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Accident-tolerant fuel: Enhancing safety

Research and development of accident-tolerant fuels is under way by three companies, including Westinghouse, which plans to insert lead test rods of its EnCore Fuel in Byron-2's reactor by 2019.

By Sumit Ray

Government-industry partnerships have historically been vital to the advancement of nuclear technology. This has held true for the progression of nuclear fuel and, most recently, for the development of a fuel more tolerant of a temporary loss of active cooling than current designs. With the goal of continuing nuclear power as a clean energy source and enhancing safety for the public, the U.S. Congress has provided renewed funding through the Department of Energy's Office of Nuclear Energy for the development of nuclear fuels and claddings with enhanced accident tolerance. In turn, competitive proposals were put forth by fuel developers to work with the government office.

It has long been understood that the uranium dioxide pellets encased in zirconium alloy cladding currently used in operating nuclear power plants have fueled nuclear fission very safely for decades. In 2011, however, events at the Fukushima Daiichi nuclear power plant units brought the realization that the current fuel systems could be challenged by extreme scenarios designated as beyond-design-basis events. Congress's action came about following the fuel melting at these units after the backup emergency generators were overcome with tsunami floodwaters and could not provide power for cooling. This situation was further exacerbated when hydrogen buildup—caused when zirconium removes oxygen from steam and leaves hydrogen—caused explosions and releases of radiation from the fuel. As a result, the Nuclear Regulatory Commission and its counterparts around the world are seeking to enhance light-water reactors' tolerance to accidents. The DOE's Accident Tolerant Fuel Program is one of the many steps governments and industry are taking toward this goal.

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The DOE defines fuels with accident tolerance in its June 2012 report to Congress titled *Development of Light Water Reactor Fuels with Enhanced Accident Tolerance*. As stated in the report, accident-tolerant fuels are those that, in comparison with the standard uranium dioxide zirconium alloy system, can tolerate the loss of active cooling in the reactor core for a considerably longer time period while maintaining or improving fuel performance during normal operations, operational transients, and beyond-design-basis events.

Westinghouse Electric Company LLC is one of three major nuclear fuel developers—the other two being Areva and General Electric—selected by the DOE to receive initial Phase 1 and continued Phase 2 funding toward this objective. Westinghouse had begun developing such a fuel in the 2003–2004 time frame. The program, however, accelerated in 2012 when Phase 1 began, reflecting the positive correlation of the government-industry partnerships toward the advancement of complex technologies.

The company's fuel system design objectives match those defined by the DOE. These are essentially to improve the fuel's reaction kinetics with steam to decrease its oxidation rate, hydrogen production, and embrittlement caused by hydrogen; improve fuel properties for lower operating temperatures and higher melting temperatures; improve cladding properties for higher melting temperatures and better resilience to fractures; and enhance the retention of fission products. In addition, as possible, the objectives include improving fuel cycle economics to make implementation of the new fuel economically viable.

The company's approach also corresponds with the program's implementation requirements to work collaboratively with industry, national laboratories, and universities to draw on the top-level experience and facilities available through existing and new alliances. The technology partners that are developing various aspects of the Westinghouse accident-tolerant fuel and their primary focuses are listed in the accompanying box. Westinghouse also instituted the formation of the Westinghouse-led Collaboration for Advanced Research on Accident-tolerant Fuel (CARAT) organization, joining with other organizations performing research work aligned with Westinghouse accident-tolerant fuel interests. Currently, the CARAT group numbers about 50 individuals from more than 30 organizations, including U.S. and international companies, universities, national laboratories, and research entities. It is a concerted and coordinated effort that is producing promising results.

Lead test rods of Westinghouse's accident-tolerant fuel product, named EnCore Fuel, will be inserted in Unit 2 of Exelon Generation's Byron plant in spring 2019. Westinghouse and its technology partners are developing this fuel with the goal of achieving significant safety and monetary benefits that will result in enhanced safety and economic value for utilities. The company is bringing EnCore Fuel to industry in two phases. The initial EnCore Fuel product that is being inserted in Byron-2's core incorporates zirconium alloy cladding coated with chromium. In the second phase, the cladding is changed to silicon carbide. Both phases capitalize on the ability of the new claddings to allow the use of high-density uranium silicide fuel pellets.

Cr-coated cladding

The chromium coating of Westinghouse's first phase EnCore Fuel product is intended to provide many intermediate safety and economic benefits. With the density and application of the chromium onto the base zirconium alloy cladding, as established during the feasibility phase, corrosion, oxidation, high-temperature steam, and in-reactor testing have been performed showing excellent results. The coating inhibits the zirconium-steam reaction, which supports extended exposure to steam and air at temperatures up to 1400 °C (2550 °F)—conditions that could occur during a loss-of-coolant accident, a reactivity-initiated accident, or a beyond-design-basis condition that extends the time the reactor goes without active cooling. This provides additional margin above the 1200 °C (2200 °F) limit currently in effect for zirconium alloy cladding alone, which in turn provides additional time for operators to restore active cooling.

The chromium coating also increases zirconium's resistance to oxidation in steam. The reduced oxidation and resultant reduced hydrogen absorption by the chromium-coated zirconium alloy cladding in normal operating temperatures (250 °C to 350 °C [480 °F to 660 °F]) are intended to prolong cladding burnup capability, enhance resistance to wear, and increase margins, while also facilitating the use of the high-density uranium silicide pellets. The improved performance of the chromium-coated EnCore Fuel product also allows for incremental reclassification of safety-significant systems within the plant, which traditionally have been very expensive to procure and maintain.

Silicon-carbide cladding

Westinghouse's second phase EnCore Fuel product changes the cladding to silicon carbide. Under development by Westinghouse and General Atomics, this new silicon-carbide cladding design has an exterior monolithic layer and an interior ceramic matrix composite layer for a robust cladding. It has an extremely high melting point (2800 °C or higher) to maintain the fuel's integrity in beyond-design-basis accident scenarios. In addition, it reacts 10,000 times slower with water and steam than zirconium for minimal heat and hydrogen generation.

The very high temperature tolerance and associated safety margin improvements offered with silicon-carbide cladding will allow for a considerable reclassification of safety-significant systems, leading to plant economic benefits. Utilities can apply systematic processes that are allowed by current regulations to identify savings that will be realized through several means. These include relaxed requirements for testing; changes in equipment and safety class designations; elimination of redundant equipment and systems and their associated maintenance costs; and reduced emergency planning and evacuation zones. Silicon-carbide cladding also has low neutron absorption, which results in increased neutrons for fission and improved fuel cycle economics during normal operation. It is important to note that silicon-carbide cladding will not burst and, therefore, will remain a low-leakage fission product barrier well into a severe accident and will

Westinghouse Program Technology Partners

Westinghouse formed an international, world-class multidisciplinary team, funded in part by the U.S. Department of Energy's direct awards to Westinghouse, General Atomics, and several of the U.S. national laboratories. The team members and their primary missions on this project include:

Westinghouse Electric Company LLC
Program lead and fuel design

General Atomics
Silicon-carbide/silicon-carbide composite cladding development

Ceramic Tubular Products and United Technologies Research Center
Silicon-carbide cladding manufacturing development

Idaho National Laboratory
High-density fuels (uranium silicide), irradiation testing (Advanced Test Reactor, Transient Reactor Test Facility), and post-irradiation examination

National Nuclear Laboratory (United Kingdom)
Industrial production of uranium silicide powder and pellets

Los Alamos National Laboratory
Studies on uranium silicide oxidation and manufacturing development

Massachusetts Institute of Technology
In-reactor testing of silicon-carbide/silicon-carbide composites and coated zirconium cladding out-of-reactor high-temperature oxidation and quench studies

Institute for Energy Technology (Norway)
Test rod assembly and testing (Halden Reactor)

Southern Nuclear Operating Company and Exelon Generation
Customer-based evaluation of accident-tolerant fuel

University of Wisconsin
Coated zirconium rods

Paul Scherrer Institute (Switzerland)
Evaluation of silicon carbide properties

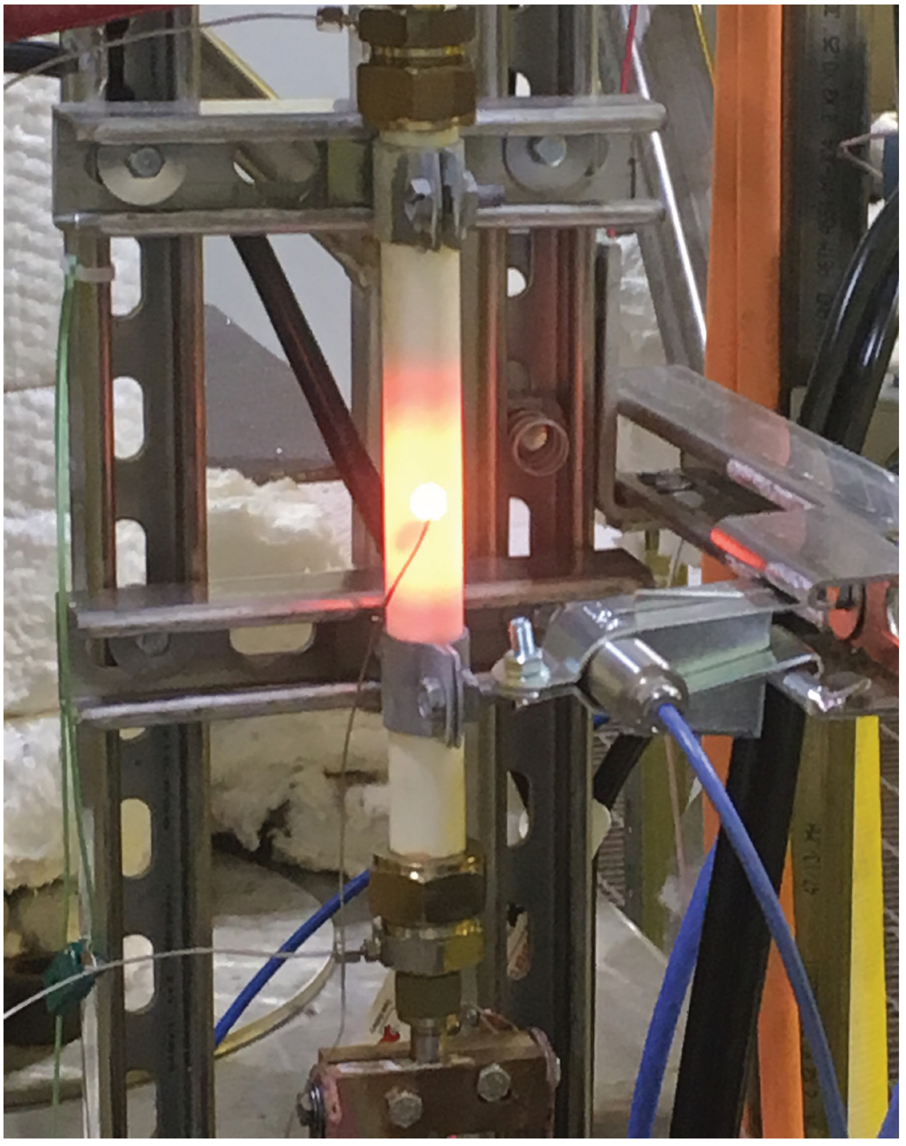

Fig. 1. A simulation of a severe accident test of silicon-carbide cladding at about 1600 °C (about 2900 °F) is carried out at Westinghouse's Ultra-high Temperature Test Facility. (Photos and graphs: Westinghouse Electric Company LLC)

Fig. 2. Before and after photos of silicon-carbide cladding severe accident testing at about 1600 °C (about 2900 °F) for 40 minutes in steam. The cladding exhibited essentially no change or damage.

not generate significant levels of hydrogen, thereby improving plant safety margins.

Ultra-high-temperature testing

In order to test the resistance of these materials to high temperatures, Westinghouse developed an Ultra-high Temperature Test Facility at its Materials Center of Excellence Hot Cell Facility in Churchill, Pa. The ultra-high-temperature test is conducted by inserting an electrically powered heater rod into a tube clad with either the chromium-coated zirconium alloy or silicon-carbide material. That tube is shielded within a ceramic tube into which steam is introduced at each end. The steam is allowed to escape through a hole in the middle of the ceramic tube so that the cladding material's surface temperature can be measured.

Westinghouse conducted preliminary tests at very high temperatures, 1400 °C (2550 °F) for chromium-coated zirconium alloy and 1700 °C (3090 °F) for silicon-carbide clad tubes. During the test shown in Fig. 1, the silicon-carbide clad tube was exposed to approximately 1600 °C (about 2900 °F) for 40 minutes in steam. There was essentially no change or damage to the silicon-carbide cladding material, as indicated in the pre- and post-test photos of the silicon-carbide cladding surfaces shown in Fig. 2. Going forward, these tests will continue in the upgraded facility and will also be used to establish the oxidation kinetic models in the Modular Accident Analysis Program (MAAP) severe accident analysis code, which is widely used as an industry standard, to assess the benefits plants can expect to realize with EnCore Fuel.

High-density fuel pellets

The high-density uranium silicide fuel pellets are being manufactured by Idaho National Laboratory (INL) for the lead test rods for Byron-2. Uranium silicide pellets have a higher uranium density, allowing 17 percent more uranium to be packed into the same volume as today's uranium dioxide pellets. This allows longer fuel cycles to be achieved while remaining below the current 5 percent uranium enrichment limit that is the design basis for most operating plants. This means that the initial and second phase EnCore Fuel products can present fuel cycle improvements that alone can save a utility millions of dollars annually, depending on current market prices for uranium material and enrichment.

Uranium silicide pellets also have higher thermal conductivity—four times more than uranium dioxide pellets—and therefore store less energy, providing a safety improvement due to the much higher linear heat rate that would have to be reached before the pellets would melt. Westinghouse is partnering with INL and the United Kingdom's National Nuclear

Laboratory to develop the manufacturing processes for uranium silicide pellets.

MAAP simulations

Recognizing the need to demonstrate tangible benefits to utilities considering using EnCore Fuel, Westinghouse has been performing calculations using the MAAP severe-accident analysis code to simulate the progress of the Three Mile Island-2 event, as well as other potential station blackout scenarios, replacing the zirconium alloy cladding with silicon-carbide cladding. Figure 3 demonstrates that silicon carbide clearly would have survived the TMI-2 event, which occurred when a pilot-operated relief valve was stuck open and allowed cooling water to escape the core, ultimately resulting in the melting of some of the fuel and the creation of a hydrogen bubble. The MAAP simulation showed that with silicon-carbide cladding, the fuel would not have melted, and almost no hydrogen would have been produced due to the cladding's resistance to high temperatures and insignificant reaction with steam. The silicon-carbide cladding provides EnCore Fuel with the highest tolerance to severe accidents of all of the materials currently under consideration for use in an accident-tolerant fuel design.

Westinghouse also applied the MAAP severe accident analysis code to simulate how silicon-carbide clad EnCore Fuel would perform during a complete station blackout event with minimal cooling. As can be seen in Fig. 4, with water injected at a low-capacity rate of 215 gallons per minute at 800 pound-force per square inch three hours into the transient from a FLEX (diverse and flexible coping) pump, the silicon-carbide cladding stays well under its melting temperature, whereas the zirconium alloy cladding would melt. This also illustrates that with silicon carbide as an accident-tolerant fuel cladding, many of the safety systems currently required to inject water for core cooling would no longer be needed to ensure adequate cooling of the fuel.

Next steps

Westinghouse is working with the NRC to obtain licensing guidance and has completed an initial review of the criteria in Section 4.2, "Full System Design," of the regulator's *Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition—Reactor* (NUREG-0800, Chapter 4). The company will work toward the goal of commercialization by implementing licensing for EnCore Fuel in three stages: (1) lead test rods, (2) lead test assemblies, and (3) full regions. Utilities will need to provide additional data and justification to take credit in their probabilistic risk analyses for EnCore Fuel to realize the full benefits of the reduced operation and maintenance costs.

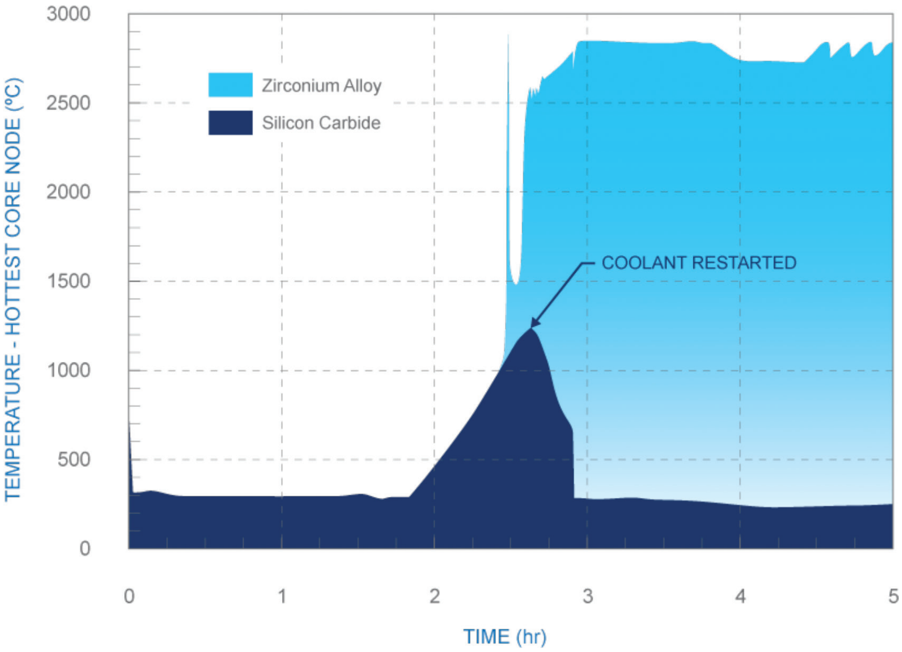

Fig. 3. Three Mile Island-2 progress simulation: Silicon-carbide cladding tolerance to heat and steam as compared to that of TMI-2's zirconium alloy cladding.

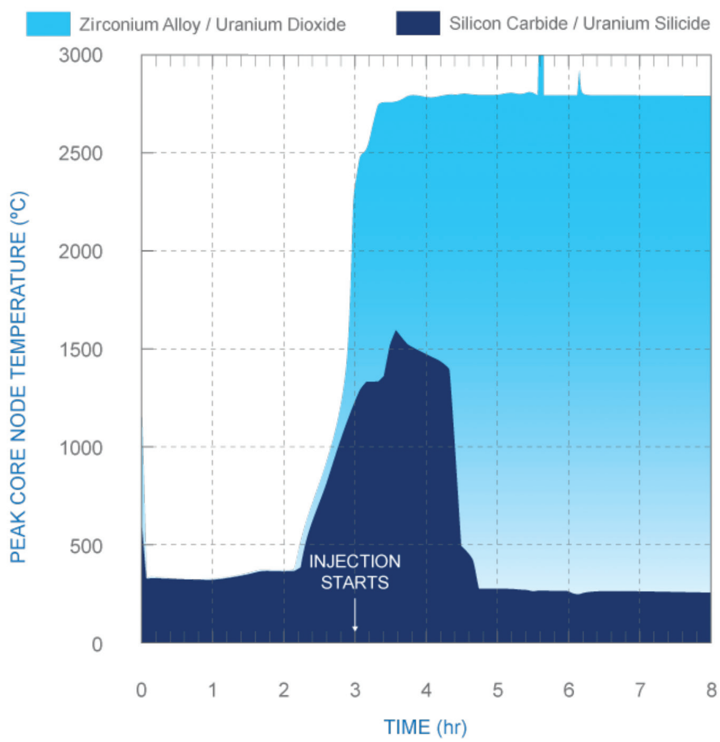

Fig. 4. MAAP modeling of a complete station blackout event with minimal cooling shows that silicon-carbide fuel will survive.

In support of licensing lead test assemblies for insertion in commercial reactors, test fuel rods manufactured this year will undergo exposure in the Advanced Test Reactor and the Transient Reactor Test Facility at INL and in the Halden Reactor, operated by the Institute for Energy Technology in Norway. The test protocols will include pressurized water reactor operating conditions and transient tests.

Westinghouse is on schedule for the insertion of the first phase of EnCore Fuel as lead test rods (with chromium-coated cladding) into Exelon's Byron-2 commercial reactor by 2019 and has further plans to insert the second phase fuel as lead test assemblies (with silicon-carbide cladding) in the 2021–2022 time frame. The stated goals of the DOE program, which are consistent with industry goals, will soon be delivered to the benefit of utilities and society as a whole. NN

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WE'RE CHANGING NUCLEAR ENERGY ... AGAIN

Westinghouse EnCore™ Fuel is a game-changing accident-tolerant fuel solution that is intended to provide design-basis altering safety and estimated economic benefits of up to hundreds of millions of dollars, as well as greater uranium efficiency.

As the leading supplier of nuclear fuel globally, Westinghouse has access to a world-class network of research, design and manufacturing partners. We are collaborating to deliver EnCore Fuel on an aggressive, accelerated schedule.

Learn more about how Westinghouse EnCore Fuel is changing nuclear energy at http://bit.ly/WestinghouseEnCoreFuel

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