

Ceramic matrix composites take flight in LEAP jet engine

January 4 2017, by Dawn Levy



CMCs in nuclear fuel cladding and reactor core structures could make reactors worldwide safer. During the 2011 Fukushima Daiichi disaster, the nuclear power plant's loss of cooling led to combustion of Zircaloy cladding, subsequent explosions and radiation release. If CMC cladding had been used instead, the fuel rods probably would have lasted until cooling was restored, said ORNL's Yutai Katoh, a world-renowned expert in nuclear materials. Credit: Oak Ridge National Laboratory, U.S. Dept. of Energy; photographer Jason Richards

Ceramic matrix composite (CMC) materials are made of coated ceramic fibers surrounded by a ceramic matrix. They are tough, lightweight and capable of withstanding temperatures 300–400 degrees F hotter than metal alloys can endure. If certain components were made with CMCs instead of metal alloys, the turbine engines of aircraft and power plants could operate more efficiently at higher temperatures, combusting fuel more completely and emitting fewer pollutants.

A quarter-century ago, the U.S. Department of Energy began a program, led by DOE's Oak Ridge National Laboratory, to support U.S. development of CMC [materials](#). In 2016, LEAP, a new aircraft engine, became the first widely deployed CMC-containing product. CFM International, a 50/50 joint venture of Safran and GE, manufactures LEAP.

The engine has one CMC component, a turbine shroud lining its hottest zone, so it can operate at up to 2400 F. The CMC needs less cooling air than nickel-based super-alloys and is part of a suite of technologies that contribute to 15 percent fuel savings for LEAP over its predecessor, the CFM 56 engine.

Presales to airlines eager to lower fuel costs are staggering—\$140 billion at list price for more than 11,000 engines. In August, the first LEAP engine started flying commercially on Airbus A320neo. Other LEAP engines will fly on the Boeing 737 MAX in 2017.

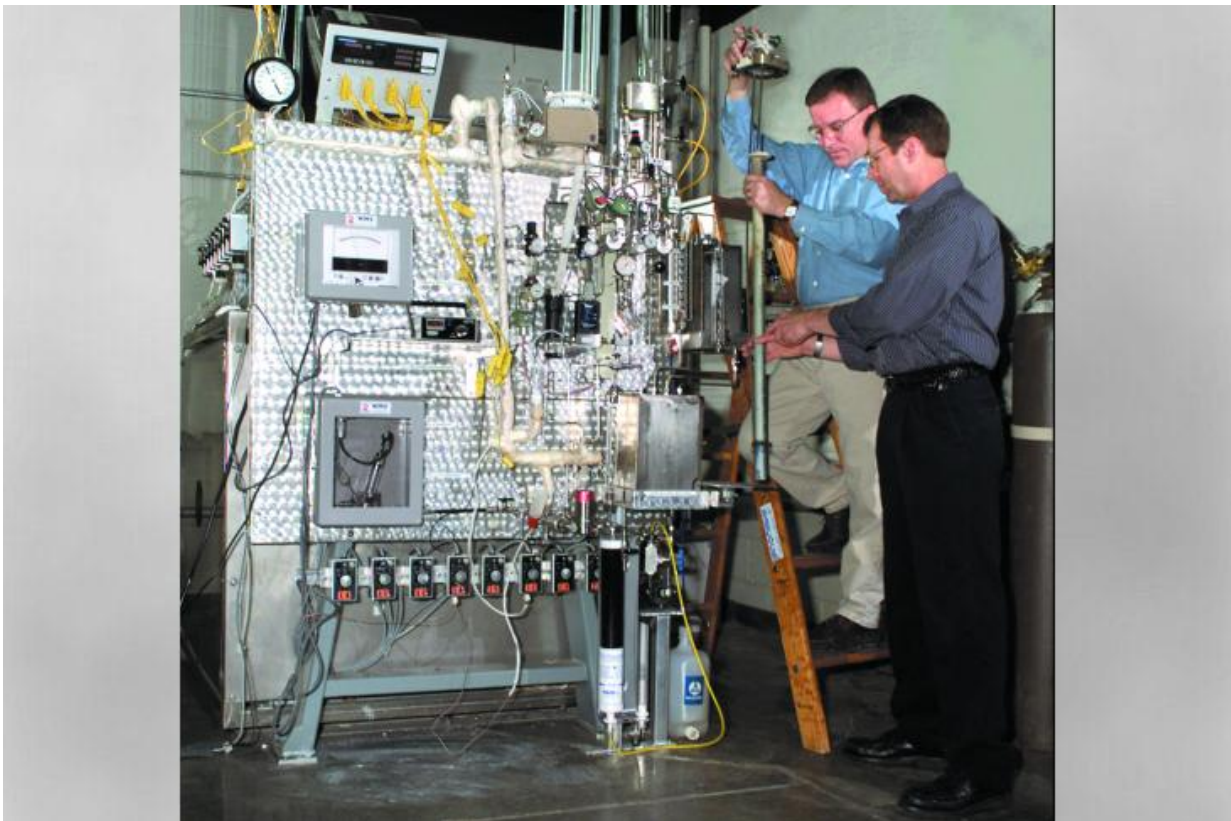
"The materials developed in the DOE program became the foundation for the material now going into aircraft engines," said Krishan Luthra, who led GE Global Research's development of CMCs for 25 years.

GE's CMC is made of silicon carbide (SiC) ceramic fibers (containing silicon and carbon in equal amounts) coated with a proprietary material containing boron nitride. The coated fibers are shaped into a "preform"

that is embedded in SiC containing 10–15 percent silicon.

ORNL's Rick Lowden did foundational work in the 1980s that paved the way for DOE programs. The key was coating the ceramic fibers.

"A ceramic matrix composite is different than almost all other composites because the matrix is ceramic and the fiber is ceramic," Lowden said. Typically, combining two brittle materials yields a brittle material, he said. But altering the bond between fiber and matrix allows the material to act more like a piece of wood. Cracks don't propagate into the fibers from the matrix around them. The fibers hold the material together and carry the load while slowly pulling from the matrix, adding toughness.



For DOE programs that ran 1992–2005, companies sent materials to ORNL for stress-testing. High-pressure furnaces called Keiser rigs subjected samples to temperatures and pressures typical of steam plants. ORNL's Jim Keiser and Mike Howell (on ladder) measured factors that degrade materials. Credit: Oak Ridge National Laboratory, U.S. Dept. of Energy

DOE's Continuous Fiber Ceramic Composite (CFCC) program ran from 1992 to 2002 and supported industrial development of CMCs by AlliedSignal, Alzeta, Amercom, Babcock and Wilcox, Dow Chemical, Dow Corning, DuPont-Lanxide Composites, GE and Textron. Its budget averaged \$10 million per year, and industry shared costs.

CFCC funded companies to make composites and national labs and universities to characterize the properties of the materials. Efforts were coordinated and funded through ORNL. Lowden wrote the program plan with Scott Richland of DOE and Mike Karnitz of ORNL and co-led support to companies with ORNL's Karren More, Pete Tortorelli and Edgar Lara-Curzio and Argonne National Laboratory's Bill Ellingson. The U.S. Advanced Ceramics Association represented industry in informing Congress of the benefits of CMCs.

"We were looking at different fibers and different interfacial coatings and different matrices," More said of ORNL's role. "We were involved in understanding the degradation mechanisms and down-selection of the more promising composites and cost-effective techniques for preparing them."

Lowden added, "We were working toward a common goal of getting ceramic matrix composites into industrial applications including high-pressure heat exchangers, land-based turbines, carburizing furnaces and radiant burners."

GE's CFCC project was to develop CMCs for industrial gas turbine engines that produce electricity. (GE manufactures both power and propulsion turbines.) A follow-on DOE program ran through 2005 and funded the most promising CFCC companies to further develop materials and components and if possible, test them in applications. Total funding was approximately \$15 million, with industry cost-sharing approaching 50 percent. GE field-tested a CMC shroud in a 170-megawatt industrial gas turbine under the program. All told, GE invested \$1.5 billion after that to commercialize the technology.

"Seed money is critical for high-risk, high-payoff technologies," Luthra said. "Material development is a long-term activity, and Oak Ridge tremendously supported the basic research."

As evidence of success, Luthra pointed to new CMC factories and jobs today. In 2002, GE acquired a CMC facility in Newark, Delaware, which has grown substantially. A new GE facility opened in Asheville, North Carolina, in 2014 for making shroud components. In addition, GE is building two adjacent factories in Huntsville, Alabama—the first to ramp up fiber production and the second to coat fibers and make tape for processing into components. At full-scale, the Asheville and Huntsville sites are expected to bring 640 high-tech jobs.

In 2019 GE will produce an engine, GE9X, with five CMC parts—two combustor liners, two nozzles, one shroud. Presales are approximately \$29 billion at list prices for 700 engines.



During DOE programs to advance industrial ceramic matrix composites, ORNL's Karren More (foreground, with Larry Walker) used transmission electron microscopy and other techniques to pinpoint causes of failure in stress-tested or field-tested materials made by companies. Without the expertise and facilities of national labs—available nowhere else—industry would have been flying blind. Credit: Oak Ridge National Laboratory, U.S. Dept. of Energy

Firing up research of ceramic composites

Long before ceramic fibers reinforced ceramic composites, ORNL researchers coated nuclear fuel with carbon and SiC to confine radioactivity inside [tristructural-isotropic \(TRISO\) fuel](#) particles. During experiments in the '70s, ORNL's Jack Lackey realized the process could be modified to manufacture ceramic composites more rapidly. With

support from DOE's Fossil Energy Materials Program, his group pioneered a process to do just that.

"You take a fibrous preform, place it in a furnace, and vapor-deposit solids on and around the fibers," explained Lowden, who was Lackey's technician. To coat the whole object uniformly, the deposition process must be extremely slow—a half-inch part might take six months to process.

However, the ORNL team found that placing a fibrous mat on a cold plate, heating the top and forcing gases through the mat sped the process from months to hours. "That's where we got involved in ceramic matrix composites," Lowden said. ORNL supplied CMCs for years to researchers evaluating CMCs for various applications.

Today, GE mass-produces CMCs using a melt infiltration process. The production capacity is being scaled to make 36,000 perfect-quality shroud segments per year by 2020. (Each LEAP engine requires 18 shrouds segments.)

During the CFCC years, the program's greatest success was an industrial gas turbine placed into operation at the Malden Mills plant in Massachusetts in 1999. The turbine sported a CMC combustor liner—developed by Solar Turbines with input from researchers at ORNL, Argonne, United Technologies, B.F. Goodrich and DuPont-Lanxide Composites—that helped improve the efficiency of the turbine. At the time, Energy Secretary Bill Richardson said the Malden Mills plant had "the lowest emissions of any industrialized heat and electric combined facility in the United States."

Since CFCC, GE has tested CMCs for more than 2 million hours, including 40,000 hours in industrial gas turbines. Jim Vartuli of GE's CMC program said DOE support on large industrial gas turbines to get

those first demonstrators gave GE confidence that the ceramics could survive high temperatures and stresses in turbines for long periods.

"GE is the only company in the world with both large industrial gas turbines and aircraft engines businesses, and this enables many opportunities for co-development of advanced technology. This is an example of the 'GE Store'—the transfer of technology and knowledge between GE businesses," Vartuli explained. "The success of the turbine tests convinced our aviation business that CMCs would be successful for aircraft engines, too."



Advanced materials take flight in the LEAP engine, featuring ceramic matrix composites developed over a quarter-century by GE with help from DOE and ORNL. Credit: General Electric

How DOE and its national labs helped industry

CFCC companies brought materials they'd made to DOE national laboratories at Argonne for nondestructive evaluation and Oak Ridge for microstructural characterization and stress and oxidation tests. "This partnership highlights the value of the national labs," More said. "We do work that is fundamental and broad to understand materials' behaviors. We provide necessary information to help the community make decisions about where to go, how to proceed." New knowledge about how materials degraded helped industry accelerate improvements and optimize manufacturing processes.

Research at ORNL ranged from development by Allen Haynes of environmental barrier coatings that could extend the lives of underlying materials five-fold to [nondestructive imaging of materials with thermal cameras by Ralph Dinwiddie](#). At Argonne National Laboratory, Bill Ellingson led development of broader nondestructive testing methods to ensure safe continued use of components by monitoring material degradation after intervals of usage. Without damaging the components, the inspections revealed how materials responded in an environment over time. With ORNL researchers, Argonne scientists developed several nondestructive inspection technologies that were instrumental in determining component performance.

ORNL's Pete Tortorelli and H. T. Lin stressed materials in environmental exposure chambers to learn their points of failure. Lab colleagues Jim Keiser and Irv Federer exposed samples to corrosive gases, temperatures up to 2550 F and pressures up to 500 psi in "Keiser rigs" that simulated conditions in turbines. These were also used by More, Tortorelli and Keiser to screen protective coatings needed in combustion environments.

Meanwhile, More characterized structures of stressed materials. "Karren

More entered the picture as our microscopist, and that changed our world," Lowden recalled. "To be able to see what was happening with transmission electron microscopy, and understand what was happening at that level, was incredible." GE had access to some techniques in-house because of its large infrastructure. "But we got invaluable help from Karren on the fiber coatings," Luthra said. "It helped us develop the fiber coatings faster."

ORNL's early findings encouraged industry to abandon carbon as a fiber coating. Carbon oxidized, turning into carbon monoxide and carbon dioxide, and volatilized, thinning the coating. ORNL engineers recommended oxidation-resistant boron nitride instead.

Moreover, Edgar Lara-Curzio modeled and tested the mechanical performance of CMC materials under different loading conditions and their resistance to fatigue, creep and rupture in ORNL's High Temperature Materials Laboratory. In collaboration with Matt Ferber and Chun-Hway Hsueh, he implemented experimental and analytical methods to characterize the micromechanics of fiber–matrix interfaces. "These measurements were essential to quantify chemical bonding between fibers and matrix, residual stresses experienced by the fibers and friction between the fibers and the matrix during fiber sliding," said Lara-Curzio, noting CMCs are tough mainly because interfacial coatings let fibers slide and bridge matrix cracks. He and Hsueh provided key information about how a single fiber slides in a ceramic matrix. Lara-Curzio, Ferber and Lowden then quantified the effect of the thickness of fiber coatings on sliding and discovered a value that optimized mechanical properties. Companies widely adopted this correlation to optimize their composites.



Seishi Yajima of Japan invented silicon carbide fiber in the 1970s, and Takemi Yamamura commercialized the process at Ube Industries. Hiroshi Ichikawa commercialized it at Nippon Carbon, and many credit his fiber, which had superior properties, as the foundation of the CMC industry. Early fibers contained oxygen, which degraded the material. Second-generation fibers were manufactured in a way that removed excess oxygen. Strong and resilient, third-generation fibers are the workhorses of silicon carbide ceramic matrix composites (shown here in gray) that make up shroud components of GE's LEAP engine (white material is an environmental barrier coating). Credit: General Electric

Back to the future

Today at GE, Luthra dreams of putting CMCs everywhere the engine

gets hot—blades, nozzles, liners. To achieve this vision, the community has many technological mountains to climb. One is developing manufacturing processes that, unlike melt infiltration, do not produce excess silicon that can volatilize and form cracks in the matrix.

"Every decade we have increased [the heat metals can take] by about 50 degrees," Luthra noted. Today CMC material can take up to 2400 F, but Luthra would like the next generation to reach 2700 F. "This is going to be as challenging as the development of the first ceramic composite," he said.

To highlight these challenges, the U.S. Advanced Ceramics Association is creating an industry-driven roadmap for the development of 2700 F CMCs for advanced gas turbines. This roadmap will inform Congress about successes of 2400 F CMCs, encourage investment in the development of 2700 F CMCs and highlight the contributions of CMCs to the creation of high-paying U.S. manufacturing jobs, national security and the environment. USACA's roadmap supports findings of a recent National Academy of Sciences study that concludes investment in gas turbine materials and coatings should be a high priority and that 2700 F CMCs could dramatically reduce or eliminate the need for cooling in engines, boost efficiency and lower weight. DOE national labs may once again be called upon to help discover high-performance materials and processes that can operate at higher temperatures and even more extreme environments.

Future CMCs will have to endure extremes on four time scales, depending on the application: 1 hour or less of hot time for launch vehicles; days for accident-tolerant fuels (e.g., if a cooling system goes out in a nuclear power plant); thousands of hours, the operating life of aircraft turbines; and over 30,000 hours for industrial gas turbines for power production.

A land-based gas turbine to generate electricity can be more demanding than an aircraft engine application because it spends much more time operating at high temperature, Luthra said. Advances in the next generation of 2700 F materials would enable breakthrough improvements in efficiency and emissions that could lower the cost of electricity.

The sky, after all, may not be the limit.

More information: Commercial Aircraft Propulsion and Energy Systems Research Reducing Global Carbon Emissions:

www.nap.edu/read/23490/chapter/1

Provided by Oak Ridge National Laboratory

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