Better bodies with biomaterials:

How ceramic and glass contribute to the $110B global market for implantable biomaterials

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Better bodies with biomaterials: How ceramic and glass contribute to the $110B global market for implantable biomaterials
Ceramic and glass biomaterials integrate with the human body in diverse ways to support human health. As aging populations and evolving healthcare approaches shift the medical landscape, increasing opportunities for both established and innovative technologies predict a strong future for ceramics and glass.

by April Gocha and Lisa McDonald

No.5 — Ceramic & Glass Manufacturing
Setting the standards: How standards enhance quality and promote reliability
Also inside!
- Industry news
- Japan Fine Ceramics Association and its international standardization activities for fine ceramics
- A short list of standards-developing organizations

Meeting
Highlights from Virtual Ceramic Expo 2020
Highlights from Virtual Ceramic Manufacturing Solutions Conference
Electronic Materials and Applications (EMA 2021)
45th International Conference and Exposition on Advanced Ceramics and Composites (ICACC21)

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As seen on Ceramic Tech Today...

Pursuing the future of energy: A review on perovskite tandem solar cell development and fundamentals

Perovskite tandem solar cell technologies improved rapidly in the past six years, but there are still challenges keeping them from commercialization. A recent review article by two researchers at the University of Surrey in the U.K. provides an expansive look at this budding industry.

Also see our ACerS journals...

A review: Recent advances in sol-gel-derived hydroxyapatite nanocoatings for clinical applications


Review on calcium silicate-based bioceramics in bone tissue engineering

By P. Srinath, P. Abdul Azeem, and K. Venugopal Reddy International Journal of Applied Ceramic Technology

A review of acellular immersion tests on bioactive glasses—influence of medium on ion release and apatite formation

By A. Nammoets-Namn, L. Hupa, D. Rohanová, D. S. Brauer International Journal of Applied Glass Science

Sign up to get journal tables of contents and new content alerts. See this CTI post for more information: https://ceramics.org/August2020tips.

Read more at www.ceramics.org/perovskiterewiew
Toward an International Year of Glass

Glass helps us live safer and more sustainable lives, from offering a sound disposal method for nuclear waste to improving osseointegration of biomedical implants to allowing for high-speed internet access. Yet this material, which is key to so many applications, is often underappreciated in society and viewed only in terms of windows and kitchenware.

Educating the public about the importance of glass in modern society is a goal for many materials science organizations, but individual efforts only go so far. What if we could bring people together in a global initiative to raise awareness of this influential material?

That is the driving force behind a recent initiative spearheaded by the International Commission on Glass (ICG) to have 2022 declared the International Year of Glass.

Since 1959, the General Assembly of the United Nations designated specific years as United Nations International Years to acknowledge fields of international endeavor and the importance of their contributions to global society. Usually, one or more Member States propose these observances, or on occasion, specialized agencies of the United Nations such as UNESCO and UNICEF may put forth a proposal. The proposal for the International Year of Glass, though, originated from a completely different source.

International Year of Glass: From conception to a thousand endorsements

The idea for an International Year of Glass was first discussed at the 2018 Fall Annual Meeting of ICG in Yokohama, Japan, per a suggestion by ACerS Distinguished Life Member David Pye. In May 2019, ICG, The Corning Museum of Glass, The American Ceramic Society, and The Glass Art Society endorsed the idea in a presentation to the Office of the United States Mission of the United Nations in New York City, which was well received.

ICG president Alicia Durán formally introduced the initiative to the ACerS community in a “Letter to the Editor” published in the September 2019 Bulletin. At the time, she noted that “Extensive planning is now underway to inform international art and scientific glass-themed societies and museums of this endeavor to secure the United Nations declaration of the 2022 International Year of Glass.”

Since then, more than 1,100 organizations from over 70 countries have expressed support for the initiative. In an email, Durán says they are now forming an international steering committee to continue working and developing the initiative, and “Fundraising campaign, proposals of activities (international and national) and spreading these activities to the planet will be some of the tasks that we can face, and solve!!”

Coming next: November presentation to the United Nations

The next big task on the way to having 2022 designated the International Year of Glass is to receive formal approval from the UN. To do that, the International Year of Glass steering committee is preparing a presentation to be given in early November to the UN General Assembly.

Agustin Santos, the Spanish Ambassador to the UN, has guided the required resolution through the General Assembly, and he will present the proposal in November through a virtual presentation. The presentation will include introducing partner organizations and personalities in the International Year of Glass project, explaining the activities planned and concepts being developed, and how they link to the UN Agenda 2030.

Volkan Bozkir, the Turkish Ambassador and recently installed President of the Assembly, has already expressed his support and will do so during the presentation as well.

After the presentation, the resolution for approving the International Year will be presented at the 75th UN General Assembly planned for December 2020.

If you wish to become a supporting institution, you can register your interest on the official International Year of Glass website at http://iyog2022.org or email the steering committee at manager@iyog2022.org. You can follow updates on the initiative on the official LinkedIn page at https://www.linkedin.com/company/international-year-of-glass-2022.
Over the last two decades and more, a considerable effort has been invested in development of optically transparent ceramic and glass-ceramic materials for functioning as various optical elements. Fabrication techniques of ceramic components has the potential of being highly cost-effective, and exhibit improved uniformity of optical properties compared to their crystalline counterparts. The prospected uses range from transparent optical military armour up to optical laser components.

The book addresses in detail that entire scope, starting with the underlying theoretical basis through technical production details, relevant materials, and current and future prospected applications. Especially, it provides a survey and analysis of currently used and studied materials, and points out some goals for near future developments.

Chapter 1 describes the book rational topic and aims in view of some historic progress, a definition of the spectral regions of interest, definition of transparency factors, and fabrication means and costs.

Chapter 2 describes the basic physics underlying the interaction of light with matter. Fundamental features of light like polarization, interference, and interaction with matter involving reflection, refraction, absorption and scattering are related to the relevant material properties like refractive indices, and acoustic and optical waves. Special attention is devoted to energy states spectroscopy of dopant rare earth and transition metal ions.

Chapter 3 surveys in detail the issue of ceramic materials processing, with attention on those mostly adequate to obtain transparent parts of optical equipment.

Chapter 4 surveys the multitude of materials used and proposed to be used for production of transparent ceramics, all in view of available production techniques and aimed-at applications.

Chapter 5 elaborates on various possible applications of transparent ceramics, mostly for security windows, optical lenses, and laser parts, but also for some, perhaps less appreciated ones like colour filters, scintillation elements, dental parts, and many more.

The book offers the thus-far broadest and deepest account of transparent ceramics. Individuals wishing acquaintance with this still emerging field, for either teaching or performing of scientific research, will definitely benefit from learning and consulting this new book.

Roni Shneck is professor in the Department of Materials Engineering at Ben-Gurion University of the Negev, Israel.
The global market for high-strength glass increased from $28.9 billion in 2018 to $30.9 billion in 2019, and is estimated to reach $31.9 billion in 2020, corresponding to a compound annual growth rate (CAGR) of 5.0% during the two-year period. The market is forecast to rise at a CAGR of 6.1% from 2020 to 2025, reaching global revenues of $42.9 billion in 2025.

High-strength glass is a category of glass characterized by high tensile or compressive strength. Its origins can be traced back to the 1660s, when German-English officer and scientist Prince Rupert of the Rhine, Duke of Cumberland presented the first tempered glass with the shape of a teardrop to King Charles II of England. However, almost 200 years went by before the first industrial process for producing tempered glass was developed.

There are seven main sectors in which high-strength glass finds current and potential applications: aerospace and defense, construction, electronics and optoelectronics, energy, life sciences, mechanical/chemical, and transportation. Applications within the transportation sector currently account for the largest share of the market, at an estimated 53.4% of the total in 2020. High-strength glass for the construction sector represents a relatively smaller share at 21.5%, while electronics and optoelectronics is estimated to account for 7.6%. All the remaining applications represent a combined share of 17.4%.

Laminated and tempered soda-lime-silica glass currently represent the largest segment (85.4%) of the high-strength glass market, with projected sales of $27.2 billion by the end of 2020. Following that, aluminosilicate glass is estimated to be valued at $2.4 billion (7.5%), borosilicate glass at $1.6 billion (5.1%), and magnesium aluminosilicate glass at $632 million (2.0%).

Sales of high-strength glass are expected to continue rising at a single-digit rate during the next five years due to a number of relevant factors, including:

- Expected general moderate growth for most industry sectors in which high-strength glass finds application,
- Higher unit price for high-strength glass compared to traditional glass,
- Stronger demand in the construction sector due to architectural trends aimed at emphasizing natural lighting and energy savings,
- Stronger demand in the electronics and optoelectronics sector due to ongoing miniaturization and fabrication of devices with very thin profile,
- Larger use in the energy sector driven by the fabrication of solar cells and photothermal devices, and
- Emerging trends, such as higher demand for lightweight materials.

The Asia-Pacific region is currently the largest consumer of high-strength glass, with sales estimated to reach $13.1 billion by the end of 2020, corresponding to a share of 41.1% of the total. The United States represents the second-largest market (25.2%) with estimated sales of $8.0 billion while Europe is expected to reach slightly over $6.7 billion (21.1%).

About the author
Margareth Gagliardi is a research analyst for BCC Research. Contact Gagliardi at analysts@bccresearch.com.

Resource

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A Case for continuous membership

You were nominated to be an ACerS Fellow! ...but wait, you have not held continuous ACerS membership. I am sorry, you do not qualify for the Fellows distinction.

What if this situation happened to you? Do you count on renewing your ACerS membership only when you attend meetings? If you miss a meeting one year, you could experience a gap in membership and an interruption of important member benefits, such as the Bulletin and online access to ACerS’ four peer-review journals and Bulletin archives.

It also makes you ineligible to receive distinctions that require continuous membership, such as becoming an ACerS Fellow (five continuous years) or Emeritus member (35 continuous years). To be eligible for Fellow and Emeritus status, ACerS encourages you to renew your membership each year. For more information about Fellows, Emeritus, or other awards eligibility, visit https://ceramics.org/members/awards.

Volunteer Spotlight

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

Delia Brauer studied chemistry with environmental chemistry at Friedrich Schiller University Jena (Germany) and University of Northumbria at Newcastle (England) before executing a Ph.D. research project on degradable phosphate glasses and glass/polymer composites for medical applications at the Otto Schott Institute, Friedrich Schiller University Jena.

After postdoctoral research projects at the University of California, San Francisco; Imperial College London; Queen Mary University of London; and Nagoya Institute of Technology (Japan), Brauer returned to Friedrich Schiller University Jena as a junior professor in 2012. She was made a full professor of bioactive glasses in 2017.

Brauer leads an international group of students and postdoctoral researchers from various backgrounds. Her research focuses on inorganic glasses as biomaterials and on the interaction between glass and water.

She has edited one book and has contributed several chapters to publications. She is regularly invited to give talks at international conferences.

Brauer served as chair of Technical Committee 04 (Bioglasses) and member of Technical Committee 23 (Education) of the International Commission on Glass. The 2015 winner of the Gottardi Prize of the ICG, she was made a Fellow of the Society of Glass Technology (U.K.) in 2016. In 2020, together with Jessica Rimsza, she served as program co-chair of the first Virtual Glass Summit organized by ACerS.

We extend our deep appreciation to Brauer for her service to our Society!

In memoriam

Edward Aitken
David J. Barber
Daniel Reardon
Willard Renner
John Roberts
Stuart Weinland

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

Names in the News

Himanshu Jain, Lehigh University’s T.L. Diamond Distinguished Chair in Engineering and Applied Science and professor of materials science and engineering, was named winner of the 2020 Journal of Non-Crystalline Solids N.F. Mott Award, which recognizes a distinguished senior scientist with a history of outstanding contributions to the science of non-crystalline solids.

Larry Wagner joined Du-Co Ceramics as automation engineer-electrical.

AWARDS AND DEADLINES

ACerS 2020 Award winners

This year’s ACerS award winners can be seen on our YouTube channel https://youtu.be/7L9sRTTNVeI.

Congratulations to all the winners!

Upcoming awards nomination deadlines

For more information about each award, visit www.ceramics.org/awards or contact Erica Zimmerman at ezimmerman@ceramics.org.

Society awards: January 15

ACerS runs a thriving awards program that recognizes the contributions of deserving individuals and companies in the ceramics and glass community. Nominations are encouraged for candidates from groups that are underrepresented in ACerS awards relative to
their participation in the Society, including women, underrepresented minorities, industry scientists and engineers, and international members.

We urge you to submit nominations for our many Society and Division awards.

**GOMD awards: January 21**

The Glass & Optical Materials Division seeks nominations by Jan. 21, 2021, for the following awards:

- The Norbert J. Kreidl
- George W. Morey
- L. David Pye Lifetime Achievement
- Stookey Lecture of Discovery
- Varshneya-Mauro-Jain Guru-Chela Travel Fund

**Bioceramics Division Awards**

In 2020, the Bioceramics Division received ACerS Board approval for the creation of four awards with a July 1 nomination deadline:

- Bioceramics Young Scholar
- Global Young Bioceramicist
- Larry L. Hench Lifetime Achievement
- Tadashi Kokubo (sponsored by Nippon Glass Co., Ltd.)

The Division announced the first recipients for two awards.

**STUDENTS AND OUTREACH**

Register today for ACerS Annual Winter Workshop

ACerS Winter Workshop, hosted by the Ceramic and Glass Industry Foundation, will be held in conjunction with the ICACC 2021 virtual meeting on Thursday, Jan. 28 and Friday, Jan. 29, 2021. The Winter Workshop provides a combination of technical and professional development sessions designed specifically for students and young professionals. For more information and to register, visit https://ceramics.org/winter-workshop-2021.

**ACerS Global Distinguished Doctoral Dissertation Award**

This award recognizes a distinguished doctoral dissertation in the ceramics and glass discipline. The awardee must have been a member of the Global Graduate Researcher Network and have completed a doctoral dissertation as well as all other graduation requirements set by their institution for a doctoral degree within 12 months prior to the application deadline. The nomination deadline is Jan. 15, 2021. For more information, visit www.ceramics.org/doctoraldissertationaward.

**PCSA student competition awardees**

Congratulations to the following awardees from the 2020 PCSA student competitions:

**ACerS PCSA Competition**

- **2020 Artistic Creativity and Viewer’s Choice Award**
  - Macro innovations from micro observations
  - by Rachel Eckert,
  - Iowa State University

- **2020 Scientific Award**
  - Promethean Sierpinski
  - by Zach Abrams,
  - Charles E. Smith Jewish Day School

**ACerS PCSA Lab Blooper Competition**

- **2020 Artistic, Scientific, and Viewer’s Choice Award**
  - Murphy’s Law always obey
  - by Anna De Marzi,
  - University of Padova
CGIF welcomes new board members

The Board of Trustees of the Ceramic and Glass Industry Foundation welcomed four new Board members at its recent meeting.

Alex Cozzi
Manager, applied materials research
Savannah River National Laboratory
Aiken, S.C.

Nola K. Pearce
Vice president/Account executive
ETS Tech-Ops
Rochester, N.Y.

Leslie Fenwick Beiter
Regional account manager–ceramics
U.S. & Canada, Almatis, Inc.
Leetsdale, Pa.

John Kieffer
Professor, University of Michigan
Ann Arbor, MI

Jeff Kohli
Director of glass research
Corning Incorporated
Painted Post, N.Y.

Nola K. Pearce
Vice president/Account executive
ETS Tech-Ops
Rochester, N.Y.

Jeff Kohli
Director of glass research
Corning Incorporated
Painted Post, N.Y.

CGIF Board of Trustee Officers for 2020–2021 are chair Mary Stevenson, president of Deltech, Inc.; chair-elect Todd Steyer, chief engineer for materials & technologies at The Boeing Company; immediate past chair Thomas Arbanas, president of Du-Co Ceramics; treasurer Steve Houseman, president of Harrop Industries; and secretary Mark Mecklenborg, executive director of The American Ceramic Society.

There can be no doubt that this year was a rough one for all of us. Despite that, the CGIF has remained diligent in finding new ways of reaching students—the future of our industry. Now more than ever, your gift to the Ceramic and Glass Industry Foundation is vital to our success in attracting students to the ceramics and glass fields as we fill the talent pipeline for industry. Please visit our website at https://foundation.ceramics.org/give or donate via your cell phone by texting the word “give” to 614-914-2685.
ANNOUNCING A NEW WAY FOR YOUNGSTERS TO LEARN ABOUT MATERIALS SCIENCE!

The Ceramic and Glass Industry Foundation is proud to introduce our Mini Materials Demo Kit, a collection of seven simple demonstrations for use practically anywhere by parents, teachers, and students who are utilizing online and at-home teaching resources.

Demonstrations included:

- WHAT IS FLUORESCENCE?
- THE SCIENCE OF SILLY PUTTY®
- MAGIC COLOR BEADS AND UV LIGHT
- WHAT IS FIBER OPTICS?
- DOES HEATING AN ALUMINUM NAIL MAKE IT HARDER?
- HOW ARE GLASS FIBERS MADE?
- WHAT IS A SHAPE MEMORY ALLOY?

The Mini Materials Demo Kit provides interesting activities for the whole family to be done at home or in the classroom and can be purchased for only $49!

Contact Belinda Raines at braines@ceramics.org for more information and quantity discounts.

Still available is the full-size Materials Science Classroom Kit for middle and high school students and classroom teachers. Purchase or donate a Materials Science Classroom Kit to a school in your area for only $250 at ceramics.org/donateakit.
Titanium-reinforced bioceramic implant induces cranial regrowth in sheep

Researchers from several Swedish universities and institutes described in a recent paper a synthetic ceramic implant they created that could regenerate bone in large cranial defects in sheep.

Cranioplasty, or the surgical reconstruction of a defect in the skull, is a practice stretching back hundreds of years, but the technique only became common during the second half of the 20th century, due largely to warfare providing an impetus to improve our ability to cover large cranial defects.

To date, autologous bone grafts, or grafts made from bone obtained from other areas of the patient, are the standard for reconstructive treatment. Yet this approach is associated with frequent complications, in particular relatively high resorption, protrusion, and infection rates and a high rate of donor-site morbidities.

In the past few decades, researchers have extensively investigated alloplastic materials, or synthetic materials that substitute for tissue, as another option for cranioplasty grafts. Calcium phosphate ceramics are one group of materials that have played a central role in modern alloplastic cranioplasty research due to their biocompatibility and osteoconductivity, i.e., the ability of bone-forming cells in the grafting area to move across a scaffold and slowly replace it with new bone.

Calcium phosphate cements in particular have gained an edge over granular calcium phosphates because of advantages afforded by the cements’ self-hardening properties, which make molding the brittle ceramic into a desired shape easier. Often, the cements are combined with or overlaid on other materials such as biodegradable fibers or titanium mesh, respectively, to augment strength of the graft.

In recent years, several studies showed calcium phosphate ceramics that consist of several phases, such as beta-tricalcium phosphate (β-TCP) and hydroxyapatite, exhibit improved or new properties compared to ceramics with a single phase. For example, high protein adsorption and osteoinduction, or the ability to stimulate cells to change into bone-forming cells. More researchers are now exploring mixed-phase calcium phosphate ceramics, such as the collaborative group of researchers in Sweden.

For their study, the researchers from the University of Gothenburg, Uppsala University, and Karolinska University Hospital and Karolinska Institutet chose a powder mixture of β-TCP/dicalcium pyrophosphate and monocalcium phosphate monohydrate for their ceramic, which they mixed with glycerol to form a paste. They molded this bioceramic paste in the form of hexagonal tiles around an additively manufactured titanium frame.

The titanium-reinforced bioceramic implant and a control implant made only of titanium were placed in sheep skulls for testing. Following analysis of observations recorded at three months and 12 months, the researchers drew several notable conclusions, including:

- **Bone growth:** In the sheep skull, the bioceramic implant promoted a higher degree of bone formation, remodeling, and osseointegration compared to the titanium implant, leading to enhanced repair of the cranial defect. Outside the skeletal envelope, only the bioceramic implant promoted bone formation and maintained bone. Regardless of the location, the regenerated bone from the bioceramic had a composition similar to that of the native bone.

In the discussion section, the researchers note two main limitations of the study: the absence of a mechanical evaluation after bone regeneration, and the absence of cellular and molecular techniques to shed light on the underlying ceramic-to-bone transformation mechanisms. Despite these limitations, the researchers say the study provided proof-of-concept for this bioceramic’s potential to promote in situ bone regeneration and osseointegration.

The open-access paper, published in *Proceedings of the National Academy of Sciences*, is “In situ bone regeneration of large cranial defects using synthetic ceramic implants with a tailored composition and design” (DOI: 10.1073/pnas.2007635117).

To date, top-down approaches to nanostructure construction are used extensively in the semiconductor industry to fabricate integrated circuits, among other things. Specifically, lithographic techniques—or techniques by which a pattern is transferred onto a surface—are typically used.

Common lithographic techniques involve using beams of light, electrons, or ions to etch patterns onto a surface. However, though these techniques work well for fabricating nanostructures on most surfaces, they run into some challenges when used to pattern 2D materials, such as causing structural damage.

Scanning probe lithography (SPL) is one type of lithography that holds potential for effectively fabricating nanostructures in 2D materials. Instead of using a focused beam of particles to etch patterns in a sample, SPL methods use a physical tip to modify the surface through various physical and chemical interactions, such as scratching, nanoindentation, or heating.

Among SPL methods, thermal scanning probe lithography (t-SPL) has gained much attention in recent years. This method involves using a heated nanotip to modify the surface of a sample, and it has now reached a high level of technical maturity, with several dedicated tools to perform reliable t-SPL.

In the recent open-access study on t-SPL, the researchers made a significant change to the setup of their experiment to fully harness the thermal component of t-SPL.

Instead of placing the 2D materials directly on an inelastic substrate, they placed a polymer layer between the 2D layer and substrate. “The polymer we use is polyphthalaldehyde (PPA) with a glass transition temperature of ≈150°C. Above this temperature, … PPA does not melt but directly sublimes,” they write in the paper.

When they pressed the heated tip into the 2D material, sublimation of the underlying polymer layer allowed the tip to achieve a deeper indentation, thus making it easier to cut through the 2D material’s chemical bonds.

The researchers used the t-SPL method to create square patterns in a variety of molybdenum-based 2D materials, with pattern sizes ranging from 20 to 200 nm. “The smallest feature we were able to cut is about 20 nm, which is the smallest reported for a direct cutting method and is similar to the resolution in [electron beam lithography],” they write.

They also note their method is not limited to cutting monolayers but also can be used to cut certain multilayers and, “most interestingly,” heterostructures. They acknowledge graphene, even at monolayer thickness, could not be fractured “as the intra-layer bonding exceeds the force that can be applied with the t-SPL tool,” but they say this limitation “could be eventually overcome with a t-SPL cantilever that can apply larger contact forces.”

In an EPFL press release, first author Xia Liu, researcher and postdoc in the School of Engineering’s Microsystems Laboratory, says their technique could prove quite useful to the semiconductor industry.

“This generic technology will be very useful in nanoelectronics, nanophotonics, and nanobiotechnology, as it will help to make electronic components smaller and more efficient,” she says.

The open-access paper, published in Advanced Materials, is “Thermomechanical nanocutting of 2D materials” (DOI: 10.1002/adma.202001232).
When master artisans passed down recipes for historic pottery from generation to generation, they determined correct firing and other processing conditions by relying on senses and experiences that could in no way be captured, even when records were kept. So it is no wonder some of the beauty and utility of historic pottery is difficult to replicate today, even by skilled artisans and engineers.

As archeologists find more artifacts, archeometrists seek to unlock the secrets of ancient civilizations and their engineers and artisans. But how can these scientists uncover key mechanical and chemical information from such priceless, irreplaceable items? How can they figure out how they were produced? Examining shards is helpful when the tests can be destructive, but it only goes so far. Instead, scientists use models to estimate and attempt to reproduce such items.

Two recent open-access articles in International Journal of Ceramic Engineering & Science discuss models that were used to better understand ceramics from different parts of the world designed for very different purposes: commerce and decoration.

Amphorae: Understanding mechanical properties of standard transport containers

With the advent of regional trade, merchants needed containers in which to store and transport goods over long distances, especially by boat. And one type of ceramic container used often in antiquity for this purpose was amphorae. Amphorae are bullet-shaped vessels, typically with long necks and handles that are affixed near the mouth of the vessel on one end and attached to the body at the other. They are specifically designed to be stacked inside cargo holds of ships in multiple layers.

While the amphorae itself had some value, the real value lay in the vessel’s...
contents. As such, if the container broke and the contents of that vessel were lost—and potentially damaged other goods in the cargo hold as well—it could result in substantial losses to the producer and the ship owner.

In the first open-access paper, Anno Hein and Vassilis Kilikoglou from the Institute of Nanoscience and Nanotechnology in Greece assessed specific design features of different amphorae for their performance (e.g., failure potential), particularly during transport. Furthermore, they used simulations to provide information to help interpret typical damages observed in archaeological finds.

The researchers ran nondestructive testing such as X-ray tomography to determine wall thicknesses while performing mechanical testing on shards to get insights into mechanical strength, tangent moduli, and plastic deformation.

They used the limited experimental information as inputs and boundary conditions for finite element modeling of the stresses that build up at the contact points of the amphorae due to static vertical loading (e.g., the weight of one layer on the next), dynamic vertical loads (ships travel over waves), and dynamic horizontal loads (ships rocking side-to-side).

The results of the modeling include compressive and tensile stresses on the exterior and interior walls of the amphorae. Excessive compressive loads are found, but the authors surmise these loads result in elasto-plastic deformation, which is not catastrophic. Tensile stresses on the outer surfaces, on the other hand, can lead to crack initiation and eventual failure. Failed amphorae artifacts show damage in the areas predicted by the modeling.

The open-access paper, published in International Journal of Ceramic Engineering-
Ru celadon: Investigating the coloring of a masterwork of Chinese ceramics

Celadon is a pottery term that refers to both a transparent, greenish glaze and the wares to which the glaze is applied. Though the term is purely European, celadon originated in China, and today notable kilns such as the Longquan kiln in Zhejiang province are renowned for their celadon glazes.

Celadons come mostly in some shade of green, but shades of pale blue—naturally Ru celadon—are highly valued, and in historical times were reserved more or less exclusively for use in the Chinese Imperial court.

In the second open-access paper, Yen-Yu Chen (Chinese Culture University) and Yi-Wun Bai and Wen-Cheng J. Wei (National Taiwan University) investigated methods to reproduce the unique color and milky opalescence of ancient Ru celadon glazed ceramics.

The color of celadon is generated by two mechanisms: chemical coloring by iron species in calcium aluminosilicate compositions; and structural coloring by inhomogeneities, specifically crystallites and voids in the celadon glass. While there is some information available about the material composition of ancient celadon—both from analysis of ancient shards and from prior studies—the fabrication methods are not well understood. For example, it is believed the porcelain was fired in a reducing environment, but there is no way of knowing the composition of the gases or their temperature—the technology simply did not exist for those measurements 1,000 years ago.

In this article, the researchers created their own celadon by varying a range of experimental conditions, including composition relative to phase stability data for the complex chemical system and firing temperatures, environments, and holding times. They measured the model systems they created against a shard of ancient celadon ceramic for color, microstructure, and chemical content of the glass and crystallites.

In the end they came close to the ancient celadon color and opalescence, giving insight into ancient firing protocols. Their work supports the combination of the chemical coloring and structural coloring mechanisms. Specifically, the dual-phase nature of the glass contributes to Rayleigh scattering while crystallites and voids contribute to the “milky” color, while the ratio of Fe²⁺ and Fe³⁺ oxidation states of iron contribute to chemical coloration.

The open-access paper, published in *International Journal of Ceramic Engineering & Science*, is “Analysis of structural effects on coloring mechanism of Ru celadon porcelain” (DOI: 10.1002/ces2.10058).

Updated small-polaron transport model accounts for complex oxide systems

An interdisciplinary collaboration between Cornell University and Technion-Israel Institute of Technology (Israel) updated a model for ceramic conduction to more accurately calculate small-polaron transport in complex oxides.

For the past 60 years, researchers described the movement of polarons through a material using a small-polaron transport model developed by Heikes and Ure in the 1960s. However, Heikes and Ure developed the model based on binary compounds. When this model is used to describe conduction in higher-order oxides with multiple cations, it quickly runs into problems, as the researchers describe in their paper.

“For instance, in the binary spinel Fe₃O₄, all of the charge-conducting octahedral (Oh) sites are occupied by Fe cations, and charge transport occurs along pathways having an alternating arrangement of Fe²⁺/Fe³⁺,” they explain. “On replacing an Fe²⁺ cation with a Mn²⁺ cation, although the donor/acceptor pair arrangement is still present, the charge transport may be affected by the differences introduced by the hopping barriers or different spinstates between the Fe²⁺/Mn²⁺ cation pairs.”

To update the conventional small-polaron transport model, the researchers investigated conduction in a tightly defined sample of epitaxial thin films of the spinel MnFeₓO₄ grown by molecular-beam epitaxy.

Experiments on the MnFeₓO₄ spinels confirmed what the researchers suspected—that charge cannot hop between manganese and iron cations. “This creates a requirement for a contiguous elemental path and leads to an additional condition for charge transport to occur: separate, decoupled percolation networks need to be formed by both Fe and Mn cations,” they write.

They also observed a preference for polarons to travel along the manganese pathways rather than the iron pathways, and the presence of asymmetric hopping barriers between cross-hopping pairs.

“To account for these observations, we introduce a percolation parameter, a polaron distribution parameter, and a cross-hopping parameter to the conventional electronic conductivity equation that correct the model for higher-order spinels,” they write.

The updated model with these additional parameters showed “excellent overlap” with the experimental trends, thus “confirming the role of percolation pathways and cross-hopping in describing the charge transport in ternary spinels.”

The paper, published in *Advanced Materials*, is “Breakdown of the small-polaron hopping model in higher-order spinels” (DOI: 10.1002/adma.202004490).

An updated ceramic conduction model may help researchers custom-tailor the properties of metal oxides in energy technologies such as lithium-ion batteries, fuel cells, and electrocatalysts.
Ceramic matrix composites contain corrosive materials in thermal energy storage

In the recent September/October 2020 issue of the International Journal of Applied Ceramic Technology, two articles from different research groups in Germany explore creating carbon/carbon-silicon carbide (C/C–SiC) ceramic matrix composites (CMCs) for use as container materials in thermal energy storage systems.

Thermal energy storage systems offer an alternative to batteries and pumped hydro for storing energy generated from renewable sources. However, the molten salts and other closely related materials that are at the center of such systems are difficult to contain due to the highly corrosive nature of the liquid materials, moderately high operating temperatures, and substantial expansion during the transition from solid to liquid.

Producing container materials that can withstand the high temperatures, thermal expansion stresses, and corrosive materials for decades of operation are key to adoption of large-scale thermal energy storage. And as the research groups in Germany showed, C/C–SiC CMCs have the potential to serve as good container materials.

In the first open-access article, researchers from the German Aerospace Research Center and the University of Augsburg in Germany describe the design, fabrication, and characterization of a C/C–SiC container for an aluminum-silicon phase change alloy.

The first stages of their study focused on fabrication and compatibility testing of C/C–SiC test bars. They found the bars withstood the liquid aluminum-silicon alloy and maintained their physical properties with no discernable interactions, such as penetration of the alloy into the test bars. Though there are potential chemical reactions between the alloy and the CMC, the researchers found no evidence of substantial reactions, which echoes the findings of other researchers.

Following the test bars, they continued with the design and fabrication of the container. They decided on low-cost, scalable techniques for fabricating the four main components of their annular container and then used these techniques as boundary conditions for finite element analysis. They used finite element analysis to determine container wall thickness by balancing the strength needed to withstand stresses that arise during phase changes against heat conduction requirements to allow efficient energy transfer.

Unfortunately, pressure testing of the container revealed cracks at the interface of two of the parts, which most likely occurred during fabrication. Though the flaw prevented the full regimen of performance testing, and several issues require further experimentation, the researchers believe the container shows promise for thermal energy storage application.

The second article, by researchers from Chemnitz University of Technology in Germany, describes a different path to low-cost fabrication of C/C–SiC composites. The researchers prepared C/C–SiC using carbon fiber reinforced polymers as the starting material. The moldable precursor polymers are shaped and cross-linked, then pyrolyzed to C/C composites under argon atmosphere. Conversion to C/C–SiC is achieved by either liquid silicon infiltration or internal siliconization, the latter of which is accomplished by mixing silicon powder into the original polymer.

The researchers explored the effects of carbon fiber fraction (weight %), silicon fraction, and silicon loading method by measuring the processing parameters of mass loss, shrinkage, and porosity, and performance parameters of strength and elongation. The results are complex, but in short, the researchers concluded that the best mechanical properties were found to be at a fiber mass content of 40%, and a silicon amount higher than 14 wt% negatively influences the whole process.

Their results show that molding C/C–SiC composites from preceramic polymer-based mixtures has the potential to be a cost-effective method for fabrication of complex structures. Further research to optimize properties and processing parameters should improve the end-product performance and allow this method to compete with the more conventional fabrication methods, such as those employed by the authors of the first open-access paper.

The first open-access paper, published in International Journal of Applied Ceramic Technology, is “C/C–SiC component for metallic phase change materials” (DOI: 10.1111/ijac.13570).

The second paper, published in International Journal of Applied Ceramic Technology, is “Properties of C/C–SiC composites produced via transfer moulding and inner siliconization” (DOI: 10.1111/ijac.13548).
Polar rather than conductive battery cathodes lead to long-term cycling stability

An international team led by Jong-Su Yu from Daegu Gyeongbuk Institute of Science & Technology (Korea) and Khalil Amine from Argonne National Laboratory conducted a recent study to determine the respective importance of two key properties—polarity and conductivity—in improving the cycling stability of lithium-sulfur batteries.

Li-S batteries have a theoretical specific energy of more than 2,500 Wh/kg, which is much higher than the average specific energy of 100–265 Wh/kg for current Li-ion batteries. However, to date the experimental values of Li-S battery specific energy have been far below theoretical values.

The main mechanisms hindering Li-S battery performance are irreversible loss of sulfur from the cathode (the polysulfide “shuttle” effect) and unstable lithium deposition on the anode. These mechanisms are not the only challenges, however. Sulfur also has low electrical conductivity ($5 \times 10^{-30}$ S/cm at room temperature), which hinders the cycling efficiency of Li-S batteries.

To improve conductivity, researchers have experimented extensively with placing the cathode’s sulfur within highly conductive carbon host materials, such as hollow porous carbon, graphene, mesoporous carbon, and microporous carbon. Unfortunately, long-term cycling stability continues to be a problem because of the nonpolar covalent bonds that carbon forms with itself, which prevent polysulfides on the carbon surface from attaching strongly, and instead they diffuse away—leading to the notorious polysulfide “shuttle” effect.

Researchers have investigated employing oxide additives, polymers, or other inorganic materials on the carbon framework to enhance polysulfide confinement and mitigate the polysulfide shuttle effect. But these methods often require complicated and expensive synthesis processes, plus they limit the accommodation of sulfur by reducing available surface area.

Shuttling of polysulfide compounds (shown as yellow and blue chains) impairs the performance of lithium-sulfur batteries. Polar host materials for the cathode’s sulfur can mitigate this effect, and researchers found this ability makes up for the materials’ low conductivity.

Based on these challenges, the question of the best host material for sulfur in Li-S batteries remains wide open.

In the recent study, the researchers wanted to determine if it is better to pursue polarity or conductivity in the cathode to improve cycling if only one of these two properties can be maximized. To answer this question, they designed two cathodes, one made from platelet ordered mesoporous silica (pOMS) and one made from platelet ordered mesoporous carbon (pOMC).

“The two cathodes were designed to be exact replicas of one another apart from the use of either silica or carbon,” Amine says in an Argonne press release. “This way, we could determine whether a more polar cathode or a more conductive cathode improved the longevity of the battery.”

Upon testing, the researchers found that while the conductive carbon host with a higher specific surface area of 1,597 m² g⁻¹ showed better initial capacity, “the polar [silica host] with a lower surface area of 844 m² g⁻¹ reveals much more stable performance for long cycles and eventually outperforms the conductive counterpart after 500 cycles.”

In addition, the silica host also demonstrated outstanding low fading rates, even at high current density, and comparable and improved areal and volumetric capacities, respectively, compared to carbon hosts.

“These outstanding areal and volumetric capacities, as well as cycle stability, which have not been achieved by even state-of-the-art carbon hosts, clearly indicate that the polar [silica] host, despite nonconductivity, has high promising potential for energy storage in [Li-S batteries],” the researchers write in the paper.

Of course, electrical conductivity is still necessary to achieve good electrochemical performance. “However, the conductivity is not a big issue in the host itself since the poor conductivity of the host can be compensated by the conducting agent involved as a required electrode material during electrode preparation,” the researchers add.

In the conclusion, the researchers note they are currently investigating ways to improve electron pathways in the silica host while maintaining the high surface polar properties, such as by adding a thin conductive carbon coating to the silica to enhance conductivity.

There are few systems that can efficiently incorporate materials that provide structural support, filtration capacity, energy generation, energy storage, electrical conductivity, gas exchange, processing power, dynamic flexibility, and regenerative potential into one integrated, highly functional, and incredibly adaptable self-contained system. Yet the human body is a system that can provide all those functions and many more, and it does so through a unique collection of highly functional materials.
Better bodies with biomaterials

Collectively those materials enable everything our bodies do, and they often retain functionality throughout the human lifespan, which worldwide is an average of 73.2 years. However, the materials are not always perfect and sometimes fail due to overuse, injury, disease, or genetics—circumstances that are becoming more common as worldwide populations age due to population dynamics and increasing life expectancies.

Globally, the number of individuals over 65 years old surpassed that of children under 5 years old for the first time in history in 2018. And while an estimated one in 11 individuals (9%) around the world were over 65 years old in 2019, the older population is expected to increase to one in six (16%) by 2050.

These trends affect nearly every aspect of life, perhaps most notably healthcare. Individuals are living longer and are remaining active until later years of life, demanding enhanced strategies to maintain longer functionality of the body’s materials.

Humans have long turned to biomaterials in diverse forms to repair, replace, or enhance bodily materials (Figure 1), establishing a global market for implantable biomaterials that was estimated to be worth nearly $110 billion in 2019. While metals, polymers, ceramics, and glass all are used for biomaterial applications, ceramics and glass have a particular advantage, says Frank Anderson, vice president of Global Research and Development at CoorsTek (Golden, Colo.). “Many technical ceramics are inherently biocompatible, chemically resistant, and inert, which gives them a unique advantage over other implantable materials,” he says.

The global market for bioceramics was valued at $14.5 billion in 2016 and is predicted to reach a value of $20.2 billion by 2021, growing at a 6.9% compound annual growth rate (CAGR). The market is mainly dominated by alumina and zirconia, which account for 75% of the market due to primary use of these materials in bone and dental implants. Other bioceramics frequently found in implantable devices include hydroxyapatite and tricalcium phosphate, and bioactive glass also has clinical applications, and glass help repair, replace, and enhance all types of bodily materials.
collectible applications with rapidly expanding potential throughout the human body.

It should be noted that while these materials predominate many implantable applications within the human body, mainly due to their acceptance and time on the market, other ceramic and glass compositions are also suitable for many of these applications, and we might expect their purview to expand in future markets.

Collectively, ceramic and glass materials enable many different kinds of implantable medical products that not only significantly contribute to human health but also constitute robust industries with rich economic impact. Table 1 provides a sample of some companies that manufacture ceramic and glass biomaterials or implantable products.

The following sections highlight a handful of applications for ceramics and glass in the human body. Although the listed applications are not exhaustive, the diversity highlighted here should provide a flavor of the vast potential of ceramics and glass within the human body.

PACKAGING: GLASS PROTECTS BOTH BODY AND DEVICE

Ceramic and glass materials are incorporated into or play supporting roles in many electronic devices implanted into the human body, such as neurostimulators and pacemakers. In these applications, a bioinert and long-lasting barrier between the device components and the harsh environment of the body is imperative to protect both—precisely a job for ceramics and glass.

For instance, glass-sealed feedthroughs and packaging often encase the batteries for implantable pacemakers, where a hermetic seal preserves both function of the device and safety of the patient.

“Glass is used to seal the terminals of pacemaker batteries. It acts as an electrical insulation material for the metal conductors. At the same time, glass creates a reliably gas-tight barrier when hermetically sealed with the electrical contact pins,” says Jochen Herzberg, medical program manager of Schott’s Electronic Packaging business unit (Landshut, Germany).

“Specially selected glass types are resistant to the highly corrosive environment in the battery. And it doesn’t deteriorate
Better bodies with biomaterials

or get brittle over time like polymers or epoxies. It enables a higher reliability and a longer device lifetime.”

To manufacture the glass-to-metal sealed packages and feedthroughs, Schott presses finely ground glass powder into a ring shape that is then sintered and assembled with the metal conductors inserted in the middle of the ring and an outer metal casing. The three components then undergo a sealing process in a belt furnace to bond the materials together.

Although this manufacturing technique provides a hermetic seal for battery feedthroughs, there is another glass technology that comes into play when miniaturization or encapsulation of heat-sensitive components is required. For those applications, Schott has another solution with its Primoceler glass micro-bonding technology. This wafer-scale technology uses a laser to precisely and locally bond glass to glass, creating a vacuum-tight bond with no additional materials.

“If you want to encapsulate, for example, a miniature sensor inside of a glass package, this is possible by stacking base wafers with spacer glass and cover or etched lid wafers, thereby creating a cavity in which the sensor device will be encapsulated,” Herzberg says. “The stacked glass wafers are then laser-sealed, resulting in a gas-tight all-glass sensor package. One major advantage of Primoceler laser bonding technology is that it all happens at room temperature. So even if the sensor is very heat sensitive, which is usually the case, it can be packaged using the Schott Primoceler process. The extremely precise laser fuses

<table>
<thead>
<tr>
<th>Company (location)</th>
<th>Annual revenue (millions)*</th>
<th>Website</th>
<th>Role in value chain</th>
</tr>
</thead>
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<tr>
<td>Johnson &amp; Johnson (Berkeley, Calif.)</td>
<td>$82,100</td>
<td><a href="http://www.jnj.com">www.jnj.com</a></td>
<td>Develops, manufactures, and supplies diverse healthcare products, including medical devices such as orthopedic products.</td>
</tr>
<tr>
<td>Stryker</td>
<td>$14,900</td>
<td><a href="http://www.stryker.com">www.stryker.com</a></td>
<td>Develops, manufactures, and supplies diverse healthcare products, including medical devices such as orthopedic products.</td>
</tr>
<tr>
<td>Kyocera Corp. (Kyoto, Japan)  • Life &amp; Environment Group, business segment that includes medical and healthcare</td>
<td>$15,404 $760</td>
<td><a href="http://global.kyocera.com">http://global.kyocera.com</a></td>
<td>Develops, manufactures, and supplies advanced materials to diverse markets; medical application is mainly ceramic hip implants.</td>
</tr>
<tr>
<td>Zimmer Biomet (Warsaw, Ind.)</td>
<td>$7,982</td>
<td><a href="http://www.biomet.com">www.biomet.com</a></td>
<td>Develops, manufactures, and supplies orthopedic products, including artificial joints and dental prostheses.</td>
</tr>
<tr>
<td>Schott AG (Mainz, Germany)</td>
<td>$2,568</td>
<td><a href="http://www.schott.com">www.schott.com</a></td>
<td>Develops and manufactures diverse ceramic and glass products, including dental materials, medical device electronic components, implant packaging.</td>
</tr>
<tr>
<td>The Straumann Group (Basel, Switzerland)</td>
<td>$1,746</td>
<td><a href="http://www.schott.com">www.schott.com</a></td>
<td>Develops and manufactures diverse dental solutions, including implants, prostheses, technologies, and biomaterials.</td>
</tr>
<tr>
<td>Morgan Advanced Materials Plc (Windsor, U.K.)</td>
<td>$1,356</td>
<td><a href="http://www.morganadvancedmaterials.com">www.morganadvancedmaterials.com</a></td>
<td>Develops and manufactures ceramic components for medical applications, such as feedthroughs for implantable devices.</td>
</tr>
<tr>
<td>Wright Medical Group NV (Middlesex, U.K.)</td>
<td>$921</td>
<td><a href="http://www.wright.com">www.wright.com</a></td>
<td>Medical device, especially orthopedic surgical solutions and biologics.</td>
</tr>
<tr>
<td>CoorsTek (Golden, Colo.)</td>
<td>$1,000†</td>
<td><a href="http://www.coorstek.com">www.coorstek.com</a></td>
<td>Develops and manufactures technical ceramics for numerous industries, including orthopedic and implantable ceramics, (including ceramic hip implants), medical device components, and pharmaceutical components.</td>
</tr>
<tr>
<td>Ceramtec GmbH (Plochingen, Germany) • Medical products</td>
<td>$727 $304</td>
<td><a href="http://www.ceramtec.com">www.ceramtec.com</a></td>
<td>Develops and manufactures ceramic orthopedic components (including ceramic hip implants), dental implants, and medical engineering devices.</td>
</tr>
<tr>
<td>Nobel Biocare (Zürich, Switzerland)</td>
<td>$2629†</td>
<td><a href="http://www.nobellbiocare.com">www.nobellbiocare.com</a></td>
<td>Manufactures and supplies diverse dental solutions, including implants, prostheses, technologies, and biomaterials.</td>
</tr>
<tr>
<td>Rauscher GmbH (Prassig, Germany)</td>
<td>$67†</td>
<td><a href="http://www.rauscher.com">www.rauscher.com</a></td>
<td>Manufacturer of technical ceramics, including ceramic medical components.</td>
</tr>
<tr>
<td>DSM Biomedical (Exton, Pa.)</td>
<td>$65†</td>
<td><a href="http://www.dsm.com/biomedical">www.dsm.com/biomedical</a></td>
<td>Develops and manufactures biomaterials including bioceramics for diverse healthcare industries.</td>
</tr>
<tr>
<td>Collagen Matrix Inc. (Oakland, N.J.)</td>
<td>$15†</td>
<td><a href="http://www.collagenmatrix.com">www.collagenmatrix.com</a></td>
<td>Manufactures collagen and mineral-based medical products for dental and orthopedic applications, including ceramic and bioglass bone grafts.</td>
</tr>
<tr>
<td>Mo-Sci (Rolle, Mo.)</td>
<td>$6†</td>
<td><a href="http://www.mo-sci.com">www.mo-sci.com</a></td>
<td>Develops and manufactures high-tech glass, including bioactive glass for medical applications.</td>
</tr>
<tr>
<td>Lithoz GmbH (Vienna, Austria)</td>
<td>$5†</td>
<td><a href="http://www.lithoz.com">www.lithoz.com</a></td>
<td>Develops and manufactures additive manufacturing technologies, particularly with ceramic materials, for diverse industries including medical applications.</td>
</tr>
<tr>
<td>CAM Bioceramics (Leiden, The Netherlands)</td>
<td>$3.5†</td>
<td><a href="http://www.cambioceramics.com">www.cambioceramics.com</a></td>
<td>Develops and manufactures bioactive calcium phosphate and coatings for orthopedic and dental applications.</td>
</tr>
<tr>
<td>Berkeley Advanced Biomaterials Inc. (Berkeley, Calif.)</td>
<td>$0.6†</td>
<td><a href="http://www.hydroxyapatite.com">www.hydroxyapatite.com</a></td>
<td>Develops and manufactures calcium-based biomaterials for medical industry, particularly bone grafts.</td>
</tr>
</tbody>
</table>

*Conversions per Google as of October 16, 2020. All financial data obtained from company reports unless otherwise noted.  
†Private company or data not available; revenue estimated from dnb.com or google.com.
and melts only the very small interface area where the glass wafers meet—an area of just some tens of microns—while leaving all other surfaces untouched.”

(Figure 2)

The possibilities of such technology are wide-reaching even within implantable device applications, but one of the first to see clinical application is in the eye.

For patients with reduced or lost sight due to retinal degradation, a company called NanoRetina (Herzliya, Israel) pioneered an artificial retina device. NanoRetina’s NR600 implant, which is designed to mimic the functionality of the eye’s highly sensitive photoreceptor cells, is a tiny chip containing an imager, 3D neural interface, and embedded photovoltaics to provide power. The device is completely encased in glass using Schott Primoceler technology (Figure 3).

“Without our glass-to-glass laser bonding technology, this would not have been possible because the encapsulated sensor inside is very heat sensitive. Only with our technology could we encapsulate it at room temperature,” Herzberg says.

Enabled by glass, NanoRetina’s NR600 implant entered a small clinical trial of 20 patients in Europe and Israel in early 2020 and already shows promising results. “The device was activated for the first time, and the result was amazing: this patient had been completely in the dark for five years, and she immediately reported seeing an image in the center of her visual field when the device was activated, and could show with her hands the size of the image that she saw,” professor Peter Stalmans, who implanted the trial device and is one of Europe’s leading retinal specialists, says in a Schott press release. “I am very impressed by this experience. I have been working for more than 20 years as an ophthalmologist, but this is the first time I witnessed a completely blind patient being given back a visual perception.”

Akin to maturation in the smartphone industry—where shrinking of components has enabled enhanced functionality in smaller devices—miniaturization is an important reason why implantable devices such as NanoRetina’s NR600 are possible today, and it can be traced back to advances in ceramics and glass, as well as other materials.

The consequences of miniaturization are not limited to better performing and more innovative devices, however—it also affects the ultimate bottom line in modern healthcare: cost.

“It starts with the surgery itself,” Herzberg says. “Imagine the pacemaker—30 years ago it was very bulky, so hospitalization time of patients was really long, increasing healthcare costs. People cannot go to work, they are on sick leave,

THE SCIENCE AND ART OF GLASS OCULAR PROSTHESSES

Although ocular prostheses are often called “glass” eyes, many modern such prostheses are actually made of acrylic.

However, prosthetics fashioned from glass—true glass eyes—still exist and are especially prevalent in Germany, Austria, and Switzerland, where more than 90% of ocularists manufacture custom glass ocular prosthetics.

These glass ocular prosthetics are individual works of glass art, handmade by an ocularist to specifically match a patient’s need. Ocularists train for about six years, gaining practical experience in addition to their education, to be able to master their art.1

Glass ocular prosthetics are uniquely made of cryolite glass, a silicate glass containing the mineral cryolite to provide a white hue that matches the look of a natural eye. The prosthetic is usually bowl or shell shaped.

Ocularists custom match a prosthetic to the patient’s other eye, using colored glass to embed details such as iris color and drawn blood vessels onto the eye, rather than painting them on, thus reducing the potential for reaction with the body. All details are part of the 100% glass prosthetic and are fired into the finished product.

Firing produces a very polished uniform surface on the prosthetic to prevent irritation within the eye socket. And unlike the hydrophobic surface of acrylic prosthetics, which can leave a feeling of dryness for the patient, glass’s hydrophilic surface provides a uniform tear film that keeps the prosthetic moist.

A video of the custom manufacturing process is available at https://doi.org/10.3791/60016.

Better bodies with biomaterials

and this is very costly for insurance companies. Today pacemakers are getting smaller and smaller because technology is getting better and better.” Smaller devices allow more minimally invasive procedures, translating to faster recovery times and shorter hospital stays, which ultimately help reduce care-related costs.

Technologies and advances that continue to allow implantable devices to assume smaller forms with enhanced performance, as well as parallel medical developments that permit minimally invasive procedures and improved surgical outcomes, are critical components of future healthcare strategies to sustainably and effectively promote the health of growing, aging populations.

**JOINT IMPLANTS: CERAMICS EXTEND IMPLANT LIFE**

Our joints, the connections between the skeleton’s more than 200 bones, provide our bodies with an incredible capacity for movement.

This ability is perhaps most appreciated in the face of reduced or lost mobility in the joints, often due to stiffening caused by conditions such as arthritis. Osteoarthritis, the most common form of arthritis, represents the single most common cause of disability in aging bodies, affecting an estimated 10%–15% of adults over 60 years old.5

As such, it is no surprise that the global market for joint replacement, implants, and regenerative product devices is expected to grow—reaching a value of $33.6 billion by 2023, growing at a CAGR of 4.8% during 2018–2023.5

Knee replacements constituted the largest share of the $26.5 billion joint replacement market (by value, not number) in 2018, accounting for 33% of the market, or $8.8 billion. Hip replacements were the next largest share, accounting for 28% of the market or $7.4 billion, followed by spinal implants (20%; $5.2 billion) and then extremities reconstruction, which comprises implant devices for the shoulder, elbow, wrist, digits, and ankle joints.

At all of these locations, ceramic implants compete with those made of polymers, metals, and combinations thereof. Due to length of time in the market, ceramics’ successful infiltration into joint replacements is most notable for hip replacements.

“Though implantable ceramics have been in the market for decades, the adoption of these materials has really happened in the last 15 years,” says Lucian Strong, vice president of CoorsTek Bioceramics (Grand Junction, Colo.), which manufactures ceramic femoral heads and acetabular liners for total hip arthroplasty, among other bioimplantable ceramic components. “The adoption is coming from the transition away from metals to ceramics due to the superior wear properties of ceramics, as well as patients’ demands for longer and more active lifestyles after joint replacement.”

Wear of polymer and metal joint implants can generate debris particles that cause inflammation around the joint, loosening the implant and potentially leading to its failure. Potential allergic reactions to metals as well as toxicity from release of metal ions from an implant into the body are also considerations.

These considerations are creating a favorable landscape for ceramic implants, and that shift is evident in data from the 2019 annual report of the American Joint Replacement Registry, a database of more than 1.5 million knee and hip arthroplasty procedures performed in the U.S. during 2012–2018. Registry data show that for total hip arthroplasty, the number of implants with ceramic heads is increasing and first surpassed those with cobalt chromium heads in 2015.9

This data, however, presents only a limited picture, as the registry captures an estimated 25%–30% of the volume of annual procedures in the U.S. Other estimates indicate that adoption of ceramic hip implants is already much higher in some parts of the world—more than 50% of hip implants performed in European countries like Austria, France, Germany, Italy, and Switzerland use a ceramic ball head, while 72% of total hip replacements in Asian countries such as South Korea have an alumina ball head.10

A large proportion of total hip replacement ceramic implants are historically alumina, although zirconia is used as well. Acceptance of zirconia was severely hindered by the 2001 recall of millions of Prozyr brand zirconia ball heads, prompted by high fracture rates in patient implants. Subsequent failure investigation of the manufacturer, Saint Gobain Ceramiques Desmarquest, determined that a switch in the type of furnace used to manufacture the implants caused an unanticipated change in temperature kinetics, resulting in insufficiently densified zirconia.11 Although the problem was traced back to a manufacturing error, the recall significantly marred zirconia’s reputation in the market.

Many modern ceramic hip joint implants now combine the best of both worlds with composites that offer improved properties of strength, toughness, and scratch resistance, for example, ones based on zirconia toughened alumina (Figure 4).

Beyond material-based considerations, additional factors also are coalescing to create a favorable landscape for ceramics implants. “Medical care has seen many transitions over time, but the latest big trend is the move to outpatient care due to rising costs,” Strong says.

Similar to how miniaturization of components allowed pacemakers to shrink in size, resulting in shorter hospital stays and lower care-related costs, parallel evolu-
tions also occurred for joint replacements. The spine provides a critical balance of flexibility and stability to the body, any modifications to the spine ideally must balance those same properties. Spinal implant devices stabilize and strengthen the spine in various ways, often by securing vertebral elements and inserting implants to shore up the intervertebral space (Figure 5). But that need for flexibility and stability makes spinal devices challenging to design.

For instance, the articulation surface for a total disc arthroplasty must not only be functional, it must be designed to account for an estimated device life of more than 40 years. Considering the estimated number and amplitude of load cycles a lumbar disc undergoes annually—based on an average adult bending an estimated 125,000 times and taking 2 million steps in that year—a disc implant is expected to endure some 85 million cycles of loading during its lifetime without wearing down.12

So these devices demand incredibly high-performance and long-lasting materials. While the usual biomedical materials have long been used in spinal implant devices—metals such as stainless steel, titanium, and cobalt-based alloys offer strength; high-performance polymers such as polyetheretherketone (PEEK) provide good value—these materials do not offer perfect solutions in the spine, where integration with existing tissue is particularly desirable for preserving functionality of the spine and maintaining longevity of the device.

“Overall, the need of the hour is to develop materials that demonstrate both biomechanical applicability and biocompatibility while being user friendly in a surgical environment,” according to a 2017 article on trends in spinal surgery (Figure 5). So it is not surprising that this field is also starting to realize the potential of ceramics and glass.

For instance, Mo-Sci (Rolla, Mo.) is developing multicomponent biodegradable spinal bone grafts from bioactive glass—containing one bioactive glass formulation that dissolves more quickly and contains compounds to stimulate vasculature growth (e.g., copper and zinc elements) in early stages of healing, and another bioactive glass formulation that forms a porous silicate glass scaffold that dissolves more slowly to provide support while natural bone formation gradually replaces the graft.

“This bone graft has shown really nice improvements in spinal fusion rates, and it actually isn’t even on the market yet,” says Steve Jung, chief technology officer of Mo-Sci. “Mixing to get this benefit from this material and this benefit from this material is sometimes a better option than trying to find this one material that could do it all. Sometimes you have to accept that there are just two really great materials you can put together and get what you want from each.”

Beyond bioactive glass, other materials also have their sights set on the spinal market. Silicon nitride spinal fusion devices manufactured by SINTX (Salt Lake City, Utah)—the only FDA-registered and ISO-certified silicon nitride medical device manufacturer in the world—and sold through CTL Amedica are working their way into this market (Figure 6).

Silicon nitride is not only bioactive, antiviral, and antibacterial but also promotes bone growth, providing an effective orthopedic solution.

Although the material currently constitutes a small portion of the overall market for spinal fusion devices, data indicates silicon nitride has significant potential, as the company reports there were fewer than 30 FDA-reported adverse events despite more than 35,000 human spine implantations over 10 years.10

SINTX anticipates many additional orthopedic applications for silicon nitride, such as dental and craniofacial applications as well as joint replacements.

“There’s a lot of concerns that metals corrode in the body. As you’re putting hips into younger and younger patients who are going to live longer, you’re not looking at 20-year outcomes. You’re interested in 30- and 40-year outcomes, and there ceramics have a very special role,” says Sonny Bal, president and CEO of SINTX.

For craniofacial applications, customized repair of defects with 3D-printed patient-specific implants is a possibility that SINTX has in mind, according to Don Bray, vice president of business development at SINTX. “If someone has a severe accident and you need to rebuild the facial bones and structure, you would want to do a CAT scan and make an exact fit. In the spine you can use some standard sizes. But because of the shape of the face, you can’t—and we think 3D printing there with our silicon nitride is key,” Bray says.
Better bodies with biomaterials

“It’s a very critical area, so having an antibacterial implant that you could coat exactly for the person is where we think this is going to go,” Bray adds. “And we don’t think it’s that far off.”

Because of silicon nitride’s favorable antibacterial and biological properties, SINTX also is developing techniques to incorporate silicon nitride into devices and products made of other materials as well. For example, silicon nitride can be mixed into polymer-based products or coated onto titanium devices to enhance biocompatibility of those surfaces, promote healing, and prevent infection and spread of viral diseases, according to Bal.

“We are looking at 3D processing procedures that we can commercialize, in which we put a very tenacious micron-level coating of silicon nitride that supercharges the metal and makes it antibacterial,” he says.

3D PRINTING: A TECHNOLOGY WITH LAYERED MEDICAL POTENTIAL

**Multimaterial implants**

At the intersection of medical care and additive manufacturing lies tremendous promise to completely change how we approach health strategies to replace, enhance, and restore function of the human body.

According to the annual Wohler’s report, the 2019 additive manufacturing industry was worth some $11.867 billion. Medical and dental applications account for about 11% of that market, and dental in particular represents a large growth segment in the latest report.

Additive manufacturing company Lithoz GmbH (Vienna, Austria) is familiar with the potential of the technology for medical and dental applications. Lithoz’s lithography-based ceramic manufacturing technology 3D prints complex structures layer-by-layer using a photo-curable polymer–ceramic slurry. After printing, green parts are debinded and sintered to remove the polymer, leaving fully dense ceramic parts.

Lithoz developed both the expertise and the custom printers to additively manufacture a diverse array of ceramic materials, everything from piezoceramics to regolith, and certainly including ceramics with medical applications such as alumina, zirconia, silicon nitride, hydroxyapatite, and tricalcium phosphate. Daniel Bomze, head of the Lithoz’s medical business unit, says the company also has success printing with bioactive glass. “We have produced several parts and some slurries already successfully with bioglass. So we know it works,” he says. Now, Bomze says Lithoz is waiting for a commercial partner who is interested in making the investment to further develop applications for additively manufactured bioactive glass.

Lithoz’s technologies can print complex geometries such as high-resolution lattice structures with openings just several hundred microns wide—optimal scaffolds to promote interaction and integration with living tissues—so medical applications are one promising direction (Figure 7). For instance, such bioceramic scaffolds could be used to repair bone defects due to injury or disease.

While ceramic and bone are a perfect match materially speaking, design of bioceramic scaffold structures is challenging because they must provide both porosity and mechanical strength, properties that often come at a tradeoff. Fortunately, natural bone can provide some inspiration. Bone’s structure consists of an outer layer of dense cortical bone filled with porous and spongy inner trabecular bone, a multimaterial strategy that uses different forms to provide two different components of bone’s function.

Lithoz is developing multimaterial 3D-printed implants that provide both porosity to promote tissue regeneration and mechanical stability to support a bone defect. These multimaterial implants incorporate a strong outer layer for structural support during the initial healing phase, composed of a ceramic material with good mechanical stability such as zirconia, with a porous inner scaffold of biore Absorbable ceramic substrate such as tricalcium phosphate or hydroxyapatite. The inner material more closely matches the inorganic component of bone, and its porosity permits cell attachment and penetration of blood vessels, allowing the body to heal and replace the bioabsorbable substrate with natural tissues over time.

Such multimaterial implants could be used to repair many types of bone defects, such as those in the jawbone. Critically, Bomze says, the material’s resorption rate can be tuned to the area of the body being targeted. “The ideal would be that the regrowth, the new tissue forms at the same speed as the implant is being resorbed. So you have the overall volume and stability, and the whole healing time is the same by tuning...
this artificial material and the natural material,” he says.

Although the individual components of these implants were implanted into a small number of human patients, with good results so far, the multimaterial implant is currently a proof-of-concept. And although the current design is printed into two separate steps, Lithoz has bigger plans for the future.

“The future will be printing it simultaneously, in one single step—you could print the cage and the inner part at the same time and then sinter them together,” Bomze says. “You can probably make even more sophisticated materials, for example a sandwich structure with an inner part of hydroxyapatite, then a shell of zirconia, and then a tiny outer coating or a third layer again of hydroxyapatite to facilitate ingrowth of the implant. And here we’re making really rapid progress.”

In that vein, Lithoz released in September 2020 a new multimaterials 3D printer called the CeraFab Multi 2M30. The printer is similar to the company’s other offerings but now includes two vats to provide the ability to simultaneously print with two different raw materials (Figure 8). This ability affords new functional applications, such as printing multiple materials in a single layer and allowing gradual compositional variation from one material to the next.15

3D-painting

Additive manufacturing is a diverse technology, so Lithoz’s lithography-based technique is one of many different approaches.

Another company, Dimension Inx (Chicago, Ill.), is innovating with printing ceramic-based biomaterials at room temperature, with no additional post-processing sintering steps required—affording the ability to incorporate organic molecules such as proteins, drugs, and antibiotics into the materials themselves before printing.

As noted in a May 2019 Bulletin article,16 “3D-painting is a materials-centric advanced manufacturing technology that permits nearly any material to be transformed into a 3D-printable ‘3D-paint’ via simple, room-temperature extrusion without the need for support materials,

BREATHEALYZERS: ANOTHER WAY TO DETECT COVID-19

In the fight against COVID-19, the main technique used to collect samples is a deep nasal swab, a procedure doctors describe as moderately uncomfortable but some patients describe as “being stabbed in the brain.”

Testing methods that are more comfortable and more easily administered would certainly be appreciated by patients and physicians alike, and researchers have explored saliva testing as an alternative, with some promising results. However, according to Edward Orton, Jr., Chair in Ceramic Engineering Pelagia-Iren (Perena) Gouma at The Ohio State University, breathalyzers may be an even easier and readily accessible way to administer tests.

Breathalyzers use selective gas sensing elements to detect certain biomarkers in breath that signal disease. Compared to swab-based testing methods, breathalyzers are noninvasive, nonintrusive, and can deliver a result in dozens of seconds.

Gouma has explored the use of breathalyzers for medical diagnostics since 2003. She started investigating the development of breathalyzers aimed specifically at detecting infectious diseases a few years ago, and she has worked extensively the past few months to use that knowledge to design a breathalyzer that detects COVID-19.

The in-development COVID-19 breathalyzer uses ceramic sensors to target biomarkers that give a response specific to that infection, and it includes advances on nanomaterials for detecting specific breath gases at concentrations that can make a diagnosis.

Gouma says her team initially tested the new breathalyzer by using gas canisters that were mixed to simulate the breath gas mixture as a result of COVID-19 infection. However, they have since moved to conducting human testing and have been testing at various COVID-19 testing sites around Columbus, Ohio.

In mid-September, they reported initial results from the ICU-focused human testing at the Ohio State Wexner Medical Center. The results showed the breathalyzer could detect acute cases of COVID-19 and can monitor the severity of the disease.

The researchers currently are seeking FDA emergency-use authorization for the breathalyzer.

For more information on Gouma’s study, as well as other breathalyzer studies taking place at Northeastern University, check out a recent Wired story on the topic at https://www.wired.com/story/could-breathalyzers-make-covid-testing-quicker-and-easier.
Better bodies with biomaterials

In the 3D-painting technique, a powder-based material is mixed with elastomer and solvents; after extrusion through a nozzle, the finished printed product requires only rinsing and sterilizing. The flexibility of the technique means that in addition to 3D printing structures out of 3D-paints, the same strategy could also be used to coat products manufactured via other techniques and out of other materials.

Importantly, 3D-painting can be applied to almost any material, including ceramics. “3D-painting is materials agnostic. It’s not dependent on what you’re making or what material you’re using,” says Adam Jakus, co-founder and chief technology officer at Dimension Inx.

As one example of the 3D-painting technology, Dimension Inx’s bone-specific 3D-paint formulation, called Hyperelastic Bone®, is primarily ceramic yet still incredibly flexible, offering significant potential for bone implants. Hyperelastic Bone can be printed in specific structures (Figure 9) as well as porous scaffolds and sheets that could be cut and custom-fit in the operating room (Figure 10).

“The really interesting thing about Hyperelastic Bone is that it’s 90% ceramic, which is technically more ceramic than is in our actual bones,” Jakus explains. Human bones contain 60%-70% dry weight of crystalline hydroxyapatite, bound by collagen and other structural and functional proteins. “But the end result is actually flexible and cuttable and shapeable, which you wouldn’t really expect for a something that’s mostly ceramic.”

That flexibility is because of Hyperelastic Bone’s unique microstructure, which forms as evaporants vaporize from the printed material after it is extruded through a printer nozzle. The rate of evaporation tunes precipitation of the elastomer, forming an optimized structure in the printed material.17 “A very specific microstructure really allows the different components of the composite, the ceramic and the resorbable polymer, to play off each other and move around and then return to their original form without breaking,” Jakus says.

Hyperelastic Bone also is microporous, which provides excellent osteoconductivity and biocompatibility. “If it’s intended to regrow bone, the body tissue needs to be able to access that material on the microstructure level and transform it,” Jakus says, although the porosity can have a drawback. “But it’s a balance if you want structural integrity and you want bioactivity. Those things are in conflict all the time.”

Since the technology is relatively well-established at this point, Jakus says Dimension Inx is now working on quality control aspects of the process, showing that it can demonstrate consistent results. “So a lot of our efforts throughout 2020 have been establishing new quality control systems and quality manufacturing systems around design and synthesis of these new materials as well as the 3D-painting process itself,” he says.

That includes establishing consistent and detailed manufacturing processes and identifying and mitigating risks—all part of the company’s preparations toward seeking FDA approval for Hyperelastic Bone devices.

3D printing inherently conjures ideas of patient-specific printed implants. And while that is an eventual direction for Dimension Inx, the company is starting with a more practical pathway—and one common for biomedical innovations—by targeting mass-produced implants of Hyperelastic Bone, a collection of standard shapes like “strips or squares or blocks,” Jakus says. “We are introducing a new material in a new manufacturing process. So I think it’s important to get the regulatory agencies, the FDA, surgeons, everybody comfortable with the material and the process first so they are then willing to take that next step to patient-matched implants.”

That acceptance is a considerable issue in the medical industry—you not only have to prove that a device or technology works (see sidebar: Regulating the pace of medical innovation), but you also have to
Infiltrating a site like the craniofacial space can then be a strategic initial target application of a new technology to gain acceptance before expanding to additional sites and applications.

Another consideration that makes the craniofacial segment attractive for innovation in additive manufacturing, especially with bioresorbable materials, is that these surgeons treat many pediatric defects. “So they’re most excited to use new materials, ceramic or not, that transform over time and grow with the patient,” Jakus says.

Tissue regeneration: the softer side of biomaterials

In terms of the body’s natural materials, ceramics and glass are most analogous to bone and tooth enamel—so it is not surprising that there are so many orthopedic and dental applications for ceramics and glass (see sidebar: Ceramics used in dentistry).

But modern developments in nanotechnology, particularly the ability to engineer nanosurfaces, nanoparticles, and nanoscaffolds, as well as more nuanced understanding of cell biology are together reshaping how we think about the potential of biomaterials.

Biomaterials were once designed to minimize interactions with the body and to eliminate any potential adverse reactions. But starting with Larry Hench’s discovery of bioactive glass 50 years ago, a more modern perspective for biomaterials no longer attempts to eschew cell biology.

“Design of a new biomaterial should always consider the need of the cells, because the cells are the engineers of our body,” says Aldo Boccaccini, professor of biomaterials and head of the Institute of Biomaterials in the Department of Materials Science and Engineering at University of Erlangen-Nuremberg (Erlangen, Germany).

Many biomaterials now aim to not only stand in for living tissues when they need to be repaired or replaced, but the materials play a more supportive role in actually helping the body perform its own healing—more like an assist rather than a complete substitution. That guidance can be used to mediate processes such as wound healing and to rebuild damaged or missing tissues, broadly contributing to the overall field of tissue engineering, or regenerative medicine.

In terms of the future of healthcare, regenerative medicine is a big business. The global market for tissue engineering...

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REGULATING THE PACE OF MEDICAL INNOVATION

While there is no shortage of innovative ideas for medical applications, bringing such innovation to the market is a whole different story.

“The medical market is slow and steady in terms of innovation,” says Lucian Strong, vice president of CoorsTek Bioceramics (Grand Junction, Colo.). “While new applications or processes may demand new materials, there is a well-defined process that is governed through the regulatory bodies around the globe. There is no simple introduction of a new material that will be implanted into a patient. Clinical data, proven over numerous years and multiple patients, is necessary for any new material to gain acceptance.”

Collecting such data takes considerable time, but it is a critical component of the regulatory processes to ensure that biomaterials and devices are safe and effective once implanted into human patients. And even before the clinical data, much additional time must be first devoted to testing and documenting effectiveness and safety in both lab settings and in animal models.

In the U.S., where the FDA regulates the approval process, bringing a medical device to market takes on average 3–7 years. Although this process unavoidably slows the pace of innovation, these pathways are critical to maintain safety and minimize potential harm to human health.

Yet even once clinical data does provide acceptance for a material, the story is still not over.

“The increasing longevity of the human race, younger patients undergoing surgical interventions, all points to a future in which we as scientists need to understand the long-term interaction of the implant with the body,” says B. Sonny Bal, president and CEO of SINTX.

Of course, it is not feasible to wait decades while collecting long-term outcomes for every new device—such observation trials would completely stifle innovation and prohibit entrance of any new product on the market.

Instead, to develop materials for the future, we need robust short-term outcome proxies that can predict long-term behavior, Bal says.

“That’s the Holy Grail.”

Bal made the analogy to how NASA uses algorithms and modeling to predict the outcomes of its missions. There are no practice runs when sending a rocket to Mars—NASA incorporates knowledge and modeling to maximally reduce the margin of error. And that, he envisions, is where biomaterials need to go.

“Instead of experimenting with humans, we need to be able to predict how a biomaterial will behave in the body just like NASA does—because there’s no room for mistakes. You do it once, and that patient has to live with it. You can’t have failures,” he says.

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Better bodies with biomaterials

and regeneration was valued at $24.7 billion in 2018 and is predicted to reach $109.9 billion by 2023, representing an impressive CAGR of 34.8%.

While bone is a significant focus of this market, it encompasses soft tissues as well, such as strategies to repair damaged cardiac and gastrointestinal tissues or engineer vascular, muscle, neural, and skin tissues.

Likewise, there is potential for many different types of materials in this broad field. “In the field of regenerative medicine and tissue engineering, there is no one material that is going to tackle all the problems,” Boccaccini says. And many of the ceramic- or glass-based strategies to heal tissues actually combine them with organic materials, in polymer composites or hydrogels, for example.

Although bioactive glasses were discovered half a century ago, their potential within regenerative medicine is still being realized today. When in contact with body fluids, bioactive glasses dissolve and release ionic dissolution products such as biologically active ions within the body. Cells, in turn, respond to these ionic products, some of which stimulate growth of new blood vessels in the tissue, a process called angiogenesis. Blood vessels nourish developing tissue with oxygen and nutrients and remove waste products, so the angiogenic response is part of what makes bioactive glass so attractive for tissue repair.

But ionic dissolution products also do more than stimulate angiogenesis—these products alter gene expression patterns in nearby cells, shifting signaling pathways that orchestrate every cellular function, such as cell migration, proliferation, and differentiation.

Although we are just beginning to unravel some of these biomolecular mechanisms, the potential exists for bioactive glass compositions and properties to catalyze a diverse array of cellular responses, precisely tuned to the target tissue and the desired effect in that tissue—whether that is modulating an immune reaction, prompting tissue regeneration, or stimulating release of growth factors to guide stem cell differentiation.

“Understanding genetic upregulation and activation by ionic stimuli released from bioactive glasses offers the possibility of developing patient-specific therapies, a huge challenge for the aging population,” per a 2015 Bulletin article on bioactive glasses.

One of the more familiar and clinically approved applications of bioactive glasses for soft tissues is in wound repair, with products such as a cotton candy-like borate bioactive glass fiber matrix to heal advanced wounds.

CERAMICS USED IN DENTISTRY

Ceramics are ubiquitous in the $10.7 billion U.S. dental industry, with applications in prosthetics, fillings, orthodontic appliances, cosmetic products, process materials, preventive products, toothpaste, and more. Below are some highlights of the roles that ceramics play in this industry.

Dental caries: From prevention to treatment

Dental caries, commonly known as tooth decay, is the most common bacterial disease of children and adults worldwide. Formerly, tooth loss due to bacteria attacking the tooth enamel was inevitable, but advances in dental materials and techniques during the last few decades have greatly reduced chances of this outcome.

Plaque removal and teeth cleaning at home and by hygienists is the first line of defense against these bacteria. Toothpastes contain many ceramic powders ranging from stannous fluoride, potassium nitrate, and several calcium phosphate compounds. Bioactive glass is also present in some toothpastes, to promote remineralization of the enamel. Sodium bicarbonate is often used by hygienists to more thoroughly remove plaque, and pumice is sometimes used as well.

When bacterial attack progresses into the enamel, a dentist will seek to remove the softened tissue and restore tooth anatomy. Small to medium bacterial lesions (cavities) are treated with ceramic composite filling material or glass polyalkenoate cement material to restore the tooth form.

When the disease progresses into the pulp, a medication that induces the pulp tissue to build a protective barrier of reparative dentine is needed. Calcium hydroxide-containing materials used to be the standard material used for this purpose, but now tricalcium silicate cements, which are based on the same materials as white Portland cement, are the “gold standard.” (These cements are set with a matrix that includes calcium hydroxide.) If the pulp becomes irreversibly infected, a root canal procedure is required. In this procedure, the pulp is removed and is replaced by a combination of rubber points shaped like a root canal and sealed with another material. The trans-polysoprene rubber points are usually filled with zinc oxide and barium sulfate. The sealing material comes in a variety of polymer and ceramic matrices, ranging from epoxy to zinc oxide—eugenol. The newest sealers are based on tricalcium silicate powders. Sometimes, glass fiber-reinforced composite posts are inserted in a root canal after a root canal procedure to help restore tooth function.

When a majority of the anatomy of a tooth is lost, the anatomy is restored with a crown. Gold foil and its alloys were the materials traditionally used for crowns, but in the 1950s, porcelain enameled crowns and bridges became the standard tooth restoration for severely damaged teeth because of their greater durability and more natural aesthetic. Today, all-ceramic crowns—such as alumina, lithium disilicate, and yttria-stabilized tetragonal zirconia—are the most common crown type because of their strength, ease of fabrication, and aesthetics. Tetragonal zirconia with 3% yttria dominates this market due to its high strength, but zirconia with higher yttria formula are also in use due to better aesthetics, despite their diminished strength.

Whenever a temporary or permanent crown or bridge is placed, dental cements are needed. Numerous ceramic- and glass-containing dental cements are used in dentistry, but the original cements were all based on zinc oxide. More recently, glass-ionomer cements evolved from the original silicate filling materials in the mid 20th century and remain popular because of their temporary fluoride release, which deters caries from forming under a crown. Resin-modified glass-ionomer cements and composites are also advantageous, by combining light-curable polymers from composites with limited fluoride ion release from the glass ionomers.

Tooth extractions: Replacing the missing teeth

Periodontal diseases and tooth fractures may lead to tooth extraction. Dental implants, or posts surgically placed into the jawbone, are increas-

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*The urethane polymers filled with about 40–70% by weight of ceramic powders, which may include radiopaque glasses, fumed silica, or quartz in combination. Requires bonding agents such as slame and a polymer primer to induce adhesion.

*In other words, glass-ionomer, composed of fluorooxaluminosilicate glass powder reacted with a polycrylic acid liquid, which bonds to tooth structure. Used for restoring tooth anatomy plus permanent cementation of crowns, bridges, inlays, onlays, posts, and orthodontic appliances.
“But you can also think of internal wounds, such as adhesives with hemostatic ability for coating internal wounds where there is a lot of bleeding,” Boccaccini says. “Here I think yet is an open area for the applications of [bioactive glass], either as a fiber or mesh or in composites.”

As research continues to characterize how cells respond to the unique materials as well as the underlying biomechanisms of these responses, soft tissue applications of bioactive glass will also continue to expand.

Mo-Sci’s Steve Jung says that bioactive glass is experiencing increasing integration in medical products due to the material’s recognition as a “premium material” and its ability to intimately interact with tissues. Bioactive glasses are being combined with other materials to make new products as well as being integrated into existing products already on the market. “They’re making these products better by the addition of bioactive glass,” Jung says.

Jung says that in veterinary medicine, there also have been some indications that bioactive glass can also repair tendons and ligaments. “To me, that kind of outcome is really what gets you thinking about sports injury-type situations—if you blow a ligament, could we develop a technology to help to heal that back together?” he says.

Beyond being implanted within the human body to aid tissue regeneration, ceramic and glass materials can also be similarly used to grow tissues outside of the body, with the vision that these tissues could eventually be harvested and implanted into or on the body as appropriate.

“The possibilities for ceramic technologies for improving the health and wellbeing of mankind are vast,” says Randel Mercer, chief technology officer at CoorsTek. “One exciting avenue CoorsTek has been working on is the use of engineered ceramic cell culturing devices. Our product, Cerahive, is used to grow human tissue cells in an environment that mimics the growth environment in the human body.” These porous ceramic substrates line the bottom of a cell culture dish to support 3D cell cultivation, allowing in vitro growth of cell spheres (Figure 11). “The future potential to ‘manufacture’ specific tissues in the laboratory could be used as a source for repairing damaged tissue in humans,” Mercer says.

**LOOKING FORWARD—A GLIMPSE OF FUTURE HEALTHCARE**

So what does the future of medical care look like, and how do biomaterials fit into that future?

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3Freedonia Group

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**Other applications: Brackets, abrasives, equipment**

Orthodontic brackets are commonly made of stainless steel, but sapphire, tetragonal zirconia, and polycrystalline alumina (with no glass bonding) are also used to manufacture orthodontic brackets because of their aesthetic appeal (they make the brackets less obvious). Ceramic coatings such as rhodium oxide are also used on orthodontic wires to disguise the orthodontic device. Diamonds, tungsten carbide, and alumina and silica abrasives are essential for dentistry to remove tooth structure and to polish or adjust any dental restorative or denture. Some abrasives are bound in rubber; others are used in paste form.

“Of course, most of the equipment used in dentistry would not be possible without ceramics, from microscopes and cameras to curing lights to air turbines handpieces; from piezoelectric devices, to general electronic devices, to office scheduling and case record software and computers,” says Carolyn Primus, medical device consultant and the 2020 Larry Hensch awardee for Bioceramics.

**Future of dental ceramics**

Biocompatibility is a top priority for medical devices, and ceramics excel in biocompatibility compared to polymers and metals. On the other hand, durability is a key concern for ceramic restoratives in dentistry, particularly composite ceramics. Current research on zirconia, for example, looks to optimize the strength and appearance of zirconia by exploring variations in the stabilizers for the tetragonal phase. Ceramic nanoparticles are another subject of much research, as nanoparticles offer a way to provide unique biological responses. Nanoparticles are not new in dentistry, however—silica nanoparticles have been used for decades in composites and toothpastes.

Compared to other fields, manufacturing in dentistry happens at a small scale. As such, “Dentistry often follows the innovations in other industries or adopts materials used in other fields,” Primus says.

For example, computer-aided design and computer-aided manufacturing (CAD/CAM) are examples of innovations from other industries adopted for dental applications beginning in the 1980s.² CAD/CAM dentistry is becoming a widespread method for making ceramic dental crowns in a dental office.

Additive manufacturing is also being adopted for dentistry. Fabrication of dentures and temporary restorations are leading the way for additive manufacturing. Lithoz GmbH (Vienna, Austria) is helping to lead the adoption of additive manufacturing for dental purposes with their lithography-based CeraFab 7500 Dental and CeraFab System Series ceramic manufacturing machines. Ivoclar Vivadent (Schaan, Liechtenstein) is also exploring additive manufacturing with their PrograPrint PR5, a digital light processing-based stereolithography printer.

As these technical innovations allow people to retain more teeth, the dentistry field will continue to grow, and the opportunities for ceramic and glass materials along with it.
Better bodies with biomaterials

The medical industry is constantly searching for new, better, and more cost-effective solutions, and advancements in the medical industry are moving at a pace so much faster than just a few years ago due to the introduction of advanced materials. With climbing healthcare costs combined with the move from inpatient to outpatient procedures, there is a pull from the market for better materials,” says CoorsTek’s Lucian Strong.

Ceramics and glass clearly fit into that future vision not only because of the role of established products such as joint implants but also due to entirely new forms and functionalities of the materials that are just starting to be discovered, realized, and matured.

“I absolutely believe that ceramics and bioactive glass have a really strong future, and their areas of use are going to diversify in a big way,” says MoSci’s Steve Jung. “Bioactive glass is 50 years old, but we’re still finding new ways to use it all the time. Old materials used in new ways or in combination with new techniques I think is the wave of the future.”

Some of those new ways, combinations, and techniques are highlighted in this article, but potential extends much, much further as well.

One particular area ripe for future innovation is technologies that address multiple different tissues simultaneously. Although an isolated tissue-specific approach often guides biomaterial developments, components of the human body operate together in systems on several different scales.

“If you look at everything in isolation, there are solutions that already exist. They may not be the best solutions, but there are ways to treat individual tissues,” says Dimension Inx’s Adam Jakus. However, most injuries or conditions involve multiple tissues, so more complex solutions are often required.

“This has been a driving force for our technology for a long time, and we set up a manufacturing technology where all the materials are complementary to each other,” Jakus says about Dimension Inx’s 3D-painting platform. “So we can manufacture a bone material with a muscle material and with a ligament material, so that in the future you could make a multitissue implant.”

Such strategies will inevitably need to leverage properties and strengths from multiple different materials. “This could be partially ceramic, partially polymer, partially biological, even partially things like graphene and graphite for electrical conductivity,” Jakus adds. “So manufacturing different material types together to match the really different material types in the body.”

Another systems-level approach that will certainly shape the future of healthcare is smart implants.

Miniaturization of devices, enabled by advances in the materials themselves, provided the feasibility for tiny sensors that can be implanted within the body to track an array of biological parameters on-demand. Such sensors provide the ability to track those parameters continuously, rather than sporadic measures taken at a doctor’s office or hospital, and monitor for any changes that could signal a potential health problem. Such rich data provides a more comprehensive view of a patient’s health as well as the ability to respond immediately to a potential disturbance in that health.

According to Schott’s Jochen Herzberg, smart implants have a prominent place in the future of medical care not only because they provide better monitoring but also in terms of reducing healthcare spending, by reducing trips to the doctor or hospital and by informing more strategic medical intervention when necessary.

“A trend that is very visible right now is smart implants and remote monitoring of patients to reduce hospitalization. For example, in-line measurements of vital signs like blood pressure inside of your body, with smart computers inside your body communicating with your doctor without being hospitalized,” Herzberg says.

Glass is already used in several different components of such devices, including hermetic seals, but its optical transmissivity offers compatibility in terms of data transmission (see sidebar: Could future bandages not only be smart, but also made of glass?).

Yet tiny implantable devices also can do more than just sense and monitor—they can also be designed with the capability to intervene as well, for instance by delivering a therapeutic.

“This is very fast moving technology. The idea is to replace conventional medical therapies with active implants so that you avoid overmedicating your whole body, for example by replacing...
chronic pain relievers with very smart implants that are active only where the pain is created rather than influencing the whole body,” Herzberg says.

Smart implants play into an overall health ecosystem increasingly focused on early detection and proactive intervention, before health conditions because problems and require more involved treatment.

These data-based monitoring strategies extend beyond implants as well, according to a Deloitte Insights report on the future of health.23 “Medical products might no longer be limited to pharmaceuticals and medical devices. They could also include software, applications, wellness products, even health-focused foods. The home bathroom of the future, for example, might include a smart toilet that uses always-on sensors to test for nitrites, glucose, protein, and pH to detect infections, disease, even pregnancy. A smart mirror equipped with facial recognition might be able to distinguish a mole from melanoma,” the report says.

Ultimately, the entire landscape of how we approach, monitor, manage, and mitigate human health is shifting. While these changes will not come without challenges to the market for biomaterials, they also offer incredible opportunity—and ceramics and glass are certainly well-positioned to capitalize on such opportunities as well as integrate critical function into the human body.

ACKNOWLEDGEMENTS

We thank Carolyn Primus for her review of and detailed suggestions for the section “Ceramics used in dentistry.”

REFERENCES

3 BCC Research, “Global markets for implantable biomaterials (AVM118A),” January 2015.
8 BCC Research, “Advanced orthopedic technologies, implants and regenerative products (HLC052D),” August 2018.
How are manufacturers handling business during the COVID-19 pandemic? That question was at the core of many discussions during Ceramics Expo Connect, the virtual version of Ceramics Expo. The industry exposition, which typically takes place in the spring, took place instead from Sept. 21–25, 2020, and it welcomed more than 1,500 virtual event attendees and more than 150 exhibitors.

Each day of the exposition featured panels, interviews, and roundtables focused on different themes, including clean and electrified technology (Monday), additive manufacturing (Tuesday), aerospace applications (Wednesday), and quality and testing (Thursday).

The exposition kicked off Monday with a panel on overcoming business continuity challenges caused by COVID-19. The manufacturers on the panel say while there are still difficulties, overall some of the necessary workarounds enacted to handle the pandemic could prove useful in the future, such as facilitating business electronically and working from home.

On Tuesday, manufacturers again were future focused in their discussions of additive manufacturing. However, they did caution that additive manufacturing should not be treated as a solution to all processing challenges but rather as just another forming process.

With all the talk of future potential, Wednesday discussions focused on one area in which ceramics are already making a difference: aerospace. The first jet engines based on ceramic matrix composites were commercially deployed in 2016, and panelists suggested more aerospace opportunities for ceramic materials in the future, including in shrouds, liners, nozzles, and blades.

In contrast to the other three days, Thursday wrapped up the exposition with a focus on current processes and how to ensure material quality and testing. Experts from multiple fields offered their expertise, including representatives from vehicle manufacturing, scientific instruments for molecular research, and clay brick making.

# Materials Challenges in Alternative and Renewable Energy 2021 (MCARE 2021)

### 4th Annual Energy Harvesting Society Meeting (EHS 2021)

Hyatt Regency Bellevue
Bellevue, WA USA

Hosted and organized by: Energy Materials and Systems Division

[ceramics.org/MCARE2021](http://ceramics.org/MCARE2021)
Current trends, applications, and processes in the ceramic manufacturing industry were the focus of the first-ever Ceramic Manufacturing Solutions Conference, which took place on Sept. 29, 2020. Originally scheduled to take place alongside Ceramics Expo in the spring, CMSC was rescheduled as a virtual event for the week after Ceramics Expo Connect in light of the ongoing pandemic.

Sixty-nine registrants from 13 countries, including 10 students, registered to attend the one-day event, which was organized into three main sessions: Testing, Quality, and Health & Safety; Ceramic Processing; and Raw Materials.

The day kicked off with a keynote presentation by Doug Freitag, technical director for government affairs at the United States Advanced Ceramics Association. Freitag spent time describing the history and current status of research on transparent ceramic armor and ceramic fiber reinforced ceramic matrix composites for gas turbines.

Following Freitag’s presentation, ACerS director of meetings and marketing Andrea Ross presented Allied Mineral Products vice president of research & development Dana Goski and manager of special projects Matthew Lambert with this year’s John E. Marquis Memorial Award, in recognition of their paper “Engineering resilience with precast monolithic refractory articles.”

During the three main sessions, several topics were discussed in regard to each theme, including

- Occupational Safety and Health Administration citations and ASTM test methods for powder characterization under Testing, Quality, and Health & Safety.
- Failure modes & effects analysis, additive manufacturing considerations, silicon nitride production, and specific volume diagrams under Ceramic Processing.
- Electric arc fusion of mullite ceramics and the role of alumina in various applications under Raw Materials.

“Working in the manufacturing environment, the CMSC event exceeded expectations; the speakers and the content of their talks were both excellent. I’m excited for this event to continue,” says coorganizer Keith DeCarlo of Blasch Precision Ceramics.
Electronic Materials and Applications 2021 (EMA 2021) is an international conference focused on electroceramic materials and their applications in electronic, electrochemical, electromechanical, magnetic, dielectric, biological and optical components, devices, and systems. Jointly programmed by the Electronics Division and Basic Science Division of The American Ceramic Society, EMA 2021 will be a virtual event on the same planned dates, Jan. 19–22, 2021.

EMA 2021 is designed for scientists, engineers, technologists, and students interested in basic science, engineering, and applications of electroceramic materials. Participants from across the world in academia, industry, and national laboratories exchange information and ideas on the latest developments in theory, experimental investigation, and applications of electroceramic materials.

Students are highly encouraged to participate in the meeting. Prizes will be awarded for the best oral and poster student presentations.

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**SCHEDULE OF EVENTS**

**WEDNESDAY, JANUARY 20, 2021**

Plenary session 1  
9:45 – 11 a.m.

Concurrent technical sessions  
11 a.m. – 4 p.m.

Networking session  
4 – 5 p.m.

**THURSDAY, JANUARY 21, 2021**

Plenary session 2  
10 – 11 a.m.

Concurrent technical sessions  
11 a.m. – 5 p.m.

Student & Young Professionals networking session  
5:30 – 6:30 p.m.

**FRIDAY, JANUARY 22, 2021**

Concurrent technical sessions  
11 a.m. – 5 p.m.

Failure: The greatest teacher  
5 – 6 p.m.

**TECHNICAL PROGRAM**

S1 – Characterization of Structure-Property Relationships in Functional Ceramics

S2 – Advanced Electronic Materials: Processing Structures, Properties, and Applications

S3 – Frontiers in Ferroic Oxides: Synthesis, Structure, Properties, and Applications

S4 – Complex Oxide Thin Films and Heterostructures: From Synthesis to Strain/Interface-engineered Emergent Properties

S5 – Mesoscale Phenomena in Ferroic Nanostructures: From Patterns to Functionalities

S6 – Emerging Semiconductor Materials and Interfaces

S7 – Superconducting and Magnetic Materials: From Basic Science to Applications

S8 – Structure-Property Relationships in Relaxor Ceramics

S9 – Ion-Conducting Ceramics

S10 – Point Defects and Transport in Ceramics

S11 – Dislocations in Ceramics: Processing, Structure, Plasticity, and Functionality

S12 – Evolution of Structure and Chemistry of Grain Boundaries and Their Networks as a Function of Material Processing

S13 – 5G Materials and Applications Telecommunications

S14 – Agile Design of Electronic Materials: Aligned Computational and Experimental Approaches and Materials Informatics

S15 – Functional Materials for Biological Applications

**OFFICIAL NEWS SOURCES**
Due to uncertainty surrounding the current global pandemic, meeting organizers, along with the meetings team at The American Ceramic Society, have decided to move the 45th International Conference & Exposition on Advanced Ceramics & Composites meeting to a fully virtual format for 2021, running live sessions containing pre-recorded talks on a new date: Feb. 8–12, 2021. This conference will be the first-ever Virtual ICACC organized by ACerS Engineering Ceramics Division, and we would like for you to be a part of it.

This conference has a strong history of being the preeminent international meeting on advanced structural and functional ceramics, composites, and other emerging ceramic materials and technologies, and this year is no different.

The technical program will reflect the growth and success of ICACC by featuring 18 symposia, five focused sessions, one special focused session, and the 10th Global Young Investigator Forum. These technical sessions, consisting of both oral and poster presentations, will provide an open forum for scientists, researchers, and engineers from around the world to present and exchange findings on recent advances on various aspects related to ceramic science and technology. The technical program reflects critical areas of interest within ceramics and advanced composites, with a particular emphasis on current trends in research, development, engineering, and application of advanced ceramics.

Hisayuki Suematsu  
Program chair, ICACC 2020  
Nagaoka University of Technology, Japan  
E-mail: suematsu@nagaokaut.ac.jp

**SYMPOSIA**

**S1:** Mechanical Behavior and Performance of Ceramics and Composites  
**S2:** Advanced Ceramic Coatings for Structural, Environmental, and Functional Applications  
**S3:** 18th International Symposium on Solid Oxide Cells (SOC): Materials, Science, and Technology  
**S4:** Armor Ceramics – Challenges and New Developments  
**S5:** Next Generation Bioceramics and Biocomposites  
**S6:** Advanced Materials and Technologies for Rechargeable Energy Storage  
**S7:** 15th International Symposium on Functional Nanomaterials and Thin Films for Sustainable Energy Harvesting, Environmental, and Health Applications  
**S8:** 15th International Symposium on Advanced Processing and Manufacturing Technologies for Structural and Multifunctional Materials and Systems (APMT15)  
**S9:** Porous Ceramics: Novel Developments and Applications  
**S10:** Modeling and Design of Ceramics and Composites  
**S11:** Advanced Materials and Innovative Processing Ideas for Production Root Technologies  
**S12:** On the Design of Nano-laminated Ternary Transition Metal Carbides/Nitrides (MAX Phases) and Borides (MAB Phases), and Their 2D Counterparts (MXenes, MBenes)  
**S13:** Development and Applications of Advanced Ceramics and Composites for Nuclear Fission and Fusion Energy Systems  
**S14:** Crystalline Materials for Electrical, Optical, and Medical Applications  
**S15:** 4th International Symposium on Additive Manufacturing and 3D Printing Technologies  
**S16:** Geopolymers, Inorganic Polymers, and Sustainable Materials  
**S17:** Advanced Ceramic Materials and Processing for Photonics and Energy  
**S18:** Ultra-High Temperature Ceramics

**FOCUSED SESSIONS**

- Special Focused Session on Diversity, Entrepreneurship, and Commercialization  
- 10th Global Young Investigator Forum  
**FS1:** Bio-Inspired, Green Processing, and Related Technologies of Advanced Materials  
**FS2:** Materials for Thermoelectrics  
**FS3:** Molecular-level Processing and Chemical Engineering of Functional Materials  
**FS4:** Ceramic/Carbon Reinforced Polymers  
**FS5:** Fractography of Ceramics
Biomimetic approach—the role of ions in bone regeneration

The challenge of bone tissue engineering (BTE) is to develop bone scaffolds that allow good integration with the surrounding tissues. Systems of particular interest are scaffolds based on calcium phosphates (CaPs), mainly hydroxyapatite (HAp), due to its chemical and structural similarity to the inorganic matrix of natural bone and its excellent bioactivity.

Scientists have used growth factors in combination with CaP to enhance bone regeneration, but negative side effects such as ectopic or unwanted bone formation throw the safety of this approach into question. An alternative way to adjust properties of synthetic materials is a biomimetic approach, in which various trace elements with a beneficial effect for bone formation are incorporated in CaPs. The introduction of even small quantities of these ions may cause changes or improvements in the biological, physicochemical, or mechanical properties of scaffolds.

Researchers have extensively investigated CaPs substituted with strontium, magnesium, zinc, selenium, and carbonate ions. Findings concerning each of these ions include:

- **Strontium** (Sr²⁺) stimulates bone formation by decreasing resorption activity and differentiation of osteoclasts, while at the same time increasing osteoblast proliferation and differentiation.
- **Magnesium** (Mg²⁺) acts as a growth factor, especially in the early stage of bone formation, where it plays a key role in bone metabolism. It influences the osteoblast and osteoclast activity.
- **Zinc** (Zn²⁺) is thought to have the same influence on osteoblast and osteoclast activity as strontium and magnesium. Furthermore, it has antimicrobial and anti-inflammatory properties. Due to that, zinc-substituted CaPs could be used as a coating for metal implants to reduce inflammatory response.
- **B-type carbonate** (CO₃²⁻) substitution is characteristic for biological apatite and thus is a highly interesting substitution in synthetic HAp. Furthermore, the CO₃-substitution enhances bioresorption and therefore osteogenic performance of synthetic material.

- **Selenium** is an essential element for the proper functioning of bone tissue, with strong antioxidant properties. Selenium can induce tumor cell apoptosis while at the same time enhance the proliferation of healthy bone cells. As such, many experiments involve selenium oxyanions (SeO₃²⁻ or SeO₄³⁻), especially in bone cancer studies.

Though these results show the benefits of introducing trace elements in CaPs, scaffolds based on HAp still face some disadvantages, such as poor mechanical properties. To overcome these disadvantages, HAp has been combined with polymers to obtain composite scaffolds for bone regeneration.

The ongoing University of Zagreb research project “Development of bioactive and bioresorbable and biodegradable titanium metal scaffolds” involved with this research project.

Currently, I am one of the researchers involved with this research project. In the future, we plan to investigate the efficacy of selective laser sintered bioinspired scaffolds for bone tissue engineering as well.

References

SETTING THE STANDARDS: HOW STANDARDS ENHANCE QUALITY AND PROMOTE RELIABILITY

JAPAN FINE CERAMICS ASSOCIATION AND ITS INTERNATIONAL STANDARDIZATION ACTIVITIES FOR FINE CERAMICS

A SHORT LIST OF STANDARDS-DEVELOPING ORGANIZATIONS
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Chinese Ceramic Society (CCS)
Indian Refractories Makers Association (IRMA)
Federation Europeenne des Fabricants de Produits Refractaires (PRE)

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ADVERTISERS LIST AND EDITORIAL CALENDAR
ENPRO AGREES TO BUY OPTICAL FILTER AND COATINGS MAKER

Charlotte, N.C.-based EnPro Industries, Inc. agreed to acquire Alluxa, Inc., a privately held, Santa Rosa, Calif.-based company. Alluxa is an industrial technology firm that provides optical filters and thin-film coatings for applications in the industrial technology, life sciences, and semiconductor markets. EnPro is financing the transaction with cash and rollover equity from Alluxa executives. The purchase price is $255 million, including rollover equity. EnPro says it has a strategy to grow by acquisition in attractive markets.

TOTAL AGREES TO BUILD SOLAR PROJECTS IN SPAIN

French energy company Total SE reached an agreement with Spanish developer Ignis to build 3.3 gigawatts of solar projects in Spain. The first projects are scheduled to start in 2022, with the rest expected to be in production by 2025. The transaction will bring Total’s portfolio of solar projects under development in Spain to more than five gigawatts by 2025, contributing to Spain’s goal of generating 70% of its electricity from renewables by 2030 and 100% by the middle of the century.

ALTONA ENERGY ACQUIRES MAJORITY STAKE IN RARE EARTH PROJECT

Australia-based Altona Energy, a mining exploration company with a focus on rare earth element projects in Africa, signed an agreement with Leadway Group Ltd. to acquire a 70% interest in a greenfield project in Uganda, the Nankoma Rare Earth Project. Altona says it wants to build a portfolio of rare-earth sites in Eastern and Central Africa. When the agreement is final, Altona will be responsible for completing a feasibility study on establishing a commercial-scale, rare-earth mining and processing operation at the site. Altona will also be the manager and operator of the project.

TOTAL AGREES TO BUILD SOLAR PROJECTS IN SPAIN

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SIEMENS, UNIVERSITY OF NEW MEXICO COLLABORATE ON RENEWABLE ENERGY

Siemens Industry and the University of New Mexico signed an agreement to collaborate on integrating renewable energy systems and microgrids. The agreement is centered around a University-owned microgrid. The microgrid assets include facilities such as a cooling tower, thermal storage tank, battery energy storage system, fuel cell, photovoltaic system, and a natural gas generator. The university is part of a statewide consortium that received a five-year, $20 million grant in 2018 to modernize the electrical grid. Its microgrid facilitates research into power system modernization, renewable energy systems, smart grids, and smart cities.

The university's microgrid was built partly to test new smart-grid technologies.

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**BERLIN PACKAGING ACQUIRES NETHERLANDS-BASED COMPANY**

Berlin Packaging announced the acquisition of Vinkova B.V., a Netherlands-based glass packaging supplier with expertise in the food and beverage sectors. The transaction is Berlin’s eighth acquisition in Europe since 2016. “Continued expansion in Europe is a central tenant of Berlin Packaging’s overall growth strategy,” says Bill Hayes, CEO and president of the Chicago-based company. The company says all Vinkova employees and locations would be retained. Financial details were not disclosed.

**SANDVIK JOINS GE ADDITIVE BETA PROGRAM**

GE Additive announced that Sandvik Additive Manufacturing joined its Binder Jet beta partner program. Sandvik has a broad alloy program for additive manufacturing on the market, marketed under the Osprey brand. The GE program uses its industrialized additive technology with technical partners to grow its Binder Jet technology. GE says the first phase involves developing the beta system into pilot lines, and eventually into a commercially available factory solution in 2021.

**GUARDIAN GLASS COMPLETES STARTUP OF PLANT IN POLAND**

Guardian Glass completed starting up its second float glass facility in Częstochowa, Poland, to help meet the demand for high-performance coated and fabricated glass products in Eastern Europe. The plant hosts two float lines, two coater lines, and a lamination line. Headquartered in Auburn Hills, Mich., Guardian Glass has six float glass plants in the United States and one in Mexico, as well as many fabrication facilities and warehouses. Guardian Glass companies also operate ten float glass plants across Europe and Russia.
CERAMIC MANUFACTURING MODULE HEADED TO SPACE STATION

Made In Space plans to launch a ceramic manufacturing module to the International Space Station. The technology is a commercial, in-space manufacturing device designed to provide proof-of-potential for single-piece, ceramic turbine blisk (blade and disk) manufacturing in microgravity for terrestrial use. This project marks the first ceramic facility on the ISS. Made In Space says the module will demonstrate the viability of manufacturing with preceramic resins in an additive, stereolithography environment. Made In Space is developing the technology with technical partners HRL Laboratories of Malibu, Calif., and Sierra Turbines of San Jose, Calif.
Setting the Standards: How Standards Enhance Quality and Promote Reliability

By David Holthaus

Standards in manufacturing are essential to ensuring quality products and to improving the accuracy and reliability of the materials used to make them.

They are also critical to promoting the safety of those who use the products, and sometimes it can literally be a matter of life and death.

In 2018, after two years of work, a committee of ASTM International, one of the world’s largest standards-developing organizations, published requirements for bullet-resistant doors on police vehicles.

The standard called for door panels to be made from a combination of ceramic and fabric, with the ceramic material acting as the strike face to break bullets that were made with steel cores. Such ammunition was increasingly being used in the high-powered weaponry that police were encountering on the streets, according to ASTM. Panels made with basic, armored steel often would not stop bullets with steel cores.

The new specification standardized protection levels and included language to help public safety agencies retrofit their vehicles or buy new ones with the safer ceramic-fabric panels.

It was a dramatic example of how standards evolve to keep up with new technology, materials, and processes.

Perhaps not as dramatic, but equally important in terms of safety and reliability, is the development and evolution of standards used to make refractories, the materials used to build structures routinely subjected to high temperatures.

The ASTM International Committee C08 on Refractories was founded in 1914. Over its history, the committee has defined what a refractory is, clas-
pecified them by type and function, and defined tests to
determine their suitability for specific applications.

In the early decades of the committee’s existence,
refractories were used to build the linings of fire-
places, kilns, and stills, among other applications. By
the end of the 20th century, refractories were used
to line nuclear reactors and in the manufacturing of
reentry heat shields for space shuttles.

The new uses demanded standardized tests to
benchmark performance and to help evaluate and
develop new materials.

Bill Headrick has been involved with creating and
refining ASTM standards for more than 30 years, and
he is currently working with Committee C08 as the
chair of the technical subcommittee on monolithics.

Headrick is head of research and development
for aluminosilicate products for the Americas at RHI Magnesita, the
world’s largest refractories company.

There are more than 100 standards relating to refractories alone, and
the manual on refractory standards is nearly an inch thick, Headrick
says. Committee members are engaged in a continuous process of eval-
uating and reviewing the standards to make sure they are up to date. In
August alone, Headrick says the committee reevaluated six standards.

“The biggest thing is making sure we’re using the best available
methods,” he adds.

For example, for years, the only method for determining the chemistry of
materials was wet chemistry, and the relevant standards only addressed
those methods. “Now, we have X-ray fluorescence, X-ray diffraction,
mass spectroscopy, and we’ve had to rewrite our standards to take into
account these better methods that give better results,” he says.

The committee is currently doing a lot of work to make standards
safer, Headrick says, and to have them align with the health and safety
requirements of employers.

Some of the standards for mea-
suring chemistry use materials
that are considered hazardous
to health, leading the com-
mittee to look for alternative
materials that are safer and can
produce similar results.

“That’s the biggest evolution
going on,” he says. “We’re
going through all the standards
and making sure they’re as safe
as possible.”

It is a deliberative process.

Every five years, ASTM standards must be reviewed and reapproved
by the appropriate subcommittee and then by the main commit-
tee. Any negative comment about the proposed standard must be
resolved before the standard can be approved.

“To pass a standard, you have to eliminate every single negative,”
Headrick says. “Once everyone is in full, 100 percent agreement, then
the standard is published. That can take a matter of months to a num-
ber of years.”

For several years now, ASTM committees and subcommittees have
worked on the standardization of the growing and developing field of
additive manufacturing, the process of fabricating parts and compo-
nents layer by layer using computer-aided design rather than traditional
manufacturing methods.

Improved technology, advanced equipment and sensors, and more
suitable materials are driving the productivity and reliability of additive
manufacturing production, yet the rapid change has pointed up the
need for standardization, says Mohsen Seifi.

Seifi is ASTM’s director of global additive manufacturing programs,
responsible for additive manufacturing programs that support stan-
dards development and other products and services at the organiza-
tion. He also oversees its Additive Manufacturing Center of Excellence,
which has the mission to bridge the gap between standardization to
research and development.

By 2008, the nascent additive manufacturing industry had reached the
point where standards were needed.

"Without standards, it’s going to be the Wild West," Seifi says.
"Industry needs standards for rapid implementation of this technol-
ogy for critical applications."
Additive manufacturing’s shortened development cycle and more efficient process means products can be designed and produced more quickly, but standardization is necessary to create consistency and reliability, and to serve as a foundation for continued growth.

“Innovation is inevitable, but without having standards in place, you can’t really drive this technology forward in terms of full implementation and adoption to satisfy regulation,” Seifi says.

“The reason is very clear,” he adds. “You need to make sure we’re all communicating the same language and making products in a repeatable and reliable fashion.”

ASTM’s committee on additive manufacturing technologies has met since 2009 and now has more than a thousand members from more than 35 countries who have developed standards that support the application and adoption of additive manufacturing for diverse materials and processes across various industry sectors.

In 2011, ASTM International and the International Organization for Standardization (ISO) signed an agreement paving the way to create joint additive manufacturing standards in order to increase collaboration and minimize duplication of efforts.

“If you are a user of this technology interested in fabricating parts and components, are you going to receive the same results if you produce a part at a service provider in the U.S. versus Europe versus Asia?” Seifi says. “That’s where standards play a critical role to make sure we manufacture products in a consistent, reliable, and repeatable manner.”

Another key reason for standards is to facilitate certification of additively manufactured parts from regulatory bodies such as the Federal Aviation Administration, NASA, Department of Defense, Food and Drug Administration, and many others.

“One a standard is out, it has the potential to become part of regulatory frameworks and can get into federal codes and referred to in federal contracts,” Seifi says.

One of the key trends on additive manufacturing standardization is understanding the challenges the technology brings in regard to data management and schema, Seifi says. The 3D printers and their sensors can generate gigabytes, sometimes terabytes, of data. “The question is, what data to collect according to what standard and format and why?” he says. “Is that data you collect findable, accessible, and reusable? Does it make sense to capture that data, and using what standard method? What kind of intelligence can we generate from the data to improve the process?”

“There are major standard gaps in this space that ASTM is trying to fill,” he adds.

In the cases of newer technologies such as additive manufacturing, and older processes such as refractory production, standards have helped advance processes, improve quality, and enable those production methods to be used reliably in a growing range of industries and applications.
A short list of standards-developing organizations

There are many organizations in the U.S. and around the world that work to develop standards for their industries. Here are some that apply to manufacturing:

- **The Association for Manufacturing Technology**
  Based in McLean, Va., the association promotes the interests of American manufacturing machinery and equipment, including the standardization of technology used to run machines. [www.amtonline.org](http://www.amtonline.org)

- **The American Nuclear Society**
  Based in LaGrange Park, Ill., the Society advances the development of nuclear science, engineering, and technology, and maintains a standards committee and board. [www.ans.org](http://www.ans.org)

- **The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE)**
  Based in Atlanta, Ga., the Society focuses on building systems, energy efficiency, indoor air quality, refrigeration, and sustainability through research, standards writing, publishing, and continuing education. [www.ashrae.org](http://www.ashrae.org)

- **American Society of Mechanical Engineers**
  Based in New York City, N.Y., the Society enables collaboration and skills development across engineering disciplines through programs in continuing education, training and professional development, codes and standards, research, and conferences and publications. [www.asme.org](http://www.asme.org)

- **ASTM International**
  Formerly known as American Society for Testing and Materials, ASTM International is an international standards organization that develops and publishes consensus technical standards for a range of materials, products, systems, and services. It is headquartered in West Conshohocken, Pa., outside of Philadelphia. [www.astm.org](http://www.astm.org)

- **International Code Council**
  Based in Washington, D.C., the Council is an association of building safety professionals and a source of model codes and standards that establish baselines for building safety. [www.iccsage.org](http://www.iccsage.org)

- **The International Organization for Standardization (ISO)**
  Headquartered in Geneva, Switzerland, ISO is an international standard-setting body composed of representatives from various national standards organizations. It promotes worldwide proprietary, industrial, and commercial standards. [www.iso.org](http://www.iso.org)

- **The International Committee for Information Technology Standards (INCITS)**
  Based in Washington, D.C., this committee is a standards development organization composed of information technology developers. [www.incits.org](http://www.incits.org)

- **The International Society of Automation**
  Based in Research Triangle Park, N.C., the Society is a technical society for engineers, technicians, businesspeople, educators, and students, and it sets standards for industry professionals in automation. [www.isa.org](http://www.isa.org)

- **National Institute of Standards and Technology (NIST)**
  Headquartered in Gaithersburg, Md., NIST is a nonregulatory federal agency within the U.S. Department of Commerce that develops and disseminates standards that allow technology to work seamlessly and business to operate smoothly. [www.nist.gov](http://www.nist.gov)

- **NSF International**
  Based in Ann Arbor, Mich., NSF International has developed more than 80 public health and safety standards, and tests and certifies products to verify they meet those standards. [www.nsf.org](http://www.nsf.org)

- **SAE International**
  Previously known as the Society of Automotive Engineers, Warrendale, Pa.-based SAE International is a standards-developing organization for engineering professionals in various industries. Its principal emphasis is on global transport industries, such as aerospace, automotive, and commercial vehicles. [www.sae.org](http://www.sae.org)

- **UL**
  Formerly known as Underwriters Laboratories, UL is a global safety certification company headquartered in Northbrook, Ill. It is approved to perform product safety testing by the U.S Occupational Safety and Health Administration. [www.ul.com](http://www.ul.com)
Japan Fine Ceramics Association (JFCA) was established in 1986 with a mission to promote the development of the fine ceramics/advanced ceramics industry. To take advantage of the most advanced technologies of fine ceramics, overall collaboration of manufacturers, users, universities, and research laboratories is required, together with the fusion of other materials.

The members of JFCA are 104 companies from different industries, such as ceramics, chemicals, metals, automobiles, electronics, power supply, and service. Through various activities, JFCA brings together and promotes cooperation among government, industry, academia, and overseas countries for the further expansion of the fine ceramics industry. The United States Advanced Ceramics Association (USACA), European Ceramics Center (PEC), and Ceramics Application are cooperating members of JFCA.

There are technical committees and consortiums in JFCA. Committees operate research groups such as Solid Oxide Fuel Cells, Power Electronics, GaN, LED, Bioceramics, Optical Ceramics, Material Function Predictive Simulation, Advanced Coating Alliance, and Ceramics Matrix Composites Consortium. In September, Fine Ceramics Roadmap 2050 Study Group was launched, which will publish the latest Roadmap in both Japanese and English versions in December 2021.

Figure 1 shows the amount of fine ceramics production in Japan, which reached $30 billion in 2018.¹

The benefits of standards for worldwide industries are extensive.² Standards help manufacturers reduce costs, anticipate technical requirements, and increase productive and innovative efficiency. Standards make trade across international borders easier and promote global competition, having a positive impact on economies.

ISO international standards help businesses of any size and sector reduce costs, increase productivity, and access new markets. Standards can help to

- Build customer confidence that the products are safe and reliable;
- Meet regulation requirements, at a lower cost;
- Reduce costs across all aspects of a business;
- Gain market access across the world;
- Improve quality, safety, and lead time of products and services;
- Lower research and development costs and improve speed to market by building on previously standardized technology or systems; and
- Provide uniformity of units measurement, enabling accuracy and confidence in commercial transactions locally and globally.

The Role of JFCA

JFCA conducts surveys and research to promote the international standardization of fine ceramics. JFCA, as a drafting organization in
the field of fine ceramics, is making international standards for high-quality, safe, secure, and highly reliable fine ceramic materials.

JFCA holds the secretariat of ISO/TC206 (Fine Ceramics) and ISO/TC150/SC7 (Tissue-engineered Medical Products) under the Japanese Industrial Standards Committee. In addition, as a national committee for ISO/TC206 and ISO/TC150 (Implants for Surgery) in Japan, we are engaged in deliberating proposals for new work items, development of projects in Japan and other countries, and maintenance and management of issued ISO standards.

ACCELERATION OF STANDARDIZATION SPEED
The speed of technological development increases to popularize new technologies globally. The conventional model shown in Figure 2, “Research & Development-Standard Development-Manufacturing / Products,” cannot catch up with its speed.

It is necessary to proceed with R&D and standard development at the same time and connect it to global manufacturing.

As shown in Figure 3, loop-shaped parallel development becomes the most effective way to establish standardization.

ABOUT INTERNATIONAL STANDARDS ORGANIZATION
International standards are published by international standardization bodies; three organizations are the representative. International Organization for Standardization (ISO) establishes international standards in a wide range of fields, except the fields of electricity, electronics, and communications. International Electrotechnical Commission (IEC) establishes international standards in the fields of electricity and electronics, and International Telecommunication Union (ITU) establishes international standards in the fields of communication, broadcasting, and information technology.

ISO is currently divided into 333 technical committees that deliberate and manage international standardization. The international standards for fine ceramic materials mainly belong to two committees: ISO/TC206 (Fine Ceramics) and ISO/TC150 (Implants for Surgery).

ISO/TC206 standardizes various forms and functions of fine ceramics. Japan is the secretariat of this committee and has a committee manager. The chair is from South Korea. The ISO/TC206 scope states as follows: Standardization in the field of fine ceramics materials and products in all forms: powders, monoliths, coatings and composites, intended for specific functional applications including mechanical, thermal, chemical, electrical, magnetic, optical, and combinations thereof. The term “fine ceramics” is defined as “a highly engineered, high performance, predominantly non-metallic, inorganic material having specific functional attributes.”

Note: Alternative terms for fine ceramics are advanced ceramics, engineered ceramics, technical ceramics, or high-performance ceramics.

The ISO/TC206 strategic business plan has the following description:
World demand for fine ceramics is projected to expand to $75 billion in the year 2020.

In order for the fine ceramics industry to further grow to contribute to the 21st century as a new materials industry, the following issues have to be overcome.

- Further promotion of research and development in terms of the material itself, development of new uses and application technologies.
- Research on manufacturing processes, and cost-reduction through corporate efforts.
- Establishment of testing and evaluation methods and standardization of the methods to prepare a basis for research and development, application, and utilization.
- Promoting international cooperation in the fields of research and development, and standardization.

Table 1 shows the composition of ISO/TC206, the number of ISO registrations, and the number under development. ISO/TC206 is divided into more specialized working groups (WGs) from WG1 to WG12. Since the committee’s inception in 1992, 136 standards have been issued. In recent years, about 10 new standards were published each year. In addition, there are 18 items under development.
New work-item proposals are deliberated by experts in the relevant working groups depending on the technical field. After approval of new business-item proposals, deliberation and approval proceed by passing through the stages of working draft, committee draft, draft international standard, and final draft international standard, to the goal of being published. It takes about three years to complete the process.

ISO/TC206 is currently composed of Participating Members from 14 countries (nine countries in Europe; five countries in Asia) and Observer Members from 20 countries. Participating Members have the right to vote and can elect experts to actively participate in the proposed project. ISO/TC206 holds a plenary meeting once a year where member countries can participate. This year, it was scheduled to be held in Brussels, Belgium, but due to the COVID-19 pandemic, the face-to-face conference was canceled, and a web conference was held by Japan.

The ISO/TC206 configuration is divided into specialized fields: subcommittee (SC) from SC1 to SC7, and working groups from WG1 to WG15. Since its inception in 1971, the technical committee has issued 166 standards, and 39 standards are under development.

ISO/TC150 currently consists of Participating Members from 29 countries, and Observer Members from 17 countries.

### RECENT INTERNATIONAL STANDARDIZATION ACTIVITIES

New work-item proposals were made from Japan to ISO/TC206 in 2020. Two proposals were made regarding the thermal characteristics evaluation method for ceramic substrates for power modules, and one proposal was made regarding the evaluation method for power generation characteristics of piezoelectric materials. One new work-item proposal was approved for a ceramic substrate for a power module, and it is currently at working draft stage.

The market size of power modules was 420 billion yen in 2019, and it is projected to be 570 billion yen in 2025 (140% of 2019). The core technology for ensuring the long-term reliability of power modules is the high-temperature resistance of power semiconductors. More specifically, it is heat that controls the change over time, and the ambient temperature and heat generated by driving the element contribute as heat sources.

We have strategically promoted the world’s first international standardization of the method for measuring the thermal properties of ceramic substrates for power electronics, which is a key element of next-generation power semiconductors.

In addition, JFCA is promoting a research project to develop international standardization of fine ceramics as a preliminary step to propose new work-item proposals to ISO. We are working on about six projects a year. Each project takes three years to research, prepare a standardization draft, and make a new proposal to ISO.
The following projects are underway as ongoing research and research projects.

- Test method for GaN crystal surface defects.
- Strength reliability test method for ceramic materials for solid oxide fuel cells (SOFC).
- Corrosion-resistant test method for fine ceramic thin films.
- Optical characteristic evaluation method for ceramic phosphors for white LEDs.
- Test method for thermal characteristics of insulating substrates for power electronics.
- Mechanical property test method for bioceramics.

All of these projects cover advanced technological fields where the market for fine ceramic materials is expected to expand, and they are developments for standardization related to property test methods for fine ceramic materials. We are aiming for international standardization to ensure high-quality, safe, secure, and highly reliable fine ceramic materials.

To secure the competitiveness of the fine ceramics industry and to develop the industry, it is necessary to differentiate products by improving functionality, strengthen price competitiveness by innovation in manufacturing processes, enhance product revolution by innovation of materials, develop new markets, and lead with speed. We hope that the international standardization promoted by JFCA will contribute to the further expansion of the fine ceramics industry.

OTHER JFCA ACTIVITIES

**CMC International Cooperation:** CMC International Cooperation was established in 2020 for developing reliability assurance technology for ceramic matrix composites. This consortium consists of the CMC center at Tokyo University of Technology, Ultra High Temperature Materials Research Center, and JFCA.

CMC International initiated development of the international standard inspection method that can overcome the problems of the conventional test method for ceramic matrix composite reliability. The method of guaranteeing reliability for use by taking advantage of the “damage tolerance” is not established yet. The first step is to prepare SiC/SiC test pieces that are damaged and defective inside. Then, we will conduct an evaluation test (round robin test) using common test pieces by overseas joint research partners of the University of Birmingham and the University of California, Los Angeles.

**Giant Micro-photonics Research:** The Giant Micro-photonics Project was established in 2020 by RIKEN Spring-8 Center (RSC), National Institute for Materials Science (NIMS), Mitsubishi Electric Co., Kounoshima Chemical, and JFCA to achieve dramatic sophistication of extremely high-power, solid-state lasers and terahertz generation by new transparent ceramic materials, or so called giant micro-photonics.

Based on these research results, the project is expected to prototype and develop a compact ultrahigh output, power density laser and develop wavelength conversion technology, which was difficult until now. It is also designed to convert to other important wavelengths and apply laser driven particle accelerators.

**Japan Ceramics Expo:** JFCA is the coorganizer of Japan Ceramics Expo, which is one of the world’s largest exhibitions alongside Ceramitec in Munich and Ceramics Expo in Cleveland, Ohio. Japan Ceramics Expo is organized by the Reed Exhibitions Japan and gathers all kinds of highly functional ceramics, materials, forming/processing equipment, burning/heating equipment, evaluation/testing/analysis equipment. It is held every year in Osaka and Tokyo.

Japan Ceramics Expo is chosen by advanced materials industry players worldwide as the best gateway to the Japanese and Asian markets. For more information, please go to https://www.ceramics-japan.jp/en-gb.html.

**Osaka Expo**
Dates: Wednesday, June 23 to Friday, June 25, 2021
Venue: INTEX Osaka, Japan

**Tokyo Expo**
Dates: Wednesday, December 8 to Friday, December 10, 2021
Venue: Makuhari Messe, Japan

**ABOUT THE AUTHOR**
Hirofumi Takemura is director of Japan Fine Ceramics Association.

**REFERENCES**
1. JFCA Fine Ceramics Industrial Trend Survey (2019)
3. METI Standardization Seminar (2020)
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December 2020 | Standards: Guideposts to quality

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**November–December 2020**  
29–Dec 3 2020 MRS Fall Meeting & Exhibit – VIRTUAL EVENT ONLY; www.mrs.org/fall2020

**January 2021**  

**February 2021**  
8–12 45th International Conference and Expo on Advanced Ceramics and Composites (ICACC2021) – VIRTUAL EVENT ONLY; www.ceramics.org/icacc2021

**March 2021**  

24–25 56th Annual St. Louis Section/Refractory Ceramics Division Symposium on Refractories – Hilton St. Louis Airport Hotel, St. Louis, Mo. www.ceramics.org

24–29 ➔ 2nd Global Forum on Smart Additive Manufacturing, Design and Evaluation (SmartMADE) – Osaka University, Nakanoshima Center, Japan; http://www.jwri.osaka-u.ac.jp/~conf/SmartMADE2021


**April 2021**  
25–30 ➔ International Congress on Ceramics (ICCC8) – Bexco, Busan, Korea; www.iccs.org

**May 2021**  
1–4 6th Ceramics Expo – Cleveland, Ohio; https://ceramics.org/event/6th-ceramics-expo

3–7 6th International Conference on Competitive Materials and Technology Processes (ic-cmtp6) – Hunguest Hotel Palota, Miskolc-Lillafüred, Hungary; www.ic-cmtp6.eu


17–20 China Ceramitec 2021 – Messe München, Germany; https://ceramics.org/en

23–28 14th Pacific Rim Conference on Ceramic and Glass Technology (PACRIM 14) – Hyatt Regency Vancouver, Vancouver, British Columbia, Canada; www.ceramics.org/PACRIM14

**June 2021**  
7–9 ACerS 2021 Structural Clay Products Division & Southwest Section Meeting in conjunction with the National Brick Research Center Meeting – Omni Austin Hotel Downtown, Austin, Texas; www.ceramics.org


**July 2021**  

**September 2021**  

**October 2021**  

17–21 ACerS 123rd Annual Meeting with Materials Science & Technology 2021 – Greater Columbus Convention Center, Columbus, Ohio; www.ceramics.org

**January 2022**  
18–21 Electronic Materials and Applications 2022 (EMA 2022) – DoubleTree by Hilton Orlando at Sea World Conference Hotel, Orlando, Fla; www.ceramics.org

23–28 46th International Conference and Expo on Advanced Ceramics and Composites (ICACC2022) – Hilton Daytona Beach Oceanfront Resort, Daytona Beach, Fla.; www.ceramics.org

Dates in **RED** denote new entry in this issue.  
Entries in **BLUE** denote ACerS events.  
➤ denotes meetings that ACerS cosponsors, endorses, or otherwise cooperates in organizing.  
Denotes virtual meeting.
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In this issue (pages 37 to 54)

Look for more business to business news in 2020:
- April
- June/July
- September
- December

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The Contributing Editor's name will be given at the end of each PED Figure that is published.

QUALIFICATIONS:
General understanding of the Gibbs phase rule and experimental procedures for determination of phase equilibria diagrams and/or knowledge of theoretical methods to calculate phase diagrams.

COMPENSATION for papers covering one chemical system:
$150 for the commentary, plus $10 for each diagram.

COMPENSATION for papers covering multiple chemical systems:
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$50 for each additional commentary, plus $10 for each diagram.

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- Hexion Inc OH

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- Dow Corning Corp MI
- Empower Materials Inc DE
- Gwent Electronic Materials Ltd UK
- Hexion Inc OH
- Master Bond Inc NJ
- Peter Pugger Mfg Inc CA
- Starfire Systems Inc NY
- Vanderbilt Minerals, LLC CT
- Zibo Guangtong Chemical Co Ltd China

#### Binders
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- Gwent Electronic Materials Ltd UK
- Hauk Tech Europe BV The Netherlands
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- Nyacol Nano Technologies Inc MA
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- Polymer Innovations Inc CA
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- Wistra GmbH Germany

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- Arkema Inc PA
- Boka Bearing Company FL
- Borregaard LignoTech WI
- Momentive Performance Materials Inc NY
- RE Carroll Inc PA
- Shamrock Technologies Inc NJ
- Superior Graphite Co IL
- Werner G Smith Inc OH
- Zschimmer & Schwarz GA

#### Organometallic Precursors
- RISE Research Institutes of Sweden, RISE Glass Sweden
- Zibo Guangtong Chemical Co Ltd China

#### Plasticizers
- Arkema Inc PA
- Borregaard LignoTech WI
- Croda NJ
- Hexion Inc OH
- Novamer Inc MA
- Polymer Innovations Inc CA
- SGS Chemicals Co Ltd Thailand
- Zschimmer & Schwarz GA

#### Polycondensation Additives
- Momentive Performance Materials Inc NY
- Starfire Systems Inc NY

#### Refractory Additives
- Almatis Inc PA
- BassTech Intl NJ
- Borregaard LignoTech WI
- Cancarb Limited Canada
- FELDCO Int Co CA
- Fusion Ceramics Inc OH
- Hunter Chemical LLC PA
- Innovnano - Advanced Materials SA Portugal
- Refractory Minerals Co Inc PA
- Vanderbilt Minerals, LLC CT
- Zschimmer & Schwarz GA

#### Rheological Additives
- Borregaard LignoTech WI
- Croda NJ
- Polymer Innovations Inc CA
- Shamrock Technologies Inc NJ
- Vanderbilt Minerals, LLC CT
- Zschimmer & Schwarz GA

#### Release Agents
- BassTech Intl NJ
- Dow Corning Corp MI
- Hexion Inc OH
- Shamrock Technologies Inc NJ
- Zschimmer & Schwarz GA

#### Sintering Aids
- Baikowski Malakoff Inc NC
- Empower Materials Inc DE
- Nyacol Nano Technologies Inc MA
- Polymer Innovations Inc CA
- Starfire Systems Inc NY

#### Suspending Agents
- Borregaard LignoTech WI
- Croda NJ
- Trinity Ceramic Supply Inc TX
- Vanderbilt Minerals, LLC CT
- Zschimmer & Schwarz GA
- ZYP Coatings Inc TN

#### Tape-Casting Additives
- Croda NJ
- Empower Materials Inc DE
- Polymer Innovations Inc CA
- Zschimmer & Schwarz GA

#### Thickeners
- Polymer Innovations Inc CA
- Trinity Ceramic Supply Inc TX
- Vanderbilt Minerals, LLC CT
- Zschimmer & Schwarz GA

#### Viscosity Stabilizers
- Hexion Inc OH
- norcross Viscosity Controls MI
- Vanderbilt Minerals, LLC CT

#### Wetting Agents
- Croda NJ
- Polymer Innovations Inc CA
- Zschimmer & Schwarz GA
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Adhesives
Aremco Products Inc NY
Arkema Inc PA
CerCo LLC OH
CoorsTek CO
Denka Corp NY
Hexion Inc OH
Momentum Performance Materials Inc NY
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O’Keefe Ceramics Inc CO
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Bharat Heavy Electricals Ltd NY

Blauch Precision Ceramics Inc NY
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CeramTec North America Corp SC
CeramTec-ETEC Germany
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Induceramic Canada
International Ceramic Engineering MA
IPS Ceramics LTD UK
Ipsen Ceramics IL
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<td>Advanced Material Fabrication</td>
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Refrac Systems AZ
Sigma Advanced Materials NY
Starfire Systems Inc NY
Technology Assessment and Transfer Inc (TAT&T) MD
Virdia3D LLC MA
Zibo Guangtong Chemical Co Ltd China

Composites, Ceramic-Polymer
Advanced Materials Associates China
Bullen OH
Cerakote Ceramic Coatings OR
novaBone Products LLC FL
O’Keefe Ceramics Inc CO
Starfire Systems Inc NY
Verity Technical Consultants LLC OH
Virdia3D LLC MA

Composites, Intermetallic
FELDCO Int’l CA
Zibo Guangtong Chemical Co Ltd China

Cutting Tools
Advanced Ceramics Manufacturing AZ
Advanced Materials Associates China
Astro Met Advanced Ceramics Inc OH
Cerakote Ceramic Coatings OR
CeramTec North America Corp SC
China Unipretc Ceramic Technology Co Ltd China
CooRTeK CO
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Thermocarbon FL
Zibo Guangtong Chemical Co Ltd China

Cylinders
Advanced Ceramics Manufacturing AZ
Cerakote Ceramic Coatings OR
CooRTeK CO
Ferrotec Ceramic Products China
Morgan Technical Ceramics Auburn CA
Suntech Advanced Ceramics (Shenzhen) Co Ltd China

Dies
Astro Met Advanced Ceramics Inc OH
North Star Equipment Inc WA
Petro Mold Company PA
Ram Products Inc OH
Refractron Technologies Corp NY
China Unipretc Ceramic Technology Co Ltd China
Zirca Inc OH

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Cerlase France
Cerinnov France
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Ceraste France
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Alumina, Activated
Alumina, Activated

Alumina, Calcined
Alumina, Calcined

Alumina, Fused
Alumina, Fused

Alumina, Reactive
Alumina, Reactive

Alumina, Single Crystal
Alumina, Single Crystal

Alumina, Tabular
Alumina, Tabular

Alumina, Zirconia Toughened
Alumina, Zirconia Toughened

Aluminum & Compounds
Aluminum & Compounds

Aluminum Nitride
Aluminum Nitride

North Star Equipment Inc WA

Peter Pugger Mfg Inc CA

Petro Mold Company PA

Ram Products Inc OH

Sheffield Pottery MA

StudioLX - Home Decor IL

Vindris3D LLC MA

CERAMIC & METALLIC POWDERS & MATERIALS

Abrasive Grains
Alumina, Calcined

Adsorbants & Catalysts
Alumina, Activated

Alumina, Fused
Alumina, Fused

Alumina, Reactive
Alumina, Reactive

Alumina, Single Crystal
Alumina, Single Crystal

Alumina, Tabular
Alumina, Tabular

Alumina, Zirconia Toughened
Alumina, Zirconia Toughened

Aluminum & Compounds
Aluminum & Compounds

Aluminum Nitride
Aluminum Nitride

APF Recycling Inc OH

MCD MI

Alumea Alumina, Calcined

Alumea Alumina, Activated

Alumea Alumina, Fused

Alumea Alumina, Reactive

Alumea Alumina, Single Crystal

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Alumea Aluminum Nitride

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Alumea Adsorbants & Catalysts
Aluminum Silicate
Goodfellow Corp PA
Sauerreisen Inc PA

Antimony & Compounds
Alfa Aesar Johnson Matthey MA
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Pred Materials International Inc NY

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Alfa Aesar Johnson Matthey MA

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Barium Carbonate
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Fusion Ceramics Inc OH
Hexion Inc OH

Barium Titanate
AVX Corp SC
BassTech Intl NJ
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Boric Acid
Sauerreisen Inc PA

Boron & Compounds
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Denka Corp NY
Electro Abrasives Corp NY
FELDCO Intl CA
Fusion Ceramics Inc OH
H.C. Starck North American Trading LLC MA
H.C. Starck Surface Technology and Ceramic Powders GmbH Germany
New Tech Ceramics Inc IA
Rio Tinto Minerals Australia

Boron Carbide
Atlantic Equipment Engineers NJ
CoorsTek CD

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Goodfellow Corp PA
Kyanite Mining Corp VA
Lienco Industries Inc NJ
Prince Minerals Inc TX

Iron Oxide
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Nutec Bickey Mexico
Prince Minerals Inc TX
Reade Advanced Materials RI

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CerPoTech AS Norway
FELDCO Intl CA
Fusion Ceramics Inc OH
GFS Chemicals Inc OH
Goodfellow Corp PA
H.C. Starck North American Trading LLC MA
H.C. Starck Surface Technology and Ceramic Powders GmbH Germany
Pred Materials International Inc NY
Prince Minerals Inc TX
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BassTech Intl NJ
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Fusion Ceramics Inc OH
Goodfellow Corp PA
H.C. Starck North American Trading LLC MA
H.C. Starck Surface Technology and Ceramic Powders GmbH Germany
Pred Materials International Inc NY
Prince Minerals Inc TX
RE Carroll Inc PA

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Alfa Aesar Johnson Matthey MA

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American Elements Inc CA

SiAION Powder
Pred Materials International Inc NY

Silica
Arkema Inc PA
Denka Corp NY
Ipsen Ceramics IL
Maryland Refractories Co OH
Momentive Performance Materials Inc NY
Nanocerat UT
Saint-Gobain Ceramics & Plastics MA
Sauerreisen Inc PA
Sibelco Benelux Belgium
U.S. Silica Co MD

Silica, Fused
APF Recycling Inc OH
BassTech Intl NJ
Bosai Minerals Group Co Ltd China
Centerline Technologies OH
Industrial Ceramic Products Inc OH
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Spheres, Glass
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RISE Research Institutes of Sweden, RISE Glass Sweden

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- See ad on pg 91
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Morgan Technical Ceramics Auburn CA
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P-Ker Engineering NY
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Advanced Ceramics Manufacturing AZ
Aremco Products Inc NY
Astro Met Advanced Ceramics Inc OH

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Christy Minerals LLC MO
CIDRA Precision Services LLC CT
CoorsTek CO
Du-Co Ceramics Company PA
FCT Ingenieurkeramik GmbH Germany
Ferro-Ceramic Grinding Inc MA
Fluid Energy Processing & Equipment Co PA
International Ceramic Engineering MA
Machined Ceramics Inc KY
McDanel Advanced Ceramic Technologies LLC PA
See ad on pg 61
Morgan Technical Ceramics Auburn CA
Ortech Inc CA
PremaTech Advanced Ceramics MA
Reade Advanced Materials RI
Refractory Machining Services PA
Refractory Minerals Co Inc PA
Refractron Technologies Corp NY
RocCera LLC NY
Stedman Machine Co IN
Union Process OH
Valley Design Corp MA
Washington Mills Electro Minerals Co NY
Zibo Guangtong Chemical Co Ltd China

Hot Repair
Fosbel Inc OH

Joining
Advanced Ceramic Technology CA
CeramTec North America Corp SC
Fosbel Inc OH
Fusion Tech/Hot Tech Group OH
Induceramic Canada
Morgan Technical Ceramics Auburn CA
P-Ker Engineering NY
Precision Ferrites and Ceramics Inc CA
Refrac Systems AZ
Refraco LLC NY
Sigma Advanced Materials NY
Starfire Systems Inc NY

Teeter Marketing Services LLC FL
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See ad on pg 61

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CerCo LLC OH
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Elan Technology CA
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Ferro-Ceramic Grinding Inc MA
Fosbel Inc OH
International Ceramic Engineering MA
Laserage Technology Corp L
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Ortech Inc CA
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Ram Products Inc OH
Refractory Machining Services PA
RocCera LLC NY
Stahl USA Inc WI
Superior Technical Ceramics Corp VT  See ad on pg 63
Technical Products Inc WI
Valley Design Corp MA
Zircar Zirconia Inc NY

Millling, Custom
Advanced Ceramic Technology CA
AVeka MN
Bullen OH
CIDRA Precision Services LLC CT
Custom Processing Services PA
Fluid Energy Processing & Equipment Co PA
International Ceramic Engineering MA
MSE Supplies AZ
Powder Processing & Technology LLC IN
Precision Ceramics FL
PremaTech Advanced Ceramics MA
Reade Advanced Materials RI
Refractory Machining Services PA
RocCera LLC NY
Sledman Machine Co IN
Union Process OH
Valley Design Corp MA
Washington Mills Electro Minerals Co NY

Nuclear Materials
Dunhua Zhengxing Abrasive Co Ltd China
Morgan Technical Ceramics Auburn CA
Peter Pugger Mfg Inc CA
Refrac Systems AZ
Verity Technical Consultants LLC OH

Piezoelectrics
APC International Ltd PA
CerPoTech AS Norway
Electrosciences Ltd UK
Haiku Tech Europe BV The Netherlands
Haiku Tech Inc FL
Meggitt Piezo Technologies IN
Sparkler Ceramics Pvt Ltd India

Powder Synthesis
CerPoTech AS Norway

Prototypes
Accuratus Corp NJ
Advanced Ceramic Technology CA
Astra Met Advanced Ceramics Inc OH
Bullen OH
Ceramtec North America Corp SC
CerCo LLC OH
CoresTek CO
Du-Co Ceramics Company PA
ESL ElectroScience PA
FCT Ingenieurkeramik GmbH Germany
Goceram AB Sweden
Industrial Ceramic Products Inc OH
International Ceramic Engineering MA
Lithoz GmbH NY
Morgan Technical Ceramics Auburn CA
Ortech Inc CA
P-Ker Engineering NY
Precision Ceramics FL

PremaTech Advanced Ceramics MA
Progressive Technology Inc CA
Ram Products Inc OH
Refrac Systems AZ
Rebrocasting Enterprises LLC NM
RocCera LLC NY
Silicon Carbide Products Inc NY

Technical Products Inc WI
Technology Assessment and Transfer Inc (TA&T) MD
Tethon 3D NE

Refractory Installation
Diamorph AB UK
Fosbel Inc OH
Refractory Consulting Services OH
Riverside Refractories Inc AL
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General Spray LLC NJ
Reade Advanced Materials RI

Seals
Astro Met Advanced Ceramics Inc OH
Bharat Heavy Electricals Ltd NY
CerCo LLC OH
Dunhua Zhengxing Abrasive Co Ltd China
Elian Technology GA
Morgan Technical Ceramics Auburn CA
Ortech Inc CA
P-Ker Engineering NY
Precision Ceramics FL
Refrac Systems AZ
Saint-Gobain High Performance Ceramics & Refractories MA
Texers Technical Ceramics Inc Canada

Spray Drying
Arch Maintenance Services GA
AVEKA MN
CeramTec North America Corp SC
CerPoTech AS Norway
Dorst America Inc PA
Elian Technology GA
General Spray LLC NJ

Powder Processing & Technology LLC IN
Verity Technical Consultants LLC OH

Superconductors
Precision Ceramics FL

Toll Blending, Processing
AVEKA MN
CerPoTech AS Norway
Custom Processing Services PA
Euro Support Advanced Materials The Netherlands
Fluid Energy Processing & Equipment Co PA
Fusion Ceramics Inc OH
General Spray LLC NJ
Gwent Electronic Materials Ltd UK
Peter Pugger Mfg Inc CA
Powder Processing & Technology LLC IN
Reade Advanced Materials RI
Refrac Systems AZ
TAM Ceramics NY

Toll Firing, Contract
ACCCO Inc/Burley Clay Products Co OH
Advanced Ceramics Manufacturing AZ
Astro Met Advanced Ceramics Inc OH
CeramTec North America Corp SC
Christy Minerals LLC MO
FCT Ingenieurkeramik GmbH Germany
FCT Systeme GmbH Germany

Glazes
American Art Clay Co Inc IN
Ceramic Color & Chemical Mfg Co PA
Cerlase France
Fusion Ceramics Inc OH
Laguna Clay Co CA
Mason Color Works Inc OH
RISE Research Institutes of Sweden, RISE Glass Sweden
Sheffield Pottery MA

Grazing Equipment
Arlimin Industries CO
Cerlase France
Du-Co Ceramics Company PA
HED Intl Inc NJ

Inks
American Art Clay Co Inc IN
Ceramic Color & Chemical Mfg Co PA
Fusion Ceramics Inc OH
Gwent Electronic Materials Ltd UK
Zibo Guangtong Chemical Co Ltd China

Lehrs
Nabertherm Inc DE
Recco Furnaces CA

Pigments
Arlimin Industries CO
Ceramic Color & Chemical Mfg Co PA
Fusion Ceramics Inc OH
Mason Color Works Inc OH

Porcelain Enamels
Cerlase France
Fusion Ceramics Inc OH
RISE Research Institutes of Sweden, RISE Glass Sweden

Precious Metals
FELDCO Intl CA
Fusion Ceramics Inc OH
Gwent Electronic Materials Ltd UK

Screen Printing Equipment
Aremco Products Inc NY
Haiku Tech Europe BV The Netherlands
Haiku Tech Inc FL

Silver Pastes, Conducting
Master Bond Inc NJ

Spray Booths
American Art Clay Co Inc IN
Laguna Clay Co CA

Stains
Ceramic Color & Chemical Mfg Co PA
Fusion Ceramics Inc OH
Mason Color Works Inc OH
Sheffield Pottery MA
Trinity Ceramic Supply Inc TX

Used Equipment
Mohr Corp MI

DECORATING

Coating Equipment
Cerakote Ceramic Coatings OR
Cerlase France
Haiku Tech Europe BV The Netherlands
Industrial Hard Carbon LLC NC
Laguna Clay Co CA

Decorating Equipment
Cerlase France

Decorating Supplies
Ceramic Color & Chemical Mfg Co PA

Enamels
Ceramic Color & Chemical Mfg Co PA
Cerlase France
Fusion Ceramics Inc OH
Mason Color Works Inc OH

Engobes
American Art Clay Co Inc IN
Ceramic Color & Chemical Mfg Co PA
Fusion Ceramics Inc OH
RISE Research Institutes of Sweden, RISE Glass Sweden
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Frits
Ceradayne Inc, a 3M Co KY
Ceramic Color & Chemical Mfg Co PA
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**Calciners**
- Applied Test Systems Inc PA
- Euro Support Advanced Materials The Netherlands
- Fluid Energy Processing & Equipment Co PA
- Harper International Corp NY
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**Controllers**
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- General Glass Equipment Co NJ
- HED Intl Inc NJ
- Paragon Industries LP TX
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**Controllers, Combustion**
- Air Products PA
- Fives north American Combustion Inc OH

**Controllers, Furnace**
- Carbolite Gero UK
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**Dryers**
- Advanced Machinery Inc MI
- Applied Test Systems Inc PA
- Basic Machinery Co Inc NC
- Ceramic Services Inc PA
- Cerilase France
- Colber Muegge LLC CT
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- Air Products PA
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**Furnaces**
- American Isostatic Presses OH
- Applied Test Systems Inc PA
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**Controllers, Temperature**
- Applied Test Systems Inc PA
- Datapaq Inc NH
- Edward Orton Jr Ceramic Foundation OH
- Nabertherm Inc DE
- Optocon AG Germany
- Paragon Industries LP TX
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**Data Acquisition Systems**
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- Cerilase France
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<td>Ceritherm France</td>
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<td>FCT Systeme GmbH Germany</td>
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<td>Harper International Corp NY</td>
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<td>Harrop Industries Inc OH</td>
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<td>HED Intl Inc NJ</td>
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<td>L&amp;L Kiln Mfg Inc NJ</td>
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<td>L&amp;L Special Furnace Co Inc PA</td>
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<td>Swindell Dressler Intl Co PA</td>
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<td>Takasago Industry Co Ltd Japan</td>
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<td>Thermcraft Inc NC</td>
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<td>Verder Scientific Inc PA</td>
<td>See ad on pg 101</td>
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<th>Kilns, Pusher Plate</th>
<th>Ceratherm France</th>
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<td>Kilns, Elevator</td>
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<td>Applied Test Systems Inc PA</td>
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<td>Ceramic Services Inc PA</td>
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<td>Euro Support Advanced Materials The Netherlands</td>
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### Electrical/Electronic Ceramics

#### Antennas, Dielectric
- Euro Support Advanced Materials The Netherlands
- O’Keefe Ceramics Inc CO
- Trans-Tech Inc, a subsidiary of Skyworks Solutions Inc MD

#### Capacitors
- Associated Ceramics & Technology Inc PA
  - See ad on pg 65
  - AVX Corp SC
- Euro Support Advanced Materials The Netherlands
- Ferro-Ceramic Grinding Inc MA
- Induceramic Canada
- Murata Manufacturing Co Ltd Japan
- Polymer Innovations Inc CA

#### Ceramic-Brazed Assemblies
- AdTech Ceramics TN
- CeramTec North America Corp SC

#### Conductors
- AdTech Ceramics TN
- CerPoTech AS Norway
- ESL ElectroScience PA
- Master Bond Inc NJ
- norEcs AS Norway

#### Crystals
- Induceramic Canada
- Kyocera International Inc CA
- Momentive Performance Materials Inc NY
- MSE Supplies AZ
- TevTech LLC MA
  - See ad on pg 83

#### Dielectrics
- AVX Corp SC
- Centerline Technologies OH
- CerPoTech AS Norway
- ESL ElectroScience PA

#### Filters, Dielectric
- CerPoTech AS Norway
- Euro Support Advanced Materials The Netherlands
- Murata Manufacturing Co Ltd Japan
- Trans-Tech Inc, a subsidiary of Skyworks Solutions Inc MD

#### Fuel Cells, Solid Oxide
- AdTech Ceramics TN
- Associated Ceramics & Technology Inc PA
  - See ad on pg 65
- Bharat Heavy Electricals Ltd NY
- CanCarb Limited Canada
- CerPoTech AS Norway
- ESL ElectroScience PA
- Euro Support Advanced Materials The Netherlands
- Gwent Electronic Materials Ltd UK
- H.C. Starck GmbH Germany
- H.C. Starck Surface Technology and Ceramic Powders GmbH Germany
- Morgan Technical Ceramics Auburn CA
- Nexcioris LLC OH
- norEcs AS Norway
- Polymer Innovations Inc CA
- Trans-Tech Inc, a subsidiary of Skyworks Solutions Inc MD

#### High-Voltage Insulators
- Akron Porcelain & Plastics Co OH
- Bharat Heavy Electricals Ltd NY
- Ceramco Inc NH
- CeramTec North America Corp SC
- Du-Co Ceramics Company PA
- Elcon Precision LLC CA
  - See ad on pg 107
- Morgan Technical Ceramics Auburn CA
- Precision Ferrites and Ceramics Inc CA
- Xiamen Innovacera Advanced Materials Co Ltd China
  - See ad on pg 93

#### Hybrid Circuits & Packages
- AdTech Ceramics TN
- AVX Corp SC
- Xiamen Innovacera Advanced Materials Co Ltd China
  - See ad on pg 93
- Precision Ferrites and Ceramics Inc CA

#### IC Packages
- AdTech Ceramics TN
- Kyocera International Inc CA
- NGK Spark Plug Co Ltd Japan

#### Insulators, Electrical/Electronic
- Accurateus Corp NJ
- AdTech Ceramics TN
- AdValue Technology LLC AZ
  - See ad on pg 43
- Akron Porcelain & Plastics Co OH
- Blasch Precision Ceramics Inc NY
- Ceramco Inc NH
- CeramTec North America Corp SC
- CerCo LLC OH
- Du-Co Ceramics Company PA
- ER Advanced Ceramics Inc OH
- ESL ElectroScience PA

#### Magnets
- Spontaneous Materials CO

#### Microwave Packages
- AdTech Ceramics TN
- Kyocera International Inc CA
- Precision Ferrites and Ceramics Inc CA

#### Multilayer Ceramic Capacitors
- Euro Support Advanced Materials The Netherlands
- Murata Manufacturing Co Ltd Japan
- Polymer Innovations Inc CA

#### Multilayer Ceramics, AIN
- AdTech Ceramics TN
- NEVZ-Ceramics, Close JSC Russia
- Xiamen Innovacera Advanced Materials Co Ltd China
  - See ad on pg 93

#### Multilayer Ceramics, Custom
- AdTech Ceramics TN
- EBL Products Inc CT
- Euro Support Advanced Materials The Netherlands
- Xiamen Innovacera Advanced Materials Co Ltd China
  - See ad on pg 93

#### Piezoelectrics
- APC International Ltd PA
- AVX Corp SC
- EBL Products Inc CT
- Meggitt Piezo Technologies IN
- Morgan Advanced Materials CA
- Polymer Innovations Inc CA
- Sparkler Ceramics Pvt Ltd India

#### Resistors, Thick-Film
- ESL ElectroScience PA
- Murata Manufacturing Co Ltd Japan
- Polymer Innovations Inc CA

#### Resonators
- AVX Corp SC
- Murata Manufacturing Co Ltd Japan
- NGK Spark Plug Co Ltd Japan
- Trans-Tech Inc, a subsidiary of Skyworks Solutions Inc MD

#### RF Components
- AdTech Ceramics TN
- Advanced Ceramic Technology CA
- Advanced Energy CO
- Murata Manufacturing Co Ltd Japan
- Precision Ferrites and Ceramics Inc CA
- Trans-Tech Inc, a subsidiary of Skyworks Solutions Inc MD

#### Semiconductors
- Cancarb Limited Canada
- Elcon Precision LLC CA
  - See ad on pg 107
- Momentive Performance Materials Inc NY
- NEVZ-Ceramics, Close JSC Russia

#### Semiconductors
- Cancarb Limited Canada
- Elcon Precision LLC CA
  - See ad on pg 107
- Momentive Performance Materials Inc NY
- NEVZ-Ceramics, Close JSC Russia
Semiconductor Energy Laboratory Co Ltd Japan
See ad on pg 91
Toto Ltd Japan

Sensors
AdTech Ceramics TN
AVX Corp SC
Bullen OH
CeramTec North America Corp SC
EBL Products Inc CT
Gwent Electronic Materials Ltd UK
Murata Manufacturing Co Ltd Japan
Neoptix Canada
Otech AG Germany
Polymer Innovations Inc CA
Quality Thermostor Inc ID
Sparkler Ceramics Pvt Ltd India
Technisonic Research Inc CT

Spark Plugs
Associated Ceramics & Technology Inc PA
See ad on pg 65
CarCo LLC OH
Federal-Mogul MI
Gwent Electronic Materials Ltd UK
NGK Spark Plug Co Ltd Japan

Substrates, Alumina
Accuratus Corp NJ
AdTech Ceramics TN
Bullen OH
Centerline Technologies OH
CeramTec North America Corp SC
CoorsTek CO
Du-Co Ceramics Company PA
Laserage Technology Corp IL
NEVZ-Ceramics, Close JSC Russia
NGK Spark Plug Co Ltd Japan
Ortech Inc CA
Saint-Gobain nonPro OH
Toto Ltd Japan
Valley Design Corp MA
Xiamen Innovacera Advanced Materials Co Ltd China
See ad on pg 93

Substrates, Aluminum Nitride
Accuratus Corp NJ
AdTech Ceramics TN
Bullen OH
Centerline Technologies OH
CoorsTek CO
Laserage Technology Corp IL
MSE Supplies AZ
NEVZ-Ceramics, Close JSC Russia
Ortech Inc CA
Starfire Systems Inc NY
Valley Design Corp MA
Xiamen Innovacera Advanced Materials Co Ltd China
See ad on pg 93

Substrates, Glass
Accuratus Corp NJ
Bullen OH
Centerline Technologies OH
Laserage Technology Corp IL
RISE Research Institutes of Sweden, RISE Glass Sweden


Thermistors
AVX Corp SC
Gwent Electronic Materials Ltd UK
Murata Manufacturing Co Ltd Japan
Polymer Innovations Inc CA
Quality Thermistor Inc ID

Transducers
APC International Ltd PA
CSC Force Measurement Inc MA
EBL Products Inc CT
Meggitt Piezo Technologies IN
Neoptix Canada
Sparkler Ceramics Pvt Ltd India
Technisonic Research Inc CT

Transformers
RoMan Manufacturing MI
Warner Power LLC MI

Ultrasonic Ceramics
APC International Ltd PA
EBL Products Inc CT
Meggitt Piezo Technologies IN

Varistors
AVX Corp SC
Kyocera International Inc CA
Polymer Innovations Inc CA

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Email: sales@innovacera.com
Note: * machining only


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| FABRICATING & FINISHING |

### Abrasives
- Allied High Tech Products Inc CA
- Diacut Inc CO
- Diamond Industrial Tools Inc IL
- Dunhua Zhengxing Abrasive Co Ltd China
- Dynacut Inc PA
- Electro Abrasives Corp NY
- Engis Corp IL
- FELDCO Int CA
- Jet Edge Waterjet Systems MN
- Reade Advanced Materials RI
- Saint-Gobain Abrasives MA
- Sigmadiamant Spain
- Stahli USA Inc WI

### Cutting Equipment
- Basic Machinery Co Inc NC
- Diamond Industrial Tools Inc IL
- General Glass Equipment Co NJ
- Haiku Tech Inc FL
- Jet Edge Waterjet Systems MN
- Liberty Machinery Co IL
- OptiPro Systems LLC NY
- Penn Tool Co NJ
- Sigmadiamant Spain
- Suntech Advanced Ceramics (Shenzhen) Co Ltd China

### Cutting Tools
- Diacut Inc CO
- Dynacut Inc PA
- Engis Corp IL
- Jet Edge Waterjet Systems MN
- New Tech Ceramics Inc IA
- Penn Tool Co NJ
- Sigmadiamant Spain

### CVD Equipment
- Advanced Energy CO
- Centeror Vacuum Industries NH
- Liberty Machinery Co IL

### Deburring Equipment
- Engis Corp IL
- Liberty Machinery Co IL
- Mohr Corp MI
- Penn Tool Co NJ

### Diamond Drills
- Diamond Industrial Tools Inc IL
- Greenlee Diamond Tool Co IL

### Diamond Hones
- Diamond Industrial Tools Inc IL
- Engis Corp IL
- Greenlee Diamond Tool Co IL
- Saint-Gobain Abrasives MA
- Stahli USA Inc WI

### Diamond Saw Blades
- Allied High Tech Products Inc CA
- Aremco Products Inc NY
- Contrust Architectural Mesh Co Ltd China
- Diacut Inc CO
- Diamond Industrial Tools Inc IL
- Dynacut Inc PA
- Engis Corp IL
- Greenlee Diamond Tool Co IL
- LECO Corp MI
- Liberty Machinery Co IL
- Saint-Gobain Abrasives MA
- Texers Technical Ceramics Inc Canada

### Diamond Saws
- Allied High Tech Products Inc CA
- Aremco Products Inc NY
- Diacut Inc CO
- Dynacut Inc PA
- Greenlee Diamond Tool Co IL
- Liberty Machinery Co IL

### Diamond Tools
- Diamond Industrial Tools Inc IL
- Engis Corp IL
- Greenlee Diamond Tool Co IL
- LECO Corp MI
- Penn Tool Co NJ
- Saint-Gobain Abrasives MA
- Sigmadiamant Spain

### Dicing Equipment
- Aremco Products Inc NY
- Diacut Inc CO
- Diamond Industrial Tools Inc IL
- Dynacut Inc PA
- Liberty Machinery Co IL
- Nutec Bickley Mexico

### Dies
- Gasbarre Products Inc PA
- Ram Products Inc OH

### Dressing Wheels, Diamond
- Diacut Inc CO
- Diamond Industrial Tools Inc IL
- Dynacut Inc PA
- Engis Corp IL
- Greenlee Diamond Tool Co IL

### Electroplating Equipment
- Haiku Tech Inc FL
- Liberty Machinery Co IL
- Penn Tool Co NJ

### Extruders
- Advanced Machinery Inc MI
- American Art Clay Co Inc IN
- Basic Machinery Co Inc NC
- Detroit Process Machinery MI
- Dorst America Inc PA
- Ipsen Ceramics IL
- Laguna Clay Co CA
- Mohr Corp MI
- North Star Equipment Inc WA
- Peter Pugger Mfg Inc CA

### Feeders
- Ingredient Masters Inc OH
- Isiform Ltd UK
- Mohr Corp MI
- Wyssmont Co NJ

### Forming Equipment
- Advanced Isostatic Presses OH
- ARBURG GmbH + Co KG Germany
- Dorst America Inc PA
- HED INI Inc NJ
- Ipsen Ceramics IL
- Isiform Ltd UK
- Lithoz GmbH NY
- Mohr Corp MI
- Quintus Technologies LLC OH
- Ram Products Inc OH

### Glass Finishing Equipment
- General Glass Equipment Co NJ
- Liberty Machinery Co IL
- Lithoz GmbH NY
- OptiPro Systems LLC NY

### Glass Forming Equipment
- General Glass Equipment Co NJ

### Glass Shear Spray
- RISE Research Institutes of Sweden, RISE Glass Sweden

### Glass Supplies
- Ipsen Ceramics IL

### Grinders, Centerless
- Diamond Industrial Tools Inc IL
- Liberty Machinery Co IL
- Precision Ferrites and Ceramics Inc CA
- Suntech Advanced Ceramics (Shenzhen) Co Ltd China

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Superior Graphite Co IL See ad on pg 73
Suntech Advanced Ceramics (Shenzhen) Co Ltd China
Washington Mills Electro Minerals Co NY

Brickmaking Equipment
- Basic Machinery Co Inc NC
- EZG Manufacturing Inc OH Inside front cover
- Laxis GmbH Luxembourg
- Stedman Machine Co IN

Casting Equipment, Pressure
- American Isostatic Presses OH
- Cerinov France
- Cerlase France
- Dorst America Inc PA
- HED INI Inc NJ
- Laguna Clay Co CA
- Maryland Ceramic & Steatite Co Inc MD

Casting Equipment, Tape
- Ferro-Ceramic Grinding Inc MA
- Haiku Tech Europe BV The Netherlands
- Haiku Tech Inc FL
- HED INI Inc NJ
- Polymer Innovations Inc CA

CNC Mills
- Elnco Precision LLC CA See ad on pg 107
- Liberty Machinery Co IL
- OptiPro Systems LLC NY
- Penn Tool Co NJ
- Suntech Advanced Ceramics (Shenzhen) Co Ltd China

Coating Equipment
- Allied High Tech Products Inc CA
- Cerakote Ceramic Coatings OR
- Dynacut Inc PA
- Haiku Tech Europe BV The Netherlands
- Haiku Tech Inc FL
- Liberty Machinery Co IL

Cold-End Coatings, Glass
- RISE Research Institutes of Sweden, RISE Glass Sweden

Controllers
- Dorst America Inc PA
- General Glass Equipment Co NJ
- Laguna Clay Co CA
- Rockwell Automation, Inc WI

Grinders, Centerless
- Diamond Industrial Tools Inc IL
- Liberty Machinery Co IL
- Precision Ferrites and Ceramics Inc CA
- Suntech Advanced Ceramics (Shenzhen) Co Ltd China

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Grinders, Cylindrical
Diamond Industrial Tools Inc IL
Liberty Machinery Co IL
Suntech Advanced Ceramics (Shenzhen) Co Ltd China

Grinders, Finished Product
DCM Tech MN
Ipsen Ceramics IL
Liberty Machinery Co IL
OptiPro Systems LLC NY
Stahli USA Inc WI

Grinding Wheels
Allied High Tech Products Inc CA
Diadac Inc CO
Diamond Industrial Tools Inc IL
Dynamit Inc PA
Engis Corp IL
Greenlee Diamond Tool Co IL
Penn Tool Co NJ
Sigmadiamant Spain
Stahli USA Inc WI

Hydraulic Systems
Isoform Ltd UK
Ram Products Inc OH

Injection-Molding Equipment
ARBURG GmbH + Co KG Germany
Goceram AB Sweden
Mohr Corp MI See ad on pg 79
Rockwell Automation, Inc WI
Suntech Advanced Ceramics (Shenzhen) Co Ltd China

Jiggering Equipment
Cerinnov France
Ram Products Inc OH

Lapping Equipment
Allied High Tech Products Inc CA
Diamond Industrial Tools Inc IL
Dynamit Inc PA
Engis Corp IL
Liberty Machinery Co IL
OptiPro Systems LLC NY
Sigmadiamant Spain
Stahli USA Inc WI

Lapping Supplies
Allied High Tech Products Inc CA
Diamond Industrial Tools Inc IL
Dunhua Zhengxing Abrasive Co Ltd China
Engis Corp IL
FELDOO Int CA
Stahli USA Inc WI

Laser Scribers
Centerline Technologies OH
Cerlase France
Laserage Technology Corp IL

Machining Equipment
Advanced Ceramic Technology CA
Dynamit Inc PA
International Ceramic Engineering MA
Liberty Machinery Co IL
OptiPro Systems LLC NY
Penn Tool Co NJ
Stahli USA Inc WI

Mandrels, Diamond
Diadac Inc CO
Diamond Industrial Tools Inc IL


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**Molds, Case**
Petro Mold Company PA
Ram Products Inc OH

**Molds, Ceramic-Forming**
Akron Porcelain & Plastics Co OH
Cerinnov France
Cerlase France
Geceram AB Sweden
Ipsen Ceramics IL
Isiform Ltd UK
Laeis GmbH Luxembourg
Laguna Clay Co CA
Petro Mold Company PA
Ram Products Inc OH
Virdis3D LLC MA

**Molds, Models**
Petro Mold Company PA
Ram Products Inc OH
Virdis3D LLC MA

**Plasma Etching Systems**
Advanced Energy CO
Liberty Machinery Co IL

**Pneumatic Systems**
Cycloenaire Corp NE
Ingredient Masters Inc OH
Ram Products Inc OH
Young Industries Inc PA

**Polishing Equipment**
Allied High Tech Products Inc CA
Diamond Industrial Tools Inc IL
Dynacut Inc PA
Engis Corp IL
LECO Corp MI
Liberty Machinery Co IL
OptPro Systems LLC NY
Penn Tool Co NJ
Sigmadiamant Spain
Stahli USA Inc WI

**Polishing Powder & Supplies**
Baikowski Malakoff Inc NC
C&L Development Corp CA
Engis Corp IL
Sigmadiamant Spain
Stahli USA Inc WI

**Presses, Compacting**
American Isostatic Presses OH
AVS Inc MA
FCT Ingenieurkeramik GmbH Germany
Quintus Technologies LLC OH

**Presses, Dry**
Advanced Machinery Inc MI
Dorst America Inc PA
Gasbarre Products Inc PA
See ad on pg 95
Maryland Ceramic & Steatite Co Inc MD
Suntech Advanced Ceramics (Shenzhen) Co Ltd China

**Presses, Extrusion**
Dorst America Inc PA
Maryland Ceramic & Steatite Co Inc MD
Mohr Corp MI
Peter Pugger Mfg Inc CA
See ad on pg 79

**Presses, Hot**
American Isostatic Presses OH
Centorr Vacuum Industries NH
FCT Ingenieurkeramik GmbH Germany
FCT Systeme GmbH Germany
Materials Research Furnaces Inc NH
Oxy-Gon Industries Inc NH
Refrac Systems A2
See ad on pg 87
See ad on pg 89

**Presses, Isostatic**
Advanced Machinery Inc MI
ARBURG GmbH + Co KG Germany
AVS Inc MA
Dorst America Inc PA
Gasbarre Products Inc PA
Laeis GmbH Luxembourg
Materials Research Furnaces Inc NH
Mohr Corp MI
Ram Products Inc OH
See ad on pg 95
See ad on pg 79

**Presses, Hydraulic**
Advanced Machinery Inc MI
ARBURG GmbH + Co KG Germany
AVS Inc MA
Digital Press Inc PA
Dorst America Inc PA
Gasbarre Products Inc PA
Laeis GmbH Luxembourg
Materials Research Furnaces Inc NH
Mohr Corp MI
Ram Products Inc OH
See ad on pg 95
See ad on pg 79

**Presses, Other**
ARBURG GmbH + Co KG Germany
Istofor Ltd UK

**Presses, Pressure Casting**
Cerlase France
Dorst America Inc PA
Peter Pugger Mfg Inc CA
Ram Products Inc OH

**Presses, Refractory Shapes**
Laeis GmbH Luxembourg

**Presses, Rotary**
Advanced Machinery Inc MI
Materials Research Furnaces Inc NH

**Presses, Tile (Ceramic)**
Laeis GmbH Luxembourg
Peter Pugger Mfg Inc CA

**PVD Equipment**
Liberty Machinery Co IL
Teeter Marketing Services LLC FL

**Roofing Tile Machinery**
Laeis GmbH Luxembourg

**Setting Equipment**
Basic Machinery Co Inc NC

**Slab Rollers**
North Star Equipment Inc WA

**Spray Booths**
Treibacher Industrie AG Austria

**Sputtering Equipment**
Advanced Energy CO
FCT Ingenieurkeramik GmbH Germany

**Superabrasives**
Diamond Industrial Tools Inc IL
Dynacut Inc PA
Engis Corp IL
Greenlee Diamond Tool Co IL
Liberty Machinery Co IL
Teeter Marketing Services LLC FL

**Surface Modification Systems**
Teeter Marketing Services LLC FL

**Tilemaking Equipment**
Basic Machinery Co Inc NC
Peter Pugger Mfg Inc CA
Ram Products Inc OH

**Tools, Modeling**
Sheffield Pottery MA
Virdis3D LLC MA
Turning Machines, Insulator
Liberty Machinery Co IL

Ultrasonic Machining Equipment
Bullen OH
International Ceramic Engineering MA
Liberty Machinery Co IL
OptiPro Systems LLC NY

Used Equipment
Advanced Machinery Inc MI
Basic Machinery Co Inc NC
Cerinov France
Diamond Industrial Tools Inc IL
Dorst America Inc PA
Dynacut Inc PA
Liberty Machinery Co IL
Mohr Corp MI
Ram Products Inc OH
Viridis3D LLC MA

Vibratory Finishing Equipment
Liberty Machinery Co IL
Penn Tool Co NJ
Rockwell Automation, Inc WI

Wheels, Cutoff & Grinding
Diacut Inc CO
Diamond Industrial Tools Inc IL
Dynacut Inc PA
Engis Corp IL
Greenlee Diamond Tool Co IL
LECO Corp MI
Liberty Machinery Co IL
Penn Tool Co NJ

Wheels, Diamond
Aremco Products Inc NY
Diacut Inc CO
Diamond Industrial Tools Inc IL
Dynacut Inc PA
Engis Corp IL
Greenlee Diamond Tool Co IL
LECO Corp MI
Liberty Machinery Co IL
Penn Tool Co NJ

GLASS PRODUCTS

Automotive Glass
Arkema Inc PA
RISE Research Institutes of Sweden, RISE Glass Sweden
Saint-Gobain Recherche France
Schott North America Inc NY

Beads/Spheres
Ceradyne Inc, a 3M Co KY
Maryland Ceramic & Steatite Co Inc MD

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Garg Process Glass India Pvt Ltd India
RISE Research Institutes of Sweden, RISE Glass Sweden
Schott North America Inc NY

Specialty Glass Inc FL
Valley Design Corp MA

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Mo-Sci Corp MO
RISE Research Institutes of Sweden, RISE Glass Sweden
Specialty Glass Inc FL

Borosilicate Glass
Bullen OH
Elan Technology GA

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Chemically Strengthened Glass
Arkema Inc PA
Garg Process Glass India Pvt Ltd India
RISE Research Institutes of Sweden, RISE Glass Sweden
Saint-Gobain Recherche France
Saxon Glass Technologies Inc NY
Schott North America Inc NY See ad on pg 41
Vesuvius SC

Container Glass
Arkema Inc PA
Cerinnov France
Ovens–Illinois Inc OH
RISE Research Institutes of Sweden, RISE Glass Sweden
Saint-Gobain Recherche France
Vesuvius SC

Fibers, Continuous
Saint-Gobain Recherche France
Vertly Technical Consultants LLC OH

Fibers, Optical
Adaman Co Ltd Japan
Corning Incorporated NY
Optico AG Germany
Schott North America Inc NY See ad on pg 41

Flat & Safety Glass
Arkema Inc PA
RISE Research Institutes of Sweden, RISE Glass Sweden
Saint-Gobain Recherche France
Vesuvius SC

Fused Silica Glass
Accuratus Corp NJ
Arkema Inc PA
Bullen OH
Imerys Refractory Minerals GA
RISE Research Institutes of Sweden, RISE Glass Sweden
Valley Design Corp MA

Glass-Ceramics
Accuratus Corp NJ
Advanced Ceramic Technology CA
Arkema Inc PA
Bullen OH
Cerilase France
Elan Technology GA

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ESL ElectroScience PA
RISE Research Institutes of Sweden, RISE Glass Sweden
Schott North America Inc NY See ad on pg 41
Specialty Glass Inc FL

Laboratory & Technical Glass
Arkema Inc PA
Garg Process Glass India Pvt Ltd India
LECO Corp MI
RISE Research Institutes of Sweden, RISE Glass Sweden
Saxon Glass Technologies Inc NY
Schott North America Inc NY See ad on pg 41
Specialty Glass Inc FL
TevTech LLC MA See ad on pg 83

Laminated Glass
Arkema Inc PA
RISE Research Institutes of Sweden, RISE Glass Sweden
Vesuvius SC

Laser Glasses
Cerinnov France
Israel Ceramic & Silicate Inst Israel
RISE Research Institutes of Sweden, RISE Glass Sweden

Lenses
TevTech LLC MA See ad on pg 83

Lighting
Osram Sylvania Inc MA

Mirrors
Valley Design Corp MA

Optical & Optoelectronic Ceramics
NEVZ-Ceramics, Close JSC Russia
Specialty Glass Inc FL
TevTech LLC MA See ad on pg 83
Vesuvius SC

Optical Substrates
Bullen OH
FELDCO Intl CA
Schott North America Inc NY See ad on pg 41
Specialty Glass Inc FL
Valley Design Corp MA
Vesuvius SC

Optical Thin Films
FELDCO Intl CA
Schott North America Inc NY See ad on pg 41
TevTech LLC MA See ad on pg 83

Solar
Ceradyne Inc, a 3M Co KY
FELDCO Intl CA
Materion Ceramics AZ
TevTech LLC MA See ad on pg 83
Texers Technical Ceramics Inc Canada
Vesuvius SC

Specialty Glass
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Corning Incorporated NY
Fusion Ceramics Inc OH
Garg Process Glass India Pvt Ltd India
Israel Ceramic & Silicate Inst Israel

Reducing Agents

Tubing & Rod
AdvValue Technology LLC AZ See ad on pg 43
Garg Process Glass India Pvt Ltd India
Morgan Advanced Materials CA
Specialty Glass Inc FL

LABORATORY EQUIPMENT & SUPPLIES

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Bayville Chemical Supply Co Inc NY
Nanofilm OH
RocCera LLC NY

Colorimeters
HunterLab VA

Density Measurement Instruments
Micrometrics Instrument Corp GA
Particle Technology Labs IL See ad on pg 99
Penn Tool Co NJ
Quantachrome Instruments FL
RocCera LLC NY

Detectors
Control Instruments Corp NJ
Penn Tool Co NJ
Rockwell Automation, Inc WI
Siemens Process Industries and Drives GA
Dimension Measurement Instruments
- CSC Force Measurement Inc MA
- Penn Tool Co NJ

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- Littleford Day Inc MI
- Recco Furnaces CA
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- Carl Zeiss MicroImaging Inc NY

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- Mo-Sci Corp MO
- RISE Research Institutes of Sweden, RISE Glass Sweden
- Taber Industries NY

Glassware
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- Garg Process Glass India Pvt Ltd India
- RISE Research Institutes of Sweden, RISE Glass Sweden

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Hardness Measurement Instruments
- Allied High Tech Products Inc CA

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- Zhengzhou Mission Ceramic Products Co Ltd China

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- Ceramco Inc NH
- CoorsTek CO
- McDanel Advanced Ceramic Technologies LLC PA
- Robocasting Enterprises LLC NM
- Xiamen Innovacera Advanced Materials Co Ltd China
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Lucideon UK
NSL Analytical Services Inc OH See ad on pg 75
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Setaram Instrumentation France
Technology of Materials CA
Washington Mills Electro Minerals Co NY

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P-Ker Engineering NY
Rauschert Industries Inc GA See ad on pg 69
Viridis3D LLC MA

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Setaram Instrumentation France
TA Instruments DE
Technology of Materials CA

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Micron Inc DE
NSL Analytical Services Inc OH See ad on pg 75
Rensselaer Polytechnic Inst NY
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SEMTech Solutions Inc UK
Technology of Materials CA

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NSL Analytical Services Inc OH See ad on pg 75

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NSL Analytical Services Inc OH See ad on pg 75

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Velco GmbH The Netherlands

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Carolina Material Technologies NC
Cyclonaire Corp NE
Ingredient Masters Inc OH See ad on pg 103
Mixer Systems Inc WI

Conveyors, Vibrating
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Carolina Material Technologies NC
OH Vibrator Co OH

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Verder Scientific Inc PA See ad on pg 101

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Texers Technical Ceramics Inc Canada
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Glen Mills Inc NJ See ad on pg 43
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#### Crucibles
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- Allied Mineral Products Inc OH
- APC International Ltd PA
- Aremco Products Inc NY
- Blasch Precision Ceramics Inc NY
- Bucher Emhart Glass SA Switzerland
- Ceramico Inc NH
- CeramTec-ETEC Germany
- Furnace Products & Services Inc PA
- Industrial Ceramic Products Inc OH
- Ipsen Ceramics IL
- LECO Corp MI
- Magneco Metrel Inc IL
- McDaniel Advanced Ceramic Technologies LLC PA
- Progressive Technology Inc CA
- Selee Corp NC
- Silicon Carbide Products Inc NY
- Zhengzhou Mission Ceramic Products Co Ltd China
- Zircoa Inc OH

#### Dead-Burned
- Fluid Energy Processing & Equipment Co PA

#### Fiber Products
- Allied Mineral Products Inc OH

#### Clay Flux
- Furnace Products & Services Inc PA
- Peter Pugger Mfg Inc CA
- RHI US Ltd NY
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Wholesale provider of raw materials to the ceramics, glass, and coatings industries.

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kthompson@ceramics.org
AACCM's member companies manufacture component products from ceramic powders at U.S. operating facilities. Its purpose is to expand the market for U.S.-manufactured components by enhancing processes and quality and to increase awareness of ceramic applications.

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http://www.associatedceramics.com
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http://www.bplittleford.com
sales@littleford.com
Manufactures processing equipment, including mixers, granulators, agglomerators, vacuum dryers, liquid dispersers, and pressure reactors. Also provides pilot-plant and lab equipment. Maintains a completely equipped test center to assist customers.

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Deer Park NY 11729
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info@bayvillechemical.net
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Ceramic Technological Institute, Corporate R&D, Bharat Heavy Electricals Ltd is engaged in industrial process and product development in ceramics, such as microwave sintering, ceramic membranes, coatings, nanomaterials, and CSP for energy sector.

BLASCHEMICAL ACCURACY INC 518-436-1263
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Albany NY 12204
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Inspiration and instruction from ceramic artists and leading professionals in the field. The Ceramic Arts Network is an online community serving active potters and ceramic artists worldwide, as well as those who are interested in finding out more about this craft. The Ceramic Arts Network includes Ceramics Monthly, Pottery Making Illustrated, CLAYtalks, the International Ceramic Artists Network (ICAN), and Ceramic Recipes.

CERAMIC COLOR & CHEMICAL MFG CO 1100 13th St New Brighton PA 15066 http://ceramiccolor.com info@ceramiccolor.com

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CERAMIC GLASS & CERAMIC RESEARCH INSTITUTE 118 Raja S C Mullick Rd Kolkata West Bengal 700 032 India http://cgrcri.res.in brmandal@cgcri.res.in

Provides scientific industrial research and development in the area of glass, ceramics, and related materials that maximizes the economic, environmental, and societal benefit for the people of India.

CERADYN INC, A 3M CO 2416 Merchant St Lexington KY 40511 http://www.3m.com/specialtyglass specialtyglass@3mm.com

800-831-0658

From manufacturing a new generation of precision electronics to enabling a world powered by clean, renewable energy, specialty glasses from Ceradyne Inc, a 3M Co, are inspiring innovation in electronic, solar power, and semiconductor applications. 3M specialty glass compounds and solar metallization paste additives are vital to many groundbreaking electronic and mechanical components. These versatile materials are precision-manufactured for unmatched consistency, batch after batch.Aland they are backed by Ceradyne’s 50 years of insight and experience. From glass design and engineering, to in-house analytical support and quality control, to scale-up and full-scale production, Ceradyne has the breadth and depth of knowledge to help customers make tomorrow’s breakthroughs today.

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Cerion specializes in the manufacturing of production and decoration machines for the ceramic and glass industries: shaping and decorating machines, laser marking machines, turn-key plants for tableware, tools, and after sales services.

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Cerion is a leader in the science of designing, scaling and manufacturing metal, metal oxide and ceramic nanomaterials for commercial, defense and life science companies developing products or systems. The cost of developing advanced expertise in nanomaterials is prohibitively expensive and time intensive, resulting in a significant barrier to entry for companies considering its adoption. Cerion provides companies with access to this expertise through all phases of the product lifecycle including applied research, development, scale-up, commercialization and manufacturing. Cerion’s position in the market is enabled by three strategic competitive advantages: a) precision design and customization of both nanoparticle size and technical attributes, b) robust processes to scale materials from prototype to low and high-volume production rates, and c) industry-leading, cost-effective manufacturing systems and production capacities.

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New Kensington PA 15068
http://www.specializedlaboratory.com

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Westbury NY 11590
http://spectroline.com
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Uniprectec is a professional manufacturer for advanced ceramics. Our materials include alumina ceramic, zirconia ceramic, boron nitride, and machinable glass ceramic. We aim to provide high quality products and solutions for our customers.

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J. Rettenmaier USA
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Nuteck Bickley SA de CV
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Particle Technology Labs
Paul O. Abbe
Plibrico Company LLC
Powder Processing & Technology, LLC
Praxair Surface Technologies, Inc
PremaTech Advanced Ceramics
QuantumScape
Rauscher Industries Inc
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Refractron Technologies Corp
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### Periodic Table of Elements

- Hydrogen (H)
- Helium (He)
- Lithium (Li)
- Beryllium (Be)
- Boron (B)
- Carbon (C)
- Nitrogen (N)
- Oxygen (O)
- Fluorine (F)
- Neon (Ne)
- Sodium (Na)
- Magnesium (Mg)
- Aluminum (Al)
- Silicon (Si)
- Phosphorus (P)
- Sulfur (S)
- Chlorine (Cl)
- Argon (Ar)
- Potassium (K)
- Calcium (Ca)
- Scandium (Sc)
- Titanium (Ti)
- Vanadium (V)
- Chromium (Cr)
- Manganese (Mn)
- Iron (Fe)
- Cobalt (Co)
- Nickel (Ni)
- Copper (Cu)
- Zinc (Zn)
- Gallium (Ga)
- Germanium (Ge)
-Arsenic (As)
- Selenium (Se)
- Bromine (Br)
- Krypton (Kr)
- Rubidium (Rb)
- Strontium (Sr)
- Yttrium (Y)
- Zirconium (Zr)
- Nb (Niobium)
- Mo (Molybdenum)
- Tc (Technetium)
- Ru (Ruthenium)
- Rh (Rhodium)
- Pd (Palladium)
- Ag (Silver)
- Cd (Cadmium)
- In (Indium)
- Sn (tin)
- Sb (Antimony)
- Te (Tellurium)
- I (Iodine)
- Xe (Xenon)
- Cs (Cesium)
- Ba (Barium)
- La (Lanthanum)
- Ce (Cerium)
- Pr (Praseodymium)
- Nd (Neodymium)
- Pm (Promethium)
- Sm (Samarium)
- Eu (Europium)
- Gd (Gadolinium)
- Tb (Terbium)
- Dy (Dysprosium)
- Ho (Holmium)
- Er (Erbium)
- Tm (Thulium)
- Yb (Ytterbium)
- Lu (Lutetium)
- Hf (Hafnium)
- Ta (Tantalum)
- W (Tungsten)
- Re (Rhenium)
- Os (Osmium)
- Ir (Iridium)
- Pt (Platinum)
- Au (Gold)
- Hg (Mercury)
- Tl (Thallium)
- Pb (Lead)
- Bi (Bismuth)
- Po (Polonium)
- At (Astatine)
- Rn (Radon)
- Fr (Francium)
- Ra (Radium)
- Ac (Actinium)
- Th (Thorium)
- Pa (Protactinium)
- U (Uranium)
- Np (Neptunium)
- Pu (Plutonium)
- Am (Americium)
- Cm (Curium)
- Bk (Berkelium)
- Cf (Californium)
- Es (Einsteinium)
- Fm (Fermium)
- Md (Mendelevium)
- No (Nobelium)
- Lr (Lawrencium)
- Rf (Rutherfordium)
- Db (Dubnium)
- Sg (Seaborgium)
- Bh (Bohrium)
- Hs (Meitnerium)
- Mt (Moscovium)
- Ds (Lawrencium)
- Rg (Oganesson)
- Cn (Nihonium)
- Fl (Flerovium)
- Mc (Livermorium)
- Tc (Technetium)
- Wn (Wolframium)
- Re (Rhenium)
- Os (Osmium)
- Ir (Iridium)
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