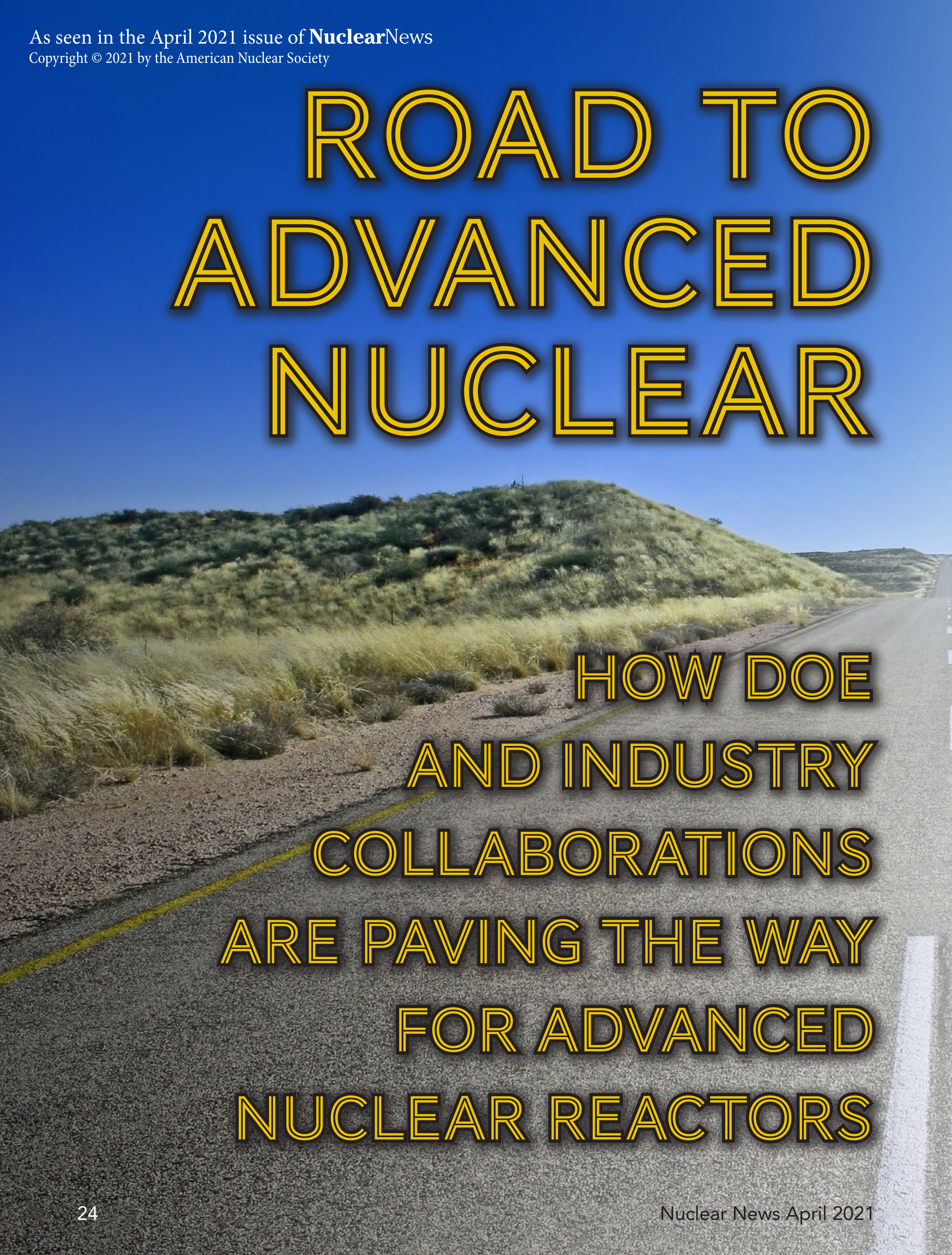

ROAD TO ADVANCED NUCLEAR

HOW DOE AND INDUSTRY COLLABORATIONS ARE PAVING THE WAY FOR ADVANCED NUCLEAR REACTORS

By Cory Hatch

As electric utilities rush to reduce carbon emissions by investing in intermittent renewables such as wind and solar, they often rely heavily on fossil fuels to provide steady baseload power.

More than 60 percent of the nation's electricity is still generated with fossil fuels, especially coal-fired and gas-fired power plants that have the ability to quickly ramp up or ramp down power to follow loads on the electric grid. Most experts agree that even with a radical advancement in energy storage technology, relying exclusively on wind and solar to replace fossil fuels won't be enough to maintain a stable electric grid and avoid the major impacts of climate change.

To complete the transition to a carbon-free energy future, one key piece of the puzzle remains: nuclear power.

Conventional light water reactors already account for roughly 55 percent of all carbon-free electricity produced in the United States. A crucial distinction between nuclear and other clean sources like wind and solar is that nuclear remains one of the few ways to generate reliable, carbon-free power 24 hours a day, 365 days a year.

But conventional LWRs have three major limitations. First and foremost is cost. U.S. utilities that have attempted new reactor construction in the past decade or so have faced major cost overruns and construction delays. Second, conventional LWRs operate most efficiently near peak capacity, which means they lose money when demand for electricity drops. And third, conventional LWRs operate at low temperatures that make them less efficient and less able to recover costs by producing process heat that can be sold for industrial applications.

To overcome these limitations, dozens of U.S. companies are developing advanced nuclear reactor technologies—microreactors, small modular reactors, molten salt reactors, liquid metal reactors, and high-temperature gas-cooled reactors, in particular.

Just as jet engines haven't completely replaced propeller planes, and electric vehicles haven't completely supplanted gasoline engines, advanced nuclear technologies won't necessarily replace large LWRs. Rather, advanced nuclear technologies have the capability to provide low-cost power that's inherently safe and flexible. These reactors will be able to fill a variety of new roles, such as load following—adjusting the power output to complement intermittent renewables. They could also produce process heat for industry and provide power for remote communities and military installations.

To make these reactors a reality, U.S. companies have spent years working hand in hand with the Department of Energy and its national laboratories to navigate funding, technical, regulatory, and siting challenges.

Now these efforts are finally bearing fruit. Advanced reactor companies—including NuScale Power, TerraPower, Oklo, and X-energy—anticipate having innovative demonstration and commercial reactors ready for deployment in the next several years.

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Building on blueprints of early advanced reactors

Like the jet engine and the electric car, most advanced reactor designs aren't new ideas but rather are inventions from another era that have been improved through new technology developments to find their niche in the modern marketplace.

Since its inception as the National Reactor Testing Station in 1949, researchers at Idaho National Laboratory have developed and tested numerous novel nuclear reactors, including the Experimental Breeder Reactor-I (EBR-I), the first reactor in the world to produce a usable amount of electricity.

EBR-I's successor, a sodium-cooled fast reactor known as EBR-II, was developed at Argonne-West (now INL's Materials and Fuels Complex). EBR-II is considered a precursor to several modern advanced reactor designs, including the Natrium reactor proposed by TerraPower and GE Hitachi Nuclear Energy.

Even an advanced reactor company like Oklo, which prides itself on using private funding to develop its technologies, credits a large part of its success to DOE programs past and present. Oklo is planning to use recycled uranium fuel from EBR-II to power the Aurora reactor, which is aiming for construction on the INL site in the early 2020s.

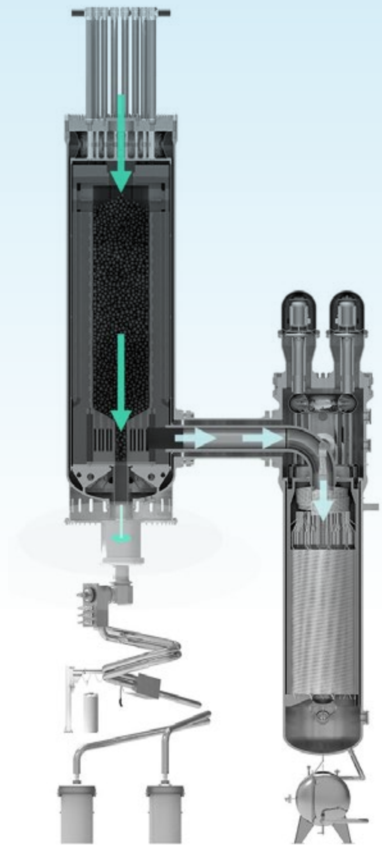
"The Aurora reactor is a technology that builds on the legacy of fast reactor development going back to the dawn of the atomic era," said Oklo cofounder and chief executive officer Jake DeWitte. "The technology—using metallic fuels—was pretty well matured."

Indeed, most advanced reactor designs are modern versions of technologies that were developed in the 1950s and 1960s. For example, X-energy's high-temperature gas-cooled reactor technology has origins at what is now Oak Ridge National Laboratory.

More recent versions of gas-cooled reactors in Germany and South Africa inspired X-energy's Xe-100 reactor design, and technicians from those projects have played a key role in designing an updated version of those reactors, said Darren Gale, X-energy's vice president of commercial operations.

ORNL was also home to the Molten Salt Reactor Experiment, another advanced reactor technology that has been resurrected for pilot and demonstration projects at INL, including TerraPower's molten chloride fast reactor technology.

"It's all out there, and so much of that is lost in this industry," DeWitte said. "You can reinvent things. You can design custom approaches, or you can draw on what's been done before. Usually, you can draw experience from earlier reactors and bring those ideas back and make them work."



X-energy's Xe-100 reactor is based on a high-temperature gas-cooled reactor design and offers flexibility in electricity/heat output. Image: X-energy

The difference between the early days of nuclear power and today's push for advanced nuclear reactors is that climate change and the resulting push for clean energy have prompted private companies and investors to fund advanced reactors, said Jess Gehin, INL's associate laboratory director for Nuclear Science and Technology.

"Government-led projects had this great history in the '50s, '60s, and '70s," Gehin said. "For the past 10 years, we've had a private sector that is driving innovation."

DOE funding support

Even with private companies leading the charge, the advanced nuclear renaissance has relied heavily on funding from the DOE and support from the national laboratories.

The most recent push for new reactor technologies began about 20 years ago when the DOE started funding research for small nuclear power plant technologies. Numerous companies have since benefited from various kinds of funding support, including cost-share programs through the DOE.

DOE funding was key in NuScale's obtaining private investors for its NuScale Power Module, a 77-MWe, factory-built pressurized water reactor, said Diane Hughes, NuScale's vice president of marketing and communications. Although LWR technology lies at the core of the NuScale design, it incorporates many features commonly found in advanced fast reactors, including its size, passive safety systems, ability to load follow, and ability to produce process heat.

"The timeline to commercialization and historical uncertainty with nuclear technologies were difficult for many investors," Hughes said. "Key to all of these investments was the prospect of a de-risked investment opportunity through cost share with the U.S. government via the Department of Energy. Financial support from the DOE has allowed NuScale to show governmental support while also providing a stable source of capital for completing commercialization of NuScale's technology."

In May 2020, the DOE announced the Advanced Reactor Demonstration Program, with three tiers of awards over the next decade-plus. Subsequently, the Advanced Reactor Demonstration tier awarded $80 million each in initial

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UAMPS balances customers, cost, and climate change with novel nuclear plant

For utilities, the modern electrical grid poses several challenges, including the eventual phaseout of fossil fuels to combat climate change and the intermittent nature of wind and solar energy.

Advanced nuclear reactors could help meet those challenges, says Doug Hunter, chief executive officer of Utah Associated Municipal Power Systems (UAMPS), the utility behind the Carbon Free Power Project (CFPP), an effort to build a nuclear plant powered by small modular reactors. The plant would be housed at INL near Idaho Falls, Idaho. UAMPS serves community-owned power systems in Utah, California, Idaho, Nevada, New Mexico, and Wyoming.

The current plan is to power the CFPP plant with NuScale Power Modules, small modular LWRs that each produce about 77 MWe. The first module is expected to go on line in 2029.

UAMPS's decision to invest in advanced nuclear reactors was driven by climate change and the potential for state and federal governments to mandate a phaseout of fossil fuels.

Currently, UAMPS's portfolio consists of about 40 percent coal and natural gas. As of 2019, fossil fuels still powered almost 63 percent of U.S. electricity generation, but several states have taken steps to reduce or eliminate fossil fuels from their energy portfolio. For example, Washington and Oregon have pledged to phase out coal by 2025 and 2030, respectively, and to increase their share of renewables.

For utilities, the question is, how do you replace fossil-fuel capacity with 24/7 baseload power that is cost competitive and responsive to intermittent renewables like wind and solar? Hunter said that for UAMPS, small modular reactors are the answer, providing a reliable energy source that is capable of efficient load following.

Since then, the big challenge has been making sure that the CFPP would be appealing to UAMPS customers and palatable to the public. Antinuclear groups have raised questions about the safety of small modular reactors, even though nuclear power is one of the safest forms of energy production and small modular reactors take safety one step further by incorporating passive safety features that rely on the laws of physics to shut down a reactor in an emergency.

The bigger concern among stakeholders, municipalities, and customers is cost. Critics have pointed to the financial troubles of conventional nuclear power projects, such as new-build projects in South Carolina and Georgia that have run over budget.

To counter these concerns, UAMPS has negotiated contractual agreements and secured financial backing—the DOE recently announced a $1.355 billion cost share for the project—to ensure that customers will have competitively priced electricity.—C.H.

funding to X-energy and TerraPower for reactor demonstrations to take place within the next seven years. The DOE expects to invest a total of $3.2 billion over the seven years for these awards, with industry partners providing matching funds.

In December 2020, the DOE announced $30 million each in initial funding for five Risk Reduction for Future Demonstration projects. Approximately $600 million is expected to be invested over seven years, with industry partners providing at least 20 percent in matching funds. This program supports the design and development of reactor technologies that can be deployed over the next 10 to 14 years.

The DOE also announced $20 million in initial funding for each of three projects under the Advanced Reactor Concepts-20 program, which supports reactor projects still in the early design phases. A total of $56 million is expected to be awarded over four years, with industry partners providing at least 20 percent in matching funds.

Research and development

These reactor projects also benefit from a wide range of research and development activities that provide advanced reactor developers with access to the capabilities and expertise of the national laboratories.

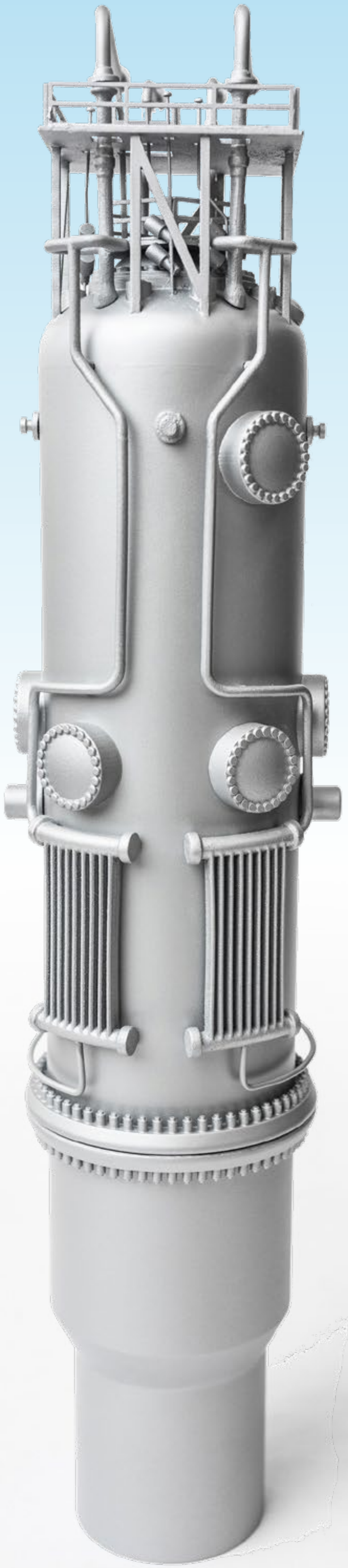
These capabilities include modeling and simulation made possible by INL's Multiphysics Object-Oriented Simulation Environment (MOOSE) platform; advanced fabrication techniques available at INL's Materials and Fuels Complex; irradiation testing at facilities such as the Advanced Test Reactor (ATR) and the Transient Reactor Test Facility at INL or the High Flux Isotope Reactor at ORNL; and analysis capabilities at INL's Hot Fuel Examination Facility.

For example, TerraPower and INL have collaborated extensively to develop higher-burnup metallic fuels. "We have fabricated metallic fuel of our special new design, put it into ATR, and performed post-irradiation examinations," said Nick Touran, TerraPower's deputy manvager of nuclear design. "That's a very specialized test capability."

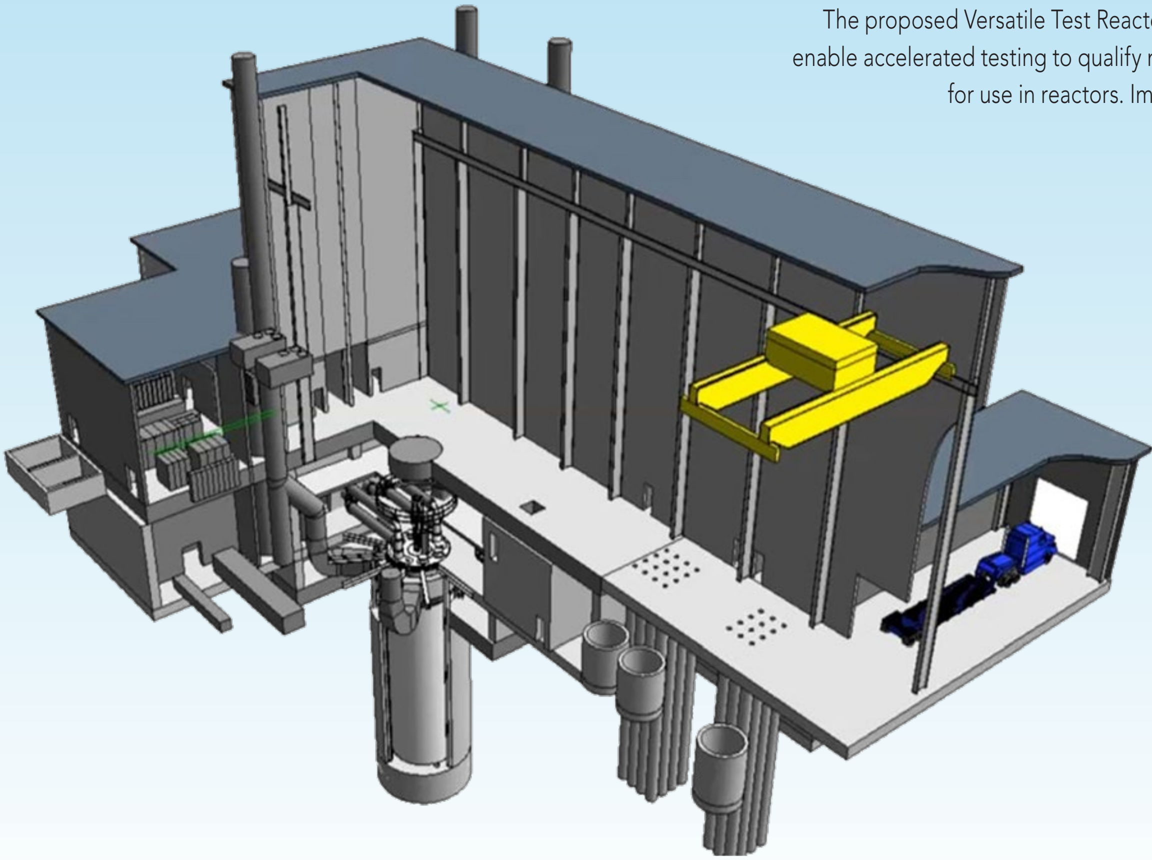
NuScale relied on DOE capabilities, particularly those available at INL, for its NuScale Power Module.

"INL, along with Oregon State University, was instrumental in the development of the original design concept under a DOE grant in the early 2000s," Hughes said. "Without these early efforts, the current NuScale design would not have come to fruition.

"Most recently, the ATR is a critical asset in development and testing of new containment materials for the NuScale design," Hughes continued.



Each NuScale Power Module operates independently within a multi-module configuration, with up to 12 modules operated from a single control room. Image: NuScale



The proposed Versatile Test Reactor would enable accelerated testing to qualify materials for use in reactors. Image: INL

"Without INL's support and technical capabilities, the NuScale design would not have progressed to its current state of development."

To make national laboratory resources available to developers as they progress toward testing and demonstrating reactors, the DOE established the National Reactor Innovation Center (NRIC) at INL. "We are enthusiastic about the designs that can be demonstrated in the next five to seven years and that will address the key requirements of affordability, resilience, environmental impact, and security," said Ashley Finan, director of the NRIC. "We are developing capabilities and facilities that will support advanced reactor demonstrators through their planning, regulatory, testing, engineering, and construction and operation efforts."

The NRIC is now developing reactor test beds and capabilities that collaborators can use for experiments and demonstration projects.

Through a collaboration with the DOE's Microreactor Program, the NRIC is also supporting the Microreactor Applications Research Validation and Evaluation (MARVEL) project. MARVEL is a 100-kWt fission reactor that will serve as a microreactor application test platform. With MARVEL, researchers and industry can perform R&D on various operational features and applications, such as off-grid electricity generation and process heat. MARVEL is expected to go on line in 2023.

In the future, the DOE's proposed Versatile Test Reactor (VTR) could provide one of the world's few large-scale fast neutron sources for endurance testing of fuels, sensors, and materials. Fast neutrons have a higher energy level than slow (thermal) neutrons and facilitate highly precise experiments. Fast neutron experimental capability is valuable for accelerated testing to qualify materials for use in reactors.

Without fast neutron testing capabilities, TerraPower sometimes must resort to using historical data to develop and license fuel for the first iteration of the Natrium reactor, Touran said.

"VTR can finish the transition to an advanced fuel form," he said. "The nice thing about VTR is that it will allow us to do types of tests that have really precise instrumentation. We'll be able to run higher resolution experiments."

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Licensing

As important as DOE capabilities are for developing new technologies, they're perhaps just as crucial for helping reactor developers navigate the regulatory process.

For example, INL and ORNL researchers have spent more than 15 years collaborating with industry to develop and test tristructural isotropic (TRISO) particle fuel—a kernel of uranium oxycarbide fuel roughly the size of a poppy seed covered by multiple layers of carbon- and ceramic-based materials. The end result is a fuel that cannot melt down and that prevents the release of radioactive fission products.

X-energy's Xe-100 reactor will use its own version of TRISO fuel fabricated into "pebbles" that each contain thousands of TRISO particles. "It is just about as robust as we can physically make a fuel right now," X-energy's Darren Gale said.

Even with TRISO fuel's long history and well-documented performance, the trick is getting X-energy's proprietary version of TRISO fuel to pass muster with the Nuclear Regulatory Commission, Gale said. "It's a combination of the fuel's mechanical performance, neutronic performance, and performance under radiation. Can it perform? That's where the labs come in."

But evaluating performance is just one piece of a larger regulatory challenge that each of these reactor companies is about to face: How do you shepherd an advanced reactor design through a regulatory process made to evaluate large LWRs?

With guidance from INL, industry and the NRC have been working on a solution. In 2016, industry began the Licensing Modernization Project, which sought to modify the U.S. nuclear power reactor regulatory framework to accommodate non-LWRs.

Then, in 2019, Congress passed the bipartisan Nuclear Energy Innovation and Modernization Act (NEIMA), which directed the NRC to establish a new budget and fee structure and licensing framework for advanced nuclear reactors.

And finally, in 2020, the NRC published new regulatory guidance for non-LWRs, making it easier for the NRC to evaluate advanced reactors, including designs that use passive safety systems that rely on the laws of physics instead of pumps and valves to shut down a reactor in an emergency.

All of these efforts have helped companies such as Oklo, which submitted a combined license application for its Aurora "powerhouse" in 2020. The application includes details on design, construction, environment, security, and operations. If approved, the application will result in an operating license for the power plant. "It was the first-ever combined license application for advanced fission," Oklo's Jake DeWitte said. "The NRC is transforming. They are learning as they go, and we are too."

DeWitte attributes Oklo's success to two factors. First, the company didn't accept any direct government funding, which allowed it to work quickly and with maximum flexibility. Second, Oklo developed an application based on the regulations, not on guidance meant for LWRs.

"It was a novel application structure," he said. "That application was significantly shorter than earlier applications, and we did it with an unprecedented level of capital efficiency."

TerraPower has engaged heavily in the Licensing Modernization Project as it seeks to license

Continued on page 33

Road to Advanced Nuclear Reactors

2029 & Beyond - Construction of Commercial Advanced Reactors

- CFPP begins operation
- TerraPower reactor begins operation
- X-energy reactor begins operation
- VTR expected to begin operation
- NuScale modular reactor ready for clients
- Oklo reactor built at Idaho National Laboratory
- CFPP reactor construction begins
- MARVEL expected to begin operation
- Site preparation begins for CFPP power plant
- Final decision to build VTR expected


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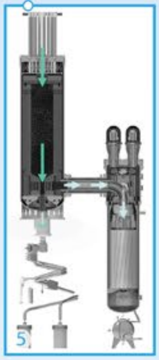
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4 - NuScale 5 - X-energy 6 - MARVEL 7 - Oklo

Future Developments

2020
- DOE awards X-energy reactor funding
- Oklo combined license application accepted
- TerraPower and X-energy receive ARDP funding
- NuScale receives NRC design approval

2019
- DOE grants Oklo a site use permit for INL
- Oklo awarded used fuel by DOE

2018
- VTR funding allocated by Congress
- Oklo submits pilot license application to NRC

2017
- NRC accepts NuScale's design application

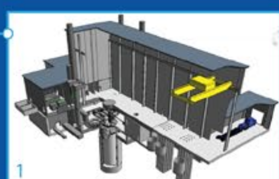
2016
- TerraPower & X-energy receive DOE reactor funding

2013
- DOE selects NuScale for funding

2009
- X-energy is launched

2008
- TerraPower is launched

2000
- DOE begins funding advanced nuclear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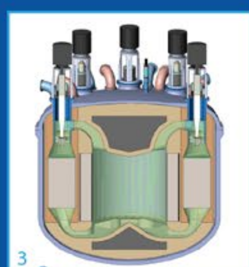
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1 - VTR
2 - NuScale
3 - TerraPower

Oklo's big dreams start with tiny Aurora

In 2020, Oklo became the first advanced reactor developer to have a combined license application (COLA) accepted for review by the NRC. The NRC's acceptance and review of Oklo's application is setting the stage for advanced reactor deployment across the world. As a venture-backed start-up, Oklo is helping to transform the economics of nuclear energy commercialization by applying innovative technologies, business models, and licensing strategies, all demonstrated by Oklo's development and submission of a license application with unprecedented capital efficiency.

Oklo is developing fast reactors that use metallic fuel. Oklo's initial reactor is the 1.5-MWe Aurora. The company is building on fast reactor technology and operational experience developed in the United States, with a particular emphasis on the Experimental Breeder Reactor-II. EBR-II extensively demonstrated the performance and safety case for metal fuel technology during its 30-year operating life. Design simplification is a key enabler for cost reduction, and notable features of Oklo's reactor include operating with a low power density, use of inherent and passive safety features, long fuel lifetime, and siting flexibility. Oklo's fast reactor technology can also tap into the vast energy reserves contained in used fuel.

Oklo has pioneered venture financing for advanced reactors, as well as a brand-new license application developed in a structure efficiently attuned to its design. Oklo's COLA submission and acceptance marked a paradigm shift for the development and deployment of advanced reactors, enhanced by important steps taken by the NRC to regulate advanced reactor technologies in connection with its review of Oklo's novel COLA.

In addition to its licensing work, Oklo has fabricated metallic fuel prototypes, gained a site use permit to build its first powerhouse at INL, and received used fuel to demonstrate fuel recovery. Oklo is on track to commercialize and develop a suite of reactors starting in the early 2020s. The future of advanced fission is just around the corner.—Oklo

its Natrium reactor. “We’ve had a lot of interaction with NRC for laying out the ground rules,” TerraPower’s Nick Touran said.

The Natrium system combines molten salt energy storage with the best aspects of the Traveling Wave Reactor and PRISM technologies, along with additional innovations and improvements. “PRISM had significant review from NRC in the ’90s, and they got lots of feedback,” Touran said. “Many elements of that design we brought into Natrium as well, so we had this huge head start in licensing.

“There’s a lot of design work to be done in order to submit the licensing basis documents to the NRC,” Touran said. “That’s going to be the bulk of our work over the next several years.”

Commercialization

In the end, if everything goes right, the reactors planned for construction over the next several years will lead these U.S. companies to their ultimate goal: commercialization.

“The key to commercialization is having confidence that the reactor design can be developed, approved, and constructed,” INL’s Jess Gehin said. “You have information related to cost because you have actually built it and sourced all the parts. You also have experience operating the reactor.” ⌧

Cory Hatch is a science and medical writer under contract with Idaho National Laboratory.

The Oklo powerhouse. Image: Oklo