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News & Highlights

Nuclear Energy Seeks Revival with Advanced Fuel Options

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In November 2020, BWX Technologies, based in Lynchburg, VA, USA, announced it had once again begun manufacturing a nuclear fuel known as tristructural isoptropic (TRISO) particles [1]. The company, which is designing a mobile reactor that will run on the fuel [2], is not the only nuclear firm that is betting on the future of TRISO. At least three other US companies have incorporated it into their advanced reactor designs [3,4].

This surge of interest in a type of fuel that no commercial nuclear power plant in the world currently uses might seem surprising. But TRISO, which was first loaded into a reactor about 60 years ago, is making a comeback. This is, in part, because of the growing demand for so-called accident-tolerant fuels that may increase plant safety and potentially help prevent disasters like the meltdown that crippled the Fukushima Daiichi nuclear power plant in Japan in 2011 [5,6]. If all goes to plan, the first TRISO-fueled commercial nuclear plant in the United States in more than 30 years, built by X-energy of Rockville, MD, USA, will begin producing power in 2027 [7]. Several other countries are planning or constructing similar facilities. For example, China's 210 MW_e demonstration plant in Shandong Province, featuring two TRISO-fueled, high-temperature gas-cooled reactors (HTGRs), is expected to begin operating in late 2021 [4].

Switching to TRISO is just one of the strategies for improving reactor fuel safety that are under development or undergoing tests around the world [8], with some experts contending that accident-tolerant fuels could even help usher in a nuclear renaissance. The argument is that these fuels could make nuclear plants not just safer, but also smaller, simpler, and cheaper—and thus more attractive options for producing low-carbon emission power [9]. Still, new plants that rely on TRISO or other accident-tolerant fuels face significant hurdles. The companies building them are deploying unproven technology and will have to complete licensing on very tight schedules [10]. And whether such plants will be economical remains unclear [10].

TRISO is safer than traditional nuclear fuel because it captures many of the dangerous fission products released by uranium decay, such as isotopes of Kr, Cs, Xe, and I [11]. Each TRISO particle typically measures about 1 mm in diameter and consists of a core of uranium dioxide or uranium oxycarbide cloaked by three kinds of protective layers—hence the "tristructural" in its name [4]. The inner layer, a carbon buffer, is surrounded by two layers of pyrocarbon and a layer of silicon carbide (Fig. 1) [4]. To produce usable fuel, thousands of TRISO particles are further embedded in graphite and formed into small cylinders or into spheres, known as pebbles, that can fit in the palm of a hand (Fig. 1) [4].

The multilayer construction of TRISO particles makes them extremely rugged [12]. In one study, researchers found that they retained most fission products after baking at temperatures of up to 1800 °C for almost 100 h [13]. This temperature is well above the 1600 °C researchers predict a HTGR's core could reach in an accident [14]. Another advantage is that TRISO releases a higher percentage of its energy, a measure known as burnup, than the fuels used in the light-water reactors that account for about 80% of today's nuclear plants [12]. TRISO fuel is not indestructible, however. The particles can crack and corrode, and their internal structure can deteriorate [11]. But the fuel "allows you to be at higher temperatures for longer," said Nicholas Brown, an associate professor of nuclear engineering at the University of Tennessee, Knoxville, TN, USA. "That is critical in accidents," he said, because it can give plant operators enough time to take steps to cool the reactor. Despite the particles' durability, spent TRISO fuel will have to be stored in the same facilities as waste from conventional light-water reactors.

The first nuclear reactor stoked with TRISO was Dragon, an experimental HTGR unit in the United Kingdom that operated from 1964 to 1975 [4]. Since the 1960s, engineers have incorporated TRISO into an additional handful of HTGRs that provided commercial power but have since been shut down. In the United States, the helium-cooled Fort St. Vrain reactor in Colorado ran on the fuel from 1979 to 1989 [15]. But because TRISO was not compatible with the light-water reactors that were becoming more common, it fell out of favor [4]. Research on TRISO fuel continued even after the commercial plants shut down, Brown said, with today's particles featuring several refinements. "In the lab and in test reactors, we have been advancing this technology," said Brown. For instance, one of the US companies developing TRISO-fueled reactors, Seattle, WA-based Ultrasafe Nuclear Corporation, embeds the particles in pellets made of silicon carbide instead of graphite, a change claimed by the company to make the fuel even more resistant to high temperatures and radiation [16].

Another reason that interest in TRISO fuel is rising is that many countries, including the United States, aim to build advanced reactors that could be smaller, more efficient, and more versatile than light-water plants [17,18]. The Fukushima accident in 2011 provided a further boost for TRISO and other accident-tolerant fuels.

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(a)

(b)

Fig. 1. (a) The large sphere (back (a)) is a pebble studded with thousands of particles of TRISO. The cut-away image (front (a)) shows the multilayer structure of an individual particle, with protective layers of pyrolytic carbon, silicon carbide, and carbon buffer covering a nugget of uranium oxide or uranium oxycarbide. (b) The image indicates the size of a single pebble. Credit: X-energy (public domain).

In the United States, the Department of Energy (DOE) has launched a risk reduction program to spur development of safer reactors and last year awarded 30 million USD to five demonstration projects, two of which rely on TRISO [2,18].

China is closest to opening a new TRISO-fueled nuclear plant. The country first used TRISO in the 10 MW high-temperature gas-cooled test reactor (HTR-10) at Tsinghua University in Beijing, which generated electricity between 2003 and 2007 [17,19]. Slated to go online in late 2021, HTR-10's larger successor, the Shidaowan demonstration plant in China's Shandong Province, received the first of its TRISO pebble fuel early in 2021 [4,20].

The United States could have at least two working TRISO-based reactors before the end of the decade. The Alameda, CA-based company Kairos Power is building a demonstration reactor called Hermes in Oak Ridge, TN, USA [21]. Instead of using water as coolant, it will circulate a molten salt of lithium fluoride and beryllium fluoride known as FLiBe [22]. The design highlights some of the potential benefits of TRISO. Construction may be cheaper and faster, for instance, because Hermes will not require a containment building, the massive cap that covers most nuclear reactors to protect against radiation leaks. "Our containment is the fuel particle combined with the molten FLiBe salt," said Micah Hackett, Kairos Power's director of fuels and materials.

Hermes, which was one of the risk reduction projects to receive US DOE grants in 2020, will be one-tenth the size of the reactor the company ultimately hopes to commercialize, said Hackett. "We want to demonstrate that we have solutions to some of the most challenging problems in advanced reactor development," which include completing construction, finishing licensing, and beginning operation on schedule, he said. The company plans to have the reactor online in 2026.

X-energy in October 2020 received an 80 million USD starter grant from the US DOE to put a TRISO-fueled commercial reactor into operation by 2027 [7]. The company's Xe-100 design is a small modular reactor that is cooled by helium gas and can generate 80 MW_e [23,24]. X-energy will install four of these reactors in Washington state, with the DOE paying about half of the estimated 2.5 billion USD cost [7,25]. The Middle Eastern country Jordan has agreed to buy four of the reactors, and Canada may also adopt the technology [26]. Ultrasafe Nuclear Corporation has also proposed building a TRISO-fueled demonstration reactor in Canada [27].

TRISO's increased safety comes at a price: The fuel requires increased enrichment. Hackett said that Kairos uses fuel enriched to a much higher percentage of U-235 than the fuel rods in a light-water reactor. Still, "we can get far more energy out of our fuel," he said. "Even though the cost of manufacturing is higher, the overall cost is lower."

Increased fuel costs are not the only potential obstacles for new TRISO-based plants. For one thing, the companies building them are racing against time. Hackett acknowledges that Kairos' goal of opening a demonstration plant by 2026 is "aggressive." X-energy's plan is even more ambitious, and experts have raised doubts about whether any of the advanced reactors DOE is supporting will be ready on schedule [10]. Furthermore, even with lower construction costs, new plants may not be able to compete with cheap energy sources such as natural gas [10]. The increased interest in TRISO could even become an impediment, Brown said, with "too many companies competing over too few resources."

Given the uncertainties about TRISO-fueled plants, researchers are exploring other ways to improve nuclear safety. Some investigations are focusing on whether altering fuel composition could prevent meltdowns [8]. Another target is the cladding that encloses the fuel rods. Made of zirconium alloy, it does not corrode at normal reactor temperatures of around 300 °C [8]. If the temperature surges, however, it begins to react with steam, becoming brittle and potentially releasing hydrogen gas. During the Fukushima disaster, hydrogen gas produced by deteriorating cladding exploded [8].

Fukushima sparked research into new strategies to protect cladding, including by coating it with various materials. "Chromium is the coating of choice," said Brent Heuser, professor of nuclear, plasma, and radiological engineering at the University of Illinois, Urbana-Champaign, IL, USA. He and his team found that a 1 μm layer of chromium delayed cladding oxidation by up to 20 h at 700 °C, and French researchers have found that thicker layers can resist oxidation at 1200 °C [28]. This approach is advantageous, Heuser said, because fuel rods with novel coatings can go into existing reactors. Chromium-coated cladding is already being tested in several reactors, as are claddings with other types of protection [8]. Another option researchers are investigating is cladding made from different oxidation-resistant materials, such as an alloy of iron, chromium, and aluminum. However, these materials would require more extensive testing than coated conventional cladding, Heuser said. Upgraded cladding would not stop an accident by itself, he said, but it would provide "coping time" of one hour or longer.

With companies and governments investing large amounts of money in strategies for increasing reactor safety, including TRISO fuel, and several projects soon to come online, the next few years should offer a clearer sense of how this focus will impact the future of nuclear power.

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