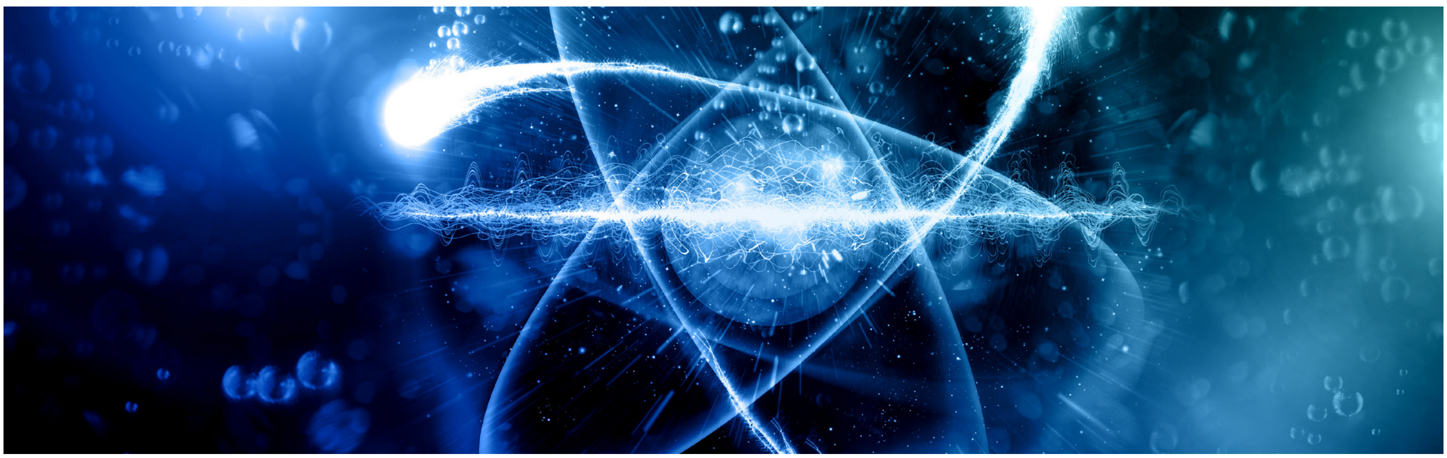
BURNS McDONNELL

WHITE PAPER

Three Innovative Reactor and Fuel Design Pathways Can Restart Nuclear Power

By Bob Arteaga, Patrick Guevel, Jim Jurczak and Glenn Neises

Advanced reactor technologies offer the potential to transform the nuclear power industry, providing safe, carbon-free electricity that addresses the plethora of challenges arising from decarbonization of power grids worldwide. Three quickly advancing options deserve careful consideration.



For decades, nuclear physicists and engineers have been working on alternative nuclear energy systems that reduce or eliminate the risk of reactor meltdowns as well as the challenge of long-term disposal of nuclear waste. Several advanced reactor technology systems have potential to address these challenges. These three are among the most promising:

- **Pebble bed reactors** that utilize tri-structural isotropic (TRISO) coated fuel in gas-cooled reactors.
- **Small modular reactors** that utilize a fraction of the uranium needed in conventional plants.
- **Liquid fluoride thorium reactors** that introduce a whole new fuel and reactor design.

Nuclear Physics 101

To understand the basics of nuclear energy, it is helpful to review the physics of uranium — the fuel that energizes the light water reactors (LWRs) that conventional nuclear plants rely on.

Uranium has two main naturally occurring isotopes — uranium-235 (with 143 neutrons) and uranium-238 (with 146 neutrons). Uranium-235 is highly fissile, meaning a very large amount of energy is released when a neutron splits an atom. This causes a chain reaction as other neutrons are released and begin spinning and striking other atoms.

Meanwhile, uranium-238, the most common of the two naturally occurring isotopes, is fertile in its natural state, meaning that its atoms absorb the neutron instead of breaking apart in a fissile reaction. Most uranium ore is uranium-238, so it must be refined to add fissile properties up to a level at which it can be used as fuel in LWRs.

This is an energy-intensive process, and once the ore is enriched to a substance called "yellowcake," it still contains plenty of uranium-238. This is another problem, because as a fertile element, uranium-238 absorbs any neutron that hits it and becomes plutonium-239. This nasty waste product of the uranium/plutonium cycle is the precursor for weapons-grade material and is why the U.S. and many other countries are concerned about geopolitical adversaries building new nuclear reactors. Even when these reactors are built primarily to supply energy, the waste products can take the form of plutonium. It's a short leap to enrich this material further for use in nuclear weapons.

Coolant Is Critical for Today's Reactors

Conventional nuclear reactors are typically configured with an array of solid uranium fuel pellets encased within zirconium-clad fuel rods and surrounded by large amounts of water in a vessel that maintains extremely high pressure. The fuel rods heat the surrounding water, turning it into high-pressure steam. These steam jets are released to drive the turbines that make electricity.

Pressurized water is vital to safe operations of the entire plant. Water acts as the moderator, which is what slows down the neutrons and acts as a coolant. Thus, water is vital in stopping the uranium chain reaction from overheating to a point at which the reactor core could melt down and/or cause a devastating hydrogen explosion, rupturing the reactor or containment vessel and releasing radioactive contamination into the atmosphere.

Once neutron bombardment begins, the uranium-235 chain reaction cannot be stopped for a very long time. Control rods, called "poisons," are used as another method to control the chain reactions. Once this begins, all that can be done is to actively and relentlessly manage the water-cooling process to keep temperatures within safe ranges, as well as maintaining functionality of the control rods. Big problems result if there are any disruptions to these functions. In each of the highly publicized nuclear incidents — Three Mile Island, Chernobyl and Fukushima — it was the loss of coolant systems (i.e., water) that led to catastrophic events.

Pebble Bed Reactors

A nuclear design pathway utilizing TRISO-coated fuel as the energy source within high-temperature gas-cooled reactors (HTGRs). Commonly called pebble bed reactors because of the size and shape of the fuel pellets utilized in the process, the design is showing great promise among the options being researched. The TRISO fuel can withstand temperatures four times greater than temperatures in conventional LWRs, and the overall system is virtually impervious to meltdowns.

A pebble bed nuclear power plant currently being designed by X-energy for Energy Northwest in Washington state could become the first to utilize TRISO fuel in an HTGR design in the U.S. With a total net rated capacity of 320 megawatts electrical (MWe), four X-energy Xe-100 Generation IV reactors could receive regulatory approval and be brought online by 2028.

X-energy has received funding from the U.S. Department of Energy (DOE) under the Advanced Reactor Demonstration

Figure 1: *The Xe-100 reactor features completely encapsulated fuel in a design that offers a new way forward for safe and secure nuclear power.*

Program that was authorized in the Energy Act of 2020. A total of $3.2 billion was authorized for two nuclear demonstration projects with funding available over the fiscal year 2022-27 budget cycles. The program is intended to speed demonstration of the most viable advanced reactor designs through cost-shared partnerships. In addition, $6 billion in funding has been authorized by the Infrastructure Investment & Jobs Act, targeting microreactors, small modular reactors and various types of advanced nuclear reactors.

TRISO Is a Leap Forward

The TRISO fuel design uses fissile uranium-235, the same material used in conventional LWRs in service today. However, instead of fuel rods, uranium in this design is placed inside a fuel kernel composed of three layers of refractory carbon and silicon carbide material. This uranium oxycarbide (UCO) kernel measures about 0.855 millimeter in diameter, about the size of a poppy seed. Then, about 18,000 of these tiny TRISO particles are embedded inside a graphite sphere, measuring about 6.35 centimeters in diameter. Each of the small individual fuel particles act as microscale containments that cannot melt down. Additionally, the uranium particles encased in the tennis ball-sized fuel pebbles are impervious to extraction and conversion for other uses such as enrichment to weapons-grade plutonium.

The Xe-100 continuously recycles about 200,000 of these fuel pebbles through a gravity feed reactor core. As fuel pebbles reach the bottom of the reactor vessel, they are extracted mechanically and checked. Those with remaining

***Figure 2:** TRISO-coated fuel is a new design featuring thousands of tiny uranium kernels encased in graphite spheres.*

life are recirculated back to the top of the cylindrical reactor vessel, while those that are spent are removed and routed for storage in a dry cask containment system.

This continuous recycling process means there is no need for refueling outages like those needed every 18 months at conventional nuclear plants. Thus, over the estimated 60-year design life of the Xe-100 reactor, these plants would be highly available power sources for the grid with estimated capacity factors of approximately 95%.

Safe Energy Alternative

Unlike conventional reactors, the Xe-100 design uses no water for cooling. Instead, it uses pressurized helium that circulates inside the reactor core as the coolant to keep temperatures within a stable range and provide the heat transfer mechanism. As an inert gas, helium is an incredible conductor without becoming radioactive.

This avoids the potential safety issues faced by LWRs when the active coolant and moderator (water) is lost, and fuel rods begin to overheat and melt down. When a pebble bed reactor is shut down, there isn't any heat left to circulate through the core because the fuel itself has limited the nuclear chain reactions inside of the reactor. Combining this fuel with an appropriate reactor design reduces the need for large concrete structures, because it is inherently safe. Advanced reactors are walk-away safe, meaning that they don't need any additional fail-safe mechanisms for removing residual heat from the core.

Process Heat Is Ancillary Benefit of Pebble Bed

The heated helium circulates through an adjacent vessel containing water, superheating it into steam at about 1,000 degrees Fahrenheit. This steam then turns a turbine to produce carbon-free electricity.

An Xe-100 plant could also be used as a source of process heat for a wide range of industrial applications such as district energy configurations for military bases, refineries, manufacturing, hospital and university campuses, desalination, and hydrogen production (referred to as pink hydrogen).

Baseload and Load Following Capacity

The Xe-100 is designed to ramp up or down at approximately 5% per minute in response to load conditions. The optimal range is between 100% and 40% of net capacity, but the reactor is able to operate at stable power levels down to 25% of capacity.

Conventional nuclear power stations struggle with ramping up or down because load changes require reactivity changes in the reactor, which are a challenge to manage. Thus, nearly all are considered baseload units because they operate most efficiently when running at full output capacity.

Because of its reactor design, the Xe-100 can function as a flexible power generating station, either in baseload or peaking operation, much like advanced class gas-fueled facilities that are being installed to counter the effects of intermittent renewable generation on the grid.

Small Modular Reactors

Among the new nuclear reactors currently in development and demonstration phases, the small modular reactor (SMR) technology is well along in the race to eventually displace today's conventional large-scale nuclear power plants and take the place of other baseload power plants.

An SMR being developed by NuScale Power and Utah Associated Municipal Power Systems (UAMPS) at an Idaho National Laboratory site has obtained approval of its Design Certification Application from the Nuclear Regulatory Commission (NRC). This puts the project on a fast track for completion, ahead of competitors in the U.S. or Canada.

A number of European countries also have announced plans to deploy NuScale SMRs along with other similar designs as part of their decarbonization goals.

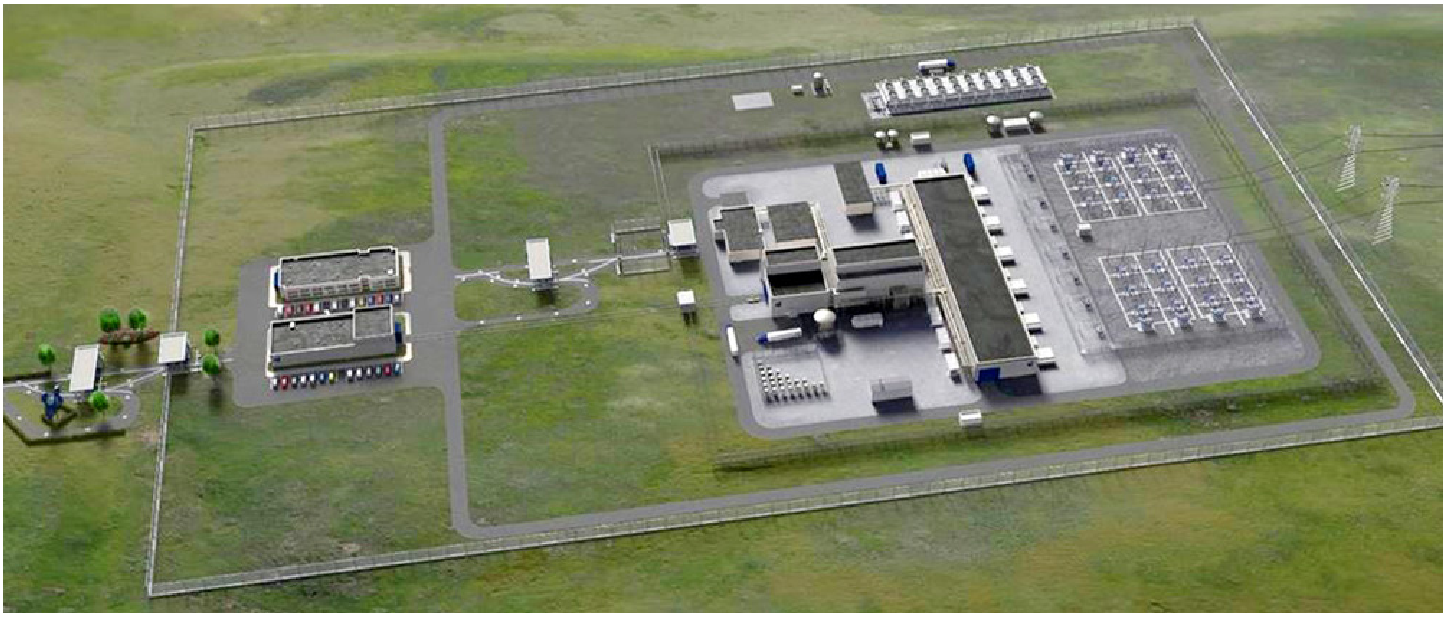


Figure 3: *The NuScale plant for the Utah Associated Municipal Power Systems is depicted here in a 3D rendering.*

Addressing Risks Via Lower Energy Density

NuScale is developing modules with power outputs ranging between 50 MW and 77 MW that can be grouped together in a number of flexible configurations.

Each NuScale Nuclear Power Module (NPM) contains only about 10% of the fuel needed by conventional nuclear reactors. Though the design still incorporates uranium-235 fuel rods, they are a fraction of the size of those deployed in conventional nuclear plants. This much lower energy density dramatically improves the safety profile because the reactor does not require an elaborate system of pumps with dedicated primary and backup power generators like those in LWRs.

The SMR design features a passive water-based cooling system that nearly eliminates the possibility of fuel damage and meltdown scenarios. The containment vessel is submerged in the reactor pool at the bottom of the unit. Heat generated by the nuclear material in the reactor core turns the surrounding water into steam, which then moves upward through a chimney. On the downward phase of the loop the steam is directed into helical coil steam power generators, an innovation that maximizes the natural circulation flow in the primary loop. As the steam cools, the water vapor condenses, moving downward through the vessel to the bottom, where it continues to recirculate without the assistance of pumps or other mechanical systems requiring auxiliary power.

Costs On Par With Natural Gas (Eventually)

Though capital costs for SMR plants are initially expected to be in the $3 billion to $5 billion range, they are expected to decline rapidly as plants enter commercial operation, with costs per megawatt-hour expected to reach parity with those of natural gas-fueled power facilities. These declines will be driven by efficiencies achieved by off-site fabrication and economies of scale as more SMR plants get built.

Because of the smaller scale of SMR plants, much less balance of plant equipment will be required. Most components can be designed and manufactured in controlled shop environments, then transported to the site by truck, rail or barge for easy installation. Construction that features more modular, skid-mounted units is vastly more efficient because it reduces the time and costs incurred for stick-built construction methods required at conventional LWR plants.

Minimal fuel costs and longer design lives also help SMRs compete with fossil-fueled plants. With expected design life cycles of 60 years or more for all types of advanced reactors, costs could swing even more favorably toward these nuclear technologies if carbon taxes are enacted for fossil plants.

Load Following Capability

Like other advanced nuclear technologies, SMRs will have the advantage of being able to ramp up or down quickly as load-following units capable of offsetting intermittent power production from renewable sources. This is another advantage over conventional nuclear power facilities, which run for the most part as baseload units for maximum efficiency.

Though SMR plants will require scheduled outages for refueling, similar to large plants, they will not be susceptible to weather-related fuel supply interruptions such as what fossil and renewable power plants experience. Though many of the

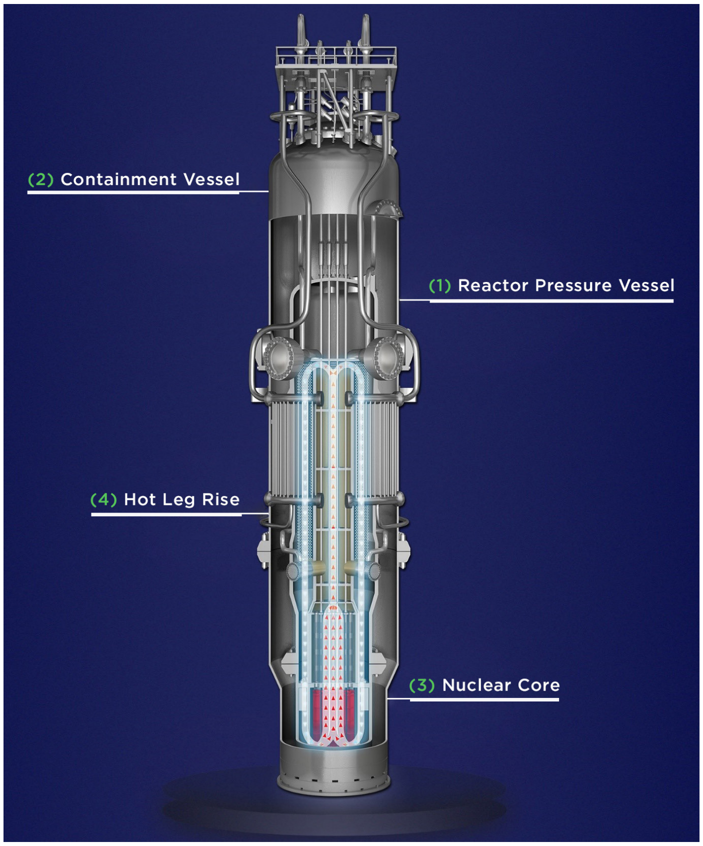


***Figure 4:** The NuScale Power Module features a 65-foot tall reactor that is 9 feet in diameter. It sits inside a 76-foot tall containment vessel measuring 15 feet in diameter. Both the reactor and containment vessel operate inside a water-filled pool built below grade. Photo credit: NuScale.*

new high-efficiency gas-fueled power facilities have excellent load-following capacity, they still are susceptible to fuel supply interruptions during periods of extreme winter weather, such as the event that shut down the Texas power grid early in 2021. SMR refueling can be scheduled during off-peak seasons to avoid creating similar issues on the grid.

In addition, because of their lower power output, SMRs can be sited in locations not served by high-voltage transmission infrastructure. This combination of siting flexibility and rapid ramping capability will help provide additional grid stability.

Liquid Fluoride Thorium Reactors

Another promising solution — researched for many years at the Oak Ridge National Laboratory in Tennessee and in similar research facilities in Germany — is a liquid fluoride thorium reactor (LFTR). Instead of using solid uranium fuel rods and water as the moderator, the LFTR uses thorium as the fuel and molten salt for both cooling and the heat transfer needed for power production. Though it is still a nuclear reactor, it is far safer and potentially less costly to construct.

How the LFTR Process Works

Using thorium as a fuel does not cause any of the issues that LWRs must deal with. On the periodic table of elements, thorium can be found on the heavy section near uranium, with 90 protons and 142 neutrons.

Almost all naturally occurring thorium is thorium-232, the exact isotope that can be used in nuclear reactors. According to current estimates, the Earth's crust contains three times more thorium than uranium. The most common source of thorium is the rare earth mineral monazite. Large known deposits of monazite sand are located in India, Brazil and Australia, and there are more than 200 thorium-rich veins in the U.S.

Thorium is fertile, not fissile, which means in a molten salt reactor it must be kick-started by absorbing a neutron from a fissile agent like uranium-235. As it is bombarded by neutrons, thorium goes through a series of reactions that transform it into a fissile material — specifically, an isotope of uranium called uranium-233. Though it is a close cousin of uranium-235, this member of the isotope family behaves very differently. Uranium-233 splits nicely and releases more neutrons than uranium-235, thus making the chain reaction even more efficient. It also doesn't produce plutonium-239.

The thorium/uranium reaction proceeds to heat the salt surrounding it, turning it into a molten state. This molten material generates convective heat that circulates through a heat exchanger in which either gas, such as carbon dioxide, or steam drives a turbine for electric power generation.

Almost all the fuel in a thorium reactor is used to generate energy, compared with uranium, which only has about 3%-5% of the material needed in a reactor. As a result, up to 250 times greater overall energy output can potentially be derived from the thorium/uranium cycle compared to the uranium/plutonium cycle.

Safety Is a Primary Benefit

Thorium reactors are inherently safe because the fuel is not fissile no matter how many nuclei are packed together. This means the chain reaction can be stopped simply by stopping the neutron bombardment and shutting down the process.

Theoretically, it is nearly impossible to have a meltdown event. Because the fuel is mixed with molten salt and in a liquid state, excessive heat causes it to expand, spreading the fissile material farther apart and slowing down the fission process. Since there isn't any pressurized water, there also is no risk of a hydrogen explosion caused by a high-temperature zirconium-water reaction. These features allow the system to be shut down automatically without human intervention.

Because the fuel in the coolant is a liquid mixture, the reactor also can be refueled while the plant is online, avoiding a costly and potentially hazardous shutdown to replace spent solid uranium fuel.

Waste from the LFTR is still highly radioactive, but there is far less of it, and it only stays radioactive for approximately 300 years, versus many hundreds of thousands of years for waste generated from the uranium/plutonium cycle.

Concluding Observations

Today we are entering a new era in which many research centers worldwide are working on advanced nuclear designs that will undoubtedly help the world address decarbonization goals.

The Xe-100 pebble bed and NuScale VOYGR reactors will soon demonstrate their effectiveness in safely decarbonizing the grid. Other solutions like liquid fluoride thorium reactors have long been researched and are ready to take the next step toward development.

There should be no hesitation in moving forward with safe new nuclear designs and fuel usage that can result in cost-effective solutions to reducing carbon dioxide emissions on a global scale.

About Burns & McDonnell

Burns & McDonnell is a family of companies bringing together an unmatched team of engineers, construction professionals, architects, planners, technologists and scientists to design and build our critical infrastructure. With an integrated construction and design mindset, we offer full-service capabilities. Founded in 1898 and working from dozens of offices globally, Burns & McDonnell is 100% employee-owned. For more information, visit **burnsmcd.com**.

26689-0222