Ceramic matrix composites taking flight at GE Aviation
feature articles

Ceramic matrix composites taking flight at GE aviation
The holy grail for jet engines is efficiency, and the improved high-temperature capability of CMC systems is giving General Electric a great advantage.
by Jim Steibel

Nonoxide polymer-derived CMCs for “super” turbines
The melting point of single-crystal blades limits further advancement in operating temperature of gas turbines with metallic materials. Ceramics, which have much higher melting points, hold the promise for future “super” turbines.
by Zhongkan Ren and Gurpreet Singh

Taking off: Advanced materials contribute to the evolution of electrified aircraft
Commercial electrified aircraft are expected to take off within the next decade—and advanced materials are playing an increasingly critical role in solving key technical challenges that will push the boundaries even higher.
by Ajay Misra

Environmental barrier coatings enhance performance of SiC/SiC ceramic matrix composites
Environmental barrier coatings protect the structural integrity and mechanical strength of ceramic matrix composites, allowing these revolutionary materials to boost gas turbine engine efficiency.
by Kang N. Lee and Mark van Roode

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GFMAT-2/Bio-4
3rd Annual Energy Harvesting Society Meeting (EHS 2019)

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As seen on Ceramic Tech Today...

Optical fibers shake up earthquake monitoring systems
A team of Lawrence Berkeley National Laboratory researchers showed “dark fibers,” unused fiber-optic cables that crisscross the United States underground, could be coopted to serve as sensors in earthquake monitoring systems.

Also see our ACerS journals...
Composite reinforcement: Recent development of continuous glass fibers
By H. Li, T. Charpentier, J. Du, and S. Vennam
International Journal of Applied Glass Science

High-performance infrared emissivity of micro-arc oxidation coatings formed on titanium alloy for aerospace applications
International Journal of Applied Ceramic Technology

Mechanical behavior of SiC joints brazed using an active Ag–Cu–In–Ti braze at elevated temperatures
International Journal of Applied Ceramic Technology

Scalable measurements of tow architecture variability in braided ceramic composite tubes
By F. M. Heim, B. P. Croom, C. Bumgardner, and X. Li
Journal of the American Ceramic Society

Read more at www.ceramics.org/journals

American Ceramic Society Bulletin covers news and activities of the Society and its members, includes items of interest to the ceramics community, and provides the most current information concerning all aspects of ceramic technology, including R&D, manufacturing, engineering, and marketing. The American Ceramic Society is not responsible for the accuracy of information in the editorial, articles, and advertising sections of this publication. Readers should independently evaluate the accuracy of any statement in the editorial, articles, and advertising sections of this publication. American Ceramic Society Bulletin (ISSN No. 0002-7812). ©2019. Printed in the United States of America. A慈s Bulletin is published monthly, except for February, July, and November, as a “dual-media” magazine in print and electronic formats (www.ceramics.org). Editorial and Subscription Offices: 550 Polaris Parkway, Suite 510, Westerville, OH 43082-7045. Subscription included with The American Ceramic Society membership. Nonmember print subscription rates, including online access: United States and Canada, 1 year $135; international, 1 year $150. Rates include shipping charges. International Remall Service is standard outside the United States and Canada. *International nonmembers also may elect to receive an electronic-only, email delivery subscription for $100. Single issues, January-October/November: member $6 per issue; nonmember $15 per issue. December issue (AmericanSource): member $20, nonmember $40. Postage/handling for single issues: United States and Canada, $3 per item; United States and Canada Expeditd (UPS 2nd day air), $8 per item; International Standard, $6 per item. POSTMASTER: Please send address changes to American Ceramic Society Bulletin, 550 Polaris Parkway, Suite 510, Westerville, OH 43082-7045. Periodical postage paid at Westerville, Ohio, and additional mailing offices. Allow six weeks for address changes. ACSBA7, Vol. 98, No. 3, pp. 1 - 64. All feature articles are covered in Current Contents.
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From rooftop to reservoir—
Benefits of floatovoltaics

The California Building Standards Commission recently upheld a decision to require solar panels on all new homes up to three stories high, effective Jan 1., 2020. In the long term, homeowners are expected to benefit, but the requirement could greatly increase upfront costs.

The idea of increasing investment in solar panels is gaining traction, but placing the burden of uptake on homeowners—or even placing solar panels on land at all—may face severe opposition from citizens concerned about panels taking up valuable agriculture land, contaminating the environment, or even damaging community aesthetics.

Where else could solar panels be installed if not on houses nor land?

According to scientists at the National Renewable Energy Laboratory (NREL), it might be time to consider moving from rooftops and instead installing on reservoirs.

“Floatovoltaics,” or floating photovoltaic (PV) panels, are traditional PV panels installed on manmade reservoirs rather than on land. The concept was first demonstrated more than 10 years ago when a large-scale floatovoltaic system was installed at a California winery, and now there are more than 100 floatovoltaic sites around the world.

Recently, NREL researchers released a study detailing potential benefits of

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Floatovoltaic systems, which include lower installation costs than land-based solar panels and preventing harmful algae blooms. However, floatovoltaic systems also face unknowns, such as effects on local wildlife and long-term performance.

“This gap in our understanding is important to reconcile as floatovoltaics have enormous technical potential,” says Rebecca Hernandez, an assistant professor of earth system science and ecology at the University of California, Davis, who was not involved in the study, in an NBC news article.

When it comes to enormous potential, NREL researchers agree—they calculated that if floatovoltaics are installed on just one-fourth of manmade reservoirs in the United States, these panels could generate about 10 percent of U.S. energy needs. (Solar panels currently generate a little over 1 percent.)


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Corporate Partner news

**Lithoz becomes member of ADAPT Consortium**

The Alliance for the Development of Additive Processing Technologies (ADAPT), an industry-academia consortium at Colorado School of Mines that advances data informatics and advanced characterization technologies to optimize for additive manufacturing, welcomed new member Lithoz, a world leader in development and production of ceramic materials and additive manufacturing systems.

“The Lithoz membership in ADAPT formally marks our commitment to expand ADAPT’s research mission to all solid materials, beyond the alloys focus we had in our first few years,” says ADAPT executive director Aaron Stebner.

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**Shawn Allan, vice president of Lithoz America (left), shows the CeraFab 7500 printer installed at the Colorado School of Mines to graduate student Sarah Sortedahl and ADAPT industry director Craig Brice.**

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PLANTS, CENTERS, AND FACILITIES

PLG Glass acquires 50,000 sq. ft. Peterlee plant
PLG Glass, part of United Glass Group Ltd., bought its 50,000 sq. ft. facility in Mill Hill, Peterlee with help of a £1.3m (US$1.68m) loan from Lloyds Bank. Since acquisition, PLG Glass created four new jobs and expects to generate revenues of £4m (US$5.17m) by 2020. https://bdaily.co.uk/articles/2019.

Hoya building next-gen HDD glass substrate production facility
Japanese optical glass maker Hoya Corp. started construction of its new production facility for hard drive platter glass substrates. These substrates could be used to make conventional 2.5-inch HDD platters as well as next-generation platters for hard drives that use energy-assisted magnetic recording technologies. https://www.anandtech.com/.

Energy Department opening battery recycling center
United States Department of Energy will open a battery recycling center at Argonne National Laboratory, aiming to reclaim and recycle critical materials from lithium-based battery technology. https://www.energy.gov/news-blog.

Alteo opening a new affiliate in India
To support alumina market growth in India, Alteo is opening a new office, Alteo India Aluminas Private Ltd., in Mumbai. This new office will offer technical support, supply reliability, and a large product range to regional customers. https://www.ceramicindustry.com/.

ACQUISITIONS AND COLLABORATIONS

Army lab and Lockheed Martin announce partnership
The United States Army Research Laboratory and Lockheed Martin Corporation entered into a five-year cooperative agreement to develop rapid prototyping methods using bioproduction and self-assembly to create building blocks of novel materials for defense optical technology and protective coatings. https://www.army.mil/news.

Optoscribe, Sumitomo Electric announce cooperation
Optoscribe, a supplier of 3D glass-based integrated photonics components, and Sumitomo Electric Industries, an optical fiber cable and component manufacturing technology supplier, announced formation of a strategic cooperation to provide multicore fiber components for datacom and telecom applications. https://www.businesswire.com.

India’s Lohia Group acquires Israeli composite specialist

LifeSaver, National Graphene Institute exclusive research partnership
LifeSaver, a UK-based manufacturer of portable and reusable water filtration systems, and the National Graphene Institute at The University of Manchester will conduct an 18-month research project to develop graphene technology for enhanced water filtration. https://www.snewsnet.com/press-release.

MARKET TRENDS

New report: Refractories market worth $26.3 billion by 2023
A new Refractories Market research report projects the refractories market will reach US$26.3 billion by 2023, at a CAGR of 2.5 percent between 2018 and 2023. Unshaped refractories are projected to be largest segment of market, and growing demand from glass/ceramic industries are expected to drive market for acidic and neutral refractories. https://www.whatech.com/market-research/industrial.

Study finds 60 percent of advanced ceramics sales concentrated in power and metallurgy
According to a recent Fact.MR study, advanced ceramics sales surpassed 40,500 million tons in 2018, with demand in electronics and power and industrial and metallurgical applications collectively accounting for approximately 60 percent of overall sales in 2018. https://globenewswire.com/NewsRoom.

Calcium aluminate cement demand to reach 1M tons on growing refractories industry
Global demand for calcium aluminate cement is forecast to reach one million tons between 2021 and 2022, according to CW Research’s Global Calcium Aluminate Cement Market Report and Forecast. The upward trend will be underpinned by the refractories industry, the biggest consumer of calcium aluminate cement. https://www.openpr.com/news/archive.html.
Kyocera named among Derwent Top 100 Global Innovators by Clarivate Analytics

Kyocera Corporation was recognized as one of the Derwent Top 100 Global Innovators 2018–19 by Clarivate Analytics, a Philadelphia-based global information solutions provider focusing on intellectual property and the sciences. Kyocera’s patent success rate (more than 18,000) and global reach were identified as outstanding, marking the fifth consecutive for Kyocera to receive this recognition. The award was presented at Kyocera headquarters in Kyoto, Japan.

Kyocera’s Junichi Jinno (left), general manager of corporate legal and intellectual property group, receives trophy from Daniel Videtto, president of Clarivate Analytics IP & Standards.
ACerS signs MOU with partners to explore two-year ceramic technology degree

Opportunities in the field of ceramic engineering technology have taken a significant step forward with the signing of a memorandum of understanding between Central Ohio Technical College (COTC), the Edward Orton Jr. Ceramic Foundation, and The American Ceramic Society. Through the February 19th MOU signing, the entities have agreed to work together to launch at COTC the only two-year ceramic engineering technology degree program in the nation.

“The American Ceramic Society was founded to serve the needs of the ceramic manufacturing industry,” said Mark Mecklenborg, ACerS executive director. “We welcome the opportunity to continue to meet the evolving needs of industry and to introduce a new generation workforce to the rewards of working with these unique materials.”

The proposed program, which includes the creation of a Ceramic Learning Lab at the COTC Newark campus, will provide students an economical path to a technical career as well as provide skilled workers for the ceramic and materials processing and product industries.

Credit: COTC

From left to right: ACerS executive director Mark Mecklenborg, COTC president John M. Berry, Ph.D., and Edward Orton Jr. Ceramic Foundation general manager Mark Lawson signed the MOU at COTC’s Newark campus on Tuesday, Feb. 19.

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Serbian Chapter of ACerS

The ACerS board approved the Serbian Chapter of ACerS, sponsored by the Serbian Ceramics Society (SCS), at the end of 2018. The SCS organizes the Advanced Ceramics and Applications VIII: New Frontiers in Multifunctional Material Science and Processing conference, which will be Sept. 23–25, 2019 at the Serbian Academy of Sciences and Arts, Knez Mihailova 35, Belgrade, Serbia. The annual ACA conferences bring together leading scientists, engineers, professors, Ph.D. students, experts, and manufacturers of advanced ceramics, glasses, and refractories to exchange information on their key achievements and research projects. To learn more about the SCS and ACA conference, please visit: http://www.serbianceramicsociety.rs/index.htm.

Volunteer Spotlight

ACerS is pleased to announce the second recipient of our new Volunteer Spotlight program through which we recognize a member who demonstrates outstanding service to The American Ceramic Society through volunteerism.

William Long is an active Emeritus member of ACerS. He was instrumental in the successful launch of the Colorado Section of ACerS and belongs to the Engineering Ceramics Division. He is an advanced ceramics and composites consulting company to assist clients in the nuclear, automotive, armor, oil and gas, and chemical process industries.

We extend our deep appreciation to Long for his service to our Society!
Trolier-McKinstry elected to National Academy of Engineering

Susan Trolier-McKinstry, ACerS Fellow and professor of ceramic science and engineering at The Pennsylvania State University, was named a member of the National Academy of Engineering. Academy membership honors those who have made outstanding contributions to “engineering research, practice, or education,” and to “the pioneering of new and developing fields of technology, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education.”

Sylvia Johnson, ACerS president, visited The Missouri University of Science and Technology in Rolla, Mo., on February 14. Johnson toured the university, gave a talk, “Brief history of thermal protection systems,” and held a discussion about ACerS. The following day she visited Mo-Sci, an area glass manufacturer and ACerS Diamond Corporate Partner.

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Laurencin awarded 2019 AAAS Philip Hauge Abelson Prize
Cato T. Laurencin, founding director of the Institute for Regenerative Engineering and the Sackler Center for Biomedical, Biological, Physical, and Engineering Sciences at the University of Connecticut, was awarded the 2019 American Association for the Advancement of Science Philip Hauge Abelson Prize. An eminent biomedical engineer and orthopedic surgeon, the prize honors his global leadership in biomedical technology innovation, public service in shaping United States technology policy, and invaluable mentorship to a generation of minority scientists.

Boccaccini elected to the National Academy of Science and Engineering of Germany
Aldo R. Boccaccini, professor and head of the Institute of Biomaterials, University of Erlangen-Nuremberg, Germany, has been elected ordinary member of the National Academy of Science and Engineering of Germany. Election to the Academy is based on scientific achievements and reputation.
Society, Division, Section, and Chapter news (cont.)

Brinkman new materials science/engineering department chair at Clemson University

Effective March 1, Kyle Brinkman is the new chair of the Materials Science and Engineering Department at Clemson University. An early goal is to establish a council to help advise the university on investment in advanced materials, one of six innovation clusters identified as strategic research priorities in the ClemsonForward plan.

Brinkman replaces Rajendra Bordia, who will remain on the Clemson faculty and focus on teaching, research, and scholarship.

One and done—pay your dues once with an ACerS Lifetime Membership

ACerS Lifetime Membership allows members to avoid future dues increases, maintain awards eligibility, and the need to renew each year. The cost to become a Lifetime Member is a one-time payment of $2,000. Join the growing list of Lifetime Members while securing ACerS member benefits for your entire lifetime.

To learn more about Lifetime Membership, contact Kevin Thompson at (614) 794-5894 or kthompson@ceramics.org.

In memoriam

Thomas F. Root
Alexander Marker

Some detailed obituaries can also be found at www.ceramics.org/in-memoriam.

AWARDS AND DEADLINES

Nominations open for three engineering awards

The Engineering Ceramics Division invites nominations for the 2020 James I. Mueller, Bridge Building, and Global Young Investigator awards. The deadline for submitting nominations for all three awards is July 1, 2019.

The Mueller Award

The Mueller Award recognizes long-term service to ECD and work in the area of engineering ceramics that has resulted in significant industrial, national, or academic impact. Award selection can be based on either criteria. The award consists of a memorial plaque, certificate, and an honorarium of $1,000. For information, contact Manabu Fukushima at manabu-fukushima@aist.go.jp.

The Bridge Building Award

The Bridge Building Award recognizes contributions to the field of engineering ceramics, including expansion of the knowledge base and commercial use thereof, and contributions to the visibility of the field and international advocacy. Award selection can be based on either criteria. The award consists of a glass piece, certificate, and an honorarium of $1,000. For information, contact Surojit Gupta at gsurojit1@gmail.com.

The Global Young Investigator Award

The Global Young Investigator Award recognizes an outstanding scientist conducting research in academia, industry, or a government-funded laboratory. Candidates must be ACerS members and 35 years of age or younger. Selection of the awardee will be based on the nomination and accompanying evidence of scientific contributions and visibility of the field, and advocacy of the global young investigator and professional scientific forum. The award consists of $1,000, a glass piece, and certificate. For information, contact Valerie Wiesner at valerie.l.wiesner@nasa.gov.

Nominations close May 15 for GOMD and Electronics Division awards

Nominations close May 15 for three awards concerning glass and electronics.

Glass & Optical Materials Division: Alfred R. Cooper Scholars Award recognizes undergraduate students who have demonstrated excellence in research, engineering, and/or study in glass science or technology.

Electronics Division: Edward C. Henry Award recognizes an outstanding paper reporting original work in the Journal of the American Ceramic Society or the ACerS Bulletin during the previous calendar year on a subject related to electronic ceramics.

Electronics Division: Lewis C. Hoffman Scholarship recognizes academic interest and excellence among undergraduate students in the area of materials science and engineering.

Award criteria and nomination forms can be found at ceramics.org/awards. Contact Erica Zimmerman at ezimmerman@ceramics.org for information.

A case for continuous membership . . . continued

The March issue of the Bulletin explained how a gap in membership can make you ineligible to become an ACerS Fellow. The same is true for Emeritus membership eligibility.

If you are over 65 years old, and have been a member for 35 or more years, you qualify for Emeritus membership. As an Emeritus member you no longer pay annual membership dues, and you pay discounted registration fees to attend meetings.

But, you must maintain 35 continuous years of membership to be eligible. So, keep your membership current. You can easily renew online each year for one or multiple years. For more information about Emeritus, Fellow, or other awards eligibility, visit www.ceramics.org/members/awards.
ACerS member helps students find career success

Claire Xiong knows firsthand the importance of being part of a scientific community. She was born into a scientific family—her father was an electrical engineer and her mother was an analytical chemist. When you are surrounded by science your entire childhood, there is a chance you may follow a similar career path.

And that is just what Xiong did.

Xiong earned a B.E. in applied chemistry and a master’s degree in inorganic chemistry from East China University of Science and Technology (Shanghai). She earned her Ph.D. in electrochemistry from the University of Pittsburgh (Pa.), studying one-dimensional nanostructured electrodes using scanning electrochemical microscopy.

As associate professor at Micron School of Materials Science and Engineering at Boise State University, Xiong’s research focus lies in the synthesis, characterization, and development of advanced functional nanomaterials for sustainable energy systems.

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MEMBER SPOTLIGHT

1896

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Professor Edward Orton Jr. began manufacturing pyrometric cones at Ohio State University in 1896. This was the start of the Standard Pyrometric Cone Company. In 1932 the company transformed into The Edward Orton Jr. Foundation.

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Member spotlight (cont.)

She joined The American Ceramic Society around the same time she started her job at Boise State.

“At that time, I was still new [at Boise State], and was trying to figure out where to find a ‘home’ in a professional society,” she explains. “I had been a member of electrochemical, electroanalytical chemistry societies, and Material Research Society.”

One of her colleagues, ACerS Fellow Darryl Butt, indirectly introduced her to ACerS during a leadership summit. “He introduced me to program managers at the National Science Foundation (NSF) and the Department of Energy,” she says. “He wanted me to meet Lynnette Madsen, who encouraged me to attend a principle investigator meeting. Everyone was so welcoming, especially to the newcomers. That’s how I ended up joining ACerS.”

Xiong is currently secretary of ACerS Electronics Division, which coorganizes the Electronic Materials and Applications meeting (EMA) every year with the Basic Science Division. Xiong has gotten to know more ACerS members by regularly attending meetings and presenting research.

“I gave a talk at MS&T [in 2018],” she says, “and discovered that people are really very supportive and friendly. You can generate more ideas, feedback, and comments about the research you’ve presented.”

Xiong also participated as a panelist on an NSF-sponsored career workshop. She explains, “It was valuable for students and faculty who are beginning their careers. They really liked the advice they got from the panelists.”

Because of the advantages she gained from new relationships and thought-leadership opportunities, Xiong encourages her students to get involved in the Society.

“It’s important for meeting organizers to provide opportunities for ACerS members and students to become involved,” she says. “We try to arrange activities at each [EMA] meeting for students and those early in their careers to get perspectives from seasoned scholars.”

Xiong talked about one of her students that she brought to an EMA meeting. “She spent time networking at the meeting and found a postdoc job,” Xiong says proudly. “These meetings are really good exposure for students.”

STUDENTS AND OUTREACH

ICG 2019 housing options

Are you attending ICG 2019 in Boston this year? If so, visit ICG 2019 Facebook event page to meet other attendees prior to the event, work out possible roommates, set up dinners with others, and utilize the page for overall networking. Search “@acersgrads” to find the GGRN Facebook page and locate the ICG event under the events tab.

Show your expertise in ACerS Next Top Demo

Show off your demonstration skills! Get a group of fellow students together and submit a video of a ceramic or glass outreach demonstration. ACerS Next Top Demo is a virtual competition organized by ACerS President’s Council of Student Advisors to educate the public while advertising the community outreach that you and your university or group already perform. Visit www.ceramics.org/pcsa to view the PCSA programs and find out how to compete, and send your video submissions for the Next Top Demo competition. Deadline is April 15, 2019.

ACerS GGRN membership for graduate-level ceramic and glass students

Build an international network of peers and contacts within the ceramic and glass community with ACerS Global Graduate Researcher Network! ACerS GGRN addresses the professional and career development needs of graduate-level research students. GGRN members receive all ACerS individual member benefits plus special events at meetings, and free webinars on targeted topics relevant to the interest of the graduate student community.

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Apply for 2019–20 ACerS PCSA

The President’s Council of Student Advisors is the student-led committee of the Society composed of ceramic- and glass-focused students. The PCSA seeks dedicated and motivated undergraduate and graduate students to help advance ACerS into the future. Interested students should visit www.ceramics.org/applypcsa to apply. Application deadline is April 15, 2019.

ACerS offers early career memberships

ACerS offers a one year Associate membership at no charge for recent graduates who have completed their terminal degree. To receive the benefits of membership in the world’s premier membership organization for ceramics and glass professionals, visit www.ceramics.org/associate.

Also, consider joining ACerS Young Professionals Network. ACerS YPN is for members who have completed their degree and are 25 to 40 years old. YPN gives young ceramic and glass scientists access to invaluable connections and opportunities. Visit www.ceramics.org/ypn for more information, or contact Yolanda Natividad at ynatividad@ceramics.org.

The aim of this school is to create a forum that brings together students, professors, and industrialists from the high and ultra-high temperature ceramics field to develop links and a common language for better research and technological innovations, to define key challenges, and discuss questions to move toward effective solutions.

The Ceramic and Glass Industry Foundation is offering up to $1,000 in travel support to selected undergraduate, graduate, and Ph.D. students from non-European based universities. To be eligible for consideration, applicants must be members of The American Ceramic Society, Material Advantage, Keramos, or the ACerS Global Graduate Researcher Network. Students wishing to apply for ACerS financial assistance are strongly encouraged to first secure support from their home institutions for the experience. To determine ACerS support eligibility, students must submit:

2. A brief letter of recommendation from a faculty member
3. A single-page letter of interest explaining
   - The relevance of this summer school to their field of study and career ambitions
   - Other sources of financial support with amounts

The required application and supporting documents can be emailed to Belinda Raines, outreach manager, at braines@ceramics.org by March 30, 2019. Visit https://bit.ly/cgiftorino for additional information.

Summer school attendees are encouraged to also attend ECerS XVI Conference, which will be held in Torino, Italy, on June 16–20, 2019.
Improved nanocatalyst stability boosts artificial photosynthesis efficiency

Though hydrogen and other alternative fuels like methanol are promoted as ways to bypass traditional fossil fuels, the main method for extracting these elements from compounds requires burning fossil fuels like natural gas and coal—meaning that creating alternative fuels produces carbon dioxide, the exact thing alternative fuels try to avoid producing. New research on artificial photosynthesis by scientists at the University of São Paulo, the University of California, Davis, and the Brazilian Nanotechnology National Laboratory, though, could help make alternative fuels a truly green alternative.

Artificial photosynthesis produces hydrogen, methanol, and other organic molecules by using solar energy to break apart water and CO$_2$. However, artificial photosynthesis is currently most successful at just producing hydrogen because that only requires breaking down water. To create organic molecules like methanol, an additional step of CO$_2$ photoelectrocatalytic reduction is required, which is a harder process to achieve. Additionally, the material commonly used to capture and catalyze water and CO$_2$ from the atmosphere—titanium dioxide nanoparticles—readily adsorbs water to its surface, but does not so readily adsorb CO$_2$.

In their study, the researchers looked to improve the photoelectrocatalytic reduction process both indirectly (increased CO$_2$ adsorption capability) and directly (interface segregation) by doping TiO$_2$ nanoparticles with barium oxide. Barium oxide was chosen as a possible dopant due to its CO$_2$ adsorption capabilities and its susceptibility to surface segregation.

“The interface segregation knowledge is one of the keys for designing the surface of any nanocatalyst,” says Andre Silva, a postdoctoral researcher at the University of São Paulo. That
is because segregation of ions is intrinsically connected to the thermodynamic stability of nanoparticles by the surface energy term. If a nanocatalyst is doped with the right ions, thermodynamic stability of the material will increase and surface energy will decrease, leading to “smaller crystallite sizes and higher specific surface area, which lead to more active sites for the reaction [to take] place,” explains Silva.

After doping with barium oxide and using a lixiviation method to quantify the barium ion content located at the surface and grain boundary interfaces, the researchers combined this knowledge with direct calorimetric measurements of surface energies and microstructural studies to reach a conclusion: surface segregation of barium ions improves nanocatalyst stability.

“This paper is a very good reference for understanding how to design nanoparticle surfaces to increase nanostability through surface segregation,” Silva says.

He adds that the study is part of a larger research program looking to decrease CO₂ concentration using artificial photosynthesis: CO₂ abatement programme—Project 31. The project is run by the Research Centre for Gas Innovation, a center supported by the São Paulo Research Foundation and Shell that studies the sustainable use of natural gas, biogas, and hydrogen, and management, transport, storage, and use of CO₂.

“The next step of the research is to perform the artificial photosynthesis tests using a reactor that is being built in our group,” Silva says. “In the future, we believe that it will be possible to have portable systems, as panels with active nanoparticles that could be placed in many places, like houses or offices, to transform the CO₂ from the atmosphere in useful organic composites.”

The paper, published in *Journal of Physical Chemistry C*, is “TiO₂ surface engineering to improve nanostability: The role of interface segregation” (DOI: 10.1021/acs.jpcc.8b12160).
Ferroelectric crystals could revolutionize optical data transmission

Researchers from Lehigh University and Lebanon Valley College collaborated with Oak Ridge National Laboratory and Corning Inc. to fabricate single-crystal waveguides in optical fibers. They showed that despite being constrained inside glass, these crystals retained their ferroelectric properties.

Instead of creating single crystals using the common liquid-solid transformation method, the researchers used a solid-solid transformation technique called single-crystal-architecture-in-glass (SCAG), which involves heating a glassy material with a laser to just its crystallization temperature to form the single crystals.

In an email, Himanshu Jain, ACerS Fellow and professor of materials science and engineering at Lehigh University, explains the researchers were unsure if the single crystals would exhibit ferroelectric properties. “At the outset it was unclear to us if such a crystal when grown and physically constrained inside the glass would be able to retain its ferroelectric behavior and corresponding active properties,” Jain says.

The researchers performed electron backscatter diffraction and piezoresponse force microscope (PFM) measurements on lithium niobosilicate glass to generate theoretical and experimental piezoresponse maps, respectively, for comparison. They found that, except for a specific region near the grain bound-
ary, both maps agreed with each other and showed what the researchers were hoping for—a ferroelectric domain structure. “The PFM maps indicate the as-grown crystals possess a non-uniform ferroelectric domain structure consisting of oppositely oriented domains on the micro- and nano-scale,” the researchers say in the paper.

Though this discovery was promising, Jain explains most photonic applications "would like to have uniform domain structure so that desired properties can be realized in a predictable manner.” So, the researchers then tried uniformly orienting the ferroelectric domain structure using the PFM cantilever tip to perform a two-step poling process. The experiment did not work at room temperature (as it does for bulk LiNbO₃ single crystal), but it succeeded when the sample temperature was elevated to 100°C. After 24 hours, the modified regions remained stable and unaltered.

Jain explains that the team has an extensive, ongoing program “to perfect the quality of single crystal architecture fabricated...
in glass, and also provide new controls on the characteristics of such crystals, such as their orientation.” Additionally, Jain says the partnership with Corning ensures the work will progress toward a realistic application in a reasonable time.

“We discuss the results every 2–3 weeks, and our partners at Corning provide feedback regularly and also facilitate testing of the structures fabricated at Lehigh at their facility,” Jain adds. The paper, published in MRS Communications, is “Ferroelectric domain engineering of lithium niobite single crystal confined in glass” (DOI: 10.1557/mrc.2018.234).

**Ripplocations describe deformation of layered solids**

Instead of basal dislocations, researchers from Drexel University and Colorado School of Mines suggest layered crystalline solids deform via nucleation and propagation of ripplocations, a phenomenon they showed for the first time on the macroscale in new research.

Ripplocations are a “micromechanism by which layered solids deform,” explains Michel Barsoum, ACerS Fellow and professor of materials science and engineering at Drexel University, in an email. The term “ripplocations” was coined by
Understanding high efficiency of deep ultraviolet LEDs

A team of Japanese researchers found deep ultraviolet light-emitting diodes (LEDs) made from aluminium gallium nitride efficiently transfer electrical energy to optical energy due to the growth of one of its bottom layers in a step-like fashion. They fabricated an AlGaN-based LED by growing a layer of aluminium nitride on top of a sapphire substrate, and then they grew a cladding layer of AlGaN with silicon impurities on top of the aluminium nitride layer followed by three AlGaN ‘quantum wells’ grown on top of this. Microscopic investigations revealed that terraced steps form between the bottom aluminium nitride and AlGaN layers and affect the shapes of the quantum well layers above them. This finding can lead to development of even more efficient LEDs. For more information, visit https://www.tohoku.ac.jp/en/press/.

Akihito Kushima and coauthors in a 2015 paper, in which they used the term to describe near-surface deformations in 2D van der Waals solids.

Barsoum and his group were curious if this 2D phenomenon would apply to materials in bulk, so they applied a ripplocation framework to deformations occurring in graphite and MAX phase materials, reported in three separate papers from 2016, 2017, and 2018. They found ripplocations could describe bulk materials as well, and decided to take their research to the next level by presenting direct macroscopic evidence for ripplocation existence.

“[This study] is the first time we can actually see ripplocations and [ripplocation boundaries] in action,” Barsoum says. They looked for ripplocations in three macroscale objects—a deck of plastic cards, thin steel, and aluminum sheets—and compared this deformation behavior to simulated models of ripplocations in graphite.

The researchers indented each stack of materials and found that once the indenter pressed the stacks to a critical indentation depth, a very rapid nucleation of multiple—and oppositely-signed—ripplocations occurred. Once the indenter was retracted,
all layers spontaneously recovered to pre-pressed states.

“This first investigation showed that ripplocations exist and are more or less fully reversible and that they dissipate energy in a manner that we have observed in layered solids at the atomic scale for more than a decade now,” Barsoum says in a Drexel University press release. “But demonstrating the same behavior in layered materials that we can see directly is an important step toward proving that the behavior happens in materials of all sizes.”

In an email, Barsoum says this paper just “scratched the surface” of what can be studied about ripplocations, so it is too early to tell if all layered solids behave this way. “I leave the door open. I think that there are layered solids that are brittle, for example, and thus do not deform by the movement of ripplocations,” Barsoum explains. “The evidence so far on some of the newly discovered MAB phases appear that they microcrack rather than ripple.”

In the future, Barsoum says there are a variety of other studies they can perform to build on this research. “There are a lot of variables that we need to test, like thickness of individual layers, friction between them, etc.”

Osaka University researchers showed anodic oxidation can heal cracks in ceramic composites, thus bypassing the need to rely on high-temperature heat treatments.

Scientists commonly rely on high-temperature heat treatments to heal cracks in ceramic composites, but at these high temperatures (generally above 1,000°C), unexpected and/or unwelcome reactions can take place in addition to desired oxidation. In contrast, anodic oxidation, unlike high-temperature heat treatment, relies on an electrochemical method to initiate oxidation and thus can take place at room temperature. Conductive metals have been repaired at room temperature using this method, but, according to the Osaka researchers, the technique has not been applied to ceramics until now.

To achieve anodization of their ceramic, the researchers explain in the paper that they needed to overcome two challenges. First, they needed to transform the ceramic material from insulating to conductive, which could be achieved by embedding metal particles into the ceramic matrix. Second, they then needed to convert these embedded metal particles into oxides.

In previous studies, the Osaka researchers dispersed fine metallic micrometric titanium particles into an aluminum oxide ceramic matrix, creating electrically conductive Al2O3/Ti composites. Based on these results, they hypothesized the titanium particles could be anodized to form titanium oxides.

They cracked their Al2O3/Ti composite using an FV–310e Vickers hardness tester and then performed the crack-healing anodization at room temperature in 1 mol/L H3PO4 electrolyte solution using platinum as the cathode and the composites as anodes. The anode and cathode were set 15 mm apart, and anodization took place under three different conditions: two conditions (A1 and A2) used a three-step process, while the last condition (A3) used a one-step process.

One of their most crucial discoveries was that while samples with higher electrical conductivity (containing more titanium particles) healed completely, samples with lower electrical conductivity did not heal as effectively.

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Researchers develop a novel chip-based device for quantum communication

Researchers at the National Institute of Standards and Technology developed a way to solve a problem in quantum communication. In quantum communication systems, the optical components that store and process quantum information typically require visible-light photons to operate. However, only near-infrared photons can transport that information over kilometers of optical fibers. The NIST team created quantum-correlated pairs made up of one visible and one near-infrared photon using chip-based optical components that can be mass-produced. To create the entangled pairs, the team constructed a specially tailored optical “whispering gallery”—a nano-sized silicon nitride resonator that steers light around a tiny racetrack. For more information, visit https://www.nist.gov/news-events/news/2019/.

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Research News
particles) were more effective for anodization, samples with lower electrical conductivity and fewer titanium particles displayed better crack-healing ability. The researchers attributed this finding to differences in fracture toughness.

The sample with lower conductivity and fewer titanium particles had a higher fracture toughness value, leading to shorter crack length during crack propagation. In contrast, the sample with higher conductivity and more titanium particles had a lower fracture toughness value, leading to longer crack length during crack propagation. “Based on the obtained results, when comparing the fracture toughness and the conductivity, the former had a stronger influence in the crack-healing ability for the same indentation load,” the researchers explain in the paper.

When looking at individual samples, the researchers found size of the crack open distance (COD) determined what current density was needed to heal the crack. For example, in samples containing 20 vol% titanium, when current density was 3 A/dm² and COD was greater than 0.5 μm, part of the crack remained unconnected. However, when COD was less than 0.3 μm, the expanded oxides sealed the crack. “For different crack sizes, the optimal anodization conditions must be experimentally determined,” the researchers say.

Though their study focused on Al₂O₃/Ti composites, the researchers say this technique is not limited to that composite system. “The results of our study can also be applied to ceramic-based composite systems other than Al₂O₃/Ti composites as a new crack-healing method for ceramics and a technique for ensuring the reliability of the ceramics themselves,” senior author Tohru Sekino, ACerS member and professor of engineering at Osaka University, says in an Osaka University press release.

Additionally, the researchers emphasize that their Al₂O₃/Ti composites could be of great importance for unexplored potential applications. “With the combination of the high strength of the Al₂O₃ ceramic and the high fracture toughness and better biocompatibility of the [titanium] metal, the resultant Al₂O₃/Ti composites are expected to be useful as structural components in engineering applications and as biomaterials with novel functions, such as room-temperature crack healing,” the researchers add in the paper.

The open-access paper, published in *Journal of the American Ceramic Society*, is “Electrochemically assisted room-temperature crack healing of ceramic-based composites” (DOI: 10.1111/jace.16264).
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- **Composite materials**: 11% 50%

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LEAP turbine engines contain ceramics.

Current
- Boeing 777
- Aluminum: 70%  
- Steel: 11%
- Titanium (and its alloys): 7%
- Composite materials: 11%

Future
- Boeing 787
- Aluminum: 20%  
- Steel: 10%
- Titanium (and its alloys): 15%
- Composite materials: 50% by weight
Ceramic matrix composites taking flight at GE Aviation

By Jim Steibel

The holy grail for jet engines is efficiency, and the improved high-temperature capability of CMC systems is giving General Electric a great advantage.

Advanced materials have played a key role in improving turbine engine performance ever since the advent of the first turbojets in the 1940s. Nickel-based superalloys are the primary high-temperature structural material used within turbines, and the advancements in metals technology are well-documented by Schafrik and Sprague.

Gas turbine aero engines employ the Brayton cycle in their operation. A critical parameter for high thermal efficiency is a high overall pressure ratio, which in turn drives high turbine flow-path temperatures. Turbine inlet flowpath temperatures are generally higher than the thermal limits of the component materials. Therefore, air from the compressor cools the components by a combination of internal and external flowpath cooling. However, minimizing the required cooling flow increases the overall efficiency of the cycle. Hence the need for developing and maturing advanced material technologies with improved high-temperature capability, such as ceramic matrix composites (CMCs).

Overall, the introduction of CMCs enables a fuel burn reduction up to two percent—few other technologies in today’s pipeline have this much capability for fuel burn reduction. Additionally, the material density of CMCs is one-third that of today’s nickel-based alloys, enabling over 50 percent reduction in the turbine component weight.

General Electric’s CMC development and maturation activities have been ongoing for more than 30 years, and the business has invested more than $1.5 billion in the last decade on the technology. Early development and investment was supported by the United States Department of Energy, Department of Defense, and NASA.
GE Aviation has invested significantly in development of CMC material and process technologies, as well as manufacturing scaleup and supply chain. This investment has enabled commercial introduction of CMC high-pressure turbine shrouds in the LEAP engine (see Figure 1a).

Certified by the Federal Aviation Authority and European Aviation Safety Agency (EASA) in May of 2016, the CMC shrouds have already surpassed four million hours of flight time in commercial LEAP engines flying on Airbus, Boeing, and COMAC aircraft. GE Aviation currently is developing the largest aircraft engine in the world—the GE9X—which has five CMC parts throughout the engine hot section (Figure 1b). These parts include one combustor inner liner and one outer liner, as well as HPT Stage 1 shrouds and nozzles, plus HPT Stage 2 nozzles. The GE9X enters service on the Boeing 777X in 2020. CMCs also are being incorporated into the architectures of advanced military engines to enable increased thrust and reduced specific fuel consumption in future platforms.

Material system capabilities

GE has developed a prepreg/melt infiltration (MI) process that has unique capabilities for fabrication of SiC/SiC CMC turbine engine components with small, complex features. The molten silicon infiltration process produces a highly dense matrix, and the prepreg process enables a relatively uniform distribution of individually coated fiber filaments. This unique microstructure (shown in Figure 2) leads to superior mechanical properties, including the material durability required for turbine engine components.

The SiC/SiC material system consists of a 500-filament stoichiometric SiC fiber tow (Hi-Nicalon Type S) produced by NGS, a joint venture between Nippon Carbon (Tokyo, Japan), GE Aviation (Evendale, Ohio) and Safran (Paris, France). The SiC fiber undergoes two coating steps to apply thin coatings on each filament in the tow bundle using chemical vapor deposition (CVD) processes. As shown in Figure 3, the coated fiber is then drum-wound to create a unidirectional tape material.

The tape is subsequently cut into shapes and stacked in tooling to create the finished part geometry after consolidation in an autoclave (Figure 4). Two high-temperature furnace operations follow. First is a pyrolysis step to remove any remaining organics, and the second step involves molten silicon infiltration to convert residual carbon to silicon carbide. The densified composite preform is then ready for machining to finalize the geometry, and inspection to ensure conformance of the dimensions and material requirements. X-ray computed tomography (CT), ultrasound (UT) and infrared thermography (IR) are the leading modalities when it comes to SiC-SiC coating steps to apply thin coatings on each filament in the tow bundle using chemical vapor deposition (CVD) processes. As shown in Figure 3, the coated fiber is then drum-wound to create a unidirectional tape material.

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Ceramic matrix composites taking flight at GE Aviation

CMC inspection. Application of an environmental barrier coating (EBC) is the final step to protect the CMC material from high-temperature water vapor. The manufacturing process, scaled-up to full production rates at GE Aviation, takes less than 30 days to convert SiC fiber to a finished part of any geometry.

Table 1 summarizes the primary thermal and static mechanical properties considered for turbine component applications. The MI SiC/SiC properties represent a range of average values for temperatures between 1,500°F and 2,400°F. In general, the mechanical properties are relatively high, with the compressive strength about four times greater than the tensile strength, achieving values that exceed 1,000 MPa. The in-plane mechanical properties have been characterized extensively to understand the cyclic durability as statistically-derived design allowables have been established for over 100 different material curves. Also, the high interlaminar strengths (exceeding 100 MPa) observed in GE’s MI CMC are a key to its use in more complex turbine airfoils.

Building the blueprint to CMC industrialization

GE Aviation is taking CMCs from the laboratory to full-rate production by establishing the first vertically integrated CMC supply chain in the U.S. By the end of 2020, GE estimates it will have about 750 employees producing up to 20 tons of CMC prepreg, 10 tons of SiC fiber, and over 50,000 CMC turbine engine components per year.

The business created an industrialization strategy for CMCs that aligns the appropriate equipment, facilities, and resources for each stage of technology maturity. The basic or fundamental research occurs at GE’s Global Research Center (GRC) in Niskayuna, N.Y., where pioneering work in CMCs was performed in the 1980s, and continues with recent technical innovations. Beyond GRC, GE’s CMC supply chain includes four unique facilities:

• A CMC fastworks laboratory at the Evendale, Ohio, headquarters to quickly evaluate the viability of CMC design changes and manufacturing process improvements.

• A low-rate production facility in Newark, Del., for both CMC raw material and components to demonstrate concept production readiness and employ lean manufacturing practices.

• A full-rate production facility in Huntsville, Ala., for raw material. The facility will begin producing SiC fiber and unidirectional tape in 2019 (Figure 5).

• A full-rate production facility in Asheville, N.C., producing CMC parts for jet engines (Figure 6).

In addition to the NGS joint venture, GE Aviation’s supply chain also includes Advanced Ceramic Coatings (a joint venture between GE Aviation and TurboCoating Corp. in Hickory, N.C.), which manufactures EBC’s at GE’s new facility in Duncan, S.C.

GE expects CMC part production to grow ten-fold over the next decade. GE Aviation’s fast and flexible vertical supply chain will allow the capability of manufacturing from fiber to finished CMC engine part for a wide range of component types. This versatility is enabled by understanding and modeling of each major process step, as well as establishing specifications and control plans for key characteristics.

GE’s progressive expansion of CMC production capability for additional engine components includes HPT nozzles, shrouds, and combustor liners for the GE9x engine. The current manufacturing readiness capability for the 9x components is at MRL 8 (pilot production demonstrated and ready for low-rate production). Plans are to achieve full-rate production this year.

GE Aviation has matured the prepreg/MI manufacturing process to MRL 10 (full-rate production) for HPT turbine shrouds. This year alone, GE expects to ship more than 1,800 CFM* LEAP engines. GE Aviation Asheville, which

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*CFM is the 50/50 joint company of GE and Safran Aircraft Engines of France
shipped around 23,000 LEAP HPT Stage 1 shrouds in 2018, plans to ship another 36,000 shrouds this year.

Asheville’s CMC site has doubled its employee base every year since opening in 2014, growing to more than 300 employees currently. The team converts the SiC fiber-reinforced tape to a manufactured part using the component fabrication steps outlined in Figure 3. The incoming unidirectional tape currently comes from the Newark, Del., plant.

GE is investing more than $200 million in its two-plant Huntsville site, with $21.9 million in supporting funding from the U.S. Air Force Research Laboratory under the Defense Production Act Title III Program. Construction of the two plants began in mid-2016 and finished recently. GE Aviation Huntsville, 130 employees strong and growing, is currently commissioning equipment in anticipation of production startup in 2019. The Alabama facility will dramatically increase U.S. capability to produce SiC ceramic fiber for high-temperature applications. The fibers will also be converted into tape in the adjacent ceramic processing facility prior to shipment to Asheville.

GE Aviation adopted Big Data principles and collects thousands of data points to link each of these CMC facilities at every stage of the manufacturing process. The scope of digitization also includes tracking product performance in customer applications. The CMC team has a real-time view through automation tools to enable maximizing product management throughout its lifecycle. These automation tools have driven productivity, cost, part delivery, and evolution of science understanding, resulting in increased part yields essential as GE Aviation and CFM anticipate near-record levels of engine demand.

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<thead>
<tr>
<th>Property</th>
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<td>Interlaminar strength</td>
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About the authors
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References
Nonoxide polymer-derived CMCs for “super” turbines

By Zhongkan Ren and Gurpreet Singh

Superalloy turbine blades for gas turbines may have been the most significant energy and transportation technology development in the last century. It empowered our military prowess, made it possible for civilian aircraft to fly halfway around the world, and now single-crystal blades are employed in gas turbines for energy conversion because of their superior creep resistance over traditional polycrystal alloys.

The single-crystal technology evolved over 50 years, through an intimate coupling between materials science, mechanical engineering, and manufacturing research. These single-crystal blades, coated with low thermal conductivity ceramics, now perform close to their melting points for thousands of hours (Figure 1). However, the melting point limits further advancement in the operating temperature of gas turbines with metallic materials.

Ceramics, which have much higher melting points than metals, hold the promise for “super” turbines in the future (Figure 2). But while ceramics have high strength at high temperatures, ceramics also suffer from thermal shock. Structural ceramics are of two kinds: oxides, like aluminum oxide (think sapphire), and nonoxides, mainly silicon carbide (SiC). Oxides generally have a high coefficient of expansion that renders them prone to thermal shock, but they also have better oxidation resistance than SiC in extreme environments (Figure 1b). The current ceramics technology is therefore based upon structures made from SiC with environmental barrier coatings made from oxides.

Work from the 1980s to 1990s on ceramics for high-temperature structures demonstrated that fibrous composites would be able to avoid brittle behavior because cracks that inevitably form in the matrix are unable to grow into the fibers if the interface is sufficiently weak. And if this condition is met then any single-fiber fractures in fiber-bundles would also be rendered harmless by displacement between the broken ends—the ends being accommodated by neighboring fibers through interfacial sliding.

Critical components to a CMC

There are three critical components to a ceramic matrix composite (Figure 3): reinforcement, interface coating, and ceramic matrix.1 Reinforcement provides strength and structural foundation or shape for the composite, gen-
erally in the form of a complex 3D woven structure designed to closely match the final shape of the component. Interface coating is a thin coating on the fiber that provides a low-strength interface between hard ceramic matrix and high-strength fiber. Ceramic matrix provides the load transfer between fibers and the majority of chemo-thermophysical properties of the composite—in some cases, the whole CMC is coated with an environmental barrier coating to further improve performance under harsh conditions.

Reinforcement in a CMC is added mainly to improve toughness. It is typically in the form of either a carbon/graphite fiber or an oxide or nonoxide ceramic fiber that can withstand high-application temperatures. Carbon fibers are generally the least expensive while nonoxide fibers are the most expensive. Although oxide-based fibers such as alumina show better oxidation resistance than nonoxide fibers, oxide-based fibers’ strength retention and creep resistance at high temperatures is compromised due to grain growth at elevated temperatures. In some cases, creep rates for oxide fiber can be two orders of magnitude greater than those of nonoxide fibers. Because of light weight, good oxidation resistance, good thermal shock resistance, and relatively high modulus and strength values, only silicon-based nonoxide ceramic fibers (tending toward SiC composition) are preferred for ultra-high temperature aerospace applications. Oxide CMCs are perhaps more suitable for relatively less demanding applications.\(^1\)

Manufacturing nonoxide ceramic fibers

Three different approaches to manufacturing nonoxide ceramic fibers exist—chemical vapor deposition (CVD), extrusion/sintering of powder slurries, and the polymer precursor route.

CVD is the oldest method for production of SiC fibers. In this method, SiC generally is deposited on a heated amorphous carbon or tungsten wire (“core”) resulting in a high-strength fiber.\(^5,8,9\) Such fibers are monofilaments with minimum diameter in the range of 75 to 100 microns, which limits their minimum bend radius and renders them unsuitable for weaving into textile or making complex-shaped ceramic parts. Such high-strength fibers, however, could be used as reinforcement in a metal matrix composite.

The extrusion/sintering to make SiC fiber involves spinning SiC powder in a polymeric binder followed by sintering. These fibers are generally thicker than 30 microns, have surface defects, and never fully densify due to difficulty in sintering a nonoxide ceramic.\(^5,9\)

Because high-temperature CMCs would require high-strength flexible ceramic fibers (diameters less than 20 microns), research on alternate routes to obtain continuous and flexible fibers had been ongoing when a discovery by...
Nonoxide polymer-derived CMCs for “super” turbines

Yajima et al.\textsuperscript{10} in late 1970s showed how high-temperature ceramic fibers could be made from certain organometallic oligomers or silicon-based polymers using a combination of polymer and ceramic processing methods. This process was later developed into a commercial technology in Japan. These fine fibers show good mechanical properties, thermal properties, and oxidation resistance, and can be woven in textile form to make complex-shaped ceramic parts. These SiC fibers are the backbone of the ceramic-fiber ceramic-matrix technology that heralds the next-generation turbine engines,\textsuperscript{6} as discussed below.

The production of these fibers involves steps (Figure 4) that are somewhat similar to those used for manufacturing carbon fibers from polyacrylonitrile (PAN).\textsuperscript{5,9–12}

1. Synthesis of preceramic polymer with desired rheological properties for spinning processes;\textsuperscript{5}
2. Melt or dry spinning of precursor into green fibers;\textsuperscript{5,9–12}
3. Curing (thermally, chemically, or radiation) of green fiber to cross-link molecular chains into duroplastic-like state, rendering it infusible during pyrolysis; and\textsuperscript{5}
4. Pyrolysis of green fiber under argon at high temperature to obtain ceramic fiber.\textsuperscript{5}

The first-generation SiC fibers based on Yajima et al.\textsuperscript{10} were spun in inert environments but required curing in air to make them infusible during pyrolysis at high temperatures. As a result, such fibers had oxygen in the ceramic upon pyrolysis and the fibers were amorphous, non-stoichiometric Si-O-C instead of crystalline SiC. The relatively poor thermal and mechanical properties of the fiber were attributed to high oxygen content of these fibers. The second-generation SiC fibers focused on reducing oxygen content by curing the green fibers under gamma or electron irradiation in inert environment. As a result, these fibers had larger SiC grains along with the graphene-like carbon.\textsuperscript{5,9–12}

The third-generation fibers were manufactured at even higher pyrolysis temperatures with addition of trace amounts of aluminum, titanium, or boron to sintering of SiC. Such fibers

### CMC MATRIX manufacturing techniques

**Infiltration** is the most common technique for creating aerospace grade SiC/SiC ceramic matrix. Fiber preforms can be infiltrated with matrix material in gaseous (CVD) or liquid (melt infiltration and polymer infiltration) form.\textsuperscript{6,9–12} The fiber preform preparation requires a rather complex approach—the preform is generally a 3D replica of the final component (e.g., combustion liner or vane) designed computationally based on function of the component, expected mechanical and thermal loadings at the site, and topology/materials properties of the fiber, matrix, and interface coating.\textsuperscript{2}

**CVD or CVI:** CVD processing involves introduction of vapors of silicon-based metal organic compounds (generally methyltrichlorosilane) along with a carrier gas, such as hydrogen, into a chamber containing heated fiber preform substrate. The silicon-based precursor decomposes at a high temperature to yield high purity SiC, which fills the preform to form the continuous matrix phase. This process is slow due to lower ceramic yields and deposition rates. Large amounts of highly corrosive vapors are produced during the deposition process, which increases the capital equipment cost and downtime. Large-size, thick CMC parts are prone to nonuniform coating and density gradients.\textsuperscript{9}

**Melt infiltration:** Molten silicon at approximately 1,500°C is introduced into a carbon or SiC fiber preform (or into a preform containing carbon particles), and SiC is formed at the interface as molten silicon reacts with carbon. The process is expensive due to high temperatures required for melting. In addition, the byproducts may react with furnace elements, causing damage or significant downtime.\textsuperscript{9} Excess or unreacted silicon could be present in the final part, which significantly degrades mechanical properties at high temperatures.

**Polymer infiltration and pyrolysis:** This technique is similar to those employed for fabrication of polymer matrix composites. The fiber preform is infused with liquid preceramic polymer that transforms into ceramic matrix upon pyrolysis (PDC route). Because of its simplicity, relatively lower processing temperatures, and ability to produce complex CMCs, this technique is relatively cost effective. Preceramic polymers with high ceramic yield and improved stability against moisture and air (long shelf life) are preferred; carbosilane-based preceramic polymers that yield stoichiometric SiC composition are most desired.\textsuperscript{9}
are essentially polycrystalline SiC with small amounts of sp² carbon phase at grain boundaries. Higher sintering temperature generally leads to larger SiC grain size, elastic modulus, strength, and creep resistance over a wide temperature range. Such fibers, however, are exorbitantly expensive, costing over €18,000/kg. The high cost of manufacturing SiC fibers is apparently related to the control of oxygen content—costly autoclave techniques are needed for synthesis of the preceramic polymer while additional pyrolysis steps are required to drive out oxygen from the ceramic fiber.

The General Electric Company recently introduced CMC components into its LEAP engines. This innovation is expected to generate tens of billions in new revenue for GE. The development of CMC-turbine blades is rumored. GE Aviation expects that increased jet engine production will increase demand for SiC fibers and tapes as much as tenfold over the next decade. The high cost of these fibers is a major barrier to future growth.

**Engineering new compounds**

Over the last 25 years, fundamental research in Si-C-O-N compounds yielded new results that show how their nanoscale structure relates to mechanical properties and thereby provides the insights needed to engineer new compounds for turbine engine applications (Figure 5):

- **Stability of the amorphous structure:** While the binary Si-C crystallizes at 1,200°C, the ternary and quaternary compounds are intrinsically amorphous, with a negative enthalpy of formation relative to the crystalline state.

- **The nanodomain network of graphene:** The Si-C-O-N materials contain a network of graphene or sp² carbon with a domain size of 1–5 nanometers. The domain boundaries consist of mixed bonds of Si-C-(N,O) while the tetrahedral of Si-(O,N) occupy the space within the domains.

- **Zero creep behavior:** The carbon network imparts unusual mechanical properties such as zero creep in the steady state at temperatures up to 1,500°C, while the interlaced Si-O-N protects the carbon from oxidation.

- **Polycarbosilane-derived nanocrystalline SiC fibers** contain grain boundaries. Although such fibers are known for their ultra-high-temperature stability, presence of grain boundaries and some low melt-

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**Developing negligible creep resistance and international student exchange opportunities**

The challenge is to develop ceramic fibers constituted from silicon, boron, carbon, nitrogen, or oxygen that exhibit negligible creep resistance at temperatures up to 1,600°C in oxidizing environments, with a target production cost of approximately $1,000/kg (Figure 4).

To address this technical challenge and create international student exchange opportunities in PDC science, the National Science Foundation awarded a five-year $4.7 million Partnerships for International Research and Education (PIRE) grant to Gurpreet Singh and co-investigators (Alexandra Navrotsky, University of California, Davis; Himanshu Jain, Lehigh University; Rishi Raj and David Marshall, University of Colorado Boulder; Elsa Olivetti, Massachusetts Institute of Technology; and Peter Kroll, University of Texas at Arlington). So far, Singh et al. have demonstrated the feasibility of drawing such low-cost fibers.

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PDC SiCNO fibers being investigated in Singh’s lab. (a): digital camera picture and (b): SEM image. Foot-long fibers of preceramic polymer could be drawn by hand using a glass rod. The challenge, however, is to maintain structural integrity of the fiber during the pyrolysis process.
Nonoxide polymer-derived CMCs for “super” turbines

Ining phases/impurities at grain boundaries may make them susceptible to deformation and creep at temperatures as low as 900°C. For example, the SiC grains may slide relative to one another due to softening at grain boundaries, leading to creep cracks and the eventual deformation of fiber. In addition, the role of small amounts of oxygen in commercial SiC fibers is poorly understood. In contrast, multi-component amorphous fibers such as SiCN, SiOC, and SiBNC could be produced by suitable selection of preceramic polymer (Table 1). Such ternary and quaternary systems are shown to improve chemical and thermal stability, The SiCNO ceramics are amorphous and contain significant amounts of oxygen, which is rendered harmless by its nanodomain structure of graphene. The synergy between the carbon network and the SiOC matrix within which it is embedded imparts thermodynamic stability to the amorphous structure, creep resistance, and, most importantly, the opportunity to manufacture fibers at low cost (polysiloxanes and polysilazanes are significantly more abundant and cheaper than polycarbosilanes—Table 1).

Ceramic fibers also generally require an interface-compliant coating (100 nanometers to 1 micron thick) and a SiC overcoating to provide a weak fiber/matrix bond in order to realize high toughness in CMCs and to protect the fiber from harsh oxidation environments, respectively. The coating, generally composed of pyrocarbon or hexagonal boron nitride (or a combination of both) has low shear strength and is applied directly to the fibers via CVD techniques. CVD of interface boron nitride and overcoat SiC is expensive, time consuming, and requires use of hazardous chemicals; as a result, the costs associated with such coatings could be 10 to 50 times on a square-meter basis than a fabric of carbon or graphitic fiber.

Future directions for nonoxide CMC materials and manufacturing processes

1. New preceramic polymers based on ternary and quaternary systems for CMC matrices: Liquid-phase high-purity, low-cost, high-yield polymers that are nontoxic and noncorrosive are being researched at both university and industry levels. Preceramic polymers that can produce amorphous ceramics with Si-X-C/N/O, where X is boron, hafnium, or zirconium, composition are of particular interest due to improved thermal stability and corrosion resistant of the resulting ceramic. Likewise, preceramic polymers that are photocurable (for example, via chemical interfacing with photo polymers) at room temperature are being studied. Polymers that contain simpler side (hydrocarbon) groups with high ceramic yield at increased heating rates are desired in order to minimize release of volatile components during pyrolysis stages and lower processing costs, respectively—larger hydrocarbons, which diffuse out during pyrolysis, could lead to increased porosity in the matrix. This task is not trivial considering that thermal stability and rheological properties of preceramic polymer are tied to the composition and molecular weight of the side groups.

2. New reinforcement fiber materials: As stated earlier, oxygen-containing amorphous PDC fibers based on ternary and quaternary systems composed of combinations of elements that form strong covalent bonds (such as silicon, carbon, nitrogen, boron, oxygen) and show resis-

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**Table 1. Cost, availability, and properties of bulk PDC ceramics.**

<table>
<thead>
<tr>
<th>Preceramic polymer*</th>
<th>Cost</th>
<th>Availability</th>
<th>PDC*</th>
<th>Density (g/cm³)</th>
<th>Modulus (GPa)</th>
<th>Fracture strength (MPa)</th>
<th>Fracture toughness (MPa·m⁻¹)</th>
<th>CTE (×10⁻⁶/K)</th>
<th>Oxidation temp. (°C)</th>
<th>Decomposition temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polysiloxane</td>
<td>Low-medium</td>
<td>Commercially available (medium availability)</td>
<td>SiCN</td>
<td>2.3</td>
<td>80 to 155</td>
<td>&lt;1,200</td>
<td>&lt;3.5</td>
<td>3</td>
<td>~1,300</td>
<td>~1,600</td>
</tr>
<tr>
<td>Polycarbosilane</td>
<td>High</td>
<td>Commercially available (limited availability)</td>
<td>SiC</td>
<td>3.1</td>
<td>405</td>
<td>418</td>
<td>4 to 8</td>
<td>3.8</td>
<td>~1,200</td>
<td>–</td>
</tr>
<tr>
<td>Polysiloxane</td>
<td>Low</td>
<td>Commercially available (large availability)</td>
<td>SiOC</td>
<td>2.3</td>
<td>&lt;113</td>
<td>&lt; 900</td>
<td>&lt;1.8</td>
<td>3.2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Polyborosiloxane</td>
<td>Very high</td>
<td>Laboratory synthesis (very limited availability)</td>
<td>SiBCN</td>
<td>2.3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>~1,600</td>
<td>~2,300</td>
</tr>
</tbody>
</table>

*Physical state of preceramic polymer and engineering properties of the pyrolyzed ceramic are strongly influenced by the molecular structure and composition of preceramic polymer and processing conditions used. Data from Journal of the American Ceramic Society and American Ceramic Society Bulletin.12–14

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rance to crystallization and high temperature creep should be the focus of future research. Such ceramics could be prepared from preceramic polymers based on polysiloxanes and polysilazanes, which are relatively cheaper and easy to mass produce compared with carbosilanes. As for fiber processing, preceramic polymers that can be melt-spun or electro-spun are preferred over traditional dry spinning techniques, to keep costs lower due to reduced number of processing steps. Likewise, polymers that allow rapid inline curing (cross-linking) and pyrolysis with high ceramic yields (greater than 85 percent) are expected to be significantly cheaper and hold low porosity and surface defects.

3. CMC failure prediction: Experimental approaches to understanding ultra-high temperature thermo-chemo-mechanical behavior of a CMC material could be cost prohibitive. To ensure rapid commercialization of CMCs would require guidance regarding material development and design of fiber preform (Figure 6).

This could be achieved to some extent by developing and employing analytical fiber and CMC material models for time-temperature deformation and rupture behavior. These models may involve computing responses under conditions that induce severe thermomechanical gradients and be able to capture progressive failure of CMCs—CMC material models that accommodate effects of high strain rate and fatigue would be needed for design of high-speed rotating components inside turbine engines.

4. Additive manufacturing of PDC CMCs: Like PMCs, a variety of additive manufacturing or 3D printing technologies could potentially be employed to manufacture CMCs from silicon-based preceramic polymers. Opportunities exist in use of preceramic polymers to produce ceramic components in a range of compositions using either conventional stereolithography printing (via chemical interfacial with photopolymers) or direct extrusion-based fused deposition modeling of composite slurries followed by pyrolysis at high temperatures. The challenge lies in the ability to produce uniform, large-area, defect-free components with desired thermomechanical properties in an economical manner. Very limited data has been reported in literature on such composites—some new reports from the Air Force Research Laboratory, HR Lab, and university researchers in Italy and the United States have started to emerge. 13

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References

Taking off:

Advanced materials contribute to the evolution of electrified aircraft

By Ajay Misra

Commercial electrified aircraft are expected to take off within the next decade—and advanced materials are playing an increasingly critical role in solving key technical challenges that will push the boundaries even higher.

Worldwide, there is significant interest to develop electrified propulsion systems for aircraft across a wide range of market segments. This is mainly driven by higher efficiency of electrical components, reduced emissions, lower operating costs, and additional flexibility in aircraft design and architecture. The segment that has received the most attention over the past 2–3 years is the urban air mobility market, which would use small electrified aircraft with 2–4 passengers for urban air taxis.

Uber has been one of the drivers for this market segment and is planning commercial introduction of electrified aircraft for the urban air mobility market starting in 2022.1 Many companies—including Airbus, Boeing–Aurora Flight Sciences, Bell, and Embraer—are developing electrified aircraft concepts to meet the needs of the urban air mobility market.2 Zunum and Eviation are also developing electrified concepts for ~10-passenger commuter

Capsule summary

EMERGING MARKET

Driven by higher efficiency and design flexibility as well as lower emissions and operating costs, electrified propulsion systems for aircraft are gaining momentum. Electrified aircraft are expected to continue an upward trajectory, although technology readiness and economic viability will dictate the timing of this expansion.

TECHNOLOGY CHALLENGES

Technology advances in major components of the electrical propulsion system will be required for evolution of electrified aircraft from small urban air mobility aircraft to regional and large aircraft. Key technical challenges will be to improve the power density and efficiency of electric motors and power conversion system, increase specific energy of batteries, and decrease weight of power transmission and thermal management systems.

MATERIALS SOLUTIONS

Advanced materials will be the enabling technology to afford higher power densities and energy densities for electrified aircraft, including high-electrical conductivity materials, superconducting materials, magnetic materials, insulation materials, and thermal interface materials. Ceramic materials offer unique opportunities to meet the needs of this expanding class of aircraft.
aircraft for point-to-point travel. This will meet the vision of thin-haul aviation, which refers to a growing market that encompasses a large distribution of short routes, each with limited and sporadic demand, but collectively with enormous aggregate volume.

Electrified propulsion for aircraft falls into three categories: all-electric, hybrid-electric, and turboelectric (Figure 1). In an all-electric concept, an energy storage device or energy conversion system (e.g., fuel cell) powers an electric motor that drives the fan for propulsion. In a hybrid-electric concept, both an energy storage device and gas turbine engine (or internal combustion engine) are used for propulsion. In a turboelectric concept, the gas turbine engine runs a generator to produce electricity, which then drives the motor and fan.

Electrified propulsion can enable the concept of distributed electric propulsion (DEP) in which the propulsors can be placed, sized, and operated with greater flexibility to leverage the synergistic benefits of aero-propulsive coupling and provide improved performance over more traditional designs. An example of the DEP system is shown in Figure 2, which is a NASA experimental plane known as X-57, designed to demonstrate the performance benefits of DEP. The concept for the X-57 employs two large electric motors, one on either wing tip, for the main propulsion of the plane. During takeoff and landing when increased lift is necessary to maintain stable flight at lower airspeeds, the X-57 will use the DEP concept, which consists of 12 small electric motors spread out across the leading edge of the wings. The distributed motors force air directly over the wing surfaces with the benefit of increased air flow over the wing at lower speeds, increasing its lift. The increased lift allows it to operate on shorter runways. Such a wing could be only a third of the width of the wing it replaces, saving weight and fuel costs.

The timing for introduction of electrified propulsion for various market segments would be a strong function of technology readiness level, market demand, and economic viability. While it is difficult to predict the evolution of electrified propulsion for commercial aviation, a notional roadmap (Figure 3) can be envisioned based on the pace of current research, development, and demonstration activities throughout the world. The electrified propulsion market for the aviation sector will potentially evolve with the introduction of urban air mobility and 10-passenger thin-haul aircraft in 2022–25, 40–50-passenger regional aircraft in 2030, and single-aisle, greater than 100-passenger aircraft in 2035 or beyond. The pace of introduction for electrified aircraft propulsion in different market segments will be
Taking off: Advanced materials contribute to the evolution of electrified aircraft

Technology needs for electrical components

Major electrical components of the electrical propulsion system for aircraft include the motor/generator, power conversion system or power electronics, power transmission system, and energy storage system (e.g., batteries). Technology advances in each of these components will be required for evolution of the electrified aircraft market segment from small urban air mobility aircraft to regional and large aircraft.

The power levels from urban air mobility aircraft are typically several hundreds of kilowatts (less than 1 MW), whereas several megawatts of power are required for regional and large, single-aisle aircraft.

The key technical challenges for electric motors are power density and efficiency. The power density needs to increase by a factor of three to five for large commercial transport. Figure 4 shows a notional roadmap for increasing power density of electric motors.

The power density of state-of-the-art electric motors for electric vehicles is on the order of 2 kW/kg. Recently, Siemens developed a 200-kW electric motor with power density of 5 kW/kg at 95 percent efficiency (Figure 5), which is finding application in small electrified aircraft for the urban air mobility market segment.4,5 For regional and large, single-aisle aircraft using MWs of power, a power density on the order of 15 kW/kg will be desirable. Power densities above 20 kW/kg will be required for large commercial aircraft.

Power densities on the order of 15 kW/kg may be achieved with conventional (or noncryogenic) motors using copper coils, whereas power densities more than 20 kW/kg will require superconducting motors that use superconducting materials at cryogenic temperatures. The efficiency of electric motors needs to increase from the state-of-the-art of about 95 percent to greater than 98 percent to mitigate thermal management challenges.

Power conversion systems (also referred to as power electronics) are critical components of the electric propulsion system. A power electronic converter consists of many elements, including a power semiconductor, inductor, capacitor, switches, and thermal management system.

The power density for a state-of-the-art power converter for aerospace applications is on the order of 5–10 kW/kg with 95 percent efficiency. However, the power density needs to increase by a fac-
tor of three to five for large aircraft using megawatts of power.

NASA’s current research and development efforts focus on achieving power density of 15 kW/kg and efficiency of 99 percent. A long-term goal of 50 kW/kg with 99 percent efficiency can potentially be realized with innovative topologies, emerging power semiconductor and passive component technologies, and innovative thermal design.

Transmitting megawatt levels of power in electrified aircraft is a major challenge. Typically, copper power transmission cables transmit non-propulsive power in current aircraft. Transmission of megawatt-level power for electrified propulsion systems would require large-diameter copper cables, which would add significant weight to the aircraft.

Large electrified aircraft with 20–30 MW power systems will require transmission voltages on the order of several thousand volts and variable frequency of 400–4000 Hz, along with the capability to operate at high altitudes. With the use of very high voltages, preventing partial discharge at high altitudes will require a prohibitively large insulation thickness.

Batteries are enabling components for electrified propulsion systems. The key parameter is specific energy (Wh/kg) for electrified propulsion applications. The specific energy of the state-of-the-art Li-ion battery used in electric vehicles is on the order of 250–270 Wh/kg at the cell level and ~150–170 Wh/kg at the pack level.

The state-of-the-art Li-ion battery can enable initial introduction of small electrified aircraft for urban air mobility with limited range. The battery can also enable 10-passenger, thin-haul aircraft with limited range. Expansion of the electrified aircraft market beyond the initial introduction with limited range requires a significant increase in specific energy of batteries.

The following are examples of potential missions enabled by higher specific energy batteries. Specific energy corresponds to pack level. The range should be considered as notional.

- **State-of-the-art (150–170 Wh/kg)**: Urban air taxi, 4-passenger, all-electric, ~25–30-mile range; thin-haul commuter, 10-passenger, hybrid electric, 300–600-mile range.
- **300 Wh/kg**: Urban air taxi, 4-passenger, all-electric, 50–60-mile range.
- **400 Wh/kg**: Urban air taxi, 4-passenger, all-electric, ~100-mile range; multiple vertical takeoff and landing aircraft missions, 4–5-passenger, hybrid electric; thin-haul commuter aircraft, 10–20-passenger, >600-mile range.
- **500 Wh/kg**: Regional, ~50–70-passenger, hybrid electric, 300–500-mile range.
- **600 Wh/kg**: Large transport, narrow body, 180-passenger, hybrid electric, 500–600-mile range.

Another major challenge is thermal management. For a 5–10-MW system that corresponds to electrified propulsion for regional and large aircraft, hundreds of kilowatts of heat would be generated due to efficiency losses in various components. Thermal management challenges include: (1) integration of heat rejection from multiple sources, (2) low-grade heat at temperatures on the order of 200°C, and (3) increasing use of composites in aircraft that lower heat rejection capability of the system.

**Role of advanced materials**

Expansion of electrified aircraft will require significant increases in power density and energy density of electrical components. Design advances along with advanced materials will help achieve the very aggressive goals for electrified aircraft propulsion systems.

**High-power density electric motor**

Major components of permanent magnet motors include permanent magnets, conductor coils, and laminated stator cores. For permanent magnets, Fe-Nd-B is the current material. However, permanent magnets with higher magnetic strength or higher values of the parameter $(BH)_{max}$, which is an indirect measure of energy density, are desired.

Novel approaches to increase $(BH)_{max}$ include development of nanocomposite magnets using a combination of hard and soft magnets, the feasibility of which has been demonstrated in thin films. There is also a need to increase the temperature capability of permanent magnets without sacrificing $(BH)_{max}$.

The conductor coil typically consists of a copper coil that carries current and generates magnetic fields. Higher power density can be achieved by increasing current density, which leads to a higher level of joule heating. Higher current density and lower heating can be achieved by decreasing the electrical resistance (or increasing electrical conductivity) of the conductor coil.

Carbon nanotubes (CNTs) could potentially have higher electrical conductivity than copper if metallic CNT can be separated from semiconductor CNT during fabrication or
Taking off: Advanced materials contribute to the evolution of electrified aircraft

through post-treatment. Development of a material with a higher electrical conductivity than copper will be game-changing for electric motors.

Temperature rise associated with high current density in copper conductor coils can increase resistivity of copper coils, which decreases efficiency and power density. Heat generated in copper coils is transmitted through the insulation material surrounding the coil to the heat sink. Advanced insulation materials with higher thermal conductivity will help maintain the copper coil temperature at the desired level at high current densities.

The insulation material must have high thermal conductivity, low electrical conductivity, and high breakdown strength to operate at high voltages. Thermal conductivity of state-of-the-art polymer insulating materials used in electric motors is on the order of 0.1 W/m•K, which needs to increase by a factor greater than 10. Adding ceramic fillers to polymers is an active area of research to increase the thermal conductivity of motor insulation materials.

The power density of motors can be increased by increasing the operating frequency, which translates to higher speeds. Laminated magnetic steel that is currently used as a stator core material in motors loses power at high frequencies as it heats up. Magnetic steel with higher silicon content is one approach to reduce core losses at high frequency. Amorphous materials, particularly metallic amorphous nanocomposite magnets, are gaining considerable attention for use in stator cores for high-frequency operation, which has the potential to significantly increase power density of motors.

Achieving power densities beyond 20 kW/kg will require superconducting motors operating at cryogenic temperatures. Superconducting materials of interest for such motors include yttrium barium copper oxide (YBCO) and magnesium diboride (MgB2). While YBCO is superconducting at 93 K, requiring liquid nitrogen cooling, MgB2 is superconducting at 39 K, requiring liquid hydrogen for cooling. There is considerable interest in MgB2 because it is easier to fabricate the material into wires, filaments, and other shapes.

In addition, additive manufacturing of electric motor components, which is in its infancy, offers significant potential to increase power density of electric motors. Additive manufacturing of multimaterial systems can enable higher fill factors for copper coils by simultaneously printing copper and ceramic insulator materials. This also provides greater flexibility for insulation materials, particularly ceramic insulation materials.

High-power density power electronics (or power converters)

Compared to state-of-the-art power electronics using silicon semiconductors, high-power density power electronics converters will be based on wide-bandgap materials, such as silicon carbide. SiC offers several advantages compared to silicon, including higher efficiency, higher switching frequency, high voltage capability, and higher maximum operating temperatures.

Passive components, such as inductors and capacitors, make significant contributions toward weight and volume of the power conversion system. High switching frequencies enabled by SiC semiconductors can significantly reduce the size of passive components. For inductors to operate at high switching frequencies, magnetic materials capable of operating at high frequencies with low losses are required. Current research focuses on developing amorphous nanocomposite magnets. Capacitors with capability for higher frequency operation are also required.

The SiC-based power electronics system offers high-temperature operation capability, which can eliminate or simplify the thermal management system with the benefit of an increase in power density. Higher-temperature power electronic devices will also enable better integration with aircraft components at higher temperatures.

Although the theoretical limit for the operation of SiC power devices can be as high as 700–1,000°C, the full potential of the temperature capability of SiC-based power electronics devices has not been realized. The practical temperature capability of SiC power electronics devices is significantly lower than the theoretical limit. Some of the barriers to achieving higher temperature capability in SiC-based power electronic systems include higher temperature capability for passive components (capacitors and inductors) and high-temperature packaging technology.

High-voltage power transmission cables

There are some unique challenges related to durability of high-voltage cable insulation materials for aircraft, including corona discharge at high altitudes, increased electrical and thermal stress resulting from high-voltage and high-frequency operation, and thermal cycling-induced degradation.

One approach to overcome the high-voltage challenges is to develop multilayer and multifunctional insulation materials based on polymers and ceramics, in which each layer has a different function (e.g., one layer with dielectric properties and another to mitigate the effect of corona discharge).

High-specific energy batteries

The high specific energies required for electrified aircraft will require use of lithium metal as an anode instead of the graphite used in state-of-the-art Li-ion batteries. While lithium metal-based batteries offer the promise of high specific energy, cyclic life and durability need to be improved.

Advanced ceramic materials (e.g., materials with optimized defect chemistry and conductivity) and manufacturing processes (e.g., processes to create engineered, 3D microstructures that can accommodate large volume expansion associated with use of lithium metal anodes) will be critical to develop lithium metal batteries.

Lithium metal-based all solid-state batteries (ASSBs) are attractive for electrified aircraft applications. For an ASSB, specific energy of the battery pack can be 90 percent of the cell specific energy, compared to 60–70 percent for liquid electrolyte-based batteries. Further, unlike batteries with liquid electrolytes, ASSBs are not prone to fire. Advanced ceramic materials and manufacturing processes are critical to realize high-specific energy ASSBs for electrified aircraft.

Thermal management

While there is a great need for advanced design and integration concepts to address thermal management challenges,
advanced materials and manufacturing processes will play an important role in the design of thermal management systems. This will require advanced thermal interface materials with high thermal conductivity.

There has been considerable interest in the use of graphene as a thermal interface material because of its very high thermal conductivity. For thermal management approaches using phase change materials, lightweight, high-heat of fusion materials with desired melting points will be required.

There is significant opportunity for additive manufacturing to enable innovative heat exchanger designs (e.g., micro-channels) that are not possible via conventional manufacturing processes.

Summary

The market penetration of electrified aircraft is expected to grow over time—but the timing of introduction of various classes of electrified aircraft will be a function of technology readiness and economic viability.

Advanced materials will enable the higher power densities and energy densities that are required for electric propulsion components. Critical materials include high-electrical conductivity materials, superconducting materials, magnetic materials, electrically insulating materials with high thermal conductivity, high-voltage insulation materials, high-temperature capacitors, battery materials, and thermal interface materials.

Ceramic materials will meet these needs through applications in high-power density superconducting motors, high-temperature capacitors, ASSBs, and as part of the thermal insulation system.

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References


The continued global increase in air travel requires commercial vehicles to become increasingly more efficient. To minimize fuel consumption and emissions, engines must operate at higher temperatures and higher efficiencies. Therefore, gas turbine hot section materials—specifically materials with lower density and higher temperature capability—are a critical technology.

Silicon carbide ceramic matrix composites (CMCs) are a game-changer for gas turbine hot section materials technology because of their excellent high-temperature mechanical properties, oxidation resistance, and light weight. Extensive development of SiC/SiC CMCs has led to fabrication of gas turbine hot section components, such as CMC shrouds, combustor liners, vanes, and blades. SiC/SiC CMCs consist of three major constituents: SiC fiber reinforcement, fiber coating to allow graceful failure, and SiC matrix. CMCs refer to SiC/SiC CMCs throughout the text.

Dense slow-growing silica scale is responsible for the excellent oxidation resistance of CMCs. Volatilization of SiO$_2$ scale by water vapor generated during combustion reactions and the resulting rapid surface recession is the Achilles heel of CMCs because it erodes structural integrity and mechanical strength. Therefore, external barrier coatings, known as environmental barrier coatings (EBCs), have been developed to protect CMCs from surface recession.$^{1,2}$

In the late 1990s, the NASA High Speed Civil Transport program developed the first generation of EBCs, represented by a three-layer silicon/mullite/barium-strontium-alumino-silicate (BSAS) coating. Then in the early 2000s, the NASA Ultra-Efficient Engine Technology program developed the second generation of EBCs based on rare-earth silicates. Extensive laboratory, rig, and engine tests then commercialized these EBCs for CMC components. Extensive detail on first- and second-generation EBCs can be found in published review papers.$^{1,2}$

More than two decades of intense efforts led to the first EBC-coated CMC component—a high-pressure turbine CMC shroud—to enter service in LEAP engines in the Airbus A320neo in 2016 and Boeing 737max in 2017 by CFM International (Cincinnati, Ohio), a joint venture between GE Aviation (Evendale, Ohio) and Safran Aircraft (Courcouronnes, France). Today, development of new EBCs with enhanced performance for next-generation gas turbines continues at national laboratories, industry, and academia.

Environmental barrier coatings enhance performance of SiC/SiC ceramic matrix composites

By Kang N. Lee and Mark van Roode

Environmental barrier coatings protect the structural integrity and mechanical strength of ceramic matrix composites, allowing these revolutionary materials to boost gas turbine engine efficiency.
Capsule summary

**IT’S GETTING HOT IN HERE**

Gas turbine hot section materials with lower density and higher temperature capability are a critical technology to improve engine efficiency. Ceramic matrix composites, protected from surface recession by environmental barrier coatings, rise to this materials challenge.

**PROTECTION FROM RECESSION**

Significant work over the past few decades has helped environmental barrier coatings better protect the structural integrity and mechanical strength of ceramic matrix composites. However, next-generation gas turbines operating at higher temperatures and pressures will require additional efforts to mitigate surface recession.

**TAKING OFF**

Several environmental barrier coating challenges remain for the continued success of ceramic matrix composites in next-generation gas turbines. However, continued efforts to improve the materials’ life and temperature capability will lead to the next breakthrough in engine efficiency.

Due to these two competing reactions—silica growth and silica volatilization—over time the CMC surface recedes, the component thins, and its mechanical properties degrade.

NASA Glenn Research Center (GRC) has generated a large amount of SiC volatility data in a high-pressure burner rig. Equations 2 and 3 summarize the results for rich and lean burn combustion conditions, respectively.¹

\[
\text{Volatility (rich)} = 82.5 \exp[-159(kJ/mol)/RT] P^{1.74} v^{0.69}
\]

(2)

\[
\text{Volatility (lean)} = 2.04 \exp[-108(kJ/mol)/RT] P^{1.50} v^{0.50}
\]

(3)

Volatility is in mg/cm²-h, T is gas temperature in Kelvin, P is total pressure in atm, v is gas velocity in m/s, and R is the gas constant, 8.314 J/mol-K.

The SiC recession rate (µm/h) can be obtained by multiplying the volatility in equations 2 and 3 by a factor of 3.1. The projected recession at 5,000 h as a function of gas velocity in a lean burn combustion environment at \( P = 10 \text{ atm} \) and \( T = 1,200°C–1,400°C \) using Equation 3 is shown in Figure 1. Several millimeters of CMC recession will rapidly consume the component thickness at about 1,260°C.

Recession rates will be even higher in next-generation gas turbines operating at higher temperatures and pressures. CMCs, therefore, are not viable in gas turbine hot sections without efforts to mitigate recession.

**Development of EBCs**

Initial work focused on coating silicon-based monolithics (SiC and silicon nitride) to mitigate contact stress damage and degradation from molten salt corrosion. Mullite (3Al₂O₃·2SiO₂) was one of the most promising candidate coating materials because it has a coefficient of thermal expansion (CTE) close to that of SiC and excellent chemical compatibility with SiC.

In the mid-1980s, Solar Turbines Inc. evaluated various refractory oxides, including mullite, zircon, alumina, yttria, yttria-stabilized zirconia, and hafnia.¹ While these coatings provide a measure of protection against molten salt corrosion, they showed deterioration from cracking and debonding. Mullite performed best among the evaluated oxides.

A major breakthrough occurred in the early 1990s, when scientists at NASA GRC identified that crystallization of amorphous mullite and the accompanying shrinkage under thermal cycling in conventionally plasma-sprayed mullite were the root cause for poor durability of previous plasma-sprayed mullite coatings.² NASA GRC subsequently developed a modified plasma spray process that enabled deposition of a crystalline mullite coating with dramatically improved thermal cycling durability.

**First-generation EBCs**

In the mid-1990s, the NASA High Speed Civil Transport program’s discovery of SiO₂ recession in water vapor triggered formation of a joint NASA–GE–Pratt & Whitney team to develop new coatings to protect CMCs from water vapor. This new class of coatings became known as EBCs.

Mullite is not a viable EBC because it recesses fairly quickly due to its relatively high SiO₂ activity (~0.3–0.4).¹ Improved mullite, however, became the basis for early EBCs.

An extensive search identified BSAS (1-xBaO-xSrO-Al₂O₃·2SiO₂, 0 ≤ x ≤ 1) as a promising candidate material.⁶ It has an excellent CTE match with SiC, low SiO₂ activity (~0.1), and a low modulus. BSAS, however, forms a detrimental glassy reaction zone in contact with the CMC due to a eutectic reaction with SiO₂ scale.

The improved mullite coating was used as an intermediate coat to elimi-

![Figure 1. Projected recession at 5,000 h as a function of gas velocity in a lean burn combustion environment at \( P = 10 \text{ atm} \) and \( T = 1,200°C–1,400°C \) using Equation 3.](Image)
Environmental barrier coatings enhance performance of SiC/SiC ceramic matrix composites

nate chemical incompatibility. Adding approximately 20 wt% BSAS to the mullite intermediate coat significantly improved thermal cycling durability. Another key improvement was the identification of silicon as a bond coat.

This first-generation EBC can be represented as silicon/mullite+BSAS/BSAS. Figure 2 shows a micrograph of this first-generation EBC after a 100 one-hour cycle tests at 1,300°C (2,372°F), \( P(H_2O) = 0.9 \) atm, \( P_{total} = 1 \) atm, and \( v = 10 \) cm/s. These EBCs were deposited using air plasma spraying.

**Second-generation EBCs**

NASA initiated research in 1999 under the Ultra-Efficient Engine Technology program to develop EBCs with higher temperature capability than first-generation EBCs. Its goals for EBC–CMC interface and EBC surface temperatures were 1,316°C (2,400°F) and 1,482°C (2,700°F), respectively.

Research identified classes of rare-earth silicates with the general formula \( RE_2SiO_5 \) (monosilicates) and \( RE_2Si_2O_7 \) (disilicates) as promising candidates, with RE elements such as yttrium, ytterbium, scandium, or lutetium. Key attributes include low SiO\(_2\) volatility in water vapor, high melting points, and close CTE match with CMCs.

Figure 3 shows the experimentally measured volatility of BSAS, RE disilicates, and RE monosilicates at \( T = 1,500°C, \) \( P(H_2O) = 0.5 \) atm, and \( P_{total} = 1 \) atm. RE monosilicates are significantly less volatile than RE disilicates and BSAS, while the volatility of RE disilicates is similar to that of BSAS.

Figure 4 shows a cross-section of a three-layer silicon/mullite/Yb\(_2\)SiO\(_5\)-coated CMC after a 1,000 one-hour cycle test at \( T = 1,380°C (2,516°F), P(H_2O) = 0.9 \) atm, \( P_{total} = 1 \) atm, and \( v = 10 \) cm/s. The EBC maintained excellent adherence and crack resistance.

A second-generation EBC-coated CMC vane was tested in a NASA high pressure burner rig (\( ~1,260°C–1,316°C, 102 \) total cycles with 2-min cycles, 5 total test hours, \( P_{total} = 6 \) atm, \( v = 24 \) m/s) next to two superalloy vanes for comparison. The EBC remained intact, while the superalloy vanes and holder suffered significant damage (Figure 5).

**Environmental durability of EBCs**

**Recrystallization**

Silicate EBC volatility scales with the SiO\(_2\) activity of silicates. The SiO\(_2\) activity of monosilicates is about two orders of magnitude lower than the SiO\(_2\) activity of disilicates. This explains the superior stability of RE monosilicates compared to RE disilicates (Figure 3). RE silicates volatilize in water vapor according to the following reactions.

\[
\begin{align*}
\text{RE}_2\text{SiO}_4 + 2\text{H}_2\text{O} (g) & \rightarrow \text{RE}_2\text{SiO}_5 + \text{Si(OH)}_4 (g) \quad (4) \\
\text{RE}_2\text{SiO}_3 + 2\text{H}_2\text{O} (g) & \rightarrow \text{RE}_2\text{O}_3 + \text{Si(OH)}_4 (g) \quad (5)
\end{align*}
\]
RE disilicate and RE monosilicate transform to RE monosilicate and RE oxide, respectively. Recession studies of RE disilicates in high-velocity–high-steam rig tests confirm the formation of a RE monosilicate surface layer. Among current silicate topcoats, RE monosilicates are the most recession-resistant. However, RE monosilicates have higher CTEs than CMCs and therefore are prone to crack in thermal cycling.

RE oxides and thermal barrier coatings such as zirconia and hafnia are very stable in water vapor, making them promising candidates as recession barriers. These materials, however, have over 2-fold higher CTE than CMCs, so thermal stresses must be mitigated before they can function as recession barriers.

**Oxidation**

Water vapor is the primary oxidant for silicon or SiC in H2O + O2 environments because the permeability of H2O in SiO2 scale is about 10-times higher than that of oxygen. In first- and second-generation EBCs, H2O permeates through the ceramic coat and reacts with the silicon bond coat, forming a layer of SiO2 scale known as thermally grown oxide (TGO) at the silicon–ceramic coat interface.

Identified in laboratory tests and confirmed in rig and engine tests, spallation due to TGO growth is one of the most frequently observed EBC failure modes. Laboratory steam oxidation tests show that EBCs fail at or near the TGO when it reaches a critical thickness. TBCs based on zirconia also typically fail at or near the TGO, which is attributed to the strain energy resulting from CTE mismatch between the TGO and substrate.

The strain energy-induced TBC failure mechanism is likely applicable to EBC failure as well, considering the two coatings have similar bond coat/ceramic coat architecture. Sources for strain energy in EBCs include growth stress due to approximately 2.2-fold volume expansion during oxidation of silicon to SiO2, TGO, thermal stresses due to CTE mismatch between SiO2, TGO, and CMC (-4–5 x 10^-6/°C), and stresses due to β to α cristobalite SiO2 TGO phase transformation at about 200°C, which is accompanied by about 5 percent volume reduction.

**Calcium-magnesium-alumino-silicate (CMAS)**

Degradation by CMAS is a glass ceiling to the upper use temperature of current TBCs, with the same challenge to EBCs. CMAS deposits form when air-breathing turbine engines ingest particulates such as sand, volcanic ash, and other siliceous debris. Ingested particulates can cause several issues.

At temperatures above about 1,230°C (2,246°F), CMAS melts and adheres to hot section components, resulting in undesirable chemical reactions with EBCs. Additionally, molten CMAS can infiltrate porous EBCs, leading to undesired stresses. Both chemical and mechanical interactions are detrimental to EBCs, ultimately leading to cracking and spallation. Current research shows that first- and second-generation EBCs do not afford adequate protection against CMAS attack under simulated aircraft engine conditions.

**EBC field testing**

Laboratory and rig testing can rapidly evaluate candidate EBC compositions and performance. Field testing complements and expands these results with data collected over longer durations and under typical service conditions.

Gas turbine original equipment manufacturers have generated valuable data since the late 1990s on the performance of EBCs in their equipment. Published assessments are available from field testing conducted under government-funded programs led by Solar Turbines Inc. during 1997–2007 and from rig and field testing of a government-funded program led by General Electric Co. during 2000–2010.

Previous reports detail the Solar Turbines work. These tests involved more than 88,974 h of engine field testing with CMC combustor liners on Centaur 505 industrial gas turbines at three customer sites. A total of 83,010 h of these engine tests were conducted with EBC-coated CMC components.

Two government contractor reports detail the GE work. These tests were shorter and included 6,903 h of engine tests of EBC-coated CMC first-stage inner shrouds on two GE 7FA utility engines.

**GE EBC-coated CMC shroud test**

The GE engine shroud tests were accompanied by rig testing, which explored ways to elucidate degradation mechanisms and improve component design. The temperature on the shroud surface was about 1,200°C (2,192°F). The first engine test was for a total of 5,366 h with 14 start–stop cycles.

Shrouds were fabricated from GE’s proprietary HiPerComp melt-infiltrated CMC with two fabrication routes, prepreg and slurry-cast. Slurry-cast CMC was also supplied by BF Goodrich (Charlotte, N.C.). A total of nine CMC shrouds—six prepreg and three slurry-cast CMCs—replaced nine out of 96 metallic shrouds in this “rainbow” field test.

The EBC was mostly first-generation three-layer silicon/mullite+BSAS/BSAS.
Environmental barrier coatings enhance performance of SiC/SiC ceramic matrix composites

The EBC was deposited by air plasma spraying at GE. Figure 6 shows an EBC-coated CMC shroud and sections. The EBC was applied both to the gas path surface and backside. The part is similar to shrouds used in engine testing.

The second engine test was for a total of 1,537 h with 497 start-stop cycles and was carried out with a full set of 96 CMC shrouds. Only prepreg melt-infiltrated CMC shrouds were used because of degradation of slurry-cast CMC shrouds in the first engine test.

That first engine test had a significant blade tip gap to avoid blade tip rub. This gap was reduced in the second test to improve performance by adding a thick abradable EBC top layer. In addition to three-layer silicon/mullite+BSAS/BSAS EBC, some shrouds also had coatings that incorporated RE silicates. The outer abradable EBC was made by spraying additional ridges of BSAS on top of the layered EBC using two spray patterns, a ridge pattern and cross-hatch pattern.

Solar Turbines EBC-coated CMC combustor liner test

The combustor liners in the Solar Turbines engine tests are concentric cylinders connected to cones in the aft position. In this test, CMC liners with minimal backside cooling were used to replace metallic liners. Diameter of the outer liner was 76 cm, and diameter of the inner liner was 36 cm. Both liners were 20 cm long. The highest temperature on the surface of an uncoated CMC combustor liner was about 1,260°C (2,300°F). The $p(H_2O)$ in the combustor section was about 1 atm.

CMCs were fabricated by chemical vapor infiltration or melt infiltration and were supplied by BF Goodrich Aerospace and DuPont Lanxide Composites Inc. The latter eventually became GE Ceramic Composites Products LLC after going through several ownership changes. CMC liners were about 3–4 mm thick and usually had a dense CVD SiC seal coat (125–500 µm thick). Pratt & Whitney/United Technologies Research Center and its EBC supplier applied the EBCs.

Figure 7 shows the EBC-coated CMC liner set. The outer liner was coated with a silicon/mullite+BSAS/BSAS EBC. EBCs were approximately 125 µm thick. EBCs increased the CMC liner life from about 5,000 h to 12,000–15,000 h. Melt-infiltrated liners performed better than chemical vapor-infiltrated liners and were therefore mostly used in the latter phases of field testing.

Testing showed that the silicon/mullite+BSAS/BSAS EBC was superior to silicon/mullite/BSAS EBC. The test was halted after 13,937 h and 61 start-stops because borescope inspection revealed a small hole in the inner liner. Over 10 years, field testing accumulated more than 88,974 h of CMC exposure, including 83,010 h with EBC-coated CMCs.

Degradation of EBCs in field test

Bond coat oxidation and spallation

Oxidation of the silicon bond coat was mostly responsible for progressive degradation of EBCs. The strain energy-induced EBC failure mechanism due to TGO was discussed previously. Water vapor permeates through the ceramic coat and reacts with the silicon bond coat, forming a layer of SiO$_2$ TGO. Cracks in the EBC, formed during processing or during service, accelerate TGO growth by providing fast pathways for water vapor.

The first-generation EBC-coated CMC combustor liner after 15,144 h of engine testing by Solar Turbines developed horizontal cracks along the (mullite + BSAS)–SiO$_2$ TGO interface and through the silicon bond coat, followed by debonding and spallation of EBC.

Figure 8 shows micrographs of the edge of a GE prepreg CMC shroud after 5,366 h “rainbow” engine test. Top shows CMC recession at the EBC spall location on a prepreg shroud. Bottom shows CMC recession under an EBC tooling bump pit on a slurry-cast shroud.23

Figure 9. Micrographs of the 5,366-h GE “rainbow” test shrouds. Top shows CMC recession at the EBC spall location on a prepreg shroud. Bottom shows CMC recession under an EBC tooling bump pit on a slurry-cast shroud.
5,366 h “rainbow” engine test. Initially, formation of TGO on the silicon bond coat led to cracks in the EBC top layers, as shown in the upper left micrograph. Ingress of water vapor along these cracks enhanced oxidation of the bond coat laterally from the crack position, forming additional EBC cracks around the corners. Eventually bond coat oxidation was severe enough to liberate entire pieces of EBC along the corners. Most other spalls noted on the hot gas path face progressed from these edge spalls or from other coating defects, such as pinholes.

**Formation of pinholes**

Figure 9 shows micrographs of pin-sized hole defects observed in two GE shrouds after the 5,366-h “rainbow” test. The CMC surface under the EBC had recessions of about 0.8–0.9 mm, which is within the 0.5–1.1 mm range predicted by the NASA volatility model.9

Holes in the EBC were mostly associated with tooling bumps on slurry-cast shrouds, but prepreg shrouds also had a smaller number of small holes in the EBC. There was undercutting of the EBC coating due to recession of the CMC. While the EBC is relatively stable in the combustion gas environment, degradation proceeds rapidly when the EBC is breached. Occurrence of these pinholes was reason to eliminate slurry-cast CMC shrouds in the second engine test.

**Edge defects and recession**

Defects may arise in EBCs at the component edges. These defects may originate in the coating deposition process or occur during service. Borescope inspection revealed edge spalls at the shroud edges (hot gas path, leading edge and trailing edge flanges) during the 1,537-h test. Edge effects also led to larger spalls after the Solar Turbines 13,937-h engine test. While visually intact, nondestructive evaluation of as-fabricated liners suggests possible debonding near the edge.

Water vapor recession is another life-limiting factor, especially over the long service lives of gas turbines in commercial applications. Severe recession was observed after the 13,937-h Solar Turbines field test, with some areas losing most of the BSAS top layer.

**Challenges for next-generation EBCs**

Development of next-generation EBCs focuses on improving EBC life and temperature capability. Oxidation is a key EBC failure mode in both laboratory and engine tests. The upper temperature of current EBCs at the EBC–CMC interface is limited by the melting point of silicon (1,414°C/2,577°F). The upper temperature of first-generation EBCs at the EBC–CMC interface is limited by the BSAS-SiO2 eutectic temperature (1,310°C/2,390°F). The upper temperature of current silicate EBC topcoats is limited by EBC–environment interactions, such as H2O recession and CMAS degradation.

**Oxidation resistance**

A logical approach to improve EBC oxidation life is to reduce TGO growth rates. TGO growth rates can be reduced by minimizing the permeability of oxidants through the coating and/or TGO. In TBC-coated superalloys, TBC life has been significantly improved by reducing Al2O3 TGO growth rates on the bond coat by adding reactive elements, such as Y, Zr, and Hf, in the Al2O3-forming bond coat. These additives reduce diffusivity of oxygen through Al2O3 TGO. One recent study illustrates an example of improved EBC oxidation life by reducing SiO2 TGO growth rates.14 Addition of Al2O3 or oxide compounds, such as mullite and YAG (Y3Al5O12), to modify plasma-sprayed second-generation EBC (silicon/Yb2Si2O7) reduced SiO2 TGO thickness by about 80 percent compared to baseline silicon/Yb2Si2O7 EBC after 1000 one-hour cycles at 1,316°C in steam oxidation.

Figure 10 compares the EBC cross-section of Si/Yb2Si2O7 and Si/Yb2Si2O7+4.66 wt% YAG+1.39 wt% mullite EBCs after 1,000 one-hour cycles at T = 1,316°C, P(H2O) = 0.9 atm, Ptotal = 1 atm, and v = 10 cm/s. The reduced TGO growth rates translate to approximately 20-fold improvement in EBC life. The TGO may have become less permeable to H2O because the oxide additives modified the SiO2 network structure.14 Further studies are underway to understand the oxidation mechanism of modified EBCs.

**CMAS resistance**

CMAS-resistant EBC research focuses on a multilayer coating architecture, where a top layer arrests CMAS penetration at or near the surface and underlying layers provide protection from oxidation. At present, gadolinium zirconate (Gd2Zr2O7), which was designed for use as a TBC layer, has shown promise to arrest CMAS infiltration.

Understanding the effect of CMAS composition as well as trace oxides in volcanic ash or regional sand on crystallization, viscosity, thermal and mechanical properties, chemical reactivity with EBCs, etc. is important to develop strategies to mitigate CMAS. Advanced EBC technol-
Environmental barrier coatings enhance performance of SiC/SiC ceramic matrix composites

The next breakthrough
CMCs hold tremendous promise to provide the materials technology required for the next breakthrough in gas turbines. EBCs are enabling technology for CMCs in the gas turbine hot section. Following the first entry into service of the EBC-coated high-pressure turbine CMC shroud in 2016, additional high-pressure turbine CMC components, such as combustor liners, vanes, and blades, are scheduled to enter into service in the near future.

Several EBC challenges still remain for continued successful CMC implementation in next-generation gas turbines. These challenges include oxidation resistance, CMAS resistance, recession resistance, and temperature capability. Other challenges also should not be overlooked, including thermo-mechanical stability, erosion resistance, and foreign object damage.

Robust EBC life models and relevant testing capabilities to validate the life models must be developed as well. Continued collaborations between government laboratories, industry, and academia are paramount to successfully address these challenges.

About the authors
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#### Sunday, June 9, 2019
- ICG Technical Committee meetings: 8 a.m. – 6 p.m.
- Registration: 3 – 6 p.m.

#### Monday, June 10, 2019
- Registration: 7 a.m. – 5 p.m.
- ICG opening ceremony, awards presentation, and plenary session: 8 – 11:45 a.m.
- Technology Fair: 9:30 a.m. – 8 p.m.
- Lunch and GOMD 100th anniversary celebration: 11:45 a.m. – 1:20 p.m.
- Concurrent sessions: 1:20 – 5 p.m.
- CTC business meeting: 2 – 5 p.m.
- Welcome reception, poster session (1 of 2), and Technology Fair: 6 – 8 p.m.

#### Tuesday, June 11, 2019
- Registration: 7:30 a.m. – 5 p.m.
- Concurrent sessions: 8 a.m. – 5 p.m.
- Lunch on own: Noon – 1:20 p.m.
- Technology Fair: 10 a.m. – 7 p.m.
- ICG Steering Committee meeting: 9 a.m. – Noon
- ICG Council meeting: 1 – 4 p.m.
- Poster session (2 of 2), technology fair, and reception: 5 – 7 p.m.

#### Wednesday, June 12, 2019
- Registration: 7:30 a.m. – 12:30 p.m.
- Michael Cable Memorial lecture: 8 – 9 a.m.
- Concurrent sessions: 9 a.m. – 12:30 p.m.
- Technology Fair: 8:30 a.m. – 12:30 p.m.
- Free time: 12:30 p.m. to end of day

#### Thursday, June 13, 2019
- Registration: 7:30 a.m. – 5 p.m.
- Concurrent sessions: 8 a.m. – 5 p.m.
- Lunch on own: Noon – 1:20 p.m.
- Dinner banquet: 7 – 9:30 p.m.

#### Friday, June 14, 2019
- Registration: 7:30 a.m. – Noon
- Concurrent sessions: 8 a.m. – 12:30 p.m.
- Lunch on own: 12:30 – 2 p.m.
- Closing ceremony: 2 – 3 p.m.

### Symposiums and Sessions

- **Symposium I:** Glass Structure and Chemistry
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Claude Delmas, CNRS research director at the Bordeaux Institute of Condensed-Matter Chemistry, University of Bordeaux 1, France
Title: From Volta to Solar Impulse: A battery journey

Mrityunjay Singh, chief scientist, Ohio Aerospace Institute, USA
Title: Fourth Industrial Revolution and its impact on sustainable societal development

Serena M. Best, professor, Materials Science, University of Cambridge, United Kingdom
Title: Optimizing bioactive scaffolds: Cellular response to calcium phosphate composition and architecture

BIO-4 PLENARY SPEAKERS

Robert M. Pilliar, professor emeritus, Faculty of Dentistry and Institute of Biomaterials and Biomedical Engineering, University of Toronto, Canada
Title: Porous calcium polyphosphates—Biodegradable bone substitutes and beyond

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Calendar of events

April 2019


30–May 1  5th Ceramics Expo – I-X Center, Cleveland, Ohio; www.ceramicsexpousa.com

May 2019


June 2019


16–18  10th Advances in Cement-Based Materials – University of Illinois at Urbana-Champaign, Champaign, Ill.; www.ceramics.org/cements2019

24–27  ACerS Structural Clay Products Division & Southwest Section Meeting in conjunction with the National Brick Research Center Meeting – Omni Severin Hotel, Indianapolis, Ind.; www.ceramics.org/scpd2019

July 2019

10–11  Ceramics UK colocated with The Advanced Materials Show – The International Centre, Telford, UK; www.ceramics-uk.com

21–26  4th Int’l Conference on Innovations in Biomaterials, Biomanufacturing, and Biotechnologies (Bio-4), combined with the 2nd Global Forum on Advanced Materials and Technologies for Sustainable Development (GFMAT-2) – Toronto Marriott Downtown Eaton Centre Hotel, Toronto, Canada; www.ceramics.org/gfmt-2-and-bio-4

August 2019


September 2019

4–6  3rd Annual Energy Harvesting Society Meeting (EHS19) – Falls Church Marriott Farview Park, Falls Church, Va.; www.ceramics.org/ehs2019

Resource:

Dates in RED denote new entry in this issue.

Entries in BLUE denote ACerS events.

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Ultra-high temperature oxidation of high entropy UHTCs

Ultra-high temperature ceramics (UHTCs), most notably refractory metal carbides, nitrides and borides, hold the key to advanced maneuverability in hypersonic vehicles. UHTCs exhibit melting temperatures exceeding 3,000°C, making them appropriate candidates to withstand extreme temperatures experienced by leading edges of aircraft during hypersonic flight. However, UHTCs’ propensity to react rapidly with oxygen may limit their sustained application.

State-of-the-art UHTCs address this limitation through addition of silicon carbide, for example, to boride UHTCs, to promote formation of a protective silica or silicate layer. Unfortunately, the highest melting temperature in the boria-silica system is that of silica, which is just over 1,700°C. Therefore, relying on formation of silica is not viable above this temperature; the liquid oxide may shear off during hypersonic flight.

A new paradigm in UHTC design has emerged in recent years, following the wake of research on high entropy alloys and entropy-stabilized oxides. Multi-principal component UHTCs or high entropy UHTCs (HE-UHTCs) are solid solutions of four or more refractory metal carbides and borides stabilized by configurational entropy. This approach has vastly expanded the UHTC compositional palette, creating new opportunities in materials design for improved oxidation resistance, mechanical, and thermal properties.

I work as part of a Multidisciplinary University Research Initiative (MURI) funded by the Office of Naval Research that seeks to understand HE-UHTCs at the fundamental level. Other collaborators include groups at University of Virginia (UVA), North Carolina State University, The Pennsylvania State University, Duke University, and University of California, San Diego.

My work in the Opila group at UVA is focused on studying ultra-high temperature oxidation behavior of HE-UHTCs and, ultimately, developing a framework to aid in design of a HE-UHTC optimized for oxidation resistance at temperatures greater than 1,700°C.

An important question regarding oxidation of high entropy materials is whether all components in solid solution will oxidize simultaneously, or whether selective oxidation will occur. When a multicomponent material is exposed to an oxidizing environment, it is expected that all species in contact with the environment will initially oxidize. As the system progresses toward equilibrium, the resulting oxide products would then be governed by their relative thermodynamic stability and the rate controlling kinetics. Recent work showed there can be large differences in the relative thermodynamic stabilities of the formed oxides, suggesting the possibility that selective oxidation will occur in HE-UHTCs—resulting in depletion of those components from the underlying material. Given that configurational entropy scales with number of components in solid solution, it is therefore critical to understand the extent to which selective oxidation and component depletion occurs in high entropy materials.

One of the biggest challenges of studying UHTCs is engineering an experimental setup for achieving ultra-high temperatures in a laboratory, without compromising the sample or the equipment. I employ a unique resistive heating experimental setup in the Opila lab. Test specimens are heated to ultra-high temperatures (at or above 1,700°C) through Joule heating in a sealed chamber, which enables experiments at various, controlled pO2 environments. The temperature-controlled region, or hot zone, is a small area in the center of the specimen, isolated from the rest of the experimental set-up and contamination risks (Figure 1).

Candidate compositions recommended by the computational work and by other collaborators will be tested using this set-up. The understanding of oxidation mechanisms gained through these studies will be used by collaborators in the MURI to optimize the design of an HE-UHTC for oxidation resistance and other properties.

References


Lavina Backman is a Ph.D. candidate at the University of Virginia, and a Virginia Space Grant Consortium Graduate Research Fellow. She worked as a manufacturing engineer before returning to graduate school to pursue a degree in materials science. Outside the lab, she loves cooking, reading science fiction, and travelling.
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