AMERICAN CERAMIC SOCIETY

# bulletin

emerging ceramics & glass technology

MARCH 2026

# Refractories for nonferrous applications

Zirconium-based crucible developments | Benefits of "fail-fast" manufacturing | High-temperature safety measures

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Pile of copper ore. Copper is the largest nonferrous metals market by unit price.
*Credit: Ziadi Lotfi / Shutterstock*

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bulletin

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As seen on *Ceramic Tech Today*...

Credit: Corning Museum of Glass

## 'Bridging' the gap between glass and conventional engineering with an all-glass bridge

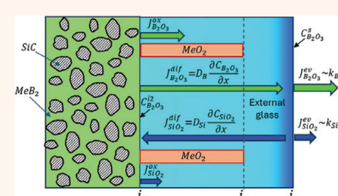
*To avoid any stress-related malfunctions, glass in architecture typically relies on the support of load-bearing materials such as concrete or steel. Researchers at the University of Pennsylvania Weitzman School of Design overcame this limitation by designing a 30-foot bridge made entirely of hollow glass units.*

Read more at https://ceramics.org/all-glass-bridge

Also see our ACerS journals...

**Oxidation kinetics of silicon carbide-containing refractory diborides. III: Critical assessment of glass viscosity and inter-diffusivity data for model parameters**
By P. Mogilevsky and M. K. Cinibulk
*Journal of the American Ceramic Society*

**Refractory metal coating-assisted SiC brazing: Microstructure, strength, and molten salt corrosion test**
By X. Quan, Q. Huang, H. Liu, et al.
*International Journal of Applied Ceramic Technology*




Credit: Mogilevsky et al., *JACerS*

**Microstructure and bonding between calcium aluminate cement-containing gahnite–alumina matrix and refractory aggregates**
By R. D. Ramteke, J. G. Hemrick, and M. K. Mahapatra
*Journal of the American Ceramic Society*

**Influence of $Cr_2AlC$ additive on the properties and corrosion resistance of $Cr_2O_3$–$Al_2O_3$ refractories**
By M. Deng, Z. Miao, T. Zhang, et al.
*International Journal of Applied Ceramic Technology*

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ACSBA7, Vol. 105, No. 2, pp. 1–44. All feature articles are covered in Current Contents.

# news & trends

## Picking up the pieces: CAN documentary looks at the effects of Hurricane Helene on ceramic artists

For generations, artists have helped us cope with our grief on both individual and society-wide scales by using visual, auditory, and tactile mediums to process big emotions that cannot be understood through words alone. But what happens when the artists themselves are at the center of a tragedy?

In September 2024, Hurricane Helene brought devastating wind, flooding, and landslides to North Carolina. During the event, which primarily affected the state's western Appalachian region, entire communities lost access to core services and communication, resulting in long-term cessations in operations for businesses.

Ceramic artists were among the business owners heavily affected by the hurricane. North Carolina is known for its strong studio ceramics tradition, and numerous artists found their facilities flooded or completely swept away during the torrential downpour.

Considering the extent of damages across the state—initial estimates are at least $79.6 billion—no one would fault those daunted by the prospect of rebuilding from such devastation. Yet numerous ceramic artists shared stories of resilience and renewal in a new documentary created by Ceramic Arts Network (CAN).

CAN is the ACerS-owned online community for potters and ceramic artists. In the aftermath of Hurricane Helene, CAN Senior Editor Jennifer Harnetty said she "was heartbroken" to see "these exceptional artists and lovely humans" impacted so deeply by the event. So, she and the CAN team set out to capture some of their stories in a video called *Picking Up the Pieces: Resilience and Recovery in the Clay Community After Helene*.

Harnetty hosted a premiere of the roughly hour-long documentary on Zoom on Oct. 14, 2025. The recording of the premiere is freely available on the CAN website at https://ceramicartsnetwork.org/clayflicks/clayflicks-video-library. Extended interviews with each artist can be found on the CAN YouTube channel at https://www.youtube.com/@CeramicArtsNetwork/playlists. ■

## Turning waste into learning: TileChalk initiative transforms tile residue into classroom chalk

Ceramics manufacturing is a time- and energy-intensive process, which means upfront costs can be substantial. But given the right market demands, investing in this industry can pay off in the long term, as we are currently seeing in the South Asian country of Bangladesh.

Traditionally, Bangladesh's economy is overdependent on a single sector: ready-made garments. This sector accounts for more than 84% of national exports and nearly 20% of national GDP.

But between 2008 and 2018, strong domestic demand from a rising middle class contributed to Bangladesh's ceramic industry experiencing significant growth in its production capacity—approximately 200%—according to a study funded by the United States Agency for International Development.

Bangladesh now exports ceramic products to more than 50 countries. But it is not yet a net exporter "Because we still have challenges in sustainable cost competitiveness, design innovation, logistics efficiency, productivity, and energy management," said Sheikh Bashir Uddin, advisor to the Ministry of Commerce, while inaugurating Ceramic Expo Bangladesh 2025. "We need to identify these [challenges] and move toward realistic solutions."

In October 2025, tile producer DBL Ceramics announced an innovative solution to one of the main challenges: what to do with the waste generated by ceramics manufacturing. The waste in this case is a type of residue sludge generated during the water recycling processes at the company's ceramics plant. As explained in a *Branding in Asia* article, DBL Ceramics determined the sludge could not be discharged into landfills without risking soil and water contamination, so they needed another way to handle the waste.

DBL Ceramics partnered with chalk manufacturers and, through six months of experimentation, found a way to reengineer the residue sludge into chalk sticks. They also developed a process to repurpose broken tiles into lightweight slate boards, and now the first batch of 10,000 chalk-and-board sets has been distributed to underserved schools across Bangladesh through partnerships with local nongovernmental organizations.

To scale the impact, DBL Ceramics made the formula for their waste-based TileChalk sticks open-source and even sent letters to competitors, urging them to adopt similar practices. The company also signed memorandums of understanding with local chalk manufacturers "to give them raw material free of charge in order to revive the dying industry," according to the *Branding in Asia* article.

Learn more about how TileChalk is created in the video at https://www.youtube.com/watch?v=XrEXeXtEP-M. ■

## Corporate Partner news

### Almatis and Bassermann Minerals expand distribution cooperation across Europe

The STOCKMEIER Group, of which includes Bassermann Minerals, will serve as a distribution partner for the entire Almatis product portfolio servicing polishing, technical ceramics, refractory, thermal management, and building chemicals markets in the United Kingdom, Scandinavia (including Finland), and Central and Eastern Europe. The move marks an expansion of a longstanding partnership between Almatis GmbH and Bassermann Minerals GmbH. Read more: https://www.almatis.com/en/whats-new

### Corning earns CES 2026 Innovation Honor for advanced glass surface treatments

Two of Corning Inc.'s glass surface treatments earned recognition in the CES 2026 Innovation Awards: Corning Gorilla Matte Pro and Corning's SurfaceIQ advanced antireflective surface treatment for automotive displays. The treatments were recognized in the Computer Peripherals & Accessories category and the In-Vehicle Entertainment category, respectively. Read more: https://www.corning.com/worldwide/en/about-us/news-events.html

### HORIBA Veloci BioPharma Analyzer Recognized Among Analytical Scientist's Top 10 Innovations

The Analytical Scientist recognized HORIBA's Veloci BioPharma Analyzer, which applies fluorescence and absorbance spectroscopy to provide rapid molecular fingerprinting and quantification, as a Top 10 Innovation. This list highlights instruments that address critical research and industry challenges. Read more: https://www.horiba.com/int/scientific/resources/news

### UBE and Zeureka enter collaborative research agreement for small molecule drug discovery in oncology

Tokyo-based companies Xeureka Inc. and UBE will collaborate in advanced computational drug discovery research using Xeureka's Free Energy Perturbation program to identify small molecule compounds that act on target molecules identified by UBE. The goal of the research is to create new drug candidates for cancer treatment. Read more: https://ube.com/ube ■

bccResearch

# Global market for thermal management technologies

The global market for thermal management technologies was valued at $18.5 billion in 2024 and is expected to grow at a compound annual growth rate (CAGR) of 8.6% to reach $30 billion by the end of 2030.

Thermal management technologies are designed to control, dissipate, and optimize heat in various electronic and industrial applications. These technologies help ensure system reliability, efficiency, and performance under high thermal loads.

Types of thermal management devices:

- **Convection cooling devices**, which account for nearly half of the market (Table 1), redistribute thermal energy by air movement. In passive cooling, only natural air currents are used, whereas in forced cooling, a fan speeds up circulation.
- **Conduction cooling devices** use direct contact with high thermal conductivity materials to transfer heat from one object to another. Internal heatsinks are used in all power supplies to help channel heat away from hot electronics.
- **Hybrid cooling devices** combine air and liquid-based cooling mechanisms. They are well suited for applications requiring high dependability and continuous operation due to their capacity to dynamically adjust to changing thermal loads.
- **Advanced cooling devices** are being developed to allow for increased heat dissipation efficiency in more compact and power-dense electronic systems. By incorporating technologies such as thermoelectric cooling, phase change materials, microchannel liquid cooling, vapor chambers, and two-phase immersion systems, these sophisticated systems surpass the conventional techniques.

**Table 1. Global market for thermal management technologies, by device, through 2030 ($ millions)**

| Device | 2024 | 2025 | 2030 | CAGR % (2025–2030) |
|---|---|---|---|---|
| Convection cooling | 8,695.2 | 8,988.6 | 10,984.6 | 4.1 |
| Conduction cooling | 6,654.0 | 7,142.5 | 10,876.1 | 8.8 |
| Hybrid cooling | 2,539.7 | 2,936.5 | 6,017.7 | 15.4 |
| Advanced cooling | 588.9 | 759.1 | 2,125.4 | 22.9 |
| **Total** | 18,477.8 | 19,826.7 | 30,003.8 | 8.6 |

Some emerging technologies that are expected to influence the future thermal management technologies market are

- **Nanostructured materials**: Have better heat transfer and thermal conductivity properties than their bulk counterparts. Nanocomposites consist of a solid matrix with nanoparticles scattered within it, while nanofluids are liquids that contain suspended nanoparticles.
- **Smart fibers and textiles**: Designed to regulate heat exchange between the body and the environment. The integration of carbon nanomaterials, such as graphene and nanotubes, into textiles has been a focus due to the materials' strong mechanical flexibility and thermal conductivity.
- **Thermal transistors**: Designed to handle the increasing heat levels in contemporary electronic systems. Conventional cooling methods struggle to maintain steady operating temperatures when processing rates and power densities rise. These devices can precisely modulate heat by utilizing innovative materials, such as strontium cobalt oxide as the active layer and zirconium oxide as the switching layer. Real-time thermal conductivity adjustment is made possible by platinum electrodes, which provide the required control input.

North America accounted for about 43% of the global thermal management technologies market revenue in 2024 due to its well-established industrial base, advanced manufacturing infrastructure, and continuous investments in high-performance cooling and heat dissipation solutions. But the Asia–Pacific region represents the fastest-growing market for thermal management technologies, driven by rapid industrialization, expanding electronics manufacturing, and increasing adoption of electric mobility and renewable energy systems.

## 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 utkantha.srivastava@bccresearch.com.

## Resource

BCC Publishing Staff, "The global market for thermal management technologies," BCC Research Report SMC024P, December 2025. https://bit.ly/December-2025-thermal-management ■

By Tim Beatty
Guest columnist

# 'Fail fast' manufacturing: How disciplined experimentation strengthens, not threatens, quality

In manufacturing, few phrases raise eyebrows faster than "fail fast." In the startup world, this business strategy is celebrated as a sign of agility. On a ceramic manufacturing floor, it can sound careless or even dangerous.

I understand that reaction. Our industry is built on precision, process control, and reliability. We work with unforgiving materials, expensive capital equipment, and customers who depend on consistency. Failure, in the traditional sense, has real consequences.

That is exactly why the "fail fast" mentality deserves a closer look. When properly understood, "fail fast" is not about lowering standards or accepting defects. It is about learning earlier in the development process before uncertainty becomes costly, disruptive, or irreversible.

## Learning before a steep cost curve

In ceramic manufacturing, many of the highest risks are embedded at the beginning of a project. New material formulations, unfamiliar geometries, novel joining methods, or unproven machining approaches often carry unknowns that only reveal themselves once time and money have already been invested.

The central idea behind "fail fast" thinking is simple: pull those risks forward. Rather than discovering problems during the qualification or scale-up stages, teams design early experiments to answer the most important questions first before sellable parts are produced.

Explained this way, the distinction becomes clear: Actual failure manifests in broken parts, missed specifications, and disappointed customers; "fail fast" learning prevents those outcomes.

## Bridging production and innovation

Manufacturing organizations constantly balance two necessary but competing priorities. Production teams focus on repeatability, yield, throughput, and delivery. Innovation teams, by contrast, operate in an environment of uncertainty, exploring boundaries and testing assumptions so that larger failures do not occur later.

Problems arise whenever these two modes of work coexist without structure. When innovation is deferred because production feels more urgent, uncertainty compounds. When experimentation encroaches on production without guardrails, risk increases. Bridging this gap requires more than alignment meetings—it requires process design.

## What 'fail fast' looks like in practice

In ceramic manufacturing, "fail fast" learning often centers on one high-risk step, such as untested machining strategies, new tool designs, or incorporating automation. Instead of validating that step last, effective teams validate it first.

A good "fail fast" experiment has three characteristics:

- **A clear hypothesis**, i.e., a specific question to be answered.
- **A simple setup** that minimizes scale, cost, and complexity.
- **Defined success criteria** that clearly outline what "working" means.

Simulation, modeling, 3D-printed test pieces, and rapid prototyping allow teams to evaluate feasibility and process limits without disrupting production or customer commitments. Speed matters here, but only when it is paired with control.

## Safety, compliance, and quality are nonnegotiable

It is important to recognize what "fail fast" does not mean:

- It does not override compliance. ISO standards, customer qualifications, and internal quality systems remain foundational.
- It applies to concepts, not production parts.
- Early experimentation must occur in controlled environments with proper safety reviews and clear separation from customer deliverables.

Organizations with strong quality systems are often best positioned to innovate responsibly because they know how to define boundaries and act on data.

## Changing the conversation around failure

Even with the right systems in place, "failure" is an uncomfortable term, especially for engineers trained to value precision. Leadership plays a critical role in reframing the conversation from fear of failure to a focus on the speed of learning.

Sharing examples of when early experiments prevented expensive rework or clarified design limits helps teams see the value of disciplined experimentation. But just as important is knowing when to stop. If safety risks cannot be mitigated, the experiments lack a clear purpose, or constant iteration creates instability, it is time to slow down.

## The real payoff

When done well, "fail fast" produces fewer failures, not more. It replaces late-stage surprises with early insight and builds confidence across engineering, operations, and quality teams.

For ceramic manufacturers facing tighter tolerances, new materials, and rising expectations, that confidence matters. In an industry defined by precision, learning early is not a luxury—it is a competitive advantage.

## About the author

Tim Beatty is president of Bullen Ultrasonics (Eaton, Ohio), a company specializing in the precision machining of advanced materials using ultrasonic and laser-based technologies. Contact Beatty at tbeatty@bullentech.com. ■

**By David Holthaus**
Industry reporter

# Industrial digitalization: 'Smart' operations can improve worker safety and well-being in high-temperature environments


**Figure 1. RHI Magnesita's digital hub improves safety and enables data-based process optimization in high-temperature furnace environments.**

Heavy industry is the backbone of economies around the world, critical to automotive production, construction, the energy sector, and everything in between. But many heavy industries are facing worker shortages.

There are more than 400,000 open manufacturing jobs in the United States, according to the Bureau of Labor Statistics.[1] With an aging workforce retiring and an insufficient pipeline of skilled workers to replace them, nearly 1.9 million manufacturing jobs may go unfilled over the next decade.[2]

There are multiple reasons for the labor shortage, but one that industry executives tend to cite is the perception of the manufacturing sector as too hard and too dirty. PaneraTech, a Fairfax, Va.-based technology provider for refractory manufacturers, discovered this proclivity when the company interviewed glass industry executives in 2024. However, after digging deeper, the company found that the job's perceived level of difficulty or grubbiness was not a reason that young engineers cited for leaving the industry. Instead, what these engineers wanted was

- Support from their organizations for continued learning,
- Opportunities to work on interesting projects, and
- Opportunities to use cutting-edge technology.

"These answers suggest that engineers are not as worried about a hot, dirty environment as they are about growth and the ability to solve interesting problems," explains the report summarizing PaneraTech's findings.[3]

In addition, the report notes that young engineers often find themselves spending a lot of time responding to emergencies—putting out "fires"—rather than working on ways to improve efficiency and productivity.

"We came to the conclusion that the new generation of engineers are not staying because of the 'firefighter culture' in manufacturing," says Yakub Bayram, CEO of PaneraTech, in an interview. "When they see that kind of culture, they just want to move on."

Bayram sees one solution to this problem being the accelerated digitalization of the glass, steel, and other heavy industries. Incorporating data-driven, automated processes into the manufacturing environment will help alleviate worker burnout and discouragement by supporting efficient operations, which encourages preventive maintenance rather than "putting out fires."

"If you have better visibility into your process, you're more proactive and have fewer fires to manage. That's where data-driven manufacturing is the only tool we see in changing this culture," he says.

PaneraTech was established in 2010 in partnership with two major glassmakers, O-I and Libbey Glass, who wanted better visibility to monitor the structural health of their furnaces. The company has evolved into providing advanced sensors and AI-driven software to monitor refractories, allowing organizations to make better decisions on preventive maintenance and asset replacement.

Its technology is designed to support workers, not replace them, Bayram says. As the PaneraTech report succinctly states, "Technology that is designed to support humans can help glass manufacturers become proactive."

Other companies are developing and implementing data-driven tools to improve productivity as well as safety on the factory floor. Excello Co., Ltd., based in Jeollanam, the Republic of Korea, specializes in real-time data extraction and analysis of high-temperature equipment and refractories. The company deploys technology capable of extracting reliable data from high-temperature environments, such as its "smart ladle" system.

Ladles are a crucial piece of equipment in steelmaking that hold the molten metal during transport and refining. The refractories lining the inside of the ladles can suffer from erosion during injection and stirring of the molten metal. Excello's "smart ladle" system extracts real-time surface temperature data of the ladle during operations, monitoring temperature changes, detecting abnormalities, and improving efficient and safe operation.

The system's initial successful launch in a Japanese steelmaking plant "is a crucial example proving the excellence of high-temperature environment data analysis technology," Excello CEO Sebastian Park said in a news release.[4] The company said it plans to accelerate the application of the technology into steel factories throughout Japan and then into global markets, including the U.S. and Europe.

Ripik.AI is a Noida, India-based startup founded in 2021. It provides a vision-AI platform to detect industrial anomalies. The platform continuously monitors video feeds and provides a real-time hotspot monitoring system, enabling early identification of thermal anomalies, which it says can drive a 25–50% increase in refractory life. Its system also provides historical video feeds and reports that enable employees to analyze patterns and trends in furnace behavior and thus make maintenance decisions with more information.

One of the world's biggest refractory manufacturers, Vienna-based RHI Magnesita, developed a digital hub for its customers to improve safety and enable data-based process optimization in high-temperature furnaces (Figure 1). The system receives all available data about the production process, such as temperature changes, optical measurements, and order cycles. Based on this information, its system uses AI to predict how refractory materials should be maintained and when they will have to be replaced.

"By embracing AI across our operations, we will be setting new standards in efficiency and reliability for the refractory industry," said RHI CEO Stefan Borgas in a published interview.[5]

These and other digitalization practices have given manufacturers a solid path to improving both industrial efficiency and worker safety. And with the probability of these changes also improving worker satisfaction, the challenge of finding and keeping talented engineers may become a less pressing concern in the future.

## About the author

David Holthaus is an award-winning journalist based in Cincinnati, Ohio, who covers business and technology. Contact Holthaus at dholthaus@ceramics.org.

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*All references verified as of Jan. 6, 2026. ■

acers spotlight

SOCIETY DIVISION SECTION CHAPTER NEWS

## Welcome new ACerS Corporate Partners

ACerS is pleased to welcome its newest Corporate Partners: **MiCo Ltd.** and **Starlab**

To learn about the benefits of ACerS Corporate Partnership, contact Yolanda Natividad, associate director of membership and industry relations, at (614) 794-5827 or ynatividad@ceramics.org. ■

## New Jersey/Metro New York/Philadelphia Section to hold signature event April 10, 2026

The ACerS New Jersey/New York Metro/Philadelphia Section, in conjunction with Rutgers University's Department of Materials Science and Engineering and the Ceramic Association of New Jersey, are hosting the 2026 Malcolm G. McLaren Lecture Symposium on Friday, April 10, 2026, at Rutgers' Busch Campus (Piscataway, N.J.).

The symposium will recognize the contributions of Helen M. Chan, professor of materials science and engineering at Lehigh University, to the field of ceramics processing. She will give a lecture titled "Novel processing of entropy stabilized and compositionally complex materials." The technical program also includes the following speakers:

- Ryan Sills, professor at Rutgers University, speaking on "High-entropy fracture: toward high-toughness ceramics"
- Tim Rupert, professor at Johns Hopkins University, speaking on "Using entropy to stabilize unique (and useful) grain boundary states"
- Jeffrey Rickman, professor at Lehigh University, speaking on "The role of entropy and complexity in materials science: Microstructure and properties"

A reception and poster session will follow the lectures. The event will run from 1:30 to 8 p.m.  For more information, contact Lisa C. Klein at licklein@soe.rutgers.edu. ■

## ACerS International Italy Chapter sponsors Italian Sol-Gel Workshop in Padova, Italy

The 10th Italian Sol-Gel Workshop was held in Padova, Italy, on Sept. 15 and 16, 2025, in the Aula Magna of the Engineering School of the University of Padova. Maria Basso, Elena Colusso, and Alessandro Martucci, professors at Padova, and Plinio Innocenzi, professor at the University of Sassari, organized the event. Thirty people from academia and industry participated, and 15 oral presentations were given.

Group photo of workshop attendees enjoying dinner after the day's events.

ACerS International Italy Chapter members.

This event sought to relaunch the series of workshops that began in Padova in 1998 on the initiative of Massimo Guglielmi, professor from the University of Padova. The last Italian Sol-Gel workshop was held in Parma in 2014, following previous workshops in Trento (2012), Naples (2010), Lecce (2008), Milan (2006), Cagliari/Iglesias (2004), Trento (2002), and Parma (2000).

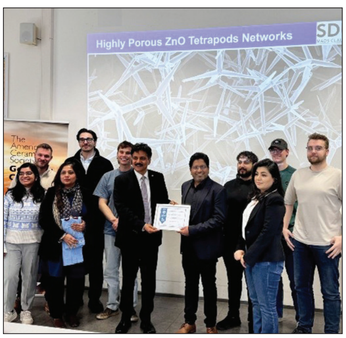
Learn more about what took place during the workshop at https://research.dii.unipd.it/nanoeng/x-workshop-italiano-sol-gel. ■

FOR MORE INFORMATION:

**ceramics.org/spotlight**

## ACerS International Germany Chapter hosts speaker

On Dec. 16, 2025, the ACerS International Germany Chapter hosted Yogendra Kumar Mishra, professor at the Mads Clausen Institute at the University of Southern Denmark, for his talk titled "Tetrapods-based advanced materials for advanced technologies." His talk was held as part of the ACerS-Cologne Materials Lecture Series and showed the importance of 3D smart nanomaterials. Following Mishra's talk, students lead discussion on everyday academic topics in a relaxed atmosphere. ■




ACerS Past President Sanjay Mathur, center left, presents Yogendra Kumar Mishra, center right, with a certificate following his lecture.

Group photo of students who attended Mishra's talk.

## ACerS International United Arab Emirates Chapter Annual Meeting recap: A vision for 2026

The ACerS International United Arab Emirates Chapter held its annual meeting on Dec. 17, 2025, marking a pivotal moment in the Chapter's strategic journey. The gathering served as a reflective and forward-thinking session, aimed at evaluating the success of the Doctoral Sprint Event and laying the groundwork for an action-driven 2026.

The meeting centered around four key areas: celebrating the achievements of 2025, especially the impactful Doctoral Sprint; strengthening outreach efforts; organizing more engaging events; and scaling the Doctoral Sprint to a broader, more inclusive platform. The Chapter's leadership and members ended the meeting with a shared vision to turn 2026 into a landmark year for Chapter growth and visibility. ■

ACerS International UAE Chapter members enjoy a meal after planning the 2026 events.

more SOCIETY DIVISION SECTION CHAPTER NEWS

## Sustainable Horizons II: Continuing the conversation on sustainability at ACerS Spring Meeting 2026

Renewable energy sources had another record-breaking year in 2025, yet greenhouse gas emissions did as well. This continued reliance on fossil fuels demonstrates we still have a long way to go to reach global sustainability goals, but the upcoming Sustainable Horizons symposium at ACerS Spring Meeting 2026 provides the perfect platform to continue this conversation.

The Sustainable Horizons symposium is an event organized within the framework of the International Alliance of Societies for a Sustainable Future (https://sfs-alliance.org/home). First held at ACerS Annual Meeting at MS&T24, it brought together researchers, educators, and professionals from diverse backgrounds to examine sustainability through multiple complementary perspectives, encouraging participants to extend their engagement beyond disciplinary boundaries. Through a combination of invited and contributed presentations, the event fostered cross-disciplinary dialogue and underscored the responsibility of scientific researchers as stewards of a resilient and sustainable future. (Read more about the inaugural symposium in the Spotlight section of the January/February 2025 *ACerS Bulletin*.)

The second edition of the Sustainable Horizons symposium will be hosted as one of three all-Division symposia at ACerS Spring Meeting 2026. This designation underscores the growing recognition of Sustainable Horizons as a distinctive and high-impact forum within the conference framework. In addition, to broaden global participation and extend engagement beyond the materials science community, ACerS approved this symposium as the sole hybrid-format offering at the Spring Meeting.

Alongside the Spring Meeting edition of the symposium, the organizers arranged a student-focused event to engage the next generation of scientists. Sponsored by ACerS and its Electronics Division, this associated program will offer prizes totaling up to $1,200. Student participants, either individually or in teams, will be expected to identify two to five actionable lifestyle changes that promote sustainability. An interest form and additional details for the student event are available at https://bit.ly/2026-Sustainability-Student-Competition.

Through this collective engagement, we can shape a sustainable future for generations to come. Further information about the symposium can be found at https://ceramics.org/2026-sustainability-symposium.

The organizers invite participation from across disciplines and career stages and welcome new ideas, perspectives, and constructive feedback. Send your inquiries to the organizers at the emails given below:

- **Alp Sehirlioglu**, Case Western Reserve University, Ohio (axs461@case.edu)
- **Jürgen Rödel**, Technical University of Darmstadt, Germany (roedel@ceramics.tu-darmstadt.de)
- **Rishabh Kundu**, Case Western Reserve University, Ohio (kundurishabh@gmail.com) ■

# MEMBER HIGHLIGHTS

## Volunteer Spotlight: Hyunjun Kim

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

**Hyunjun Kim** is senior scientist at AeroVironment Inc. (Dayton, Ohio). He received his B.E. in materials science and engineering from Inha University, Republic of Korea, and his Ph.D. in materials engineering at Purdue University. Before pursuing his Ph.D., Kim worked at OCI in Korea as a research engineer.

Kim's research interests include ceramics processing, ceramic matrix composite fabrication, and optical ceramics. Specifically, he has published papers on tape casting, extrusion synthesis and lasing properties of polycrystalline yttrium aluminum garnet (YAG) fibers, and fabrication of transparent lanthanum cerium oxide. He has also filed patents for fabricating polycrystalline YAG cladding on single crystal YAG fibers and the production of polycrystalline silicon nitride fibers.

Kim currently serves as chair of the ACerS Dayton/Cincinnati/Northern Kentucky Section.

We extend our deep appreciation to Kim 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.*


**Christopher Berndt**, FACerS, Distinguished Professor of surface science and interface engineering at Swinburne University of Technology, was selected by the Indian Institute of Metals as a 2025 Distinguished Fellow. He received the award during a ceremony in Hyderabad, India, in December 2025 (second from right in the accompanying picture).

**Aldo R. Boccaccini**, FACerS, University Professor and head of the Institute of Biomaterials at the University of Erlangen–Nuremberg, Germany, was honored with two Doctor Honoris Causa distinctions. He was conferred the title by Alexander Dubček University of Trenčín in Slovakia for his contribution to the establishment of the FunGlass Center as an international partner. He also received the title from the International University of Catalonia in Barcelona, Spain, for excellence in biomedical materials research.

**Alexandra Navrotsky**, FACerS, DLM, Regents Professor and director of the Center for Materials of the Universe at Arizona State University, received an honorary doctorate from ETH Zürich in Switzerland. Navrotsky traveled to Zürich in November 2025 to accept the honorary doctorate (right in the accompanying picture) and delivered a lecture titled "Adventures in Thermodynamics." ■

## IN MEMORIAM

*Hisayuki Suematsu*

FOR MORE INFORMATION:

**ceramics.org/membership**

# more MEMBER HIGHLIGHTS

## Ceramic Tech Chat: Juan Pablo Gevaudan

*Hosted by ACerS Bulletin editors, Ceramic Tech Chat talks with ACerS members to learn about their unique and personal stories of how they found their way to careers in ceramics.*

In the November 2025 episode of Ceramic Tech Chat, **Juan Pablo Gevaudan**, assistant professor of architectural engineering at The Pennsylvania State University, talks about how his childhood desire to protect the environment led to his eventual work in cement, describes some of the research taking place in the cement industry to reduce carbon emissions, and shares how his identity as a Latino and Hispanic scientist plays a role in his approach to learning and teaching.

Check out a preview from his episode, where he talks about the childhood experience that inspired his desire to help protect the environment.

*"I remember when I was going up to Monterrey in Mexico, I would go with my family, and we would do these picnics up in the Chipinque Park that overlooks the whole city of Monterrey. When I was up in the mountains, I could see the smog in the city, and that really blew my mind as a kid because I said, 'Wow, I was just down there, and I had no idea that I was breathing in this contaminated air.' And I think that really started to make me think about this tension between development and preserving the natural environment around us."*

Listen to Gevaudan's whole interview—and all our other Ceramic Tech Chat episodes—at https://ceramictechchat.ceramics.org/974767. ■

# AWARDS AND DEADLINES

## Refractories scholarship opportunity

The Refractories Institute annually provides academic scholarships to a limited number of qualified students enrolled in degree programs who have expressed interest in refractory manufacturing through their coursework or related activities. Scholarships consist of one-time grants of $5,000 per student and are available to college undergraduate or graduate students who are pursuing a degree in ceramic engineering, materials science, or similar discipline. Students must be studying in North America and must be enrolled full-time for the 2025–2026 academic year.

Deadline for applications is **April 15, 2025**. For more information, visit https://www.refractoriesinstitute.org. ■


**2025 TRI scholarship recipient Mary Lucy (left), undergraduate student at Missouri University of Science and Technology, accepts the certificate from Steven Ashlock (right) during the TRI Fall meeting in November 2025.**

FOR MORE INFORMATION:
**ceramics.org/awards**

# more AWARDS AND DEADLINES

**Nomination deadlines for Division awards: May 15, 2026**

Contact: **Vicki Evans | vevans@ceramics.org**

| Division | Award | Deadline | Contacts | Description |
|---|---|---|---|---|
| GOMD | Alfred R. Cooper Scholars Award | May 15 | Steve Martin swmartin@iastate.edu | Recognizes undergraduate students who demonstrated excellence in research, engineering, and/or study in glass science or technology. |
| EDIV | Edward C. Henry Award | May 15 | Eric Patterson eric.patterson@nrl.navy.mil | 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. |
| EDIV | Lewis C. Hoffman Scholarship | May 15 | Eric Patterson eric.patterson@nrl.navy.mil | Recognizes academic interest and excellence among undergraduate students in ceramics/materials science and engineering. |

## Opening doors to materials science for rural Missouri high school students

For students at South Shelby High School in northeast Missouri, materials science recently moved from an unfamiliar term to a hands-on, eye-opening experience. With support from the Ceramic and Glass Industry Foundation (CGIF), a hands-on classroom project introduced more than 100 students to materials science concepts through experiments that connected chemistry, engineering, and everyday life.

The project reached 42 chemistry and conceptual chemistry students and 58 physical science students using the CGIF Mini Kits to bring materials science directly into their required coursework. For many students, this project was their first exposure to materials science as a discipline, and for some, it sparked a new sense of possibility.

Rather than adding extra content to an already full curriculum, materials science lessons were intentionally embedded into existing chemistry and physical science units. Short, focused activities, many completed in under 30 minutes, allowed students to explore materials behavior during units on chemical reactions and thermochemistry. Each activity concluded with discussions about how the concepts are applied in real-world industries and careers, helping students connect classroom science to potential future professions.

The hands-on nature of the project proved especially impactful. Students bent and fused glass, created magnets, and designed glass jewelry, gaining firsthand experience with materials processing.

One of the most popular activities was the "Engineering Concrete" lesson, where students designed reinforced concrete pucks and tested them under extreme conditions, including drop tests, impact tests, and compression from a rolling tire. Students enthusiastically refined their designs, often researching reinforcement strategies outside of class.

One student who typically struggled with engagement became deeply invested in the concrete puck challenge. His design outperformed others in two of the three tests, and he confidently explained the science behind his success to classmates.

"The students rallied around him," his teacher, Lisa Stevenson, recalls. "He had learned the major concepts and applied them in a meaningful way."

Materials science also helped students reinterpret familiar experiences in their community. For example, many students regularly attend a local festival where blacksmiths demonstrate traditional metalworking techniques. After completing a thermal processing activity using simple bobby pins, the students began making connections between atomic-level changes and the blacksmithing practices.

"So many light bulbs came on," Stevenson shares. "They realized that what they were seeing at the festival was the same science happening at the atomic level."

These connections fueled new interests among students, including welding, bladesmithing, and materials processing, fields closely tied to both industry and craftsmanship.

Perhaps most significantly, the project introduced students to materials science as a career path. While many were familiar with civil and mechanical engineering, materials science was largely unknown. Exposure through hands-on learning changed that perception.

"This [materials science] would be such a cool job," one student says. "You get to test and design new stuff that helps people."

CERAMIC AND GLASS INDUSTRY FOUNDATION


**A student heats a steel bobby pin as part of the "Thermal Processing" lesson in the Materials Science Classroom Kit.**

**A student gathers materials in preparation for a lesson from the Materials Science Classroom Kit.**


**Two students at South Shelby High School experimenting with a Bunsen burner.**

Another student, preparing to begin college in engineering, has since chosen to take a materials science elective and is considering making it his major.

In a region where agriculture is a primary livelihood, not every student will become an engineer, but every student benefits from understanding how materials shape the tools, technologies, and products that support their lives. By bringing materials science into the classroom, this project empowered students to think critically about the world around them and imagine how science and engineering can help solve real-world problems.

*Help us continue to empower the next generation of ceramic and glass professionals by giving now at https://ceramics.org/donate.* ■

## Crystal–glass hybrid offers stable thermal conductivity under extreme temperature variations

Researchers in the United States and Europe showed that tridymite, a form of silicon dioxide described in the 1960s as typical of meteorites, exhibits temperature-invariant thermal conductivity over a wide temperature range. The results of this study, which could lead to improved refractory design, were made possible thanks to a thermal transport formula developed more than six years ago by the study's authors.

In 2019, Ph.D. student Michele Simoncelli and Professor Nicola Marzari at Swiss Federal Institute of Technology Lausanne collaborated with Francesco Mauri, professor of theoretical solid-state physics at the University of Rome Sapienza, to derive a general formula of thermal transport that describes the phenomenon equally well in both ordered and disordered materials. Their Wigner transport equation (WTE) achieved this feat by unifying the Boltzmann transport equation for simple crystals and the Allen–Feldman formulation for harmonic glasses.

After graduation, Simoncelli continued to work with Marzari and Mauri on thermal transport problems throughout his career transitions. In their new study, they used WTE to predict that tridymite may exhibit temperature-invariant conductivity in both the quantum and classical temperature regimes. They teamed up with Sorbonne University researchers Etienne Balan, Daniele Fournier, and Massimiliano Marangolo in France, who obtained permission from the National Museum of Natural History in Paris to perform experiments on a sample of tridymite carved from the meteorite that landed in Steinbach, Germany, in 1724.

Thermoreflectance analysis of the meteorite sample confirmed predictions: The tridymite's thermal conductivity remained essentially constant over the experimentally accessible temperature range of 80 K to 380 K.

Though the thermal properties of meteorites may seem far removed from industrial applications, the researchers point out that tridymite has also been found on the surface of refractory silica bricks. As a result, materials derived from tridymite "may be exploited to increase the efficiency of steel furnaces," they write.

The paper, published in *Proceedings of the National Academy of Sciences*, is "Temperature-invariant crystal–glass heat conduction: From meteorites to refractories" (DOI: 10.1073/pnas.2422763122). ■

## Ceramic sherds digital database supports archaeological education, identification, and public engagement

There are various features that can be used to identify what object a ceramic sherd came from during archeological digs, including the color, texture, and shape of the piece. Now students and other researchers can sharpen their ability to identify these features in both field and laboratory settings thanks to the new Ceramic Digital Type Collection created by the archaeology team at the South Carolina Department of Natural Resources' (SCDNR) Cultural Heritage Trust Program.

The digital collection is based on the Program's physical collection, which consists of artifacts discovered on SCDNR properties. The idea for this collection came from master's student and former team member, Jacob Hamill, who was studying for his ceramics typology exam using detailed, handmade paper flashcards. Two Heritage Trust Program team members, Gabe Donofrio and Charles Scarborough, both Public Outreach Archaeologists and specialists in photogrammetry, then executed the idea to digitize the physical pieces into 3D objects.

"The foundation for the digitization was laid by earlier SCDNR Heritage Trust Program projects and team members," says Scarborough in an email. Adds Donofrio, "it builds on several iterations of internal projects the Heritage Trust Program team has worked on in the past."

With the help of other team members, Scarborough and Donofrio first had to identify well-preserved and representative examples of different ceramic types from the physical collection.

"The SCDNR Heritage Trust Program curation includes type collection cabinets," explains Donofrio. "Those cabinets house many of the ceramics featured in the Sketchfab collection, and so it was a quick and easy process to access different ceramic types."

Donofrio and Scarborough then developed the digitization process, which relies on photogrammetry, a technology that

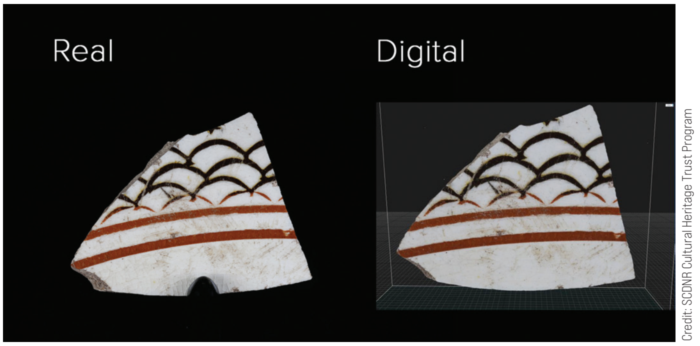



**Figure 1. Comparison of a ceramic sherd and its digital counterpart.**

extracts geometric information from 2D images to generate 3D models of objects (Figure 1). The digitization process steps are

1. The object is set up on a turntable so it can be rotated to take photos of all sides. A scale bar is placed alongside the object, which allows precise scaling of the object in the software.
2. Multiple photos of the artifact are taken at several different angles.
3. The photos are input into one of two software programs, RealityScan or Agisoft Metashape, to produce point clouds, or a rough representation of the scanned object. Scarborough says that RealityScan is faster at producing the clouds and usually leads to higher detail in the final model than Agisoft, but Agisoft allows for more control over the process if the points are not going together smoothly.
4. The point cloud is used to make a solid untextured model that includes all the surface details seen on the real object.
5. The final step is texturing, which creates a finished colored model that resembles the real object.

Each model is uploaded to the web platform Sketchfab, and after consultation with other team members, annotations and descriptions with contextual data such as ceramic type, time period, and other notable features are added.

"We focused on providing clear, general descriptions that are useful for a wide range of people [so that] the collection

## Materials in the news

### Novel design for high-efficiency silicon single-photon detector

Researchers developed a silicon single-photon detector that reaches 84.4% photon detection efficiency at 785 nm. The novel design features a thick-junction silicon single-photon avalanche diode with a doping-compensated avalanche region to reduce noise and improve electric-field uniformity. A backside-illumination architecture increases the likelihood that each absorbed photon triggers an avalanche. To support this architecture, a 50-volt active-quenching readout circuit rapidly switches the detector between armed and idle states to maximize avalanche probability. For more information, visit https://ieeephotonics.org/announcements.

### Magnetic honeycomb lattice sweetens quantum materials development

Oak Ridge National Laboratory researchers synthesized a magnetic honeycomb of potassium cobalt arsenate and conducted the most detailed characterization of the material to date. They discovered that its honeycomb structure is slightly distorted, causing magnetic spins of charged cobalt atoms to strongly couple and align. Tuning these interactions may enable the formation of a state of matter known as a quantum spin liquid. Unlike permanent magnets, in which spins align fixedly, quantum spins do not freeze in one magnetic state. Collective magnetic excitations could emerge from such quantum materials and be used as building blocks for next-generation quantum technologies. For more information, visit https://www.ornl.gov/news.

is approachable, especially for students, interns, or anyone just beginning in ceramics or archaeology," explains Scarborough.

The collection, which became available in July 2025, is housed on the Heritage Trust Program's Sketchfab page and received more than 700 views within its first month.

"We expect usage to grow as we continue to develop the collection and incorporate it more directly with our interns for use in artifact identification," Scarborough says.

SCDNR is not the only digital ceramic collection. But what makes SCNDR's digital collection different is that the digitization team attempts to reproduce the physicality of the object on the model with detailed surface textures, geometry, gloss variation, and reflections.

"If we do this accurately," Donofrio explains, "there are differences in gloss types that can be communicated through the 3D model, which wouldn't otherwise be possible to view in a photograph or description."

Meg Gaillard, Heritage Trust Archaeologist in charge of the digitization team, also believes their collection is unique because it is used for public engagement in a multifaceted way.

"One example is the in-production children's book *Fort Frederick: A SCDNR Heritage Preserve and the World It Changed* by Reece Spradley, in which artifacts illustrated in the book link to 3D models. These models can be 3D printed and showed to school kids on a tour of the site or within a classroom setting," she says.

The book is currently in the development stage, and Gaillard says they hope to test it in schools and on public tours at properties in 2026. She adds that The Heritage Trust Program hopes to produce a children's book for each of their 19 Cultural Heritage Preserves.

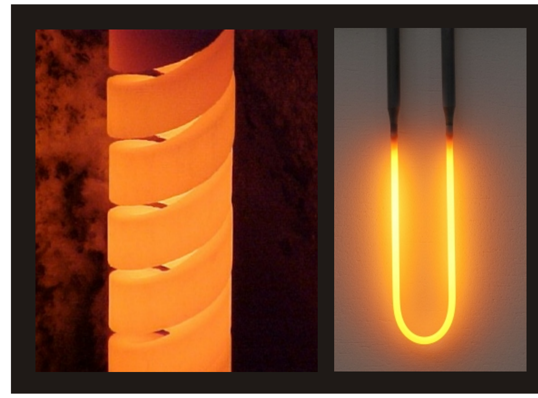
The digital collection team is now planning to integrate all the provenance data (when and where the artifact was excavated) into their 3D production pipeline. In other words, the context of the object will not be separated from the digital files during the scanning process. Plans are also underway to add new ceramic types while filling gaps in existing categories.

View the collection at https://skfb.ly/pxLRs. ■

### Rare earth element extraction can be doubled with new microwave technique

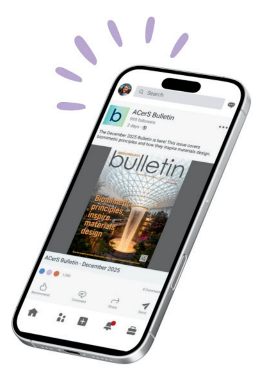
Northeastern University researchers discovered a new way to extract rare earth elements out of coal tailings, the cast-off soil and rock left behind by coal mining. By pretreating the coal tailings in a solution of water and sodium hydroxide and then bathing them in nitric acid while controlling the temperature of the reaction through a specialized microwave reactor, the researchers found that they could extract rare earths two to three times more efficiently than in the standard methods used on coal byproducts. However, they caution that both logistical and chemical questions remain before this method could scale for commercial purposes. For more information, visit https://news.northeastern.edu. ■











## Molten salt reactors: Climate goals revive interest in previously discounted nuclear technology

Nuclear power is having a resurgence in popularity as a source of low-carbon energy. However, traditional fission reactors use enriched uranium as fuel and produce highly radioactive solid waste that must be stored for centuries. These drawbacks make it difficult to secure permission for new reactor construction.

There is another type of nuclear reactor that has been conceptualized almost from the beginning of nuclear technology: molten salt reactors (MSRs). These reactors are a type of non-light water reactors, meaning they are not dependent on water for cooling. Instead, these reactors are cooled with molten salts rather than water and can use fluid fuel as well.

These differences make MSRs inherently safer. Why, then, are these reactors not more commonly used? That question can be answered almost entirely by the Cold War.

### History of molten salt reactors

Nuclear technology was developed as a power source in the first half of the 20th century, in an era when the most compelling use case was to make devastating bombs. As a result, nuclear reactor technologies that supported weapon development became the preferred designs.

Oak Ridge National Laboratory in Tennessee had a very successful MSR program through the 1960s (Figure 1), which resolved the main technical hurdles to commercial MSR deployment. However, the program was terminated by President Nixon in 1972 in favor of breeder reactor technology.

Breeder reactors convert nonfissile materials, such as uranium-238 and thorium-232, to fissile materials, such as plutonium-239 and uranium-233, respectively. Breeder reactors can produce more fissile materials than they consume while also not using up the valuable stock of uranium-235, which was needed for nuclear weapons (plutonium-239 is commonly used in thermonuclear bombs as well).

The most common type of reactor in use today is the pressurized water reactor, such as those used at Fukushima in Japan. The main drawbacks to this design are the relatively short fuel lifetimes (three to seven years) and safety concerns—in the case that both the power supply and cooling system experience total electrical failure, a nuclear meltdown may be impossible to prevent.

So, against the background of renewed interest in nuclear power as a low-carbon energy source, molten salt reactors are again being considered.

### Advantages of MSRs

Molten salt reactors operate at lower pressure than pressurized water reactors (PWRs), using molten salts as the coolant rather than pressurized water. Although this design confers engineering benefits, the molten salt is quite corrosive. Essentially, you are swapping the challenge of high-pressure engineering for the challenge of high-corrosivity engineering.

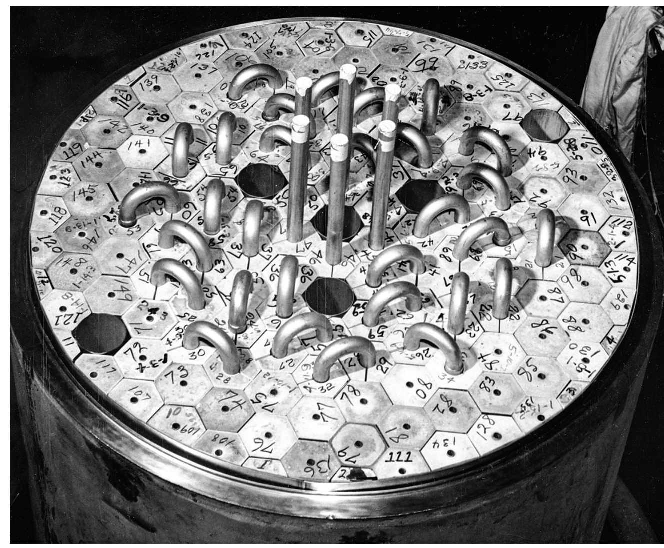




**Figure 1. The Aircraft Reactor Experiment, shown above, was a molten salt reactor design with a beryllium oxide reflector. Its operation as part of the Aircraft Nuclear Propulsion program in November 1954 led to the development of several reactors, including the Molten Salt Reactor Experiment.**

Nonetheless, MSRs enjoy other substantial advantages compared to PWRs. For example, because they are low-pressure systems, MSRs can be miniaturized more easily than PWRs. Plus, they can use a variety of fuels and coolants. Additionally, they operate at higher temperatures, providing better efficiency in electricity generation. The thermodynamic efficiency of MSRs ranges from 45–50%, in contrast to the efficiencies of 33–35% in traditional reactors. MSRs also have a greater margin of passive safety. If the power to the reactor fails, the fuel drains away under gravity, eliminating the potential for an accidental meltdown.

One promising MSR model uses the nonfissile material thorium as a fuel. Thorium is much more abundant than uranium on Earth, and it happens to be a byproduct of monazite mining, which is the main ore for rare earth elements (REEs). Typically, 6–7 wt.% of monazite is thorium, and 55–60 wt.% is REEs. Because REEs are so valuable, recovery of thorium from monazite is economical and helps reduce mine waste.

Additionally, though thorium itself is not fissile, it can be used to fission plutonium-239 sourced from spent conventional nuclear fuel, thereby disposing of nuclear waste.

### High-performance ceramic materials in MSRs

The high temperature of the molten salt coupled with the corrosivity of the coolant and fuel demand materials that can operate for many years without maintenance. In many MSRs, the reactor vessel and the coolant system are constantly exposed to radiation. When a repair is needed, the fuel salt must be drained and flushed out thoroughly before any work is done.


Credit: PNNL, YouTube

**Figure 2. Renewed interest in molten salt reactor technology has led researchers at Pacific Northwest National Laboratory to work on solutions for the design, construction, and operation of full-scale molten salt reactors.**

Advanced ceramic materials such as silicon carbide and its composites have both the temperature tolerance and corrosion resistance to function in MSRs at the desired level of performance and safety. These materials are also radiation tolerant and so can be used for structural components in the MSR. But the combined effects of radiation and corrosion cause eventual damage to the silicon carbide parts, too—hardening the ceramic and making it brittle. Understanding why and how this happens is one of the key knowledge gaps left to overcome in MSR designs.

In the wake of the Fukushima nuclear disaster, a lot of research has been aimed at the development of accident-tolerant fuels. Such fuels are another area where silicon carbide ceramics can be used. MSRs featuring salt-cooled solid fuel cores can use tristructural isotropic (TRISO) particle fuel. In these particles, a uranium fuel pellet (uranium nitride, uranium oxide, or uranium carbonate) is coated with layers of ceramic and carbon-based materials to prevent the release of fission products. These fuels further increase the safety margins of MSRs. TRISO fuels cannot melt at the temperatures present in the reactor, preventing a core meltdown.

Nuclear fuel design is a key determinant in the size and configuration of the reactor. Next-generation nuclear reactors are similar in design to their PWR predecessors, and anywhere that ceramic materials can be used in PWRs, they can be used in advanced reactors.

### The future of MSRs

Interest in MSR technology is steadily growing, as evidenced by government entities such as Pacific Northwest National Laboratory expanding their laboratory capabilities to research this technology (Figure 2). Funding opportunities for MSRs are growing, too. For instance, *MIT Technology Review* named Kairos, a molten-salt cooled reactor company that uses TRISO fuel, to its list of 2024 Climate Tech Companies to Watch. Kairos will receive U.S. Department of Energy funding to build its test reactor in Tennessee.

China is currently building the world's first commercial thorium MSR in Gansu province, near the Gobi Desert. An advantage of MSRs in desert regions is that they are not cooled by water. The reactor, with a capacity of approximately 100 MW, is due to enter service in 2030.

There are additional challenges to commercialization, such as the lack of design safety standards and MSR-specific supply chains. Fortunately, these challenges are not insurmountable, so molten salt reactors remain a promising technology to help support climate goals. ■

## Acetonitrile-based electrolyte improves temperature range of Li-ion batteries

As lithium-ion batteries are adopted into more and more applications, some of their performance limitations are becoming more noticeable, such as their sensitivity to temperature.

In general, fast charging of Li-ion batteries can only take place between 5°C to 45°C (41 to 113°F). Below 0°C (32°F), plating of metallic lithium occurs on the anode that leads to a permanent degradation in performance and safety. Above 50°C (122°F), charging and discharging is subject to gas generation that might cause a cylindrical cell to vent and a pouch cell to swell.

The electrolyte is the main cause of these temperature limitations. So, developing new electrolyte formulas could help expand the temperature range in which Li-ion batteries can viably operate.

The organic compound acetonitrile is a promising alternative due to its high ionic conductivity as well as chemical and oxidative stability. However, acetonitrile tends to decompose in the presence of graphite, another major battery material used as the negative electrode, so researchers must find a way to stabilize acetonitrile in the presence of graphite.

In 2021, researchers at multinational Japanese chemical company Asahi Kasei published an open-access paper describing a solution to suppress the reductive decomposition of acetonitrile. Three years later, in June 2024, the company announced that it had achieved proof-of-concept with this proprietary acetonitrile-based electrolyte, in collaboration with a battery maker, using cylindrical lithium-iron phosphate batteries. In November 2025, Asahi Kasei and German battery manufacturer EAS Batteries signed a license agreement for the use of Asahi Kasei's acetonitrile-containing electrolyte technology in EAS's ultrahigh-power Li-ion battery cell. The market launch of this new cell is planned for no later than March 2026. ■

Credit: Ziadi Lotfi / Shutterstock

# The nonferrous metals market: Supply and regulatory pressures inspire strategies for a resilient future

By Margareth Gagliardi

Nonferrous metals serve foundational roles in the electrification, renewable energy, and digital transformation.

Nonferrous metals are metals that do not contain iron in significant amounts. These metals typically are nonmagnetic, corrosion resistant, electrically and thermally conductive, and lightweight, making them ideal for applications in the emerging markets mentioned above.

Even as demand for these metals surges, supply chains face geopolitical and environmental challenges. Overcoming these challenges will require innovations in various sectors, including the development of advanced refractories to deliver high-quality materials through safe and effective metallurgical processes.

## Market momentum: Nonferrous metals powering global growth

Of the more than 90 nonferrous metallic elements on the periodic table, only about 10 have significant importance in industrial applications (Table 1). In 2025, these top metals accounted for more than 90% by volume and 58% by value of the nonferrous metals market, with aluminum and copper leading the charge.

Aluminum demand is nearly three times that of copper; however, as seen in Table 1, the copper market is larger in value because of copper's much higher unit price. As of the end of 2025, copper traded at roughly four times the price of aluminum.

The total market value for nonferrous metals, including precious and nonprecious metals, is projected to have healthy growth during the next five years, rising at a compounded annual growth rate (CAGR) of 6.0%, from $1.2 trillion in 2025 to $1.6 trillion globally in 2030.[1,2] The key growth drivers for this market are as follows:

- **Urbanization:** Expansion of cities and infrastructure worldwide is creating greater demand for components such as aluminum windows, copper plumbing, and transportation-related elements.
- **Electrification:** Transition to electric power in transportation and industry is in progress. Nonferrous metals are essential for electrical wiring, motors, power transmission lines, electric vehicle (EV) batteries, and energy storage systems. As an example, an EV uses 80 kg of copper versus 23 kg in a conventional car.[3]
- **Sustainability:** There is growing pressure to reduce carbon footprints and adopt greener technologies. Nonferrous metals enable production of lightweight structures that improve fuel efficiency and are critical in renewable energy systems such as solar panels and wind turbines. Global decarbonization policies are creating unprecedented demand for nonferrous metals.
- **Recycling:** The emphasis on circular economy and resource efficiency is intensifying. Nonferrous metals are highly recyclable without losing their properties, allowing for lower manufacturing costs and a reduced environmental impact.

Although aluminum and copper are projected to maintain the dominant share of the nonferrous metals market during the next five years, the markets for cobalt, nickel, and titanium will expand more rapidly because of their critical role in emerging technologies and strategic industries.

Cobalt and nickel are essential for lithium-ion batteries used in EVs and renewable energy storage systems, which drive the global energy transition. Other key applications of these two metals include superalloys for turbines and jet engines, which like the energy applications are experiencing exceptional market growth worldwide, thus creating unprecedented demand. Titanium is also increasingly demanded in aerospace and defense applications due to its exceptional strength-to-weight ratio and corrosion resistance.

Nonferrous metals are not only vital to industry but also in applications that save lives. Titanium and cobalt alloys are revolutionizing implants, surgical instruments, and advanced medical devices, enabling innovations in orthopedic surgery, cardiovascular stents, and diagnostic technologies.

## Supply chain volatility, regulatory pressures, and energy costs

Despite the increasing demand for nonferrous metals, this market faces some major challenges: supply chain volatility, environmental regulations, and energy costs.

Nonferrous metals typically are sourced from geographically concentrated resources. For example, as seen in Table 2,[4–11] China produced 44.4% of worldwide copper and 59.7% of aluminum metal in 2024, while Indonesia accounted for 38.4% of nickel production (these figures include both primary and secondary metals). Other key producers of nonferrous metals are India, Russia, Canada, Democratic Republic of the Congo, and Chile.

In 2025, Chile's copper output slowed as Santiago-based Codelco, one of the world's largest copper producers, faced operational setbacks, including a major tunnel collapse at El Teniente mine and declining ore grades across several sites. At the same time, new mining regulations, which were introduced in the country to streamline permitting, also reinforced compliance rigor by requiring standardized evaluations and digital traceability.[12] These events underscore the persistent supply risks and regulatory pressures in key producing regions.

Political instability, trade restrictions, and logistics disruptions are additional causes of sudden price spikes, while global events, such as pandemics and conflicts, amplify risks for raw material availability and shipping. As a result, the United States and its allies are promoting initiatives aimed at increasing internal supply. Copper, aluminum, nickel, zinc, and titanium are on the U.S. 2025 List of Critical Minerals,[13] triggering stockpiling and diversification efforts.

**Table 1. Nonferrous metals market by metal, 2025–2030 ($ in billions).***

| Metal | 2025 | 2030 | CAGR% 2025–2030 | Key drivers |
|---|---|---|---|---|
| Copper | 305.1 | 397.0 | 5.4 | Electrical wiring (including power grid upgrades, telecom, and data centers), renewable energy (including energy storage), EV infrastructure, electronics, plumbing, heat exchangers |
| Aluminum | 197.8 | 258.8 | 5.5 | Construction, automotive (including EVs), packaging, electrical wiring and power systems, aerospace |
| Nickel | 41.8 | 58.6 | 7.0 | Stainless steel, alloys (including superalloys), EV batteries, electronics, high-temperature applications, coins |
| Zinc | 32.3 | 41.6 | 5.2 | Galvanizing steel, die-casting alloys, automotive parts, coatings, batteries, renewable energy, fertilizers, electronics |
| Titanium | 30.4 | 41.8 | 6.6 | Aerospace and defense, medical implants, automotive (including EVs), chemical processing, energy, marine applications |
| Lead | 22.9 | 29.8 | 5.4 | Batteries, cable sheathing, ammunition, radiation protection, roofing, pigments |
| Chromium | 19.6 | 24.5 | 4.6 | Stainless steel, superalloys, electroplating, pigment and chemicals, refractories |
| Cobalt | 18.1 | 27.2 | 8.6 | EV batteries, aerospace, industrial alloys, electronics, medical implants |
| Tin | 7.1 | 8.6 | 4.0 | Food packaging, alloys, electronics, coatings |
| Magnesium | 5.7 | 7.6 | 5.8 | Automotive (including EVs), aerospace and defense, electronics and consumer devices, industrial applications (including alloys), medical devices |
| Others – nonprecious metals | 62.4 | 85.5 | 6.5 | High-strength steel, energy (including nuclear and renewables), cutting tools and industrial tooling, aerospace and defense, magnets, electronics, green tech |
| Others – precious metals | 431.3 | 593.0 | 6.6 | Jewelry, investments and bank purchases, electronics, renewable energy, healthcare |
| **Total** | **1,174.5** | **1,574.0** | **6.0** | |

*Table data was independently obtained by specialty market research firm AMG NewTech.

**Table 2. Top producers of common nonferrous metals in 2024 (based on both primary and secondary metals).***

| Metal | Country | Quantity (thousand metric tons) |
|---|---|---|
| Copper | China | 12,000 |
| | Congo | 2,500 |
| | Chile | 1,900 |
| | Japan | 1,600 |
| | *World total* | *27,000* |
| Aluminum | China | 43,000 |
| | India | 4,200 |
| | Russia | 3,800 |
| | Canada | 3,300 |
| | *World total* | *72,000* |
| Nickel | Indonesia | 1,850 |
| | China | 1,700 |
| | Russia | 250 |
| | Canada | 210 |
| | *World total* | *4,820* |
| Zinc | China | 6,840 |
| | South Korea | 850 |
| | India | 830 |
| | Spain | 510 |
| | *World total* | *13,670* |
| Titanium | China | 275 |
| | Japan | 70 |
| | Russia | 25 |
| | Saudi Arabia | 20 |
| | *World total* | *400* |

*Table data was compiled by AMG NewTech based on various sources (References 4–11).

**Table 3. Energy intensity and greenhouse gas emissions per ton of common nonferrous metals (primary process).***

| Metal | Typical energy intensity (GJ/t) | GHG emissions ($tCO_2e/t$) | Key sources |
|---|---|---|---|
| Copper | 32–102 | 3–4 | Smelting and refining stages |
| Aluminum | 131–211 | 8–15 | Electrolysis in Hall-Herout cells powered by carbon-intensive grids |
| Nickel | 100–572 | 7–27 | Smelting and refining stages |
| Zinc | 13–53 | 1–3 | Roasting and electrolysis |
| Titanium | 115–529 | 8–11 | Chlorination of titanium ore and magnesium reduction (Kroll process) |

Legend: GJ/t = Gigajoule per metric ton of metal; $tCO_2e/t$ = metric ton of $CO_2$ equivalent per metric ton of metal
*Table data was compiled by AMG NewTech based on various sources (References 14–23)

Current production of nonferrous metals relies primarily on traditional high-temperature smelting processes because these methods are very cost effective and scalable (see sidebar "Metals production: Why refractories are essential"). However, these traditional manufacturing techniques are energy intensive and generate substantial emissions and waste (e.g., red mud from alumina refining and $CO_2$ from smelting). These pollutants are subjected to increasing regulatory scrutiny, while rising energy prices inflate production costs and erode competitiveness.

Table 3 shows the energy intensity and greenhouse gas emissions (GHGs) for the primary processes used to manufacture the top five nonferrous metals.[14–23] Values change quite broadly based on the specific method used, but most of them greatly exceed the typical energy and emissions values for steel (22 GJ/t and 2.3 $tCO_2e/t$, respectively).[14] Primary aluminum, for example, requires at least six times more energy than steel, while its fabrication process releases more than three times the amount of GHGs.

Environmental and corporate responsibility regulations also address wastewater discharges from metal manufacturing; effluent limits and pretreatment standards for nonferrous metals forming; restrictions on exporting metal scrap to countries lacking equivalent environmental and social standards; exposure limits for fumes, dust, and other hazards during manufacturing and recycling; as well as best practices for air emissions, noise control, and worker safety.

The effect of these regulations is nuanced because even though they can enable long-term opportunities, such as healthier work environments and more secure supply chains, they can create constraints that hamper production in the short term. Short-term constraints include higher compliance costs and delays as well as carbon taxes and decarbonization mandates. Furthermore, due diligence expenses, or the costs incurred during the investigation phase before approving new projects, delay procurement and contribute to slower approvals, higher initial costs, and supply chain bottlenecks.

Overcoming these challenges and building a resilient supply chain requires action on multiple fronts. As Charles Johnson, president and CEO of the Aluminum Association, notes in an Aluminum Association press release,[24] "Even if we could flip a switch and turn on every idled aluminum smelter tomorrow, the U.S. industry cannot currently produce nearly enough metal to make the products that Americans rely upon. ... greater self-sufficiency will require an all-of-the-above approach to energy, trade, and recycling policy to ensure that U.S. manufacturers have abundant, affordable metal."

## Innovation in action

Table 4 highlights companies that are leading the nonferrous metals industry toward a resilient future by developing strategies for stable, cost-effective, and environmentally friendly production. From low-carbon smelting technologies to diversified portfolios, these strategies demonstrate the industry's commitment to resource security, sustainability, and innovation to meet future market demand.

Many of the main innovation pathways being explored currently are in direct response to the challenges detailed in the previous section. For example, environmental and corporate responsibility regulations accelerate the adoption of green smelting, recycling, and artificial intelligence (AI)-driven efficiency,[25] which can lower costs over time and open premium markets for low-carbon metals.[26,27] Compliance standards are also attracting capital from sustainability-focused funds, improving long-term resilience. Recent industry reports and case studies suggest that companies that adapt early can gain competitive advantages and market share,[28] as demand for nonferrous metals remain strong despite regulatory friction.

Current state-of-the art, low-carbon processes, such as hydrometallurgical methods, renewable-sourced electrolytic refining with inert anodes, and emerging direct electrochemical reduction, are very promising in terms of carbon footprint but represent a niche, as they are mainly used for low-grade ores or when very high-purity metals are needed. Consequently, traditional processes remain the primary method for producing nonferrous metals, and improving refractory materials is key to making metal production more efficient and sustainable. The most important refractory-related initiatives are discussed below.

**Development of green refractories:** These materials have a lower environmental impact because they reduce $CO_2$ emissions during production,[29] be that through replacing traditional raw materials with recycled aggregates, industrial byproducts, and alternative binders (e.g., geopolymers) or by using renewable energy to power their fabrication process. The long-term durability and performance of green refractories in the demanding conditions of nonferrous metal production remain an open question, however, one that will shape the future of sustainable metallurgy.

**Development of high-performance refractories:** Refractories with better resistance to thermal shock and chemical attack are being developed to enhance their durability and lifespan, which correlates with extended furnace life and reduced downtime for maintenance.[30] In addition, additive manufacturing allows precise fabrication of refractory products, decreasing material waste and installation time.

**Energy-efficient refractory design:** The aim is to reduce heat losses and improve furnace insulation to minimize energy consumption. This goal can be achieved by utilizing lightweight insulating refractories for hot-face lining, applying high-emissivity coatings to refractory linings, and employing high-temperature wool as a backup insulation behind dense refractory bricks.[31]

**Development of hydrogen-based metallurgy:** Processes utilizing hydrogen plasma for ore reduction are also being developed. These nascent processes provide an impetus for the refractory industry to develop new compositions (e.g., high-corundum or mullite-based materials) because conventional refractory materials can be compromised in the hydrogen environment.[32]

**Digitalization and smart monitoring:** Digital transformation is achieved by embedding Internet of Things sensors in the backup layer or near the hot face for real-time monitoring of temperature, heat flux, and wear. AI-driven predictive maintenance is increasingly adopted to extend refractory life, reduce downtime, and optimize energy consumption. AI is also being applied to optimize alloy design, improve smelting efficiency, minimize process waste, and create digital twins. Chinese manufacturers are leading the way in exploring AI in nonferrous metal production. For example, in 2024, Bejiing-based Aluminum Corp. of China established an AI computing center and developed the industry's first general-purpose large language model, called Kun'an, that is designed specifically to help optimize operational workflows throughout the entire nonferrous metals production process, from exploration and mining to smelting and recycling.[33]

**Recycling and circular economy programs:** Spent refractories generate large quantities of waste annually. Recycling programs aim to recover this waste and reuse it to produce new refractories.

Just as refractories are being recycled back into new products, the nonferrous metal industry is also rapidly advancing production of secondary metals, i.e., metals that are recovered from scrap, waste, and used products rather than mined from ore. Tight ore supplies for nonferrous metals such as copper

### Metals production: Why refractories are essential

Metallic elements are typically found in nature within stable oxides or sulfides. High temperatures are traditionally required to efficiently separate them as molten metal from slag, which avoids impurity entrapment and makes large-scale production economically viable.

However, these extreme conditions create a harsh environment for the processing equipment. Molten metals and slags are highly corrosive and lead to erosion, while thermal cycling can cause severe mechanical stress. These challenges are where refractory materials come in: They can be engineered to provide heat resistance, chemical stability, and structural integrity, forming the protective lining of furnaces, kilns, electrolytic cells, and other equipment. Without refractories, the high-temperature processes that make modern metal production possible would simply not exist.

While iron and steel production dominates refractory consumption (60% or more), nonferrous metals also account for a significant share of consumption at approximately 30–40% of the total refractories market.[a]

Approximately 75–85% of nonferrous metals have melting points greater than 500°C. They include most transition metals (e.g., nickel, chromium, titanium), refractory metals (e.g., tungsten, molybdenum, tantalum), and lanthanides and actinides (rare earths and nuclear metals). However, even nonferrous metals with relatively low melting points, such as tin (~230°C), lead (~328°C), and zinc (~420°C), will use refractories for thermal insulation, corrosion resistance, wear resistance, and purity control. Therefore, refractories find application during processing of virtually all nonferrous metals.

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Table 4. Key players in the nonferrous metals market. Companies marked with ‡ are state-owned enterprises.

| Company (Headquarters) | Main nonferrous products | Strategies for secure, sustainable, efficient, and/or innovative nonferrous metals production |
|---|---|---|
| **Alcoa** (Pittsburgh, Pa.) | Aluminum | • Controls large, high-quality bauxite reserves<br>• Pioneers low-carbon smelting technology (ELYSIS) along with Rio Tinto |
| **Aluminum Corporation of China (Chinalco)‡** (Beijing, China) | Aluminum | • Vertical integration structure<br>• Invests in overseas mining projects (e.g., Guinea)<br>• Implements technologies that save energy and reduce emissions in smelting processes |
| **Anglo American** (London, U.K.) | Copper, nickel, platinum group metals | • Portfolio of high-quality, long-life copper assets, particularly in South America |
| **BHP** (Melbourne, Australia) | Copper, nickel | • Diversified, future-facing portfolio provides resilience against commodity price cycles<br>• Partners with equipment suppliers to optimize ore-to-metal conversion efficiency<br>• Pilots green technologies such as furnace electrification and renewable energy for copper smelting |
| **Boliden** (Stockholm, Sweden) | Copper, zinc, lead, precious metals | • Expert in smelting and refining complex metal concentrates<br>• Maximizes value from byproducts using circular economy practices |
| **China Hongqiao Group** (Binzhou, China) | Aluminum | • Deep vertical integration from bauxite to aluminum processing<br>• Leverages renewable hydropower and advanced refractory bricks in smelting operations to reduce energy consumption |
| **China Minmetals‡** (Beijing, China) | Various | • Diverse portfolio including copper and rare earths allows strategic control over the critical metals supply<br>• Uses new refractory compositions to extend surface life |
| **Codelco‡** (Santiago, Chile) | Copper | • Controls the largest copper reserves globally<br>• Uses refractories designed to prevent the release of harmful compounds<br>• Partners with suppliers of oxygen-enriched smelting-compatible refractories to reduce emissions |
| **Emirates Global Aluminium (EGA)** (Abu Dhabi, UAE) | Aluminum | • One of the world's largest aluminum companies outside of China<br>• Produces certain premium products using green manufacturing practices, such as solar powered processes |
| **First Quantum Minerals** (Vancouver, Canada) | Copper, nickel | • Large operations in Africa and the Americas ensures control over the supply chain from ore to refined metal<br>• Uses advanced bricks to extend service life and developing low-carbon refractory solutions |
| **Freeport-McMoRan** (Phoenix, Ariz.) | Copper, molybdenum, gold | • World's largest publicly traded copper producer (subject to investor-driven ESG mandates)<br>• Owns the Grasberg minerals district in Indonesia, one of the world's largest copper and gold deposits<br>• Controls the full copper value chain from mining to smelting and refining<br>• Has ongoing initiatives to recover copper and valuable compounds from spent furnace linings<br>• Develops low-carbon refractory compositions |
| **Glencore** (Baar, Switzerland) | Copper, zinc, nickel, cobalt, aluminum | • Top global cobalt producer<br>• Integrated business model spanning mining, smelting, and a world-leading marketing (trading) division<br>• Develops next-generation refractory materials for high-temperature, oxidative environments |
| **Hindalco Industries/ Novelis** (Mumbai, India) | Aluminum, copper, zinc | • World's largest producer of flat-rolled aluminum products<br>• Major aluminum recycler<br>• Uses advanced carbon and alumina-based refractories in electrolytic cells to reduce wear and replacement frequency |
| **KGHM Polska Miedz** (Lubin, Poland) | Copper, silver | • Operates one of the largest copper and silver deposits in the world<br>• Fully integrated business chain from mining to refining<br>• Uses insulating refractory materials to reduce heat loss and improve furnace energy performance |
| **Lundin Mining** (Toronto, Canada) | Copper, nickel, zinc | • Leverages high-quality, long-life assets and strategic joint ventures to ensure a secure, efficient supply chain<br>• Deploys smart monitoring systems for furnace conditions and predictive maintenance to optimize refractory performance |
| **Norilsk Nickel (Nornickel)** (Moscow, Russia) | Nickel, copper, palladium | • Controls the world's largest high-grade nickel–copper–platinum group elements deposits in the Norilsk-Talnakh area<br>• Generates its own power through hydroelectric plants in Siberia<br>• Explores hydrogen-based technologies for smelting and refining |
| **Norsk Hydro** (Oslo, Norway) | Aluminum | • Produces aluminum with a low-carbon footprint using hydropower and proprietary, energy-efficient technology<br>• Uses advanced treatment and recycling of spent pot linings to recover fluoride and carbon for reuse |
| **Rio Tinto** (London, U.K.) | Aluminum, copper, titanium | • Strong focus on pioneering proprietary low-carbon smelting technology (ELYSIS) along with Alcoa<br>• Integrated operations enable secure and efficient production |
| **RUSAL** (Moscow, Russia) | Aluminum | • Major global aluminum producer with significant influence in the supply chain<br>• Leverages Siberian hydropower resources to produce low-carbon aluminum |
| **Southern Copper** (Mexico City, Mexico) | Copper, molybdenum, zinc | • Holds the largest copper reserves in the industry, with main deposits in Mexico and Peru<br>• Uses advanced refractory systems compatible with oxygen-enriched smelting to improve efficiency and reduce emissions |
| **Vale S.A.** (Rio de Janeiro, Brazil) | Nickel, copper | • Largest nickel producer in the Americas<br>• Uses its nickel and copper supplies to support the growing EV market and energy transition |
| **Vedanta Resources** (London, U.K.) | Aluminum, zinc, copper | • Highly diversified across multiple metals<br>• Integrated domestic scaling capability |
| **Zijin Mining Group‡** (Longyan, China) | Copper, gold, zinc | • Worldwide operations help resist geopolitical and logistical disruptions<br>• Rapid acquisition and feedstock development strategy ensures a secure, long-term supply for smelting and refining operations<br>• Invests in low-carbon refractory systems compatible with electrified smelting and oxygen-enriched furnaces |

Source: AMG NewTech

and zinc due to slow mine development are a key reason to accelerate the scale-up of secondary sourcing and reduce reliance on virgin ores.

Another reason to adopt secondary metals in production is because metal recycling leads to significant energy savings. For example, the energy intensity of secondary aluminum is on average 8.3 GJ/t versus 174 GJ/t for primary aluminum, corresponding to a 95% reduction. This significant reduction is possible because unlike primary smelting that requires high-temperature, large-scale furnaces lined with high alumina and magnesia chrome bricks, recycling operations typically use modular furnaces lined with monolithic refractories operating at lower temperatures. Globally, at present, 32% of aluminum and copper produced is recycled metal, with this share continuing to rise.[34,35]

Besides the economic benefits of secondary metal usage, many companies are focusing on the sustainability aspect by highlighting opportunities and competitive advantages in their annual reports and public statements.

"Climate change is at the heart of everything we do for two reasons. First of all, we have to admit that we have a significant carbon footprint and we have to address that," states Jakob Sausholm, CEO or Rio Tinto, in a *Financial Post* article.[36] "We also do it because ... addressing climate change for the world is about building a whole new energy source. It's about electrifying society; it's about building renewable energy. It will require more aluminum, more copper, and more battery materials plus a number of other critical minerals. It's a huge opportunity for us."

## Securing the future of nonferrous metals

As geopolitical and environmental challenges constrain supply of nonferrous metals, the industry is using these constraints as motivation to develop improved and novel production processes. In particular, advancements in the refractory industry address these challenges in numerous ways. For example, refractories with superior thermal shock resistance and chemical stability can extend furnace life and reduce downtime, while smart refractories with embedded sensors and predictive maintenance enable real-time monitoring of wear and thermal conditions. Furthermore, refractories containing recycled aggregates can reduce reliance on virgin raw materials.

Through these innovations and other developments, the nonferrous metals industry is on a solid path to ensuring it meets the rising demand for these metals while strengthening the resilience of global supply chains.

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# Corrosion of zirconium-based refractories by molten glass

By Cristian Perez Velasquez, Maziar Montazerian, and John C. Mauro

Credit: Benoit Daoust / Shutterstock

Zirconium is a crucial component of refractories used in the glass industry because it enables the design of materials with high strength at elevated temperatures, low thermal conductivity, high resistance against thermal shock, and minimal reaction with molten glass.

Despite their good behavior, zirconium-based refractories still must be replaced periodically due to wear, primarily because of a complex corrosion phenomenon that combines three general physical and chemical processes: penetration, dissolution, and erosion.[1]

In this paper, the corrosion of zirconium-based refractories used as a glass contact material in melting tanks is described and discussed.

## Basics of zirconium-based refractories

### *General classification*

Zirconium-based refractories are generally classified into three types:

- **Dense zircon refractories** are characterized by a typical composition of alumina (0.0–2.5 wt.%), zirconia (64–68 wt.%), silica (30–35 wt.%), and minor concentrations of other components such as $Fe_2O_3$ and $Na_2O$. Their microstructure is simple and consists mainly of sintered zircon ($ZrSiO_4$) particles with small pores.
- **Fused cast alumina–zirconia–silica (AZS) refractories** are composed of around 43–50 wt.% alumina, 33–42 wt.% zirconia, and 13–20 wt.% silica, with the possibility of having small amounts of other components such as $B_2O_3$, $Na_2O$, $Fe_2O_3$ or $TiO_2$. Their microstructure consists of zirconia grains and domains of alumina-zirconia eutectic composition embedded in a glassy aluminosilicate phase.
- **Fused cast high zirconia (HZ) refractories**, similar to dense zircon refractories, are used when the quality and corrosion requirements are especially demanding. These materials are characterized by a composition rich in zirconia (above 94 wt.%) as their main component and other components are 1.2 wt.% of alumina and 4 wt.% of silica, indicating a small vitreous phase content (about 6%). Unlike AZS refractories, the microstructure is formed by zirconia grains and a low content of glassy phase, which is identified as a thin interface layer along grains.[2]

### *Thermomechanical properties*

During service, refractory materials are subjected to large temperature changes up to 1,600°C. Throughout the heating process, the material's microstructure undergoes changes that can slightly modify its behavior compared to the material at ambient conditions. In zirconium-based refractories, one of the

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most important changes during heating up is the phase transformation that zirconia ($ZrO_2$) undergoes, typically at a temperature near 1,157°C. During this transformation, its structure changes from monoclinic to tetragonal, resulting in a decrease in volume without any change in its chemical composition.

This transformation is one of the major issues in zirconia-based refractories because this change is responsible for microcrack generation on the material microstructure, which can lead to future failure. This phenomenon particularly affects the AZS and HZ refractories, as zirconia is a principal component of their microstructure. To mitigate volume-change effects and reduce crack formation, the glassy phase is incorporated into these materials.

Generally, thermal shock and zirconia transformation may result in a decrease in the mechanical properties of the refractories, mainly due to the generation and extension of cracks on their microstructure. However, the corrosion resistance is also impacted because these defects result in free spaces that can be filled by molten glass, penetrating the refractory easily and accelerating its wear. Hence, a refractory that can keep a dense microstructure as free as possible of pores and cracks, even after temperature variations, may exhibit better resistance against glass penetration and increase its corrosion resistance.

***Manufacturing techniques***

The microstructure of refractories is influenced by manufacturing parameters, which in turn significantly affect their properties. As a result, the manufacturing process plays a crucial role in determining the overall performance of the refractory.

In general, two primary methods are used to manufacture zirconium-based refractories: the fused cast process and sintering. The first one is used predominantly for the manufacture of AZS and HZ refractories. This process starts with mixing raw materials that are melted in an arc furnace and then poured into molds to anneal and solidify. The blocks are later removed from the molds, inspected, and finished.[3] This process, in general, allows manufacturers to obtain higher densities and lower apparent porosity (0–2%) in the refractories, but it may be more expensive than other refractory manufacturing processes.

On the other hand, the sintering process is commonly used to manufacture dense zircon refractories. This process involves the consolidation of the raw material (powder) through forming and sintering. Although this process may exhibit higher apparent porosity (10–19%) than the fused cast method, when mechanical pressing is applied, the use of fine raw materials and more advanced processes such as hot isostatic pressing can reduce porosity. Likewise, it offers more flexibility in composition and can be used for particular applications.

## Corrosion in zirconium-based refractories

Because of their different microstructures, phases, and components, the corrosion mechanisms for zirconium-based refractories may change from one type to another.

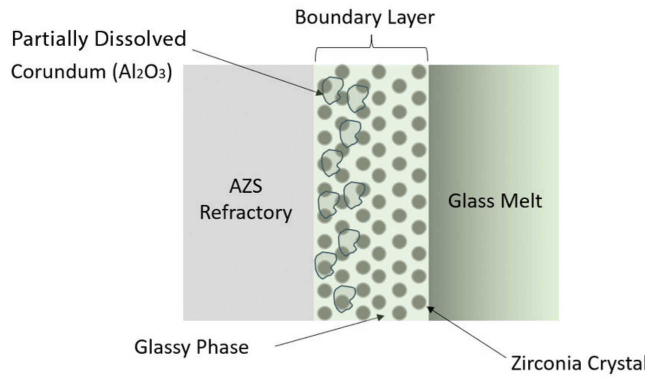



**Figure 1. Illustration of the interface between AZS refractory and glass melt, showing the boundary layer where partial dissolution of corundum-phase alumina occurs and zirconia crystals migrate into the glass melt.**

Corrosion in AZS refractories occurs at high temperatures when alkali elements, such as sodium, present in the molten glass start to diffuse into the glassy phase, causing its exudation and pore formation. This exudation also leads to both the dissolution of alumina in the corundum phase and the release of less soluble zirconia crystals, a process that occurs in a boundary layer formed as a result of the reaction between the refractory and molten glass (Figure 1). The generation of pores causes AZS refractories to lose their permeability, and molten glass can diffuse into the refractory, increasing the corrosion rate progressively until the refractory material fails.

In contrast, the corrosion in dense zircon refractories is governed by the decomposition of zircon crystals at high temperatures into zirconia and silica, which may be dissolved and combined with glass components.[4] Generally, as a result of the high solubility of silica in the glass, it rapidly dissolves in the interface, while the zirconia crystals with a lower solubility remain surrounded by glass. Hence, the glass surrounding the zirconia is characterized by a different chemical composition from the initial glass (resulting from its mixing with silica and zirconia), which alter some of its properties.

Corrosion processes can also vary depending on the kind of glass that is in contact with the refractory as well as thermal conditions, among other factors. Guzman et al. investigated wear on AZS bricks located in a glass tank after several years of service in contact with soda lime silicate glass.[5] They summarized the corrosion process in four well-defined stages: penetration of alkali elements, exudation of glassy phase, cracking, and erosion. The alkalis from the glass penetrate the alumina–zirconia and zirconia phases, reacting with alumina to form a sodium aluminosilicate layer. These layers, which are characterized by high surface tension, enhances exudation of the glassy phase and ultimately lead to the formation of cavities and cracks that reduce the strength of the refractory.

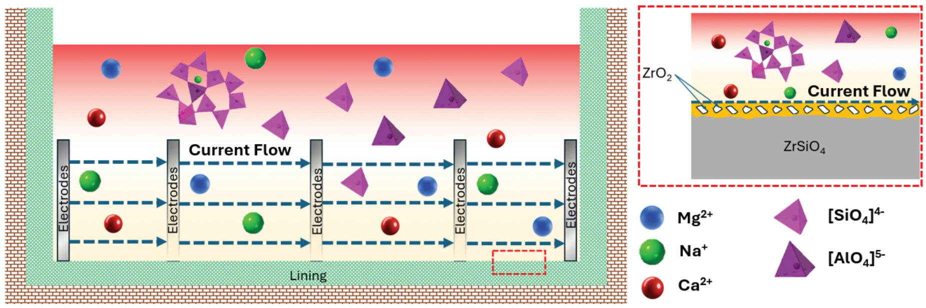


**Figure 2. Interaction between molten glass and the furnace lining in electric furnaces, illustrating the change in current flow path caused by zircon decomposition. The inset on the right highlights the formation of a zirconia layer at the refractory surface and the migration of ionic species ($Na^+$, $Ca^{2+}$, $Mg^{2+}$) and structural units ($[SiO_4]^{4-}$, $[AlO_4]^{5-}$), which accelerate wear.**

In addition, the corrosion process in special glasses (e.g., borosilicate, aluminosilicate, lead silicate, phosphate glasses) has also been studied. Hong Li et al. studied the corrosion of AZS refractories by calcium aluminosilicate and soda-lime silicate glasses,[6] which are utilized in the development of glass-ceramics at temperatures up to 1,480°C under static conditions. In general, the viscosity of these glasses decreased rapidly at temperatures above 1,200°C and then could penetrate the AZS microstructure. In the beginning, calcium oxide and sodium oxide are diffused into the refractory, and liquidus temperature decreases at the glass–refractory interface, forming new mineral phases such as anorthite and gehlenite, which later are washed out, causing continuous corrosion of the refractory.

## Corrosion tests: Current approaches and limitations

Refractory corrosion tests are mainly classified into two groups: static tests, in which the motion of fluid in contact with refractory is not simulated, and dynamic tests, in which the refractory and fluid are in relative motion. In both cases, simulating the exact conditions of service life is difficult due to the overwhelming number of variables to consider, including sample geometry and size, stress distribution, time and thermal gradient, among other variables. However, testing small scales is cheaper than field trial testing, which provides impetus for researches to improve on these techniques.

Examples of new or improved corrosion testing include the continuous wear testing device developed by Kircher et al.[7] This technique, based on the rotating cylinder test, evaluates the corrosion under dynamic conditions by analyzing different parameters simultaneously during the test, such as the weight of the samples as a function of time and sample surface. Also, Poirier et al. proposed the use of X-ray diffraction at high temperatures combined with Rietveld quantification to determine the corrosion kinetics.[8] This combination allows evaluation of the mechanisms involved and the phase changes in the process, which could help improve the knowledge and prediction of the phenomena of refractory degradation.

Even with these improvements, the most significant modeling efforts to refractories by various authors pertain to studies performed in the steel and metals industry. This focus highlights a clear lack in models that can elucidate the corrosion models and tests for glass industries. To enable the development of better refractory corrosion models and tests for glass manufacturers, we must improve our understanding of the thermodynamic and kinetic processes involved in the corrosion of zirconium-based refractories by molten glass.

## Considerations for understanding the corrosion of zirconium-based refractories

### *Thermal stability and temperature effects*

In principle, the melting temperatures of refractories are a good starting point for corrosion evaluation, as they strongly influence phenomena such as diffusion in the host material. Therefore, at least initially, compositions with higher melting points may have a longer service life, so thermal stability plays a crucial role in understanding refractory corrosion resistance.

In the case of zirconium-based refractories, it is well known that high temperatures may result in the dissociation of zircon crystal into silica and zirconia. Although there is an essential variation in the decomposition temperature across different studies (varying from 1,540–1,683°C), all studies have concluded that the reaction accelerates dramatically with rising temperature. The substantial variations observed may be attributed to other factors such as refractory composition, purity, the refractory density, the stabilizing oxide, and particle size. It has been demonstrated that even small amounts of impurities such as iron, titanium, and alkalis increase the degradation of zircon, and decreasing particle size can lead to dissociation reactions occurring at lower temperatures than expected.[9,10]

The dissociation of zircon into silica and zirconia may not only increase molten glass penetration within the refractory, as described earlier in the section on corrosion in zirconium-based refractories, but may also result in a decrease in the electrical resistivity of the refractory surface. In electrical furnaces, this decrease may produce changes within the current path because the current can now be conducted through the refractory block's surface instead of molten glass (Figure 2). Such a change in the current path can accelerate wear, which can lead to glass leakage and process issues due to nonhomogeneous heating in the tank.

Increasing the temperature not only accelerates thermal decomposition of the refractory but also a rise in the solubility of the refractory components in the glass melt. According to Manfredo et al.,[11] in soda lime silicate glasses, the component that is dissolved faster in the melt is the alumina, the main component on AZS refractories, due to its higher solubility in the molten glass (almost twice that of zirconia). However, other oxides such as tin oxide and chromium oxide show less dissolution even at higher temperatures (close to 1,600°C) due to their lower solubility. Hence, components with less solubility in the glass melt may enhance the refractory corrosion resistance, as reported by Toperasu et al.[12]

***Thermodynamics***

The thermodynamic approach is an essential tool in the study of refractory corrosion because it allows researchers to elucidate different important parts of the process, such as the reactions that can take place, the products that can be formed, and the solubility of different components, among others.

Although a nonnegligible number of thermodynamic studies and approaches have been applied to the glass industry, most of them have been focused on the corrosion of refractories by vapors and gases used on the superstructure and crown of the furnaces[13,14]; the application of thermodynamic calculations to study the corrosion on contact glass refractories, such as the zirconium-based materials, is limited. Therefore, there is a notable opportunity to increase the application of these methodologies to analyze the corrosion potential and processes in different glass systems.

We recently studied the effect of [CaO]+[$Al_2O_3$] content within a group of fiberglass compositions on the zircon refractory decomposition. The results indicated that, although there is no linear trend, in general, the increasing of [CaO]+[$Al_2O_3$] results in a lower zircon breakdown temperature, with drops up to 350°C compared with the typical value for pure zircon (1,673±10°C). Furthermore, thermodynamic calculations revealed that $Na_2O$ is the most reactive oxide when interacting with zircon, obeying the acidobasicity relationship between the refractory and the glass oxides, so that more basic components (e.g., sodium oxide, calcium oxide, and magnesium oxide) can react more strongly than the less basic and acidic glass oxides (e.g., alumina and titania) with zircon, characterized by acidic nature.

***Kinetics***

Zirconium-based refractories are soluble in the melts they contain, so they will eventually dissolve entirely. Thus, the dissolution rate is an essential parameter to define when the corrosion process is evaluated.

Considering that the dissolution reaction involves diffusion and can also be affected by the viscosity of the molten glass, the temperature dependence of the process is evident. Hence, this dependence is usually represented by the Arrhenius equation. However, not all systems can be fit by an Arrhenius plot because they exhibit behavior far from exponential temperature dependence, as is the case for mullite.[15] Therefore, the Arrhenius dependence should be used only in specific cases when the liquid is far from being saturated with components from the solid.

During glass making, the refractories that are in direct contact with the glass (e.g., bottom, sidewall, throat) can experience different types of forces generated by density and surface tension variations within the melt, as well as by mechanical forces generated by equipment in the tank. These forces have an evident impact on the dissolution reaction, and so the dissolution of the refractories commonly considers four possible cases[16]: stagnant liquid or molecular diffusion, natural or free convection, forced convection, and surface tension gradient driven.

The corrosion on refractories is commonly assumed to be a mass-transport governed process, where various temperature-dependent variables, such as viscosity, density, diffusion coefficients, and concentration gradients, may influence the dissolution rates of the refractory components. In addition, the theoretical dissolution rates for different conditions that can take place within the melting furnaces have been established and validated experimentally for ceramic materials by a few authors.[17–19]

However, many of the refractories used in the glass industry contain three or more phases, and many of the glass compositions are multicomponent systems. So, obtaining the values of some of the parameters experimentally is complicated. Therefore, most times theoretical models cannot accurately estimate the dissolution rates. Hence, to extend and enhance the kinetics approach, it is suggested to look for experimental methods that allow parameters to be acquired easily, develop new models or update existing ones, and accompany this kind of analysis with thermodynamics and thermal stability considerations.

***Effect of glass composition***

The chemical composition of the glass is another critical parameter to consider when analyzing the corrosion process in zirconium-based refractories. Generally, we can assume that components with a similar nature are less prone to react to each other, while on the contrary, important differences likely result in a chemical reaction; hence, from that previous statement, an initial classification in acid and basic oxides can be considered.

With dense zircon refractories, thermal decomposition dominates the corrosion process, where the breakdown temperature may vary depending on the components of the molten glass. Mauro et al. mention that, as a general rule, glass compositions with high reactivity with zircon will show lower breakdown temperatures than the more inert glass compositions.[20]

From a reaction viewpoint, the decomposition of zircon into zirconia and silica provides an opportunity for those dissolution products to combine with other components in the glass melt.

Kato and Araki investigated the effect of glass composition on the corrosion of zirconia and zircon refractories.[4] They found that alkali components, such as sodium oxide, are the most corrosive for both refractory types. Furthermore, in the case of zirconia, the corrosion rate increased significantly due to the presence of CaO.

In the case of the AZS refractories, the main chemical interaction between the refractories and the melt is the action of the alkali-earth and alkali elements in glass. According to Guloyan and Pustyl'nikov,[21] these ions initially penetrate the refractory through the glassy phase, decreasing its viscosity and generating a breakdown of structure cohesiveness. Similarly, new components, such as alkali aluminosilicates, can be formed through the interaction of alkalis, primarily sodium ions, with refractory components (e.g., alumina, zirconia, and silica). Furthermore, ions such as $Al^{3+}$, $Zr^{4+}$, and $O^{2-}$ also appear due to the interaction, influencing the thickness and density of the boundary layer in the interaction zone.

Min'ko et al. found after static corrosion tests between 1,440–1,500°C that the most aggressive components for zirconium-based refractories are the oxides of boron, sodium, calcium, lead and barium.[22] Moreover, the alkaline earth oxides tend to be more corrosive than alkaline oxides; hence, when high calcium glass compositions (CaO > 20 wt.%) are used, the zirconium-based refractories are insufficiently stable.

Due to the high number of glass compositions used in the glass industry, as well as the nonnegligible effects of even small changes on the composition in the corrosion rate of the refractories, it is not an easy task to achieve a complete and totally clear understanding of the impact of the glass composition on the corrosion process. However, based on previous studies, it can be discerned that alkali oxides such as sodium and potassium oxides, together with oxides such as calcium, sulfur, chromium, nickel, lead, barium, and iron, compose the group of the most corrosive agents to zirconium-based refractories, mainly because of their high mobility, basic nature and decreasing effect on the glass melt viscosity.

## The future of zirconium-based refractory corrosion assessment

Zirconium-based refractories represent one of the best materials used as glass-contact refractories in melting furnaces. However, corrosion remains one of the most meaningful challenges, so it is critical to understand this process properly to increase the corrosion resistance of melting furnaces and precisely predict service life.

Nowadays, there is a considerable amount of knowledge regarding the corrosion process of zirconium-based refractories when employed in glass-contact areas, but questions about the process still remain. The development direction for zirconium-based refractory corrosion tests should be mainly focused on the following points:

I. **More studies on dense zircon refractories:** Existing literature and research on zirconium-based refractories focuses on the fused cast refractories, AZS and HZ. There is thus an apparent gap regarding the dense zircon refractories, which are often used in industrial furnaces. Future research should be conducted to further understand dense zircon refractories and clarify the differences and similarities with respect to the other families. In addition, although there are general kinetics models and thermodynamics approaches to analyze the refractory corrosion, the development of new and specific models for zirconium-based refractories could be a valuable tool.

II. **Consideration for novel glass compositions:** In the coming years, new glass compositions such as the aluminosilicophosphate (LionGlass™® composition developed at The Pennsylvania State University) will enter commercial production to help meet global demands to reduce carbon impact. Therefore, the impact of different common oxides used in glass manufacturing on the corrosion of commonly used zircon-based refractories must be fully clarified so that the implementation of new compositions can be done without important process restrictions.

III. **Implementation of advanced computation tools:** Recently, the use of computational tools has been increasing to evaluate refractory corrosion in other industries, such as in steel manufacturing. Nevertheless, the glass industry does not seem to follow the same trend, and limited research in this field has been done. To speed up the process and reach a superior understanding of the corrosion process in zirconium-based refractories, the implementation of computational tools such as machine learning, molecular dynamics, and Monte Carlo methods, which have been used to study other kinds of refractories in specific applications,[23,24] should be encouraged.

IV. **Exploring dopant benefits:** Solubility of refractory components in molten glass plays one of the most important roles in corrosion of the refractories. Therefore, it is necessary to look for the inclusion of other known oxides with lesser solubility in the molten glass than zirconia, alumina, and silica, which represent the main components in the zirconium family of refractories. However, adding new components must ensure the main advantages of zirconium-based refractories in the manufacture of glass products, such as the minimization of defects and their versatility, to demonstrate a high performance against different types of glasses.

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# Zirconia crucibles:

## Enabling reliable melting of platinum group metals

Credit: Zircoa

**Zirconia crucibles in various sizes and compositions, designed for diverse alloy systems and operating temperatures up to 2,300°C.**

**By Ronny Simon, Jake Mochoskay, and Tobias Schmidt**

Crucibles are a key piece of equipment in the world of high-temperature processing, serving as containers for molten materials while they are refined and cast.

Ceramics are the main material used for creating crucibles, but the specific type of ceramic used depends on the material being melted. In the case of platinum group metals (PGMs) and alloys, their high melting points (Table 1) significantly limit the choice of ceramics that can be used for melting compartments.

Zirconia crucibles offer several advantages for processing PGMs. Thanks to developments by companies such as zirconium oxide specialist Zircoa (Solon, Ohio), a range of zirconia products exists to accommodate various alloy types, operating parameters, and target benefits.

### PGM applications and processing needs

Pure metals or alloys of platinum, palladium, or rhodium are known to be used in the jewelry industry. However, the much more widely—albeit hidden—uses of these metals involve various industrial processes and aggregates:

- Catalysts for petroleum refining, chemical production, and automotive catalytic converters.
- Melting tanks and stirrers in glass fabrication or bushings for glass fiber production.
- Electrical and electronic components such as thermocouples, contacts, or electrodes, or in conductive and resistive pastes deposited on ceramic substrates in advanced semiconductors.

Because PGMs are rare, expensive, and chemically stable, recycling is both an economically and environmentally important part of the PGM supply chain. First, PGM scrap is collected from the applications mentioned above, and then it is subjected to various crushing, screening, and mechanical pretreatment processes before being melted down. Various methods can be used for melting the scrap, but zirconia crucibles as a melt compartment in an induction furnace are a common option. The precious metals are collected in a metal phase while impurities such as oxides and unwanted metals are captured in the slag. Fluxes with lower melting points support the separation.

For PGMs, the highest purity of the products is mandatory, so the recycling process calls for stringent operating parameters. These requirements make the process chemically and mechanically demanding for the crucible, especially due to the presence of glassy or siliceous slags. Solutions such as zirconia crucibles with superior thermal, chemical, and mechanical stability are thus needed for the process.

**Table 1. Platinum group metals and alloys and their melting points.**

| PGMs and alloys | Melting point (°C and °F) | |
|---|---|---|
| Platinum (Pt) | 1,768°C | 3,215°F |
| Palladium (Pd) | 1,555°C | 2,831°F |
| Rhodium (Rh) | 1,964°C | 3,567°F |
| Ruthenium (Ru) | 2,334°C | 4,233°F |
| Iridium (Ir) | 2,445°C | 4,435°F |
| Osmium (Os) | 3,033°C | 5,491°F |
| PtRh10 | ~1,850°C | ~3,360°F |
| PtRh20 | ~1,890°C | ~3,430°F |
| PtRh30 | ~1,930°C | ~3,510°F |
| PtIr10 | ~1,800°C | ~3,270°F |
| PtRu10 | ~1,800°C | ~3,270°F |

Source: Zircoa

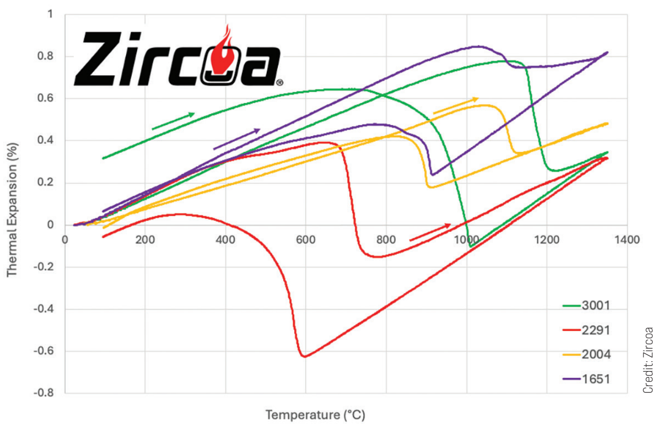


**Figure 1. Thermal expansion of Zircoa's crucible compositions upon heating and cooling.**

## Benefits of zirconia crucibles for PGM processing

Zirconia crucibles offer several advantages for PGM processing compared to other ceramics such as alumina, silica, magnesia, or silicon carbide:

- Reliable performance at extreme temperatures up to and above 2,100°C.
- Excellent chemical stability, meaning no reaction with the melt.
- Exceptional thermal shock resistance, which enables consistent performance throughout extended heating and cooling cycles.
- Highly smooth contact surfaces, minimizing contamination of melt.
- Sustainability benefits due to its multi-use capability (reuse frequency determined by the application).

While other ceramics can offer some of these benefits, zirconia crucibles combine the necessary temperature resistance, mechanical properties, surface quality, and chemical inertness in an ideal way.

## A comprehensive range of zirconia crucibles

A long-standing commitment to materials, processes, and applications engineering has allowed Zircoa to develop a range of zirconia crucible compositions, which are designed to maximize the crucible lifetime and minimize melt contamination. These crucibles are optimized for different purposes:

- **Composition 3001**: This magnesia partially stabilized zirconia (MgO-PSZ) exhibits exceptional resistance to thermal shock and erosion. It has low thermal expansion properties and excellent nonwetting characteristics, which makes it an excellent all-around product for casting PGMs. An 1,850°C continuous temperature load and brief overheating of the melt is typical in practice.
- **Composition 1651**: This calcia partially stabilized zirconia (CaO-PSZ) is often the preferred choice for corrosive alloys requiring melt temperatures of 1,900°C and above. This option provides enhanced resistance to erosion under these extreme conditions.
- **Composition 2291**: This yttria partially stabilized zirconia ($Y_2O_3$–PSZ) is a premium choice with highest inertness at maximum application temperature of up to 2,300°C. This inertness makes it the preferred choice for platinum–rhodium alloys.
- **Composition 2004**: This zirconium silicate, also known as zircon, combines beneficial properties at high temperatures with robust resistance to aggressive glassy or siliceous slags that occur during "dirty refining" applications.

Each of these compositions takes into account the fact that zirconia has three distinct crystal phases depending on the temperature: monoclinic, tetragonal, and cubic. The addition of stabilizers such as magnesia, calcia, or yttria shifts the temperature at which the phase transition occurs. Controlling these transitions is important because they can cause significant volume changes, particularly the transition from monoclinic to tetragonal. (Note: This volume change is very slight in zircon-based compositions.)

To maximize the life of zirconia crucibles, designing the thermal cycle to pass slowly through transition temperatures is recommended because it minimizes the thermal gradients, which can cause localized stress and cracking. Figure 1 illustrates different linear expansions during heating up and cooling down cycles for Zircoa's various compositions. These behaviors dictate the temperature ranges in which the heating and cooling rates must be reduced to give the material sufficient time to compensate for the change in volume (Table 2).

**Table 2. Temperature ranges for Zircoa's zirconia crucibles.**

| COMPOSITION | APPLICATION TEMPERATURE | PHASE TRANSITION TEMPERATURE | |
|---|---|---|---|
| | | Heating up | Cooling down |
| | | monoclinic → tetragonal | tetragonal → monoclinic |
| 3001 | 1,850°C | 1,100°C to 1,300°C | 1,100°C to 700°C |
| 1651 | 1,900°C | 1,000°C to 1,100°C | 950°C to 800°C |
| 2291 | 2,300°C | 700°C to 900°C | 750°C to 500°C |
| 2004 | 1,800°C | 1,025°C to 1,150°C | 925°C to 800°C |

Source: Zircoa

## Future zirconia crucible development

Zircoa's mission statement, "Deliver What Matters," reflects the company's commitment since its founding in 1952 to identify and develop solutions that support customer operations and innovations globally. By engineering crystalline structure, stabilizer systems, grain size, and other properties, Zircoa's team can help optimize the performance of future zirconia crucibles based on customer-specific requirements.

## About the authors

Ronny Simon is product manager of crucibles and Jake Mochoskay is sales and marketing manager at Zircoa Inc. (Solon, Ohio). Tobias Schmidt is sales engineer at Zircoa GmbH (Wiesbaden, Germany). Contact Simon at rsimon@zircoa.com. ■

# UPCOMING MEETINGS


## APRIL 12–17, 2026

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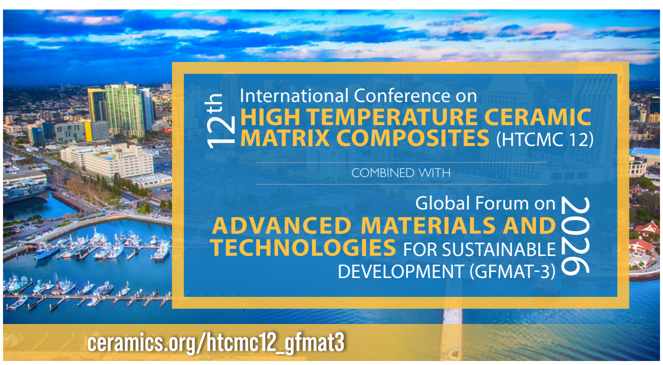


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**SHERATON SAN DIEGO HOTEL & MARINA,**
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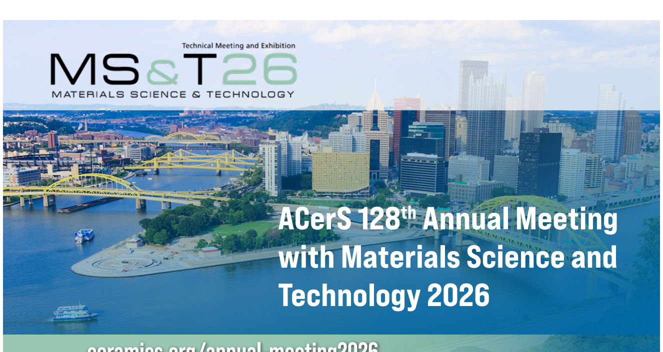


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**Brittney Hauke**
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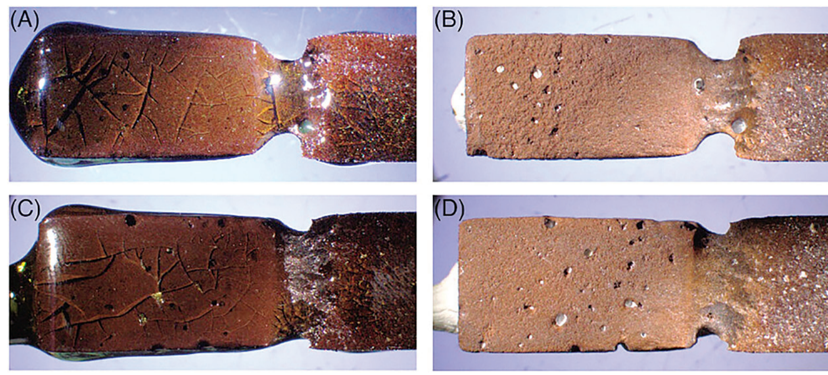
# Advances in refractory ceramics for nonferrous applications

Refractory ceramics are the backbone of the steel industry, serving as the protective lining on vessels used to contain the corrosive molten metal. But refractories support many other high-temperature processes and applications as well, ranging from glass and cement production to nuclear energy generation and space travel. This column explores some of the ways that refractories are being used outside the synthesis of steel.

Refractory blocks line the melters used in the vitrification of nuclear waste, but the highly corrosive glass melt thins the refractory blocks faster than average steel production (see "Deciphering the Discipline" on page 44). Being able to predict the lifetime of refractory ceramics used for nuclear waste vitrification is thus of great interest from a safety, time, and cost perspective.

Currently, refractory corrosion by high-level waste glasses is tested using the American Society for Testing and Materials (ASTM) C621-09 standard, which is a static test method that compares the isothermal corrosion resistance of refractories. This method is time and resource intensive, especially regarding nuclear waste glasses, where the glass compositions are varied and so require an unrealistic number of tests. That is why Amoroso et al. developed a new method based on modifying ASTM C621-09 in the article "A new method for measuring refractory corrosion of ceramics in glass."[1]

The new method by Amoroso et al. introduces a hydrofluoric acid cleaning step to remove the residual glass from a corroded sample (Figure 1) as well as automates the measurement of the dimensions of each test specimen. These changes resulted in an increase in measurement throughput while also reducing measurement variation when compared to the standard methodology.




Credit: Amoroso et al., Journal of the American Ceramic Society

**Figure 1. Digital images of refractory samples after 48 hours of corrosion, showing (A) residual glass and (B) after hydrofluoric cleaning, and after 27 hours of corrosion, showing (C) residual glass and (D) after hydrofluoric cleaning.**

Additionally, the hydrofluoric acid cleaning step did not have an adverse effect on the dimensions of the test specimen. The authors estimate that this cleaning method could increase experimental throughput by an order of magnitude.

Refractories are also used as protective linings in cement kilns, where again, the refractory material is the determining factor of both kiln efficiency and service life. Recently, research to increase the performance of these refractory materials for use in cement rotary kilns has been conducted with the aim of reducing heat loss. This research has important implications for energy conservation and emissions reduction.

Magnesium–calcium refractory materials are being studied for cement applications because they have adequate high-temperature, corrosion, and thermal shock resistance and are already widely used in cement rotary kilns. In the paper "Preparation and processing optimization of magnesium–calcium refractory aggregates" by Meng et al.,[2] these materials were prepared using a high-temperature sintering of dolomite and magnesite bound together with polyvinyl alcohol.

What sets this study apart is that, until now, there have been no systematic studies on the relationship between processing, structure, and properties of magnesium–calcium refractory aggregates. But by varying the calcium oxide content and various synthesis parameters, the authors were able to study the evolution of the pore architecture and performance of the aggregates.

They found that when the calcium oxide content was 40 wt.%, the sample demonstrated optimal mechanical strength and thermal shock performance. Furthermore, the addition of water promoted the sintering of the refractory aggregates while improving the mechanical properties. However, too much water can lead to a decrease in thermal shock resistance.

These articles are just a few examples of the ceramic refractories research that is being conducted and reported in ACerS journals. To read more, visit the ACerS journals homepage at https://ceramics.onlinelibrary.wiley.com.

## References

[1]J. W. Amoroso et al., "A new method for measuring refractory corrosion of ceramics in glass," *J. Am. Ceram. Soc.* 2026, **109**(1): e70380.

[2]K. Meng et al., "Preparation and processing optimization of magnesium–calcium refractory aggregates," *Int. J. Appl. Ceram. Technol.* 2025, **22**(6): e70023.

# Calendar of events

## March 2026

**3–26** ★ Survey of Raw Materials – Virtual; https://ceramics.org/course/moody-raw-materials

**12** ➨ International Day of Ceramics; https://ceramics.org/international-day-of-ceramics

**24–26** ➨ ceramitec 2026 – Trade Fair Center Messe, München, Germany; https://ceramics.org/event/ceramitec-2026

**30–April 1** 61st Annual Greater Missouri Section / Refractory Ceramics Division Symposium on Refractories – Hilton St. Louis Airport Hotel, St. Louis, Mo.; https://ceramics.org/rcd2026

**31–April 2** ➨ Smart Additive Manufacturing, Design & Evaluation (Smart MADE 2026) – The University of Osaka Nakanoshima Center, Japan; https://sites.google.com/view/smartmade2026

## April 2026

**12** ★ Introduction to Thermal Spray Coatings: Science, Engineering, and Applications – Hyatt Regency Bellevue on Seattle's Eastside, Bellevue, Wash.; https://ceramics.org/course/berndt-intro-thermal-spray-coatings

**12** ★ Fractography of Ceramics and Glass: An Introduction – Hyatt Regency Bellevue on Seattle's Eastside, Bellevue, Wash.; https://ceramics.org/course/swab-fractography

**12–16** ACerS Spring Meeting — Bellevue, Wash.; http://ceramics.org/acersspring

## May 2026

**4** ★ AI/ML Workshop: Transforming R&D, Manufacturing and Commercial Operations – Huntington Convention Center of Cleveland, Cleveland, Ohio; https://ceramics.org/course/ai-workshop-ceramics-expo

**5–6** ➨ Ceramics Expo 2026 – Huntington Convention Center of Cleveland, Cleveland, Ohio; https://ceramics.org/event/ceramics-expo-2026

**31** ★ Testing of Materials in Extreme Environments – Sheraton San Diego Hotel & Marina, San Diego, Calif.; https://ceramics.org/course/hypersonic-testing-htcmc-gfmat

**31–June 5** 12th International Conference on High Temperature Ceramic Matrix Composites and Global Forum on Advanced Materials and Technologies for Sustainable Development – Sheraton San Diego Hotel & Marina, San Diego, Calif.; https://ceramics.org/htcmc12_gfmat3

## June 2026

**7–12** ➨ Solid State Studies in Ceramic Science Gordon Research Conference – Mount Holyoke College, South Hadley, Mass.; https://www.grc.org/solid-state-studies-in-ceramics-conference/2026

**8–10** Structural Clay Products Division & Southwest Section Meeting 2026 – DoubleTree by Hilton Canton Downtown, Canton, Ohio; https://ceramics.org/clay2026

**10–12** 16th Advances in Cement-Based Materials – University of Miami, Coral Gables, Fla.; https://ceramics.org/cements2026

**15–25** ➨ CIMTEC 2026 – Perugia, Italy; https://ceramics.org/event/cimtec-2026

## July 2026

**8–10** ➨ International Conference on Self-Healing Materials – Drexel University, Philadelphia, Pa.; https://icshm2026.org

**12–16** ➨ American Conference on Neutron Scattering 2026 – Detroit Marriott at the Renaissance Center, Detroit, Mich.; https://ceramics.org/acns2026

## August 2026

**31–Sept. 1** ➨ The International Conference on Sintering – Eurogress Aachen, Aachen, Germany; https://www.sintering2026.org/en

## September 2026

**6–11** ➨ 11th International Congress on Ceramics – Sapporo Convention Center, Sapporo, Japan; https://www.ceramic.or.jp/icc11

**29–Oct. 1** ➨ International Thermal Conductivity Conference and International Thermal Expansion Symposium 2026 – Renaissance Columbus Westerville-Polaris Hotel, Westerville, Ohio; https://ceramics.org/itcc2026

## October 2026

**4–7** ACerS 128th Annual Meeting with Materials Science and Technology 2026 – David L. Lawrence Convention Center, Pittsburgh, Penn.; https://ceramics.org/annual-meeting2026

Dates in **RED** denote new event in this issue.

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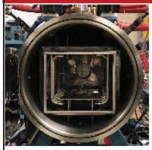

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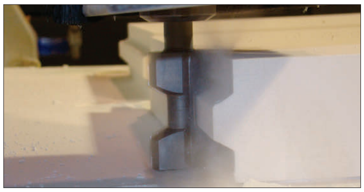

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**By Radek Pezl**

Guest columnist

# The dual challenge facing refractories: Chemical dissolution and mechanical failure

Inside a glass-melting furnace, refractories operate under continuous chemical and mechanical pressures. When failure occurs, it is rarely the result of a single weakness. More often, it reflects the combined effects of chemical corrosion and mechanical stress—the two processes that mainly govern how refractories age in service.

The effects of refractory aging are typically far from uniform because corrosion behavior changes depending on where and how the refractory is exposed.[1] In Richard Pokorny's group at the University of Chemistry and Technology Prague, we focus on how conditions within the molten glass itself—such as melt velocity, temperature distribution, and glass composition—affect refractory material loss.

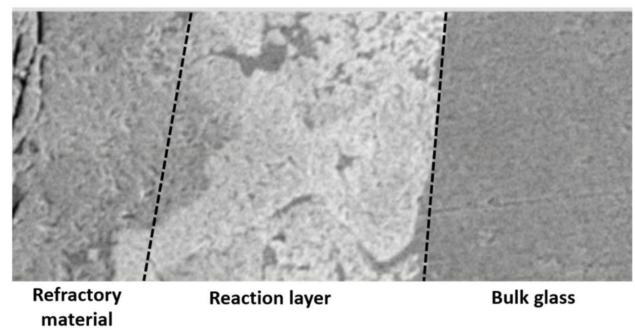
Below the melt surface, corrosion is strongly influenced by melt movement. As glass flows along the refractory wall, dissolved refractory is continually removed and replaced by fresh, aggressive melt. Under these conditions, material loss is largely controlled by diffusion of the refractory constituents through the melt boundary layer at the refractory interface, and corrosion rates increase with bulk melt velocity.[2]

At the melt surface, or the interface where glass melt, atmosphere, and refractory meet, degradation is not governed by bulk melt flow but by local surface phenomena. Marangoni convection associated with surface tension gradients caused by dissolving refractory components produces strong convective flow in the melt meniscus, leading to corrosion behavior that is practically insensitive to bulk melt velocity deeper in the furnace. However, due to the intensity of Marangoni convection, it is also the region where material degradation is most severe in practice.[3]

This distinction between corrosion processes below and at the melt surface has important practical consequences. Materials that perform well near the melt line may degrade more rapidly compared to others in the submerged region. Evaluating refractory performance using a single corrosion rate therefore risks overlooking where, and how, the material will actually be challenged in operation.

At the same time, chemical dissolution alone does not determine refractory lifetime. When molten glass contacts an oxide refractory, chemical reactions governed by local phase equilibria at the glass–refractory interface can lead to the formation of interfacial reaction layers (Figure 1). These layers often slow further dissolution by acting as a diffusion barrier,[4] which typically makes them beneficial.

However, this chemical protection also introduces a mechanical vulnerability. The reaction layer differs physically from the pristine refractory body, particularly in how it responds to temperature changes. Under steady conditions, such layers might remain intact. But in real furnaces, temperature fluctuations can occur. Routine events such as batch charging, changes in furnace load, or glass withdrawal disturb the thermal balance. In waste glass vitrification, this vulnerability is amplified. Periodic pouring causes melt levels to fluctuate, while cold feed material contacting the walls imposes severe thermal shock on refractory surfaces.




Credit: Radek Pezl

**Figure 1. Scanning electron microscope image of a refractory–glass interface, showing the formation of a reaction layer.**

As temperature rises and falls, the surface layer and the refractory beneath it expand and contract at different rates. Stress accumulates at their boundary until the bond can no longer be sustained. When that happens, the layer detaches in the form of spalling. This detachment exposes fresh refractory directly to molten glass, and corrosion accelerates until a new layer can form.

As the above paragraphs demonstrate, modeling refractory wear and tear is far from a simple process. It is essential to account for both the chemical and mechanical factors to achieve realistic lifetime estimates, and elucidating these factors remains a central focus of our ongoing work.

## References

[1]W. E. Lee and R. E. Moore, "Evolution of in situ refractories in the 20th century," *Journal of the American Ceramic Society* 1998, **81**(6): 1385–1410.

[2]R. Pezl et al., "Dynamic and static corrosion of chromium-alumina refractory in simulated nuclear waste glass," *Ceramics International* 2025, **51**(29, Part A): 60583–60591.

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*Radek Pezl is a master's student at the University of Chemistry and Technology Prague, Czechia. He researches complex refractory wear phenomena occurring during nuclear waste vitrification. His hobbies outside of school include mountain biking, hiking, and playing darts.* ■

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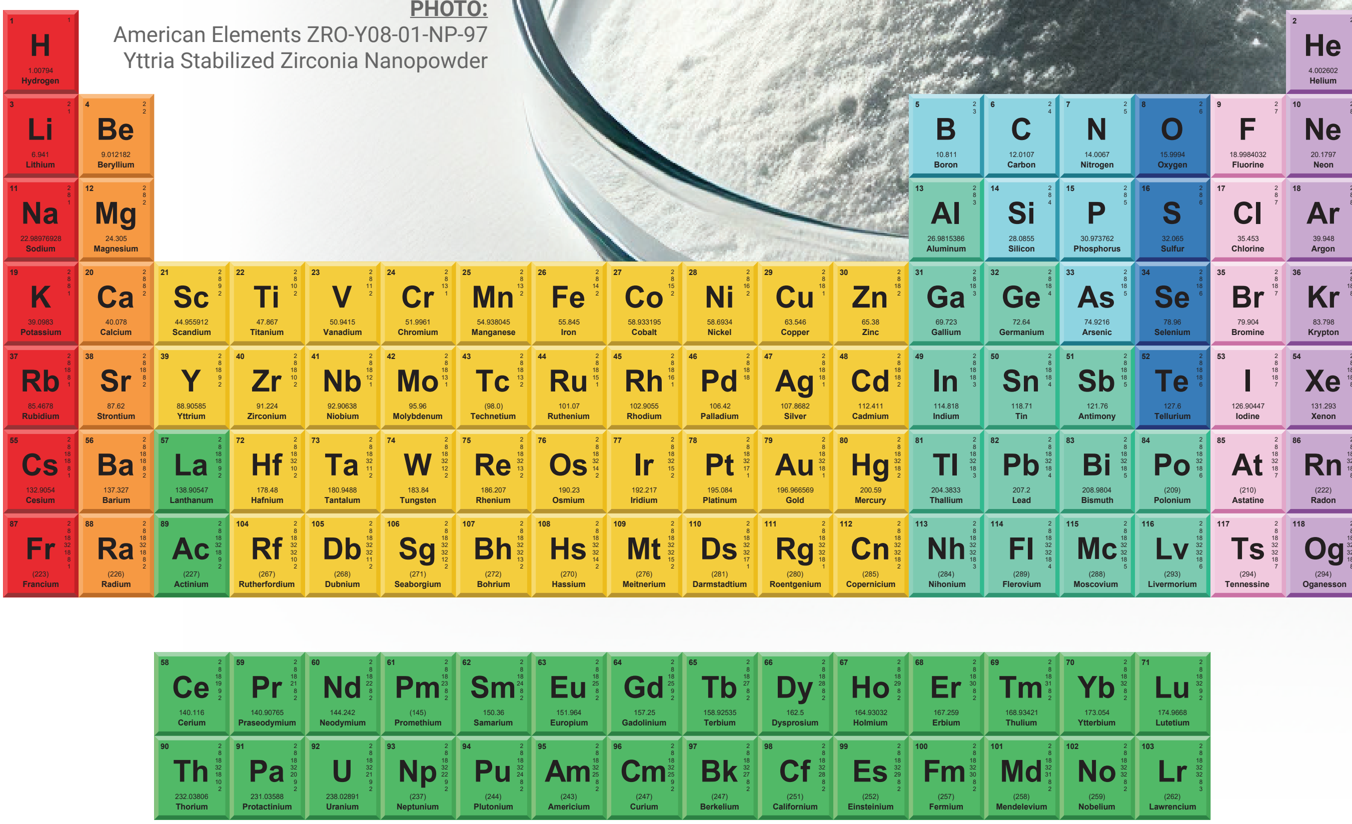


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