS technologies

The global carbon capture, utilization, and storage technology market had a value of $2.0 billion in 2020 and is anticipated to grow at a compound annual growth rate (CAGR) of 15.0% to reach nearly $5.2 billion by 2026.

CCUS involves implementing the following processes in an integrated manner.

- Separation of CO_2 from mixtures of gases (e.g., from flue gases).
- Compression of this CO_2 to a liquid state.
- Transportation of the CO_2 to a storage site or conversion facility.
- Injection of the CO_2 into a geologic formation or conversion of the CO_2 into marketable products.

There are three major carbon capture systems. In each case, specific capture technologies such as absorption, adsorption, or membranes are used for separating CO_2 from the gas mixture.

- **Pre-combustion capture**, also known as syngas/hydrogen capture, removes or separates the carbon in fuel before the combustion process.
- **Post-combustion capture** separates CO_2 from flue gas resulting from the air combustion of fuels at the end of the production process.
- **Oxy-fuel combustion** involves substituting pure oxygen for the combustion air so that a CO_2-rich flue gas is produced, which requires minimum processing before use or permanent storage.

Table 1. Global market for CCUS technologies, by technology type, through 2026 ($ millions)

Technology type	2020	2021	2026	CAGR % (2022–2027)
Pre-combustion capture	922.0	1,201.4	2,332.6	14.2
Post-combustion capture	643.9	847.5	1,787.9	16.1
Oxy-fuel combustion capture	404.4	529.4	1,075.0	15.2
Total	1,970.2	2,578.3	5,1995.5	15.0

A decade ago, CCUS projects were vertically integrated, with a capture plant having its own downstream transport and storage system. Now, there is a trend among CCUS projects to share transport and storage infrastructure.

Hydrogen fuel

Global investments in building the hydrogen economy totaled nearly $19.4 billion in 2021 and are anticipated to grow at a CAGR of 12.9% to reach $38.5 billion by 2027.

Currently, hydrogen is used mostly in chemical production and oil refining. In the future, hydrogen is expected to play a crucial role in various sectors, including transportation (powering vehicles), residential (heating homes), and industry (firing processes).

There have been significant advancements in hydrogen production, storage, and distribution technologies in recent years.

Regarding production, there is development of new electrolysis technologies.

- **Alkaline electrolysis:** A relatively simple and low-cost method that uses an alkaline solution as the electrolyte.
- **Proton exchange membrane electrolysis**: A method that uses a proton-conducting membrane to separate the hydrogen and oxygen produced during electrolysis.
- **High-temperature electrolysis:** A method that uses heat, in addition to electricity, to split water into hydrogen and oxygen.

Regarding storage, the following areas witnessed notable advancements.

- **Metal hydrides:** These materials can absorb and release hydrogen in a controlled manner.
- **Carbon nanotubes:** These tiny tubes can store hydrogen at high densities.
- **High-pressure tanks:** Advances have been made in the design and manufacture of high-pressure hydrogen tanks, which allows these tanks to store larger amounts of hydrogen in a smaller volume.

Regarding distribution, the following advancements were made.

- **Hydrogen fueling stations:** There are different types of fueling stations, such as those that produce hydrogen on-site through electrolysis and those that receive hydrogen via truck or pipeline.
- **Hydrogen transport:** Developments occurred in the use of special containers that can transport liquid hydrogen by truck or ship; however, hydrogen transport via pipelines still faces challenges.

About the author

BCC Publishing Staff provides comprehensive analyses of global market sizing, forecasting, and industry intelligence, covering markets where advances in science and technology are improving the quality, standard, and sustainability of businesses, economies, and lives. Contact the Staff at Helia.Jalili@bccresearch.com.

Resources

BCC Publishing Staff, "Carbon capture, utilization & storage technologies" BCC Research Report EGY037F, April 2022. www.bccresearch.com.

BCC Publishing Staff, "Global hydrogen economy: Merchant hydrogen and hydrogen purification technologies" BCC Research Report EGY055F, April 2023. www.bccresearch.com. ■

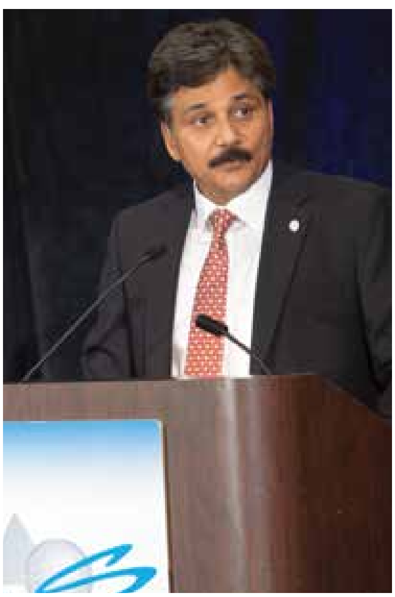
SOCIETY DIVISION SECTION CHAPTER NEWS

Welcome new ACerS Corporate Partner

ACerS is pleased to welcome its newest Corporate Partner.

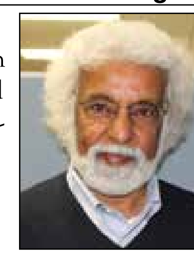
INMATEC Technologies GmbH

To learn about the benefits of ACerS Corporate Partnership, contact Marcus Fish, director of development and industry relations, at 614-794-5863 or mfish@ceramics.org. ■



Ceramic and Glass Industry Foundation receives transformational gift

The American Ceramic Society and its educational outreach arm, the Ceramic and Glass Industry Foundation, received a $1.25 million donation from the Sastri Family. This donation is the largest received in the history of the Foundation. The donation will provide programmatic and ongoing support for the CGIF, which aims to attract more students to the field of ceramic and glass materials science through innovative outreach programming.



Suri Sastri

"We are truly honored to receive a transformational gift of this magnitude and to partner with the Sastri Family to accelerate the mission of the CGIF," says Mark Mecklenborg, executive director of ACerS. "This investment will help us provide the resources, opportunities, and training that will shape the future of the field."

"This landmark donation will be a catalyst for our organization, allowing us to elevate our programs and support for the next generation of ceramic and glass professionals," adds Marcus Fish, director of development and industry relations at the CGIF. "We are thrilled to have this level of investment in our mission and cannot wait to see the impact it will have in the field."

The donation will provide continuing endowment support for the CGIF. It will also provide annual support for new and innovative outreach program initiatives that will help ignite student interest in ceramic and glass science.

Dr. Suri Sastri, the donor, is founder, chairman, and CEO of Surmet Corporation. Founded in 1982, Surmet is a global leader in ALON and spinel transparent ceramic technologies and products. The vertically integrated company is headquartered in Burlington, Mass., with facilities in Buffalo, N.Y., as well as Murrieta, Calif. Sastri, an innovator holding multiple patents and tens of publications, leads materials technology developments at Surmet.

"Surmet was founded on the premise that today's materials are not adequate to meet the challenges of tomorrow's systems, machines, and applications," Sastri says. "Similarly, we need to prepare our younger generation to meet the talent needs of the future, and I believe that future is going to be in the field of materials such as ceramics and glasses."

Sastri is a long-time advocate for student-focused programs and outreach. This generous gift represents the Sastri Family's commitment to the CGIF's mission of ensuring that the industry can attract and support the next generation of ceramic and glass professionals.

The Ceramic and The Glass Industry Foundation was created in 2014 by The American Ceramic Society. The CGIF coordinates programs in the areas of K–12 student outreach, university–industry networks, scholarships, student travel grants, and student leadership development programs. Visit foundation.ceramics.org to learn more. ■

FOR MORE INFORMATION:

ceramics.org

ACerS Bulletin new digital platform rolls out!

We announced in the March issue that the *Bulletin* is transitioning to a new digital format beginning with the May issue, and here it is! All members and subscribers should have received an email linking directly to the new digital platform. We hope you enjoy it as much as we do.

Members and subscribers will receive a paper copy of this May issue as usual. However, the June/July issue will be sent only to subscribers and to members who request a paper copy. Members whose membership category includes a complimentary *Bulletin* may opt in to print with these easy instructions.

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Are you a Bulletin subscriber?

If you are a nonmember subscriber to the *Bulletin*, you will continue to receive your print copy as usual—no additional steps required! ■

IN MEMORIAM

David Wilder

Adrian C. Wright

Some detailed obituaries can also be found on the ACerS website, www.ceramics.org/in-memoriam.

ACerS signs MOU with Japan Fine Ceramics Association

The Society signed a three-year renewable memorandum of understanding with the Japan Fine Ceramics Association (JFCA). JFCA's mission is to promote development of the fine (advanced) ceramics industry by bringing together stakeholders across government, industry, and academia.

"JFCA's mission and ours align well, and the Society welcomes the opportunity to partner with JFCA for the good of the global advanced ceramics industry," says Mark Mecklenborg, ACerS executive director.

The MOU opens a pathway for the organizations to promote each other's meetings, exhibitions, and publications to their respective global memberships. In the future, new joint initiatives may be developed.

JFCA recently published "FC Roadmap 2050," a technology and market roadmap for fine ceramics through 2050. The publication presents 27 roadmaps in nine sectors: mobility, telecommunications, medical care and welfare, energy, infrastructure, environment, sensor, battery, and semiconductor materials and devices. Learn more at https://ceramics.org/fineceramicroadmap2050. ■

more SOCIETY DIVISION SECTION CHAPTER NEWS

Award for best contributions to the 'Processing of Ceramics' wiki

The JECS trust of the European Ceramic Society funded an award for the best contribution to the "Processing of Ceramics" wiki. Among several excellent contributions, three articles were selected for "Best Contribution" awards.

- First place (500€): *Field assisted sintering technology/spark plasma sintering*, by **Martin Bram** and **Ralf Steinert** (Forschungszentrum Jülich, Germany).
- Second place (300€): *Cold isostatic pressing*, by **Ralf Steinert** and **Martin Bram** (Forschungszentrum Jülich, Germany).
- Third place (200€): *Tape casting*, by **Maximilian Gehringer** (TU Darmstadt, Germany).

The awards committee included Amanda Krause (Carnegie Mellon University, USA), Gary Messing (The Pennsylvania State University, USA), and Rodrigo Moreno (Institute of Ceramics and Glass CSIC, Spain). The committee warmly thanks all authors and contributors to this wiki.

Both new contributions and extensions of existing content are highly welcome! The wiki can be reached at https://apps.fz-juelich.de/ceramics/index.php?title=Main_Page. ■

Washington DC/Northern Virginia/Maryland Section judges Future City Competition

Future City is a national STEM competition for middle school students to create a sustainable city of the future. Recently, ACerS and the Ceramic and Glass Industry Foundation sponsored two Future City awards at the national level: Best Use of Ceramics and Best Use of Glass.

The national competition took place in person on Sunday, Feb. 19, 2023, at the Hyatt Regency Washington on Capitol Hill. Winners in the Best Use of Ceramics and Best Use of Glass categories hailed from California and Missouri, respectively. Congratulations to these innovative young students!

Best Use of Ceramics in Technology and for Sustainability

Team name: Flambe Bay

Team members: Isabel Bitonio, Vivaan Daxini, Rishika Gautham, Siyona Kher, Grace Lin, Alina Liu, Nithin, Mahesh Chakravarthy, and Yuan Xing, all from Stratford Middle School, Calif.

Best Use of Glass in Technology and for Sustainability

Team name: Keal Grünestadt

Team members: Kyle Tedrick, Larkin Baker, Ash Hill, and Elliott Showers, all from St. Clair Jr High School, Mo. ■

Volunteer spotlight

ACerS Volunteer Spotlight profiles a member who demonstrates outstanding service to the Society.

Shiv Prakash Singh is an experienced senior glass scientist at the International Advanced Research Center for Powder Metallurgy and New Materials (ARCI), Hyderabad, India. He obtained his Ph.D. in glass science and technology from the CSIR-Central Glass and Ceramic Research Institute, Kolkata, India, in 2012. He then worked for several years at the Federal University of São Carlos, Brazil, and Karlsruhe Institute of Technology, Germany.

With more than 15 years of glass research experience, Prakash Singh has studied a wide range of oxide, oxynitride, and metallic glass systems. His research focuses on nanostructured glass, glass-ceramics, and glass coatings.

Prakash Singh is an active member of ACerS since 2015. He is an associate editor for *Journal of the American Ceramic Society* and a steering committee member of the Young Professionals Network. He is also involved in the activities of the YPN Connect and YPN Communication subcommittees and the student mentor program of ACerS.

We extend our deep appreciation to Prakash Singh for his service to our Society! ■

Names in the news

Members—Would you like to be included in the Bulletin's Names in the News? Please send a current head shot along with the link to the article to mmartin@ceramics.org. The deadline is the 30th of each month.

Cato T. Laurencin, FACerS, Albert and Wilda Van Dusen Distinguished Endowed Professor of Orthopaedic Surgery and professor of chemical and biomolecular engineering, materials science and engineering, and biomedical engineering at the University of Connecticut, is chief executive officer of The Cato T. Laurencin Institute for Regenerative Engineering. The new cross-campus institute supports a core mission of UConn to foster new ways of thinking and new approaches to find answers in medicine, science, engineering, and technology. ■

AWARDS AND DEADLINES

Nomination deadlines for Division awards:
May 15, May 30, July 1, July 31, and Aug. 4, 2023

Contact: Karen McCurdy | kmccurdy@ceramics.org

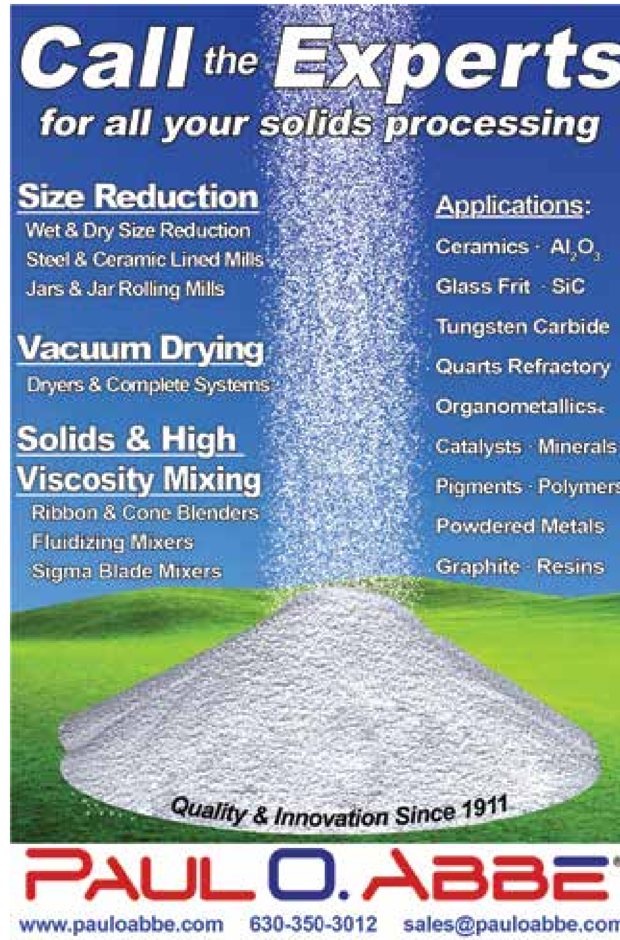
Division	Award	Nomination Deadline	Contacts
GOMD	**Alfred R. Cooper Scholars**	May 15	Steve Martin swmartin@iastate.edu
EDiv	**Edward C. Henry**	May 30	Reeja Jayan breeja@cmu.edu
EDiv	**Lewis C. Hoffman Scholarship**	May 30	Reeja Jayan breeja@cmu.edu
EMSD	**Outstanding Student Researcher**	July 31	Charmayne Lonergan charmayne.lonergan@pnnl.gov
BSD	**GEMS**	August 4	John Blendell Blendell@Purdue.edu
ECD	**Jubilee Global Diversity**	July 1	Michael C. Halbig michael.c.halbig@nasa.gov
ECD	**Global Young Investigator**	July 1	Jie Zhang jiezhang@imr.ac.cn
ECD	**James I. Mueller**	July 1	Palani Balaya mpepb@nus.edu.sg
ECD	**Bridge Building**	July 1	Young-Wook Kim ywkim@uos.ac.kr

ACerS Annual Honor and Awards Banquet at MS&T22 in Pittsburgh, Pa., October 2022.

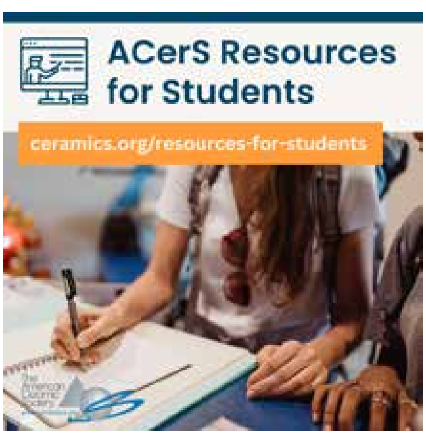
FOR MORE INFORMATION:

ceramics.org/members/awards

Description
Recognizes undergraduate students who demonstrated excellence in research, engineering, and/or study in glass science or technology.
Recognizes an outstanding paper reporting original work in the *Journal of the American Ceramic Society* or the *Bulletin* during the previous calendar year on a subject related to electronic ceramics.
Recognizes academic interest and excellence among undergraduate students in the area of ceramics/materials science and engineering.
Recognizes exemplary student research related to the mission of the Energy Materials and Systems Division of ACerS.
Recognizes the outstanding achievements of graduate students in materials science and engineering. The award is open to all graduate students who are making an oral presentation in any symposium or session at the Materials Science & Technology (MS&T) meeting.
Recognizes exceptional early- to mid-career professionals who are women and/or underrepresented minorities (e.g., based on race, ethnicity, nationality, and/or geographic location) in the area of ceramic science and engineering.
Recognizes an outstanding young ceramic engineer or scientist whose achievements have been significant to the profession and to the general welfare of the community around the world. Nominations are open to candidates from industry, academia, or government-funded laboratories across the world.
Recognizes the enormous contributions of James I. Mueller to the Engineering Ceramics Division and the field of engineering ceramics. It is the intent of this award to recognize the accomplishments of individuals who have made similar contributions.
Recognizes individuals outside of the United States who have made outstanding contributions to engineering ceramics.



STUDENTS AND OUTREACH



If you submitted an abstract for MS&T23, you may be eligible for the GEMS Awards

The Basic Science Division organizes the annual Graduate Excellence in Materials Science (GEMS) Awards to recognize the outstanding achievements of graduate students in materials science and engineering. The award is open to all graduate students who are making an oral presentation in any symposium or session at the Materials Science & Technology meeting.

In addition to their abstract submission, students must also submit a nomination packet to John Blendell, chair of the GEMS Awards Selection Committee, by **Friday, Aug. 4, 2023**. For further details regarding the GEMS Awards and what to include in your nomination packet, go to www.ceramics.org/GEMS. ■

An abundance of student opportunities available at MS&T23

There are many opportunities available for students at this year's ACerS Annual Meeting at MS&T. Make sure to sign up for the following student contests:

- Undergraduate student poster contest
- Undergraduate student speaking contest
- Graduate student poster contest
- Ceramic mug drop contest
- Ceramic disc golf contest
- ...and more!

For more information on any of the contests or student activities at ACerS Annual Meeting at MS&T, visit www.matscitech.org/MST23 or contact Yolanda Natividad at ynatividad@ceramics.org. ■

New ACerS webpage puts student resources at your fingertips

ACerS offers an abundance of opportunities for students. For those who are focusing on ceramics and glass, ACerS can help them earn recognition, gain access to the latest technical information, and build networks necessary for success.

Visit ACerS' new webpage for students at ceramics.org/resources-for-students to learn more about these resources, such as

- Awards and scholarships,
- Financial support,
- Student Mentor Program,
- Learning Center,
- Job Search Resource Center,
- ...and more! ■

ACerS Young Professionals Network and Associate membership

If you have completed your university career and/or are between the ages of 25–40, you are eligible—and encouraged—to join the ACerS Young Professionals Network. YPN gives young ceramic and glass scientists access to invaluable connections and opportunities. For more information, visit www.ceramics.org/ypn. Join this growing community by logging in to your ACerS Personal Snapshot and marking "Young Professionals Network (YPN)" under the Interest Groups and Communities tab.

Did you also know that ACerS offers a one-year Associate membership at no charge for recent graduates who have completed their terminal degree? Join today to receive the benefits of membership in the world's premier membership organization for ceramics and glass professionals. Start your free year-long membership by visiting www.ceramics.org/associate or contact Yolanda Natividad at ynatividad@ceramics.org. ■

FOR MORE INFORMATION:

ceramics.org/students

CERAMIC AND GLASS INDUSTRY FOUNDATION

ENLACE program funded by the CGIF links the US and Mexico

It is your first summer as an undergraduate student in Mexico. Wanting to expand your knowledge over break, you decide to apply for research opportunities in the United States, but you cannot find any that will accept you as an international student. Enter: the ENLACE program.

The ENLACE summer research program is a binational organization connecting high school and undergraduate students from Mexico and the U.S. through the University of California, San Diego (UCSD). UCSD professor Olivia Graeve, FACerS, founded ENLACE in 2013, and in 2018, the Ceramic and Glass Industry Foundation helped fund the growing program with a $10,000 grant.

Credit: Graeve, UCSD

2022 ENLACE participants pose in front of the library at the University of California, San Diego.

"I am a citizen of both countries, and I am interested in giving opportunities to students from both countries, and [I want] to establish great relationships between students from both countries," Graeve says.

Graeve earned her bachelor's degree in structural engineering from UCSD in 1995 and her Ph.D. in materials science and engineering from UC Davis in 2001. Part of her motivation to start ENLACE, which is also the Spanish word for "link," was how her own undergraduate research paved her path to pursue graduate school.

ENLACE participants are placed in lab settings at UCSD based on their interests and then work on projects in that lab throughout the summer. They also go on field trips, view webinars, hear guest speakers, and attend workshops designed for first-generation students.

In addition to a minimum $1,000 scholarship awarded to each participant, ENLACE also receives industry aid to cover up to the full cost of program tuition for students. However, Graeve says that students must be able to speak English to attend ENLACE because it takes place in the U.S.

Alan Hirales-Ahuatzin is a Ph.D. student in nanoengineering at UCSD who found ENLACE while looking for summer research opportunities. He first participated in ENLACE as an undergraduate student from the Universidad Nacional Autónoma de México in Mexico City.

"Unfortunately, many research opportunities here in the U.S. are directed toward national citizens, or people who have residency at least," he says. "ENLACE opens those kinds of opportunities for not only international students, but also for national students as well."

Hirales-Ahuatzin credits ENLACE for being the reason why he attends graduate school at UCSD today.

"The more you know, the more you realize that you don't know anything, right?" he says. "So it's always a magnificent opportunity to discover new things not only about research but also about yourself."

Graeve once overheard two girls at the program, one each from Mexico and the U.S., talking during ENLACE and realized the program also helps students discover new perspectives by working with people of all different backgrounds.

"They are living an experience that is unique and different and that neither of them has ever had, and it doesn't matter what is outside of that UCSD experience, it equalizes people, and I think that is very powerful," Graeve says.

Graeve plans to include master's students next summer and hopes to grow the materials science and engineering department at UCSD through ENLACE and other diversity efforts. She believes that scientists and engineers are a crucial facet to society.

"Who is going to develop the technologies that can save our planet and at the same time provide what is necessary for the human population on this planet?" she says. "Scientists and engineers."

While ENLACE might be one of the largest undergraduate summer research programs in the country, Graeve is grateful to the people, companies, and organizations like the CGIF who have aided in the program's success.

"You have made a difference in supporting my program and allowing me to grow it," Graeve says. "It is educating students to become the future, in this case, ceramic engineers, and I think that's great. And my level of gratitude is infinite for what you have done as a Foundation. So, thank you very much." ■

Beyond the average: How spatial and temporal structural deviations affect glass-forming oxides

Many fundamental glass processes remain conceptually ill-understood despite the ubiquity of glass. This uncertainty is due largely to the complexity of the glass atomic structure.

Unlike metals and ceramics, which consist of highly ordered, long-range structures, glasses consist of disordered, short- and medium-range structures that are not thermodynamically stable. Because of this instability, glass slowly but steadily evolves over time toward a metastable supercooled liquid state.

These deviations of the glass atomic structure in space and time are referred to as spatial and temporal fluctuations, respectively. Fluctuations can significantly affect the macroscopic properties of a glass, yet most studies to date do not account for these deviations.

A lack of theoretical and experimental tools to quantify and assess the impacts of fluctuations is partially why fluctuations are traditionally not considered. But it is also due to the tendency to view materials as having particular property values rather than acknowledging that, in most cases, these values are averages containing fluctuations.

Fortunately, fluctuations are gaining more attention in the theoretical statistical physics community. Critical works have helped advance understanding of the fundamental physical nature of model glassy systems by considering the effect of fluctuations.

"However, a comprehensive review of the physical chemistry of spatial and temporal fluctuations of structural glass materials (e.g., oxide, metallic, and chalcogenide glasses) is currently missing," researchers write in a recent paper.

The researchers are led by ACerS Fellow John Mauro, Dorothy Pate Enright Professor and associate head for graduate education at The Pennsylvania State University, and Penn State Ph.D. candidate Katelyn Kirchner. The group includes numerous students and professors from Penn State, plus colleagues from Federal University of São Carlos in Brazil, Hokkaido University in Japan, Aalborg University in Denmark, and the University of California, Los Angeles.

To help fill this gap, their new paper comprehensively reviews various experimental and computational techniques used to characterize and evaluate the effects of spatial and temporal fluctuations on commercially relevant glass systems, primarily oxide glasses. Some highlights from the 67-page review are below.

Credit: Katelyn Kirchner

Penn State Ph.D. candidate Katelyn Kirchner working on 2D glasses during her recent stay in Hokkaido University, Japan, where she worked with professor Madoka Ono.

Kinetic and thermodynamic origins of glass fluctuations

After providing a precise and mathematical description for the term "fluctuations," the researchers then explain the community's current understanding for the thermodynamic and kinetic origins of fluctuations in glass-forming systems. Specifically,

- **Thermodynamics** is the driving force for the transition from the nonequilibrium (thermodynamically unstable) glassy state to the equilibrium (metastable) supercooled liquid state. Properties such as heat capacity, thermal expansion coefficient, and compressibility can be calculated from quantified fluctuations in thermodynamic parameters.
- **Kinetics** sets the rate and intermediate steps required for the transition to occur. Kinetically driven properties of

Research News

Novel method for crafting chiral nanostructures with lasers

By carefully controlling the direction of a laser beam's vibrations, Wuhan University researchers created a variety of chiral structures made of platinum oxide in unique shapes, such as twisted micropillars and spiral superstructures. Such nanostructures could lead to the development of new types of advanced sensors or solar cells, as well as new types of optical displays. The researchers are testing more materials to identify which can be fabricated in the same way, for example, other semiconductors like cadmium sulfide. For more information, visit https://www.nanowerk.com. ■

Visualizing spatial distribution of electric properties at microscales with liquid crystal droplets

Existing sensor probes for microelectrical devices can measure only their average electric properties, providing no information on their spatial distribution. Researchers from Ritsumeikan University, Japan, visualized the electric field and electrostatic energy distribution of microstructured electrodes by recording the motion of liquid crystal droplets under an applied voltage, making for high detection accuracy (5 μV/μm) and spatial resolution (10 μm). For more information, visit https://en.ritsumei.ac.jp. ■

specific interest for glass-forming systems, and where temporal fluctuations are most critical, include glass relaxation, crystallization, and phase separation.

Computer simulations based on molecular dynamics, Monte Carlo, and statistical mechanics are a common way to model kinetic and thermodynamic properties.

Techniques for characterizing fluctuations

Numerous spectroscopic and diffraction techniques that are used to characterize short- and medium-range order structural units in glasses can also provide insights on various features of spatial and temporal fluctuations. For example,

- Nuclear magnetic resonance allows for Q^n speciation,
- Diffraction or vibrational spectroscopy techniques can reveal bonding fluctuations,
- Raman spectra can lead to ring size determination, and
- Small-angle scattering can measure density fluctuations.

While experimental techniques can provide indirect signatures of the structure of glasses with high precision, they come at the high cost of time and equipment. So, these techniques are often paired with computational approaches, such as the molecular dynamics and statistical mechanics simulations mentioned in the section above.

Computer modeling allows hypotheses to be tested in a time- and cost-effective manner before the most promising conjectures are confirmed with experiments.

However, there are challenges with developing computational techniques for studying spatiotemporal fluctuations in glass-forming systems, including the applicability of models over relevant time and length scales and the ability to discern physically meaningful fluctuations from calculation noise.

Role of spatiotemporal fluctuations in structure–property–performance relationships

The second half of the paper, sections 6–10, is dedicated to describing the role of spatiotemporal fluctuations in several important structure–property–performance relationships, including glass relaxation, crystallization, and phase separation; effects on mechanical and optical properties are also discussed.

Ultimately, the researchers conclude that "When tailoring a glass design with unusual properties or specific applications in mind, the overarching question is how fluctuations can be leveraged as an additional parameter to the composition and thermal/pressure history."

"By explicitly considering the magnitude of fluctuations with this list of parameters, glass applications with stringent requirements on mechanical and optical properties can be more finely tuned, especially in relation to newly developing large-scale manufacturing techniques, such as additive manufacturing," they write.

The paper, published in *Chemical Reviews*, is "Beyond the average: Spatial and temporal fluctuations in oxide glass-forming systems" (DOI: 10.1021/acs.chemrev.1c00974). ■

New solid-state NMR strategy cracks open the 'black box' of crystal nucleation in glass

Researchers in Brazil shed unprecedented light on the structural changes that take place in a glass during relaxation and crystal nucleation.

Though glass-ceramics are widespread in commercial applications, the process by which a crystal nucleates and grows within a glass during heat treatments remains a conceptually ill-understood phenomenon.

In the new paper, researchers led by ACerS Fellow Edgar D. Zanotto, senior professor at the Federal University of São Carlos and director of the Center for Research, Technology, and Education in Vitreous Materials (CeRTEV), developed a novel method that combines atomistic computer simulations with quantitative nuclear magnetic resonance spectroscopy to study the structural changes in lithium disilicate.

Analysis with this method revealed that, upon heating, distribution of the network building blocks (–Si–O–Si–) within lithium disilicate glass stay mostly unchanged. In contrast, the network modifier cations (Li^+), which are very mobile within the glass at the annealing temperature, continuously approach a structural configuration that resembles the crystalline state.

"Given enough time, the first tiny crystal nuclei will be born, followed by many more, which will ultimately grow until the whole material is crystallized," the researchers explain in an email.

These results confirmed a previous hypothesis that Zanotto and colleagues proposed in a 2015 paper, that network modifier arrangements in homogeneously nucleating glasses are closely related to those in respective isochemical crystals.

While this confirmation is exciting, the researchers emphasize that the newly developed NMR strategy itself holds exciting prospects for glass science.

"The NMR strategy we developed combined with computer simulations is generally applicable for many glass types, including optical glasses, bioactive glasses, and ion-conducting glasses containing suitable NMR active nuclear probes, and it is expected to help solve many persisting puzzles around structural relaxation, nucleation, and crystallization processes," they write in an email.

The paper, published in *Acta Materialia*, is "Structural rearrangements during sub-T_g relaxation and nucleation in lithium disilicate glass revealed by a solid-state NMR and MD strategy" (DOI: 10.1016/j.actamat.2022.118318). ■

High-speed cameras offer real-time measurements of thermal shock cracking in ceramics

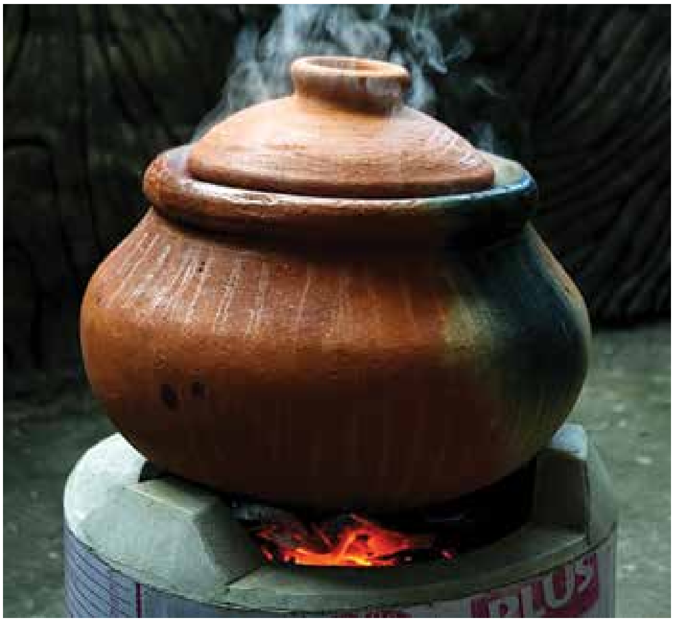
In a recent paper, researchers from several universities and a state laboratory in China designed a method for real-time measurement of thermal shock cracking in opaque ceramics.

Despite the well-known susceptibility of ceramics to thermal shock, there is little experimental verification of real-time crack growth due to this phenomenon. Instead, most experiments on thermal shock performance of ceramics collect data on crack morphology and residual strength after thermal shock has taken place.

In the past decade, numerous theoretical studies on the initiation and propagation of thermal shock cracks were published. Plus, some studies succeeded in experimentally measuring thermal shock cracking of transparent ceramics through tracking the reflection and refraction of light.

The new method proposed by the Chinese researchers is based on digital image correlation (DIC). DIC is an optical method that employs tracking and image registration techniques for accurate 2D and 3D measurements of changes in images before and after surface deformation. Due to its nondestructive nature, high availability, and simplicity, DIC is widely used to study fracture processes in various materials, such as asphalt concrete and magnesia refractories.

For DIC to accurately track changes between images, the observed material must feature a random distribution of gray shades across its surface that the DIC camera can identify. These shades can be a natural part of the material's surface or paint applied before testing.



Credit: Elmer nev valenzuela, Wikimedia (CC BY-SA 4.0)

Only certain types of ceramic cookware can be used over an open flame due to the susceptibility of ceramics to thermal shock cracking.

In their study, the researchers added gray shades to their samples by first spraying a thin layer of black speckle on the surface and then spraying a thin layer of white speckle. They sprayed samples of both alumina (Al_2O_3) and zirconia ($3Y\text{-}ZrO_2$) because these ceramics "significantly differ in thermal conductivity and fracture toughness, and our previous simulation finds that they have a significant difference in crack growth rate," thus allowing for good comparison, the researchers write.

Thermal shock testing was carried out by water quenching the samples. The speckled ceramic sheets were clamped in a sandwich configuration between two quartz glass fixtures and then placed in a muffle furnace at 400°C for 30 minutes. Immediately after removal from the furnace, the samples were sprayed with water while a high-speed camera took images of the thermal shock cracking at 1,000 frames/second. The final cracks were then dyed with blue ink so that crack morphology could be scanned and compared with DIC results.

Analysis of the data showed that crack morphologies determined by the DIC method matched very closely with the dyeing method. Additionally, as expected, the researchers confirmed different crack growth rates for alumina and zirconia, with the crack growth rate of alumina close to three times that of zirconia.

Thus, "It can be considered that this paper presents an in-situ measurement method for the initiation and propagation of water-quenched thermal shock cracks in opaque ceramics," the researchers conclude.

The paper, published in *Journal of the European Ceramic Society*, is "Measurement of ceramics cracking during water quenching by digital image correlation" (DOI: 10.1016/j.jeurceramsoc.2022.12.060). ■

New ultrafast optical nanoscopy method measures carrier dynamics in wider bandgap semiconductors

Researchers led by the University of California, Berkeley, proposed a method that combines ultrafast nanoscale measurements and theoretical modeling to probe carrier behavior in semiconductors with wider bandgaps.

Time-resolved terahertz spectroscopy, which probes the properties of matter with short pulses of terahertz radiation, has been widely used to study charge carrier dynamics in bulk and nanostructured semiconductors. Its application on the nanoscale has been further developed through integration of scattering-type scanning near-field optical microscopy and pump–probe microscopy.

"However, given the limited photon energy, the efforts have been primarily focused on studying carrier dynamics in narrow bandgap semiconductors, such as InAs and $Hg_{1-x}Cd_xTe$, or graphene plasmon," the researchers write in their paper.

Their optical nanoscopy method integrates near-field scanning optical microscopy and pump–probe optics "to enable high resolution at both spatial and temporal scales," says Costas Grigoropoulos, senior author and A. Martin Berlin Chair in Mechanical Engineering and Distinguished Professor of Mechanical Engineering at UC Berkeley, in a UC Berkeley press release.

Their setup consists of an 800-nm femtosecond laser beam split by a beam splitter into a probe beam and a pump beam. The pump beam is frequency doubled to 400 nm by a nonlinear crystal (beta barium borate) and then amplitude-modulated by an acoustic-optic modulator.

The probe beam passes through a mechanical delay stage, and then both beams are merged and directed via a parabolic mirror to a platinum-coated atomic force microscope (AFM) tip with an oscillating frequency.

The scattered probe light is collected by the parabolic mirror and redirected to an avalanche photodiode detector (APD), where it is interfered with a reference beam from the reference mirror. A long-pass filter is placed before the detector to block the scattered pump beam.

Finally, the APD signal is sent to a lock-in amplifier for signal demodulation at the same modulation frequency of the pump beam to suppress background noise.

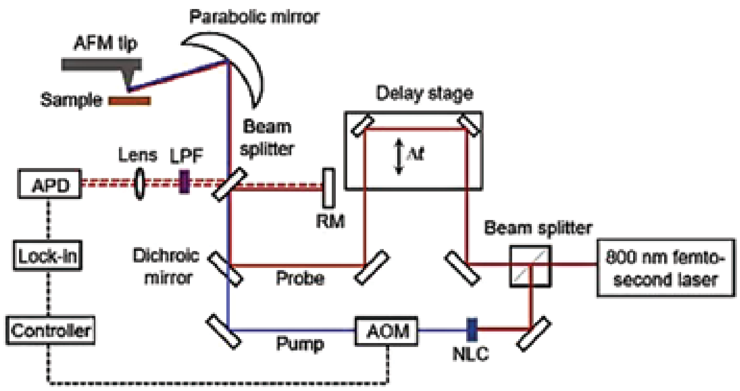
The researchers tested their setup on silicon nanowires, a semiconductor material with a relatively larger bandgap. The bandgap of silicon is 1.12 eV; narrow bandgap semiconductors have bandgaps smaller than 1.11 eV at room temperature.

The experimental data validated that the point-dipole model provides a good qualitative description of the carrier behavior.

Based on these findings, the researchers state their method will be useful in analyzing other wider bandgap semiconductors, such as gallium arsenide (bandgap of 1.42 eV).

Additionally, the method "provides a promising tool to study other nonequilibrium thermodynamic phenomena in nanomaterial systems, including phase transitions, energy and charge transfer, and phonon propagation," they conclude.

The paper, published in *Nano Letters*, is "Ultrafast optical nanoscopy of carrier dynamics in silicon nanowires" (DOI: 10.1021/acs.nanolett.2c04790). ■



Experimental setup of the new optical nanoscopy system. NLC: nonlinear crystal; AOM: acoustic-optic modulator; APD: avalanche photodiode; LPF: long-pass filter; RM: reference mirror. Reprinted with permission from Li et al., *Nano Letters*. Copyright 2023 American Chemical Society.

Strategies for managing hot spot development during microwave and flash sintering

Microwave sintering and the newer flash sintering technique offer improved energy efficiency over traditional sintering techniques. Instead of heating up an entire furnace to sinter the part, these methods achieve total or partial heating within the ceramic itself through a coupling between the material and an electromagnetic or electrical field.

However, because heating occurs within the sample, ceramics processed using microwave or flash sintering commonly experience hot spots, i.e., the development of local overheating in certain regions.

Understanding the mechanisms that drive hot spot development can help researchers manage this phenomenon. A recent paper provides a useful look at these factors and describes possible ways to manage hot spot development.

The authors of the paper come from Université Grenoble Alpes and Normandie Université in France. They begin by describing typical setups for microwave sintering and flash sintering experiments before diving into the specific mechanisms that drive hot spot development in each case.

Causes of hot spot development

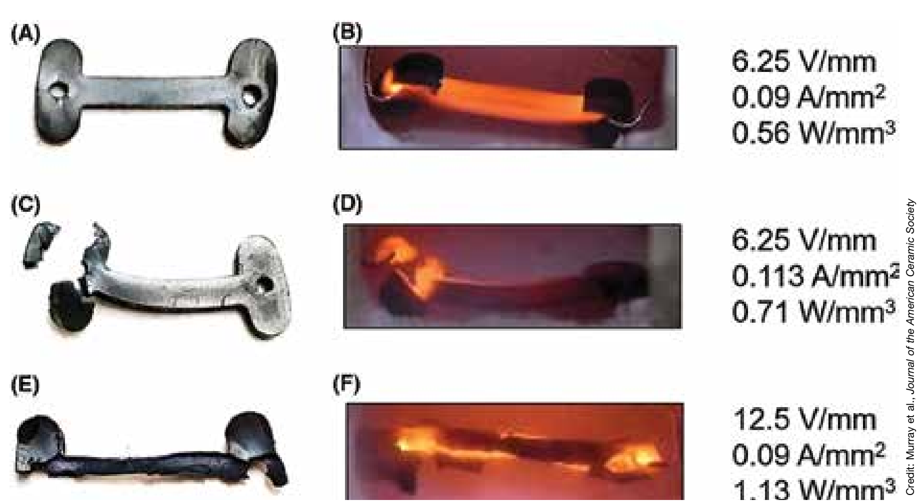
Overall, the simple reason hot spots develop during microwave and flash sintering is because of thermal instabilities in the samples triggered by high power and high heating rates, high positive temperature coefficients, and/or low heat conductivity (i.e., low heat dissipation).

In the case of microwave sintering, thermal instabilities typically manifest as hot spots on the surface of the sample, though hot spots within the sample are possible as well. Hot spots can also develop inside the insulating material placed around the sample.

In the case of flash sintering, thermal instabilities generally develop along a preferential current path, which results in a "hot line" rather than a hot spot.

Several factors determine where thermal instabilities will occur within a sample.

- **Inverted thermal gradients**. According to the authors, bulk heating in both microwave and flash sintering naturally produces a thermal gradient that is "inverted" with respect to the usual gradient obtained by surface heating in a classic furnace. This inverted gradient provides an inhomogeneous temperature profile at the scale of the specimen size, "suitable to trigger an instability in any large enough specimen," they explain.
- **Defects in the field distribution**. Review articles often point to uncontrolled field nonuniformity in multimode microwave cavities as a cause of thermal instabilities. (I.e., cavities in which microwave energy bounces around inside the applicator.) The field, and therefore the dissipated power, depend on the sample shape and position in the cavity. In flash sintering, the field results from the application of voltage at specific contact points. If the sample is not symmetric, the slight off-centering can lead to thermal instabilities. Additionally, the quality of the contacts is a significant potential source of defects leading to localization.
- **Composition inhomogeneity**. In microwave sintering, the presence of particles of a highly absorbing material in a weakly coupling matrix is a cause of hot spots. In flash sintering, local composition inhomogeneity induces preferential current paths that lead to the development of hot spots or lines.

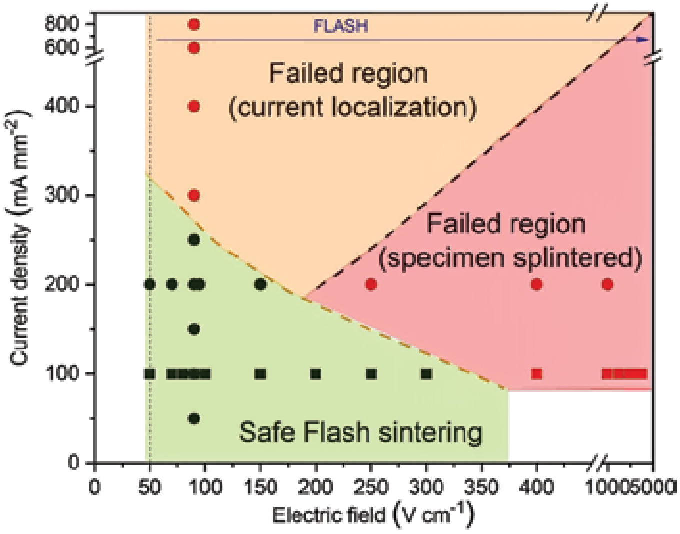


Images (A, C, E) after and (B, D, F) during flash sintering of copper oxide samples with varying applied power densities. The sample with the lowest applied power density (A, B) has a homogeneous orange glow, while the two samples with higher applied power densities (C–F) break during the flash event due to the development of hot spots.

Strategies for managing hot spot development

Because thermal instability tends to develop from any source of localization—be it field nonuniformity or sample inhomogeneity, as described above—the first strategy for managing hot spots involves suppressing, limiting, or compensating for the sources of nucleation.

Thermal insulation is one option for reducing thermal exchanges. In the case of flash sintering, one study achieved some success using different types of insulation on a small cross-section of dog-bone-shaped samples. However, thermal insulation does not prevent localiza-



Credit: Prasad Mishra et al., Journal of the American Ceramic Society (CC BY-NC 4.0)

Example of a "processing map" for voltage-to-current controlled flash sintering of gadolinium-doped ceria.

tion in microwave sintering (hot spots can develop inside this material, as mentioned above).

Adapting the application of current is another way to balance the natural thermal gradient. For flash sintering, one study tested a "current path management" approach on numerical models and experiments in the case of a flat dog-bone-shaped specimen.

Regarding adaption of current in microwave sintering, a commonly used technique is the so-called hybrid microwave heating. In this process, materials with a significant ability to couple with microwaves and a weak evolution of the permittivity with temperature are placed close to or around the sample. These materials act as "susceptors" that both transform the MW energy into heat—which is then classically transmitted to the sample—and limit the field applied to the sample itself.

While the first strategy aims to prevent hot spots, the second strategy for managing hot spots aims to limit or delay their development long enough to achieve satisfactory density.

The first option is to use a controlled heating rate, as very high heating rates can trigger thermal instability. The hybrid heating technique described above achieves this option sufficiently for microwave sintering. For flash sintering, a fixed current step limits the dissipated power in the sample but does not by itself stop localization. Several studies created "processing maps" revealing the maximum constant current density that can be used before localization starts to occur.

Based on results achieved with these strategies so far, the researchers conclude that "Although localization is almost unavoidable, both types of approaches contribute to obtain acceptable conditions for the densification of homogeneous ceramic parts while keeping the expected advantages of field assisted techniques, namely, fastness and energy saving."

Finally, there is the possibility of using hot spots to achieve beneficial results. For example, researchers from Tel Aviv University in Israel developed the concept of localized microwave-heating intensification, and they identified applications such as drilling of glass, thermite reaction ignition, and local sintering of metal powder.

The paper, published in *Advanced Engineering Materials*, is "A viewpoint on hot spots in microwave sintering and flash sintering" (DOI: 10.1002/adem.202201742). ■

Small scale, big discoveries: Reducing thickness of antiferroelectric films turns them ferroelectric

In a recent open-access paper, researchers from several universities and national laboratories in the United States and France report the surprising discovery that below a certain thickness, antiferroelectric films will become completely ferroelectric.

Ferroelectricity is the property of certain materials to have spontaneous electric polarization that is reversible through application of external electric fields.

Antiferroelectric materials are similar to ferroelectric materials in that both consist of an ordered (crystalline) array of electric dipoles. However, adjacent dipoles in antiferroelectrics are oriented in opposite directions, causing them to cancel each other out and resulting in no polarization on the macroscale. In contrast, ferroelectric dipoles all point in the same direction, resulting in macroscopic polarization.

An electric field of sufficient magnitude can induce antiferroelectrics to undergo a phase transition to a ferroelectric phase (i.e., parallel dipole ordering). This behavior makes antiferroelectrics of interest for use in high-energy density capacitors. However, to optimize their use in this application and other miniaturized electronic devices, researchers must understand how size affects the properties of antiferroelectrics.

Traditionally, gathering data on size effects in antiferroelectrics is complicated by how antiferroelectric thin films are made. The films are grown on commercially available substrates with different lattice structures. Lattice mismatch between the substrate and the thin film strains the antiferroelectric, so decoupling the strain effects from the size effects is challenging.

To overcome this challenge, the authors of the recent open-access paper introduced a sacrificial buffer layer between their lead-free sodium niobate ($NaNbO_3$) thin film and substrate. This buffer layer allowed the film to be detached from the substrate after it was grown to the desired thickness.

Once detached, the researchers used a variety of experimental approaches to assess the strain-free films at thicknesses ranging from 9 nm to 164 nm.

Piezoresponse and optical measurements revealed that when the $NaNbO_3$ films are thinner than 40 nm, they become completely ferroelectric. For thicknesses above 40 nm, the films contain a mixture of antiferroelectric and ferroelectric regions. But if a sufficient electric field is applied, the antiferroelectric regions undergo a nonreversible transition to ferroelectric, resulting in a completely ferroelectric thin film at thicknesses up to 164 nm.

These unexpected results prompted the researchers to use first-principles calculations to determine what drives the antiferroelectric-to-ferroelectric transition. They determined that surface effects—specifically, the c/a ratio—is the main cause.

The c/a ratio relates the lattice parameters of a crystal structure. The higher the ratio, the more distorted the lattice structure.

When film thickness decreases, there is a higher c/a ratio, and this structural distortion helps stabilize the ferroelectric phase. In contrast, a thicker film features a lower c/a ratio, which favors the antiferroelectric phase.

The researchers caution that many factors were not accounted for in the first-principles calculations, such as the presence of structural defects or inhomogeneities. As such, agreement between experiments and theory should be considered qualitative rather than quantitative.

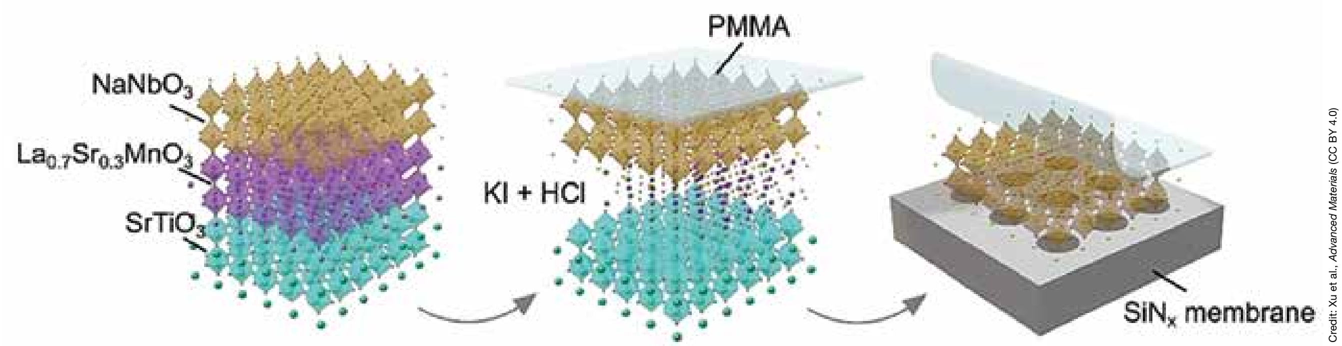
They also mention the possibility that the ferroelectric phase is a result of the synthesis process.

"Note that the *Pbcm* antiferroelectric phase is more stable than the ferroelectric Pmc21 phase when $NaNbO_3$ is unstrained. Therefore, the ferroelectric phase is favored in the as-grown $NaNbO_3$ on $SrTiO_3$ [the substrate]," they write.

"The relaxation from the strained ferroelectric phase to the unstrained antiferroelectric phase would require overcoming an energy barrier … If such an energy barrier increases in thin membranes due to dimensionality or surface effects, the thin membranes could remain frozen in their initial ferroelectric state during the lift-off process," they add.

In an email, lead author Ruijuan Xu, assistant professor at North Carolina State University, says they are now working on fabricating $NaNbO_3$-thin-film-based capacitors to probe electrical properties on the macroscale.

The open-access paper, published in *Advanced Materials*, is "Size-induced ferroelectricity in antiferroelectric oxide membranes" (DOI: 10.1002/adma.202210562). ■



Schematic illustrating the lift-off process for $NaNbO_3$ thin films. By dissolving the $La_{0.7}Sr_{0.3}MnO_3$ buffer layer in a mixed KI and HCl solution, the $NaNbO_3$ thin film is released and transferred onto a 200-nm-thick SiN_x membrane with arrays of holes in a diameter of 2–10 μm.

Model reveals how nanopores form in 2D materials hit by highly charged ions

Researchers from the Institute for Theoretical Physics and the Institute of Applied Physics at TU Wien in Austria used simulations to investigate nanopore formation mechanisms in 2D materials hit by highly charged ions.

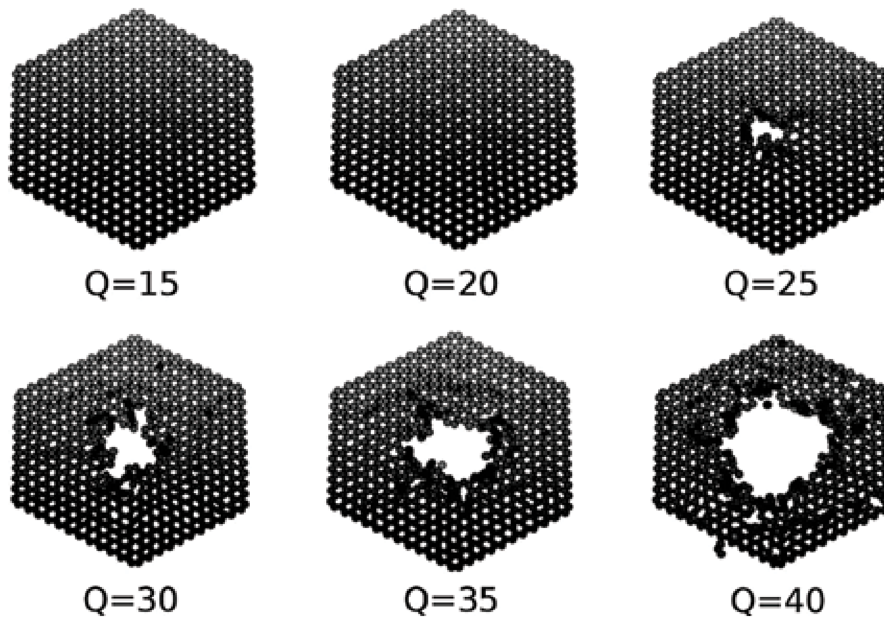
Highly charged ions, or atoms in which all or most of the electrons have been removed, are one tool that researchers use to accurately manipulate and modify 2D heterostructures. When shot into a 2D heterostructure, these ions act like hand grenades, releasing energy as they rapidly capture electrons from the atoms around them. This reaction results in the formation of nanometer-sized pores in the 2D heterostructure.

Researchers have tested the response of various 2D materials to highly charged ion bombardment, including graphene and molybdenum disulfide. While sometimes the ions penetrate the 2D material without any noticeable change, at other times, the 2D material at the impact site is completely destroyed.

To understand why different materials react so differently to highly charged ion bombardment, the researchers of the recent study investigated nanopore formation mechanisms in fluorographene. Fluorographene is graphene that has been fluorinated, meaning it consists of carbon and fluorine atoms. It is considered one of the thinnest insulators, and the chemistry of fluorographene is a budding discipline because it can lead to various graphene derivatives.

The researchers' simulations consisted of a classical molecular dynamics simulation (for the motion of the target atoms) combined with a Monte Carlo model (for the diffusive charge transport within the layer). Within the simulations, graphene flakes appeared as several concentric rings around the impact point of the highly charged ion. Atom motion was followed until the lattice was free of charges; in other words, until the charges migrated beyond the outermost ring.

Additionally, the researchers included the Stillinger–Weber potential within their model. This potential, which has



Restructuring of carbon layers due to the impact of a highly charged ion with initial charges (Q_{in}) ranging from 15–40 for a fixed hopping time of 7 au. The threshold for pore formation at this charge mobility is around Q_{in} = 25.

been successfully used in describing various 2D materials, states that the bond energy is related to both the distance between atoms and the bond angles. The researchers explain they included this potential "due to its small numerical cost while successfully reproducing the splitting of graphene grains into graphene nanoplatelets when strained."

Based on these simulations, the researchers determined that it is not the momentum of the highly charged ions that is mainly responsible for pore formation but the 2D material's charge mobility.

"Graphene has an extremely high electron mobility. So this local positive charge [the highly charged ion] can be balanced there in a short time. Electrons simply flow in from elsewhere," explains senior author Christoph Lemell, associate professor of theoretical physics, in a TU Wien press release.

In contrast, materials such as molybdenum disulfide have a slower electron mobility, and so electrons cannot flow in from elsewhere fast enough. A mini explosion thus occurs at the impact site: the positively charged atoms from which the ions took their electrons repel each other, and a nanosized pore forms.

This dependence of pore formation on charge mobility explains why highly fluorinated graphene is more susceptible to pore formation—fluorination alters the band structure of graphene, thus reducing charge mobility.

The open-access paper, published in *Nano Letters*, is "Model for nanopore formation in two-dimensional materials by impact of highly charged ions" (DOI: 10.1021/acs.nanolett.2c03894). ■

Deep decarbonization of glassmaking

By Christopher W. Sinton

Decarbonizing energy-intensive manufacturing processes such as glassmaking requires a mix of strategies across the entire value chain.

At the end of the day, many like to relax with a glass of wine or a bottle of beer. As you open that bottle, you are holding a piece of glass that is responsible for between 60 and 160 grams of CO_2 emitted into the atmosphere.[1*]

In the United States, the government aims to achieve a net-zero greenhouse gas (GHG) emission economy by 2050.[2] The U.K. and Europe have the same net-zero goal for 2050, as well as a shorter term goal by 2030 to reduce GHG emissions by 68% and 55%, respectively, compared to 1990 levels.

How does the glass industry reach that goal?

While 2050 may seem decades away—after all, many engineers and researcher working on these problems today will be retired by 2050—the magnitude of the manufacturing process changes and capital investments shift the urgency of acting into a near-term, easily foreseeable timeframe.

For example, "Float glass furnaces typically have a lifespan of 20 years. To meet the 2050 net-zero carbon target, a CO_2-neutral furnace must be developed by 2030. Achieving such an ambitious target requires years of development," says Cyril Jean, R&D portfolio manager at Saint-Gobain Glass.

Significantly reducing the amount of CO_2 emissions associated with energy-intensive industries such as the glass industry is paramount to mitigating the effects of climate change. Incremental changes in the glass industry have led to an overall decrease in carbon intensity (kg CO_2 emitted per kg of glass made), but a near net-

*Assumes a 300 tpd air-fuel furnace with electric boost and 50% cullet emitting 332 kg CO_2 per metric ton glass (Reference 1) and beer and wine bottles of 180 g and 500 g, respectively. This estimate does not include emissions associated with a bottle after it leaves the plant.

zero or "deep decarbonization" of glass manufacturing is the ultimate goal.

The first step to decarbonization is to account for how much greenhouse gases are emitted by a company across the full manufacturing value chain. Green House Gas Protocol,[3] an organization that provides standards, guidance, tools, and training to measure and manage GHG emissions, offers a standardized framework for evaluating the embodied emissions of an entity.

The framework divides an entity's GHG emissions into three categories or scopes. Scope 1 covers emissions from sources that an entity owns or controls directly, for example, from burning fuel in a furnace. Scope 2 are offsite emissions, such as the electricity purchased and used within the glass manufacturing process. Scope 3 emissions are all GHG sources not within scope 1 and 2 boundaries, including those from sources up and down the value chain, for example, emissions associated with raw material suppliers.

Once the carbon emissions are accounted for, the next step is to develop a strategy to accomplish significant reductions. The U.S. DOE roadmap for industrial decarbonization includes four key technology pillars to significantly reducing carbon emission: energy efficiency; low-carbon fuels/energy sources; industrial electrification; and carbon capture, utilization, and storage (CCUS).[4] To this list, we add the glass-specific issue of decarbonizing raw materials. Here we explore each of these areas in detail.

Energy efficiency

Energy efficiency is an important and logical part of decarbonization—less energy from fossil fuel combustion means lower CO_2 emissions. Improvements in the energy efficiency of furnaces are the major reason why the carbon intensity of the glass industry has dropped over the decades, as shown in Figure 1. These measures include better furnace and burner design and controls, oxy-fuel firing, and increased post-consumer cullet use.

Oxy-fuel firing can improve the energy efficiency of a furnace by avoiding the nitrogen present in air-fired furnaces and reducing the volume of

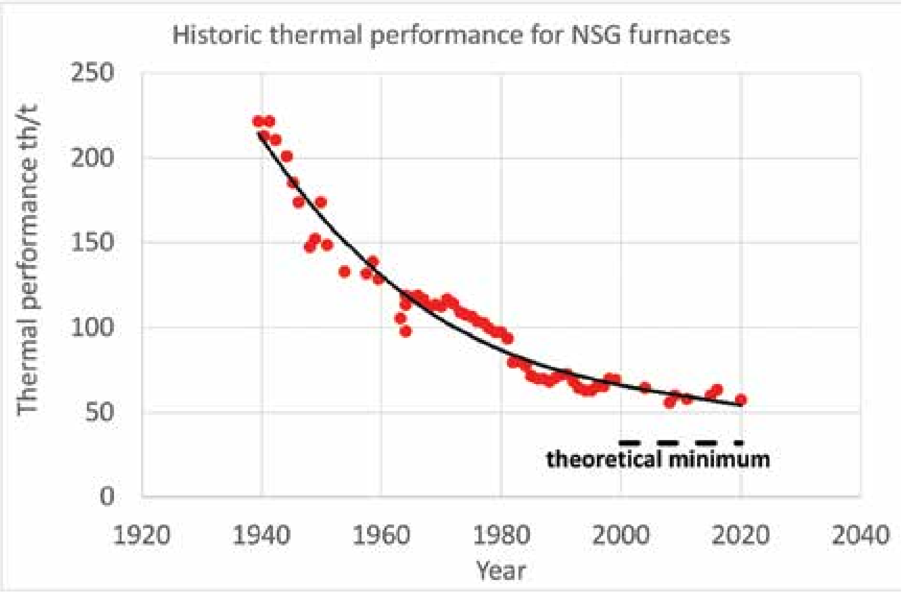


Figure 1. Historical thermal performance (therms per metric ton) for NSG glass furnaces. One therm is 100,000 BTU, or the approximate energy content of 100 cubic feet of natural gas at standard temperature and pressure.

flue gas. More than 300 commercial glass furnaces worldwide have been converted to oxy-fuel since 1991, including 50 container glass furnaces and 10 float glass furnaces.[1] Conversion to oxy-fuel not only reduces NO_x emissions, but it also can lead to a 10–20% reduction in energy use depending on whether a heat recovery system is used. Oxy-fuel firing also promotes decarbonization because the resulting flue gas is concentrated in CO_2 and amenable to reuse or geologic sequestration (see later discussion).

Raw mineral batch reactions are endothermic, requiring more energy consumption to bring the glass batch to temperature. Using post-consumer cullet eliminates a portion of these endothermic reactions, and energy consumption can be reduced by up to 0.3% for every 1% by weight of cullet in the batch. Additionally, cullet has the added value of having already been processed and is therefore a previously decarbonized raw material.

"Cullet is the key resource for decarbonization of the building glass industry, minimizing our consumption of virgin raw materials and energy and finally reducing the quantities of end-of-life waste generated by the building industry," according to François Guillemot, low-carbon glass project manager at Saint-Gobain Glass.

Increasing the energy efficiency of existing furnaces is important, but continuing to rely on fossil fuels will not get the industry to the goal of deep decarbonization. The next step is to use a low-carbon energy source.

Low-carbon fuels

The dominant source of CO_2 emissions associated with glassmaking is from the energy needed to reach melting temperatures of the raw materials and to maintain the melt for refining. Most glass in the U.S. is produced using natural gas (usually methane) derived from fossil deposits. There are several feasible substitutions for natural gas that are low in fossil carbon or are derived from sources that have no net increase in atmospheric CO_2.

Biofuels

For furnaces that use natural gas, the most straightforward path to decarbonizing thermal energy is to switch to a "carbon-neutral" gas.

The methane in natural gas is produced by thermogenic decomposition of fossil organic matter. In contrast, biogenic methane, or biogas, is produced by the anaerobic decomposition of organic material. It is considered carbon neutral because the CO_2 emitted to the atmosphere during combustion is the same that was taken in by photosynthesis from the source plant material. Important pro-

100% Natural gas | 50% H_2 | 100% H_2

Figure 2. Glass melting trial in a flat glass furnace using a single port burner showed glass melting in progressively hydrogen-rich fuel mixes starting with 100% natural gas, 50% each natural gas and hydrogen, and 100% hydrogen.

ducers of biogas are landfills, wastewater treatment facilities, and large-scale livestock operation manure digesters. The U.S. also has some stand-alone digesters that process food and yard waste.

Raw biogas is up to 60 vol.% methane with the remainder consisting of mainly CO_2 and small amounts of hydrogen sulfide. Removal of moisture and sulfur allows the biogas to be used on-site to generate electricity in reciprocating engines or microturbines. Additional treatments can make a gas of at least 90% methane (referred to as renewable natural gas or RNG) that can directly replace fossil-based natural gas in pipelines.

Early trials appear promising. For example, Saint-Gobain Glass reported the successful one-week operation of its float furnace in 2022 in Aniche, France, using 100% biogas.[5]

While it is technically feasible to use biogas, potential hurdles for increasing its use include a lack of sufficient volume and competition with on-site electricity generation and its use as a transportation fuel. If future RNG production increases to quantities that allow it to be injected into existing natural gas pipelines, that will improve the delivery of RNG to users, but it could be difficult to track which facility can apply this method to their decarbonization accounting.

Liquid biofuels such as bio-oil (also called biodiesel) and ethanol are currently derived from corn and soy with a limited supply of biodiesel deriving from used food oils. Ethanol is not a feasible glass furnace fuel, but bio-oil could be used.

Trials have been completed by Encirc and Pilkington using fatty acid methyl ester derived from waste animal and vegetable oil. Bio-oil was burned at the Encirc Derrylin factory in Northern Ireland for an extended trial producing low-carbon bottles. Pilkington's St. Helens (U.K.) float furnace was fired on 100% bio-oil for four days with no impact on glass quality. Waste-derived bio-oil offers a potential source, but obtaining the quantities needed to continuously supply a furnace is an issue.

Bio-syngas

Synthesis gas (syngas) is a combustible mixture of hydrogen and carbon monoxide generated by heating a solid fuel in a low-oxygen environment. Syngas is currently manufactured from fossil fuels to produce hydrogen (see following section) for ammonia and methanol. But syngas can also be made from biomass, including municipal solid waste. A feasibility study was completed in 2022 for a syngas facility at Pilkington's St. Helens float facility in collaboration with KEW Technology (Birmingham, U.K.).[6] Furthermore, synthetic liquid fuels can be made from syngas using the Fischer-Tropsch process, which was developed almost a century ago by Germany during WWII to synthesize liquid fuels from coal.

Green hydrogen

Hydrogen is a highly combustible gas and emits no CO_2 when burned. Hydrogen on Earth is extremely reactive and, therefore, is usually tightly bound up in compounds such as water, biomass, and hydrocarbons. Separating hydrogen from its compounds takes energy, so it is considered an energy carrier similar to electricity. The exception is the recent discoveries of natural hydrogen deposits in subsurface reservoirs that may contribute to our supply of the gas.[7]

Hydrogen is an important industrial gas used for oil refining, ammonia production (fertilizer), steelmaking, and methanol synthesis. Most hydrogen is produced from natural gas through steam methane reformation (SMR), which separates the carbon and hydrogen to make syngas. Hydrogen can also be generated by electrolysis of water, but so far water electrolysis has been much more expensive than SMR.

Hydrogen can play an important role in industrial sectors with emissions that are difficult to remove as long as it comes from a low-carbon source. Hydrogen is graded based on its carbon intensity: "gray" hydrogen is from SMR, "blue" hydrogen is produced when the carbon removed during SMR is captured and geologically stored, and "green" hydrogen is from electrolysis of water using electricity sourced from zero-carbon generators. The ideal goal is to transition to green hydrogen.

Using hydrogen in a glass furnace is feasible. Pilkington demonstrated in 2021 that a flat glass furnace can be used to effectively melt glass (Figure 2). A single port of the furnace was converted to allow a blend of hydrogen and natural gas to be fired. In this instance, "gray" hydrogen was used because low-carbon "green" hydrogen is currently not available. Trials that progressively increased the volume fraction of hydrogen in the fuel mix demonstrated that effective melting can be achieved using 100% hydrogen. Of note, at high hydrogen percentages, the flames in the furnace become effectively invisible.

The low energy density of hydrogen means that the volume of fuel increases three times for the same energy input. The hotter flame temperatures also lead to an about 20% increase in NO_x generation, which is less than predicted by computational fluid dynamics modeling.

In the U.S., current infrastructure to generate and deliver gray hydrogen clusters around petrochemical hubs, such as the Gulf Coast. However, the U.S. government has signaled its support of low-carbon hydrogen through the passage of two recent bills.

- **The Investment and Jobs Act of 2021** contains $9.5 billion funding for hydrogen, including $8 billion for building a hydrogen hubs infrastructure. The hydrogen hubs are still in the competition phase, and the Great Lakes Clean Hydrogen coalition was encouraged by the Department of Energy to submit a full application. The proposed hub near Toledo, Ohio, would generate hydrogen by electrolysis using nuclear power-sourced electricity and create a distribution system that can provide for nearby industrial users, including several glass producers.
- **The Inflation Reduction Act of 2022** provides a 10-year production tax credit for "clean hydrogen" production facilities, which is a sliding scale dependent on carbon emissions used to generate the gas.

Strong government backing could provide the market impetus to develop green hydrogen, and glass plants adjacent to hydrogen hubs will be best suited to initially adopt hydrogen fuel to replace natural gas.

There are other technical hurdles, such as the development of enough efficient electrolyzers. Additionally, the glass industry will need to compete with other industries that use hydrogen, such as ammonia/fertilizer production and steel manufactures that are using direct reduction methods. Finally, it is more efficient to use low-carbon electricity directly to melt glass where possible rather than use it to generate hydrogen.

Low-carbon electrification

Some existing glass furnaces use only electricity to provide process energy. These furnaces are mostly cold-top vertical melters used to produce 5 to 80 tpd.

An electric glass melter is more thermally efficient than a fuel-fired system, and there are no direct emissions related to fuel combustion. They are simpler because there is no need for regenerators or recuperators and, therefore, are less costly to build.[8] However, electric furnaces have much shorter times between rebuilds than gas furnaces, cannot handle large proportions of cullet, and have practical limitations to scaling to the capacity of gas-fired furnaces.[9]

Some gas-fired furnaces use electric boosting to add energy directly into the melt to increase pull rate and improve glass quality. For conventional horizontal, combustion fired furnaces, electric boost has a practical limit of providing 15% of the energy requirement, but it can reach 35% in some situations.[9]

Newer hybrid melter designs maintain a hot top with fuel combustion, and submerged electrodes can increase electrification; however, it cannot fully remove the need for fuel. Manufacturers of new hybrid furnaces claim they can operate with as much as 80% of the energy coming from electricity. Saint-Gobain Glass is developing a hybrid electric pilot-scale furnace with AGC in Barevka, Czech Republic.[10] They will use data from these pilot tests to design a full-scale furnace, as well as repair a float furnace with such a design.

Fiberglass manufacturing presents particular challenges toward electrification. According to Jonathan McCann, principal materials engineer at Johns Manville (Littleton, Colo.), glass fiber melting with only electricity would be difficult for reasons associated with glass quality requirements, refractory selection, and the low alkali (R_2O) content of the composition. So, the reinforcement fiberglass industry has taken a more gradual approach to increasing the proportion of electric boost energy to combustion energy.

In the insulation fiberglass segment, electric melters are well established as an effective way to melt insulation fiberglass; however, a significant amount of fossil fuels are typically used for both the fiberization and the curing of fiberglass product. For the home insulation industry, elimination of these sources of carbon presents the bigger technical challenge.

If a glass producer wanted to fully decarbonize their product by moving to electrical melters, it would still need to be able to have access to zero-carbon electricity. The CO_2 indirectly emitted from electric melting is a function of the mix of power generation sources supplying the power grid. Powerplants using coal and natural gas emit CO_2 directly into the atmosphere while hydro, nuclear, solar, and wind do not.

In the U.S. in 2021, approximately 0.39 metric tons of CO_2 was emitted for each MWh of electricity generated. In other words, a ton of glass from an electric melter in the U.S. indirectly emits almost 1 metric ton of CO_2 (on the basis of 2.4 MWh per ton of glass produced).[1] This statistic can differ by region or state. For example, a MWh of electricity in Washington emits 0.1 metric tons of CO_2 while Kentucky plants emit 0.80 metric tons of CO_2 for the same amount of output. These values reflect the large proportion of hydroelectricity in Washington and the dominance of coal in Kentucky. Scope 2 GHG emissions for electricity can be calculated based on region in the United States, so location does matter.

On-site solar panels or wind turbines cannot supply the power and reliability needed, and manufacturers generally prefer to buy green power rather than go into the low-carbon energy conversion business. Reducing the CO_2 emission factor of delivered electricity toward zero is not easily controlled by a manufacturer. Moving operations to a region that currently has or is trending toward a high proportion of low-carbon generating electricity would theoretically be possible, but it is not practical for many reasons, including issues such as access to raw materials, nearness to end-user customers, and the ethics of abandoning manufacturing plants.

Carbon capture, utilization, and storage

Carbon capture, utilization, and storage (CCUS) refers to capturing CO_2 from an emission source and transporting it to where it can be used or injected underground for long-term storage.

Carbon capture from a point source such as a glass furnace can be done either before or after combustion. Pre-combustion capture would use SMR to generate blue hydrogen from natural gas and route the separated CO_2 elsewhere. Post-combustion capture of CO_2 in an air-fuel burner requires passing the flue gas through an amine absorber that can capture up to 90% of the CO_2. The amine solution is then sent to a heater to release the concentrated CO_2 for compression and transport.

One challenge with glass furnaces is the relatively high levels of NO_x and SO_x, which are not compatible with amine-based capture technologies. Additional waste gas cleaning (i.e., above that required to meet emissions regulations) is required to use these technologies. Oxy-fuel furnaces do not need an amine absorber system; however, water vapor must be removed from the flue gas before the concentrated CO_2 is ready for use or storage.

Carbon offset credits

Carbon offsetting means reducing or removing GHGs in one place to compensate for an entity's emissions from somewhere else. A single carbon offset credit represents a metric ton of CO_2 or equivalent GHG that has been reduced, avoided, or removed from the atmosphere. The credits can be certified by governments or an independent certification body and can be traded through a carbon market.

The global carbon offset market is valued at approximately $1 billion and is growing as companies attempt to reduce their carbon footprints. However, not all offset credits are equal. Some "nature-based" credits are derived from projects that estimate emission reductions from avoided land use or development, such as conserving an area slated for timber harvest. For example, the owner of a parcel of rainforest slated for clearcutting is paid not to harvest the trees. Calculation of the avoided emissions will depend on the assumptions and the model used. Forest-based credits are currently one of the most common available.

High-quality offsets need to be additional (would not have occurred without a specific associated project), permanent, accurately estimated or quantified, and not cause significant social harm. One criticism of offset credits associated with new wind and solar projects is that they do not pass the additionality test. That is, they would be built without the need for offset credits because they are cost-competitive without them, although they may be the lowest cost option for companies that want to offset their emissions. Credits associated with carbon capture and geologic storage result in quantifiable reductions in GHG emissions, but they will cost significantly more.

Because of the diversity of available offset products, it can be difficult and time-consuming to assess the quality of offsets, particularly in the voluntary market. In the compliance market, government agencies (such as the California Compliance Offset Program) tend to be in charge of verifying the quality of offsets.

Carbon offsets can be a tool to help a company to meet its emission reduction goals, but it cannot be the primary strategy. A manufacturer should first reduce GHG emissions on-site prior to resorting to offsets to obtain zero emissions. ■

Other technologies, more amenable to glass furnace waste gas compositions, are also being investigated. Pilkington is undertaking trials with C-Capture Ltd. using their solvent-based technology at their plant in St. Helens, U.K.[11]

The process of injecting CO_2 underground is already used by petroleum producers for tertiary or enhanced oil recovery of light and medium crude, where CO_2 injected into a well pushes the oil toward a production well. The irony of this process is that it increases our ability to extract and burn fossil fuels, thereby increasing atmospheric GHG. However, it does demonstrate that the CO_2 can be collected, transported, and injected into geologic storage. Currently about 5,000 miles of CO_2 pipelines exist in the U.S., mostly Texas, for enhanced oil recovery.

Other geologic storage options include deep saline aquifers, depleted natural gas and oil basins, and deep, unmineable coal seams. DOE estimates the U.S. has geologic CO_2 storage capacity of between 2.6 trillion to 22 trillion metric tons with the majority of that in deep saline aquifers.[12]

As of 2022, one U.S. facility, an Archer Daniels Midland ethanol plant in Decatur, Ill., was injecting CO_2 into a deep saline aquifer.[9] Equinor, the Norwegian energy company, has been testing CO_2 injection underneath the sediments of the North Sea. This process is not the same as deep ocean sequestration, which involves pumping CO_2 at thousands of meters below the water surface. Deep ocean sequestration has several inherent problems. The CO_2 will eventually come back to the sea surface, and it lowers the seawater pH due to increased carbonic acid.

For CCUS to be technically feasible for a glass furnace, it should be an oxy-fuel system so that the expense of an amine absorber is not needed, and the plant should be located adjacent to a CO_2 pipeline. This rapidly developing technology area has not yet been specifically proven in the glass industry, but it shows promise as it matures.

Decarbonizing raw materials

Approximately 20% of CO_2 released from a typical soda lime silica glass comes from the reaction of the raw materials. Sodium carbonate (soda ash), limestone (calcium carbonate), and sometimes dolomite (a mixed calcium and magnesium carbonate) comprise the main components of a soda lime silica glass batch. These materials are low cost and plentiful. However, when these carbonate minerals are heated and the carbonate decomposes, CO_2 is released into the atmosphere.

It will be difficult to replace limestone and dolostone as the primary source of calcium and magnesium in glass given the widespread deposits and low cost. Calcium oxide, or quicklime, is made from burnt limestone, which only displaces the location of CO_2 emission; plus, quicklime hydrates and poses human health hazards.

Most U.S. glass manufacturers use Wyoming trona (Na_2Co_3–$2NaHCO_3$–$3H_2O$) as the source of soda ash. Trona, by way of a glass melting furnace, transfers carbon from the ground into the atmosphere. Synthetic (Solvay) soda ash is made by reacting sodium chloride with CO_2 derived from calcining limestone, so that the CO_2 emissions at the glass plant originated in limestone; this process also transfers carbon from the ground to the atmosphere.

One potential way to reduce carbon emissions from soda ash is to use the Solvay process with CO_2 derived from a CCUS stream rather than calcined limestone. If the process is coupled with waste brine from seawater desalinization, the resulting soda ash is the product of two waste streams.[13] This approach is in the conceptual stage but could be brought to market with sufficient financial incentives.

As previously discussed, increasing the amount of cullet in a batch is the most straightforward way to reduce the CO_2 emissions associated with raw materials, and it also reduces melting energy and reduces waste streams. In the U.S., post-consumer container glass cullet is used mainly in container glass and discontinuous insulation fiber glass. Both of these glass sectors can use up to 80% of cullet in the batch. Flat glass manufacturers cannot use container cullet but can use flat glass cullet, if available.

The major hurdle for increasing the amount of cullet is that only about a third of glass containers in the U.S. are recycled, and that rate has remained flat for decades.[14] Flat glass manufacturers can use pre-consumer cullet, but post-consumer cullet is essentially nonexistent because of the cost to recover flat glass during building and vehicle demolition in the U.S. (According to Saint-Gobain, the EU is working on post-consumer cullet adoption.) Furthermore, flat glass generally has higher quality standards than container glass and a lower threshold for impurities.

Conclusions

Decarbonization of glass manufacturing is feasible through multipronged strategies. Energy efficiency measures should continue, which includes an increase of cullet use where possible. The most important step is the implementation of low-carbon fuels and electrification. Future glass melters will be hybrid systems that use low-carbon electricity boosting coupled with low-carbon fuels, such as green hydrogen. CCUS is possible, but it would need an oxy-fuel furnace located near a CO_2 pipeline and transmission system. Decarbonization of raw materials is perhaps the most challenging part and should initially come from increased use of cullet. Emissions from soda ash could be reduced by using CCUS-derived Solvay material if that is ever developed. High-quality carbon sequestration credits (see sidebar: *Carbon offset credits*) can be used to offset emissions that cannot be feasibly achieved by the glass manufacturer.

The deep decarbonization of glass manufacturing can be achieved, but it will take time and changes to the current system. It will also require considerable funds and a mix of government support, incentives, and possibly regulations. If these goals are reached, we can enjoy our evening drink from a zero-carbon bottle.

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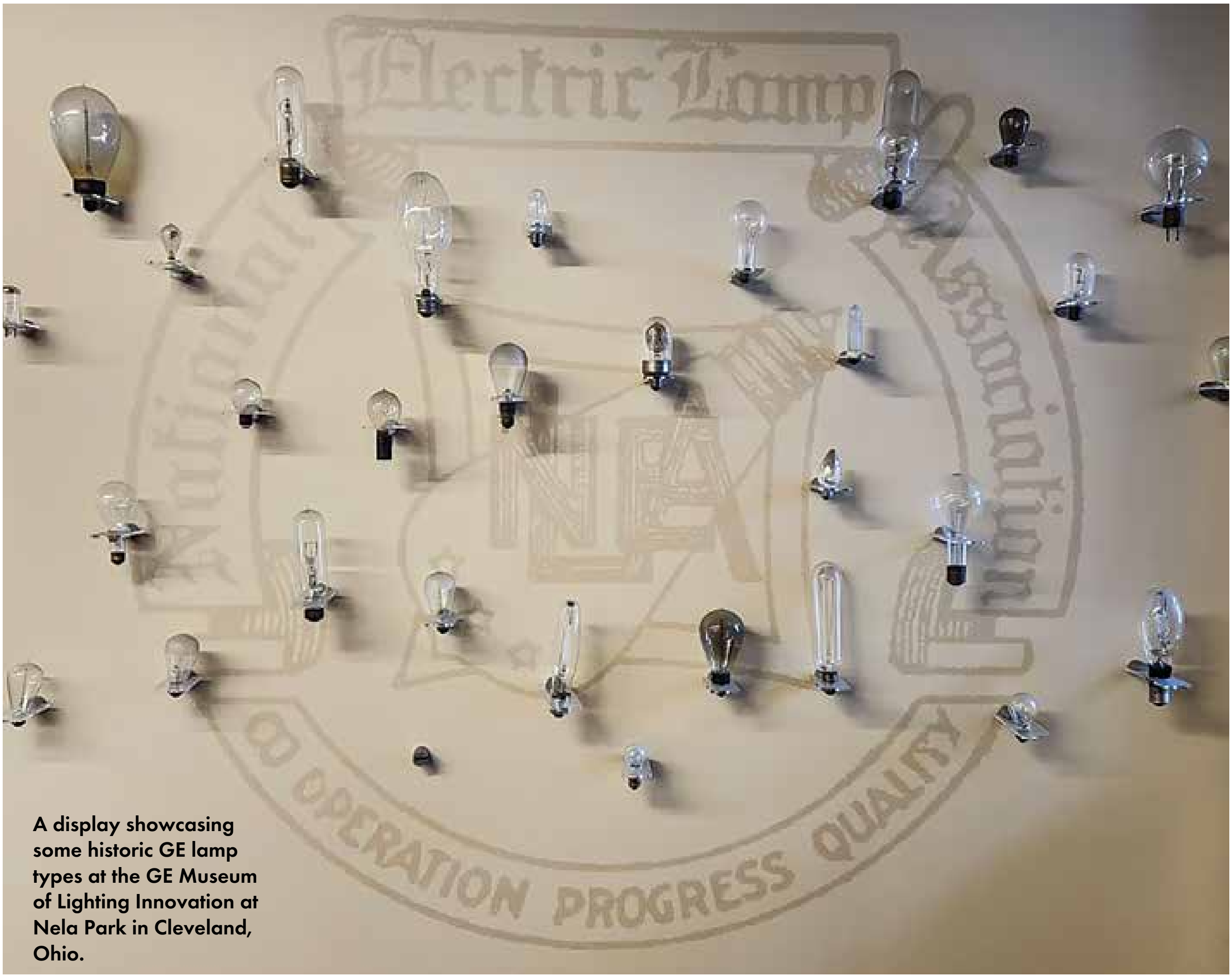


A display showcasing some historic GE lamp types at the GE Museum of Lighting Innovation at Nela Park in Cleveland, Ohio.

Credit: Jim Dakin

GE Lighting at Nela Park:

A legacy and a future

By Samantha Dannick and Mechele Romanchock

GE Lighting helped pioneer the concept of a campus-like industrial park with its operations at Nela Park—and its historical record will be preserved for future researchers and innovators thanks to dedicated work by a group of GE Lighting retirees.

Since the invention of the first incandescent lamps at the end of the 19th century, there have been enormous advances in brightness and efficiency made possible by advances in glass and other materials.

Many individuals and institutions have played a role in the development of the technology, but "the history of electric lighting cannot be understood without accounting for [General Electric]," emphasizes Harold "Hal" Wallace, curator of the Electricity Collections at the Smithsonian National Museum of American History.

GE Lighting (now a Savant company) is headquartered at Nela Park outside of Cleveland, Ohio. This company helped pioneer the concept of a campus-like industrial park. Being aware of the history of industry and innovation "allows us to understand how we arrived at where we are today [and] identify trends and contexts that help inform choices we make moving forward," says Wallace.

All quotes within this article come from email correspondence with the informants.

A brief history of GE Lighting

According to Glenn Kohnke, an independent researcher of the history of glass technology, for the last 100+ years, the "primary home of lighting research, technology, commercialization, and education" in the United States was Nela Park. The site gets its name from the National Electric Lamp Association, which was absorbed by GE in 1911.

Nela Park was designed to bring employees and functions from all the different divisions of GE Lighting together in one place to enhance productivity, the communication of ideas, and employee satisfaction. The site contained facilities such as a bank, a pool, a library, and an employee store.

Although many of the amenities were downsized over time, the campus atmosphere remained strong. James "Jim" Dakin, a 37-year veteran of GE Lighting, says, "the best part for me was daily interaction with people from all branches of the business and with all different sorts of expertise. Furthermore, we were all working together toward the same goals."

Some sources claim that Nela Park was the first designed industrial park, but, as with most innovations, "firstness" can be a nebulous concept. The humorous but true Sivowitch Law of Firsts articulates, "whenever you prove who was first, the harder you look, you will find someone else who was more first." Regardless of the park's "firstness," the scale of operations of GE Lighting should not be understated—for the first half of the 20th century, they controlled more than 90% of the U.S. lighting market.

The significance of glass innovation by GE Lighting is well summarized by Dakin. By the end of his career with GE (retiring in 2012), Dakin was chief engineer at GE Lighting, where he oversaw a global team responsible for reviewing and approving all product changes (e.g., introduction, design, manufacturing) prior to product release.

He states, "glass is an important enabling technology for all products up until LED. There were lots of different kinds of glass required for different temperatures, different chemical environments, different glass–metal seals, among other examples. We had to process lots and lots of glass at very high speeds with very few defects. We could not have done this without world leadership in the underlying glass technologies."

In addition to product innovations, there were numerous process developments at Nela Park. Manufacturing on a large scale required innovations in materials, plant design, equipment, and more. Additionally, the Lighting Institute at Nela Park focused on educating people who worked with lighting from outside of GE. Users, installers, sales personnel, architects, and others were able to attend classes to learn about lighting design and technology.

Nela Nerds to the rescue

In 2020, Savant Systems, Inc. (Hyannis, Mass.) acquired GE Lighting. Although the headquarters of GE Lighting will remain at Nela Park, Savant decided to downsize its presence at the 92-acre campus and subsequently sold the site to a real estate development firm in 2022.

Throughout the various buildings and storage areas of Nela Park, there was a treasure trove of significant historical materials, some going back to the early 1880s. The materials included marketing and communication materials, photographs, drawings, films, physical artifacts, internal technical reports, and more.

Recognizing the importance of these materials, Gerald Duffy, vice president of engineering at Savant, turned to the self-styled "Nela Nerds," a group of GE Lighting retirees who have kept in touch via email and Zoom, to determine a way to preserve this enormous amount of history.

In March 2022, the Nela Nerds began reaching out to cultural heritage institutions with the hope of finding future homes for the materials from Nela Park. Dakin, one of the lead Nela Nerds on this project, indicates that the group "focused on museums of a regional or national stature that [they] thought might have specific interest."

In a series of trips to Cleveland by various parties, the materials were dispersed to several new homes. Regional history materials went to the Western Reserve Historical Society (Cleveland, Ohio).

Group photo of volunteers from heritage organizations, retired GE employees known as the "Nela Nerds," and current employees from GE Lighting, a Savant Company participating in one of the collaborative group work days to salvage historical records from Nela Park in Cleveland, Ohio. Standing L to R: Mechele Romanchock, Glenn Kohnke, Hal Wallace, Nicholas Zmijewski, Joe Howley, and Jerry Duffy. Sitting L to R: Terry McGowan, Sri Rahm, Jim Dakin, Mary Beth Gotti, Sharon Stewart, and Rolf Bergman.

Credit: Theo Romanchock

GE Lighting at Nela Park: A legacy and a future

Materials documenting industrial history and electrical innovation went to the Hagley Museum and Library (Wilmington, Del.), the Industrial Archives and Library (Bethlehem, Pa.), the San Antonio Museum of Science and Technology (San Antonio, Texas), and the Smithsonian National Museum of American History (Washington, D.C.). Materials focused on glass went to the Corning Museum of Glass (Corning, N.Y.) and Alfred University Libraries (Alfred, N.Y.).

The Corning Museum of Glass received materials from the (predominantly) non-R&D glass operations, including correspondence, advertising, internal publications, technical drawings of production facilities, photographs, and more. The collection of reports documenting the glass R&D at Nela Park was donated to Alfred University Libraries, home of the Samuel R. Scholes Library of Ceramics, where they will be processed and made available for researchers. (The reports on nonglass research activities were donated to the Hagley Museum and Library.)

While this research is no longer on the cutting-edge of modern lighting and glass production, looking to prior work still provides critical foundational knowledge and potential inspiration for current and future researchers.

Based on an inventory of the donated glass reports, Kohnke remarks, “overall, the value of these reports lies in the fact that they have not seen the light of day in more than 35 years and few, if any, were ever published externally. The reports were written between the 1930s and 1980s, so few of the authors are still alive to recall any of this work or the events surrounding them. This is the only record that remains.”

Nela Park Building 322, which housed the Lamp Laboratory.

The future of lighting thanks to Nela Park

Looking back on the amazing history of GE Lighting at Nela Park, the company was, at minimum, among the first in most lighting innovations between Edison’s bulbs and LEDs. The technologies, products, and processes developed there can continue to inform researchers in glass and materials science and in other areas. Beyond the technology, the value of collaborating with people from a wide range of areas and communicating with end-users is also worth remembering.

Thanks to the recognition and support of GE Lighting, the efforts of the Nela Nerds, and the coordination of relevant cultural heritage institutions, the historical record of Nela Park will be preserved for future researchers and innovators.

Processing the collections of donated materials will take some time, but interested researchers can contact the recipient organizations for more information.

Acknowledgements

With thanks to Jim Dakin, Gerald Duffy, Glenn Kohnke, Kevin Martin, Joe Schill, Hal Wallace, and Nick Zmijewski for their insights and assistance with this article and this project, and to GE Lighting, a Savant company.

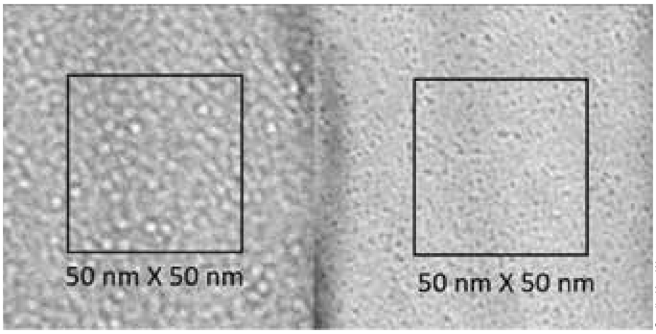
About the authors

Samantha Dannick is the engineering and scholarly communication librarian and Mechele Romanchock is the director of libraries at Alfred University Libraries (Alfred, N.Y.). Contact Dannick at dannick@alfred.edu or Romanchock at romanchockm@alfred.edu.

Further reading

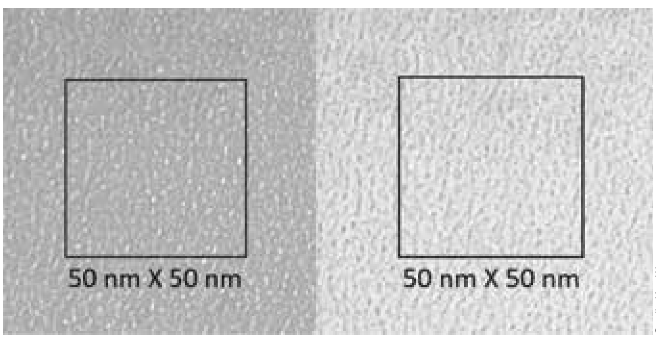
A Century of Light by James A. Cox (1979) ■

3D-printed ceramics after ISS spaceflight



Credit: Kun Wang

Figure 1. Batch A control sample. Under focus and over focus, respectively.



Credit: Kun Wang

Figure 2. Batch A experimental sample. Under focus and over focus, respectively.

By Alexander Bailey, Kun Wang, Darren Stohr, Ryan Jeffrey, and Xingwu Wang

TEM and resistivity data show that radiation and other spaceflight conditions had a perceptible impact on a 3D-printed ceramic material.

In November 2019, twelve 3D-printed ceramic samples were sent to the International Space Station (ISS). For approximately 260 Earth days, these samples were exposed to the space weather environment on the Sidus Space External Flight Test Platform.

The samples consisted of two experimental batches, A and B. For detailed descriptions of sample preparations and two batch designations, see Reference 1.

After the samples returned to Earth, they were evaluated for radiation damage and structural integrity. Ideally, results would show which batch retained its mechanical properties best after experiencing thermal cycling during flight and mechanical vibrations during launching and landing.

Pre-screening evaluation indicated that batch B samples displayed a weakened structure. Specifically, cracks appeared at the interface between the coating/glazing layer and the bulk sample. Thus, only batch A samples demonstrated desirable mechanical characteristics fit for future flight tests.

These experimental samples were then compared to control samples that did not undergo spaceflight using transmission electron microscopy and resistivity testing. In Figures 1 and 2, TEM images (obtained with under-focus and over-focus techniques) of respective samples are illustrated.

Note the bubble-like features in the crystalline phase of the experimental and control batch A samples. The presence of bubble-like features in the control sample is solely due to interactions with the gallium-ion beam during sample preparations for TEM measurements. For the experimental sample, there is an increased feature density, which indicates evidence of interactions between space radiation and the ceramic material. A numerical investigation into the change of the feature densities revealed an approximate 70% increase in the bubble-like feature population of the experimental sample.

Resistivity testing was also performed to investigate the temperature dependence. After taking resistivity measurements across a 50°C thermal gradient, it was discovered that the experimental samples exhibited a reduction in resistivity sensitivity to temperature change. The magnitude of this sensitivity change was approximately 2.86E+08 (Ωm/°C).

These two changes observed in the TEM and resistivity data for the experimental specimens indicate that radiation and other spaceflight conditions had a perceptible impact on the ceramic material. The origin of the observed bubble-like features may be the result of radiolytic processes that generate oxygen gas in metal oxides.

Further spaceflight testing is required to investigate these potential issues with 3D-printed ceramic materials that are subjected to space weather and radiation. Radiation detection/calibration instrumentation will be needed in the spaceflight testing fixture to systematically study the radiation effects. Finally, extensive TEM testing will need to be performed to provide further understanding of the bubble-like feature densities observed in the control and experimental batch A samples.

Acknowledgements

In addition to the authors, the following researchers contributed to this study.

Alfred University (Alfred, N.Y.): Yonggang Yan (researcher)

L2 Aerospace, DBA OmniTeq (Melbourne, Fla.): Sam Deriso (chief engineer) and Jim Royston (founder and CEO)

Sidus Space (Cape Canaveral, Fla.): Carol Craig (founder and CEO), Anthony Boschi (mechanical designer), and Mike Bush (software developer)

About the authors

Alexander Bailey, Kun Wang, Darren Stohr, and Xingwu Wang are researchers at Alfred University (Alfred, N.Y.). Ryan Jeffrey is the principal engineer at Sidus Space (Cape Canaveral, Fla.). Contact Wang at fwangx@alfred.edu.

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17–19 ➨ 8th Highly-functional Ceramic Expo Osaka – INTEX Osaka, Osaka, Japan; https://www.ceramics-japan.jp/en-gb.html

30–June 1 MagForum 2023 – Grand Hotel Dino, Baveno, Lake Maggiore, Italy; http://imformed.com/get-imformed/forums/magforum-2023

June 2023

4–8 ACerS Glass & Optical Materials Division Annual Meeting (GOMD 2023) – Hotel Monteleone, New Orleans, La.; https://ceramics.org/gomd2023

5–8 ACerS 2023 Structural Clay Products Division & Southwest Section Meeting in conjunction with the National Brick Research Center Meeting – Omni Austin Hotel Downtown, Austin, Texas; https://ceramics.org/clay2023

14–16 13th Advances in Cement-Based Materials – Columbia University, New York, N.Y.; https://ceramics.org/cements2023

21–22 16th International Seminar on Furnace Design: Operation & Process Simulation – Hotel Horal, Velke Karlovice, Czechia; https://www.gsl.cz/news/events/16th-int-seminar-on-furnace-design-operation-process-simulation

July 2023

2–6 ➨ XVIIIth Conference of the European Ceramic Society (ECerS) – Lyon, France; https://www.ecers2023.org

August 2023

21–24 Materials Challenges in Alternative & Renewable Energy 2023 (MCARE 2023) combined with the 6th Annual Energy Harvesting Society Meeting (EHS 2023) – Hyatt Regency Bellevue, Bellevue, Wash.; https://ceramics.org/mcare-ehs-2023

27–31 ➨ 11th International Conference on High Temperature Ceramic Matrix Composites – Ramada Plaza Jeju Hotel, Jeju, Korea; https://www.ht-cmc11.org

27–31 ➨ The International Conference on Sintering 2023 (Sintering 2023) – Nagaragawa Convention Center, Gifu, Japan; https://www.sintering2021.org

30–31 EMC Ceramists Additive Manufacturing Forum (yCAM) 2023 – Leoben, Austria; https://euroceram.org/2023-ycam-forum-in-leoben

September 2023

12–15 China Refractory Minerals Forum 2023 – InterContinental, Dalian, China; http://imformed.com/get-imformed/forums/china-refractory-minerals-forum-2023

26–29 ➨ Unified International Technical Conference on Refractories (UNITECR) with 18th Biennial World-wide Congress on Refractories – Kap Europa, Frankfurt am Main, Germany; https://unitecr2023.org

October 2023

1–4 ACerS 125th Annual Meeting with Materials Science & Technology 2023 – Columbus Convention Center, Columbus, Ohio; https://matscitech.org/MST23

November 2023

5–10 ➨ 15th Pacific Rim Conference on Ceramic and Glass Technology – Shenzhen World Exhibition & Convention Center, Shenzhen, China; https://ceramics.org/event/15th-pacific-rim-conference-on-ceramic-and-glass-technology

6–9 ➨ Glass Week 2023 (previously Conference on Glass Problems) and GMIC Symposium – Columbus, Ohio; glassproblemsconference.org

January 2024

28–Feb 2 48th International Conference and Expo on Advanced Ceramics and Composites (ICACC 2024) – Hilton Daytona Beach Oceanfront Resort, Daytona Beach, Fla; https://ceramics.org/icacc2024

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13–16 Electronic Materials and Applications (EMA 2024): Basic Science and Electronic Materials Meeting – Denver, Colo.; https://ceramics.org/ema2024

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14–18 International Congress on Ceramics – Hotel Bonaventure, Montreal, Canada; www.ceramics.org

August 2024

18–22 ➨ 14th International Conference on Ceramic Materials and Components for Energy and Environmental Systems – Budapest Congress Center, Budapest, Hungary; https://akcongress.com/cmcee14

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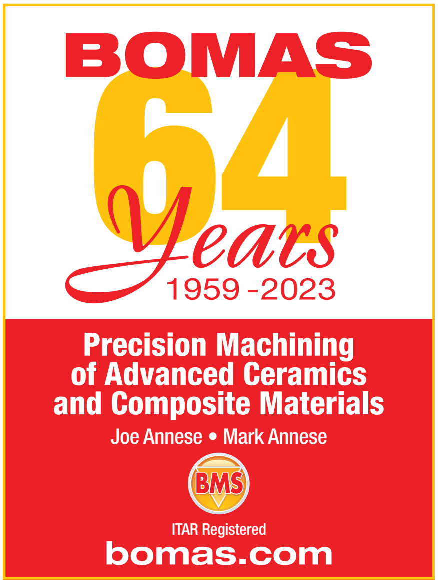

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Sierra Astle and **Shaylee Traugh**
Guest columnists

LionGlass: A phosphate-based approach to carbon-neutral glass manufacturing

From windows, cups, and windshields to smartphone screens and even tissue scaffolds, glass is inescapable in today's world. Though its uses in civilization are beneficial, this material does not just impact our lives—glass manufacturing also impacts the environment, and not always in a good way.

Every year, approximately 86 million tons of carbon dioxide is produced from the manufacturing of glass.[1] The carbon dioxide comes from using fossil fuels to heat the high-temperature melting furnaces, as well as from the reaction products of the carbonate batch materials.

Pursuing carbon neutrality in the glass manufacturing sector would help address several of the United Nations Sustainable Development Goals.[2] These goals include responsible consumption and production and climate action. This progress in glass manufacturing would also contribute to one of the National Academy of Engineering's 14 grand challenges, developing carbon sequestration methods.[3] If less CO_2 is being produced, then less CO_2 needs to be captured and stored.

Glass manufacturers can work toward a carbon-neutral future with the help of materials scientists by creating compositions with a low melting temperature and that release little to no CO_2 when processed.

Phosphate-based glasses are the perfect place for materials scientists to start looking for new, improved, and more sustainable glass. Currently, soda lime silicate glasses account for approximately 90% of all glass made.[4] These glasses are used to produce many everyday items, such as windows,[5] but they require high melting temperatures of 1,450–1,500°C and release CO_2.

The use of phosphate as a main component in glass allows it to be made without the use of carbonate materials, such as limestone or soda ash. As such, subsequent CO_2 emissions are lowered. Additionally, phosphate-based glasses often have lower melting temperatures than silicate glass, which would lead to a higher energy efficiency and lower melting cost.[6]

A new low-carbon, low-energy consumption phosphate-based glass is currently being explored at The Pennsylvania State University (Figure 1). Dubbed LionGlass, it is being engineered to have a melting point 20–33% lower than the melting temperature of standard soda lime silicate glasses.

Credit: Shaylee Traugh

Figure 1. Bar of LionGlass made at The Pennsylvania State University for mechanical testing.

LionGlass is also being batched, melted, and tested for various properties needed in window applications. For example, windows need a certain mechanical strength, such as resistance to scratches or crack propagation. They must also have acceptable thermal properties—a window that lets all the heat out of a home is hardly cost effective or green!

Because glass is inescapable, we must make it more sustainable for our Earth. Phosphate-based glasses such as LionGlass have the potential to help improve the sustainability of future glass manufacturing.

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Sierra Astle is an undergraduate at The Pennsylvania State University, studying materials science and engineering. Following graduation in spring 2023, she plans to pursue a Ph.D. in materials science and engineering. In her free time, Sierra enjoys learning guitar, hiking, and trying new recipes.

Shaylee Traugh graduated from The Pennsylvania State University with a B.S. in materials science and engineering in 2019. She worked as a process engineer for 3 years before returning to Penn State, where she is a first-year Ph.D. student in John Mauro's group studying glass. Shaylee enjoys visiting wineries with her partner and experiencing new hiking trails. ■

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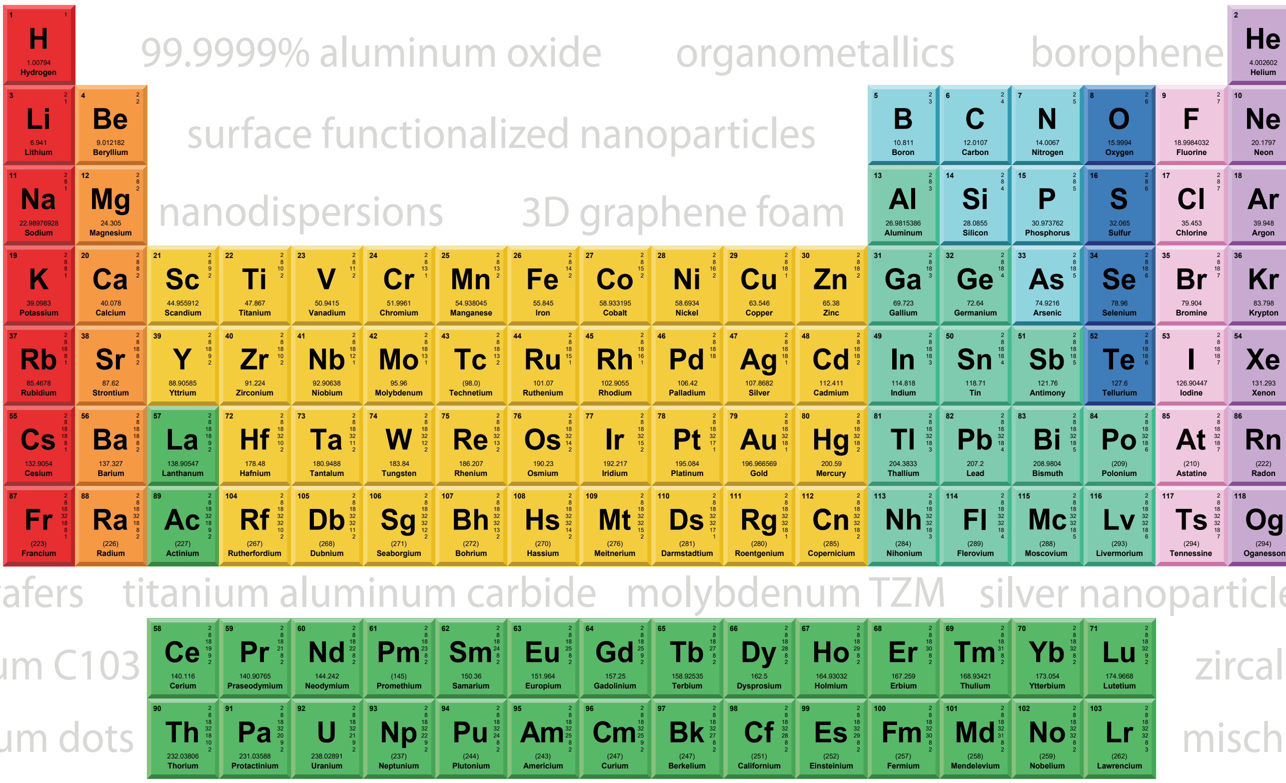
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