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Nuclear Power Plant Temelin is located about 24 kilometers from the South Bohemian capital České Budejovice, Czech Republic. Electricity is generated in two production units with VVER-1000 Type V-320 pressurized-water reactors. Source: Shutterstock



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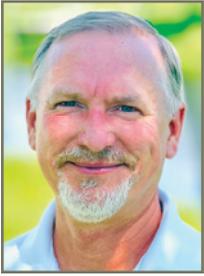
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Financing the Nuclear Renaissance

Aaron Larson

At the 2023 United Nations Climate Change Conference (COP28) in Dubai, United Arab Emirates, last December, 25 countries underlined the role of nuclear energy in their climate strategies by issuing a “Declaration on Tripling Nuclear Energy by 2050.” The U.S. was among the countries endorsing the declaration, which recognizes the key role of nuclear energy in achieving global net-zero greenhouse gas emissions by 2050 and keeping a 1.5-degree-C limit on temperature rise within reach. The declaration also highlighted the need for secure supply chains and encouraged shareholders of the World Bank, international financial institutions, and regional development banks to include nuclear energy in their lending policies.

Sourcing capital for any mega project is difficult, but getting financial institutions to back nuclear power projects can be particularly challenging. As William D. Magwood IV, director-general of the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), wrote in the Foreword of the agency’s recently released “Effective Frameworks and Strategies for Financing Nuclear New Build” report, “mobilising investments in nuclear energy is further complicated by the recent track record of nuclear new build projects that have faced significant costs overruns and delays.”

Interest Rates Massively Affect Cost

Magwood further noted, “Undoubtedly, financing, alongside supply chain readiness and workforce, is one of the most pressing challenges that countries around the world must address to succeed with plans for new nuclear energy projects.” Financing conditions impact the levelized cost of electricity (LCOE) through the cost of capital, ultimately influencing the competitiveness of new nuclear power plants.

The NEA report notes that LCOE for new nuclear power plants is particularly sensitive to the cost of capital, owing to the importance of fixed investment costs relative to variable costs, and the long

construction period. An example was presented in which financial costs accounted for two-thirds of the costs of nuclear electricity when the cost of capital was 9%, but dropped to less than one-third when the cost of capital was lowered to 3%.

The report provides eight case studies, taking stock of the range of financing frameworks and strategies that have been recently implemented or are presently under consideration for nuclear new-build projects around the world. The NEA said its objective was “to establish a common vocabulary and the basis for comparative analysis to identify and discuss key lessons learnt about the relative merits of different strategies for financing nuclear projects.” Projects analyzed in the report included Vogtle 3 and 4 in the U.S., Olkiluoto 3 in Finland, and the Barakah plant in United Arab Emirates, among others.

Key Insights on Nuclear Financing Frameworks

The nuclear financing case studies identified four key insights on the drivers and features of different financing frameworks. The NEA said these should be carefully considered upfront for all future nuclear energy projects. The notable findings were:

- Financing frameworks are deeply intertwined with national and industrial contexts. From a policy perspective, this means that lessons learned need to be contextualized before they can be transferred to another setting. “To do so requires a solid understanding of how a financing framework connects to policy and industrial environments,” the report says.
- A long-term national commitment to nuclear energy and strong upfront project planning are necessary conditions for devising and implementing successful frameworks for nuclear financing. However, systemic project issues may need to be addressed before a final investment decision can be reached.
- De-risking construction is key to attracting additional sources of funding and

to reducing the cost of capital. Project developers must try to mitigate risks before construction and have the ability to absorb them during construction. Ultimately, all risks are largely born by ratepayers and/or governments, which are best able to absorb low-probability risks with high impacts, such as construction cost overruns.

- Aligning stakeholders’ interests must be an overarching objective. Nuclear energy involves significant financial, safety, environmental, and geopolitical considerations, making it necessary to engage stakeholders, including governments, safety authorities, local communities, and investors, over a long period. While a key aspect of nuclear financing frameworks is to formulate clear decisions about risk allocations, this process should be implemented in a way that keeps in sight the need to ultimately align stakeholders’ interests through efficient contracting.

Banks and Financial Institutions Signal Support

World Nuclear Association noted that 14 financial institutions expressed support for nuclear power while representatives were in New York City for Climate Week NYC, an event that included more than 600 activities spread across the city during the last week of September. World Nuclear Association said, “The financial institutions recognized that global civil nuclear energy projects have an important role to play in the transition to a low-carbon economy. They further expressed support for long-term objectives of expanding nuclear electricity generation and the broader nuclear industry to accelerate the clean energy transition.” The group of financial institutions that signaled their support were Abu Dhabi Commercial Bank, Ares Management, Bank of America, Barclays, BNP Paribas, Brookfield, Citi, Credit Agricole CIB, Goldman Sachs, Guggenheim Securities LLC, Morgan Stanley, Rothschild & Co., Segra Capital Management, and Societe Generale. ■

—Aaron Larson is *POWER’s* executive editor.

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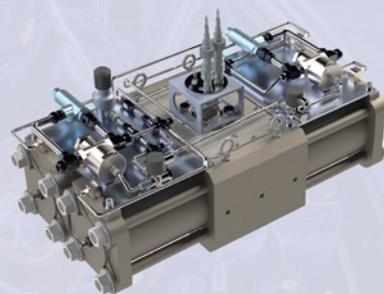


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The nuclear industry faces a tremendous opportunity as the world strives to limit global temperature rise to within 1.5°C of pre-industrial levels. However, this opportunity comes with significant challenges, primarily the need to design and construct new nuclear capacity at an unprecedented rate and scale, while ensuring safety and sustainability. Another challenge will be the necessity to operate and maintain these new reactors for longer periods than those of the current generation. Additionally, a considerable portion of the new reactors is expected to be small modular reactors, including both Generation III+ and Generation IV types.

All this creates completely new requirements regarding design methodologies, materials, operating models, supply chain capacity, localization, flexibility, training, skills, resources, regulation, site selection, lead times, and obsolescence.

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Can Nuclear’s Big Recent Wins Propel a True Global Revival?

While the past year has marked stunning triumphs for nuclear energy, experts caution that high costs, regulatory bottlenecks, and the need for market alignment remain major hurdles on the path to a true nuclear renaissance.

Sonal Patel

Nuclear energy is at an inflection point. In 2023, nuclear contributed 9.2% of the world’s total power production with an installed capacity of 371.5 GWe from 413 reactors globally. While that figure still represents a relative waning—especially if compared to nuclear’s share of 18% in the late 1990s—in September 2024, the International Atomic Energy Agency (IAEA) issued projections that point to a dramatic sectoral revival. While the agency’s high-growth scenario is ambitious—anticipating a rapid expansion that could reach up to 890 GW by 2050—even its conservative scenario is optimistic, envisioning 458 GWe by 2050 (Figure 1). The agency pointed to several prevalent drivers. Among them are climate goals that now recognize nuclear as indispensable to achieve COP28 pledges and growing international coalitions, including from 25 nations, that will work to triple nuclear capacity by 2050. Nuclear has been championed as a key solution to counter renewable variability and climate change

resilience, and address energy security amid geopolitical strain.

Proceeding with urgency, several countries have already acted to bolster their goals with a slew of supportive policy measures designed to manage financial and operational risks. In tandem, the nuclear industry’s long-missing market signals are growing more pronounced, riding on soaring energy demand projections from economic growth, urbanization, electrification, and lately, the scramble from tech giants to secure power for their energy-intensive data centers, and for semiconductor and chip fabrication.

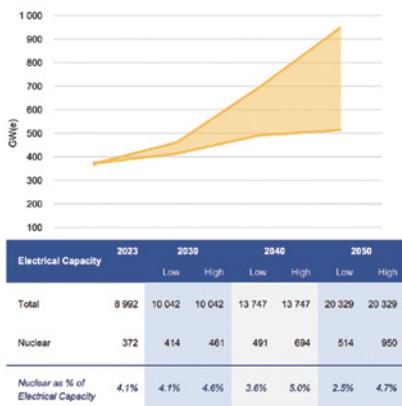
Still, while the momentum is stunning for the industry that has long lagged, industry experts caution these are still early signals of progress. “Overall, we still have more than half of our generation coming from fossil fuels. To solve that problem, based on our modeling, we’re going to need at least 150 GWe of nuclear in addition to all the other energy sources—and by 2050, if that’s our net-zero goal,” said Adam Stein, director of Nuclear Energy Innovation at thinktank the Breakthrough Institute. “The question is, is it people trying to get things moving forward incrementally, or is it actually the start of the ramp up? Is it going to be a renaissance, or is it going to be just a lot of money thrown at a couple of little projects? That’s what we still have to see.”

latory, and institutional challenges.

Perhaps the most longstanding is that nuclear plants are exceptionally capital-intensive. According to the U.S. Department of Energy (DOE), estimated overnight capital costs—without financing costs, as if a plant were to be built literally “overnight”—vary significantly, depending on region and reactor type. Vogtle 3 and 4, AP1000 reactors brought online over the past 18 months (and the first new U.S. reactors built in more than three decades), presented an overnight cost of \$11,000/MWh. However, the cost of Vogtle Units 3 and 4 was adversely impacted by “construction with an incomplete design, an immature supply chain, and an untrained workforce,” the DOE notes. The AP1000 design is now complete, there is now supply chain infrastructure, and Vogtle trained more than 30,000 workers, which should all help to bring costs down on future builds (Figure 2).

The World Nuclear Association (WNA) also underscores that cost escalation has been historically stark. In France, construction costs increased from €1,170/kWe in the 1970s for Fessenheim to €8,100/kWe in 2022 for the EPR at Flamanville, owing largely to the decline in reactor build rates and heightened safety standards. At the same time, however, series builds demonstrated in successful projects in China, South Korea, and the United Arab Emirates have revealed the cost-cutting potential of standardization and steady workflows, it says. “The economics of nuclear power are much improved if a number of standard models can be ordered. The economies of series production then come into effect, and the fixed overhead costs of design and permitting involved in the supply of nuclear grade components and systems can be spread over a large number of units,” it notes.

“Possibly of equal importance is the reduction of construction and permitting risk that is associated with building

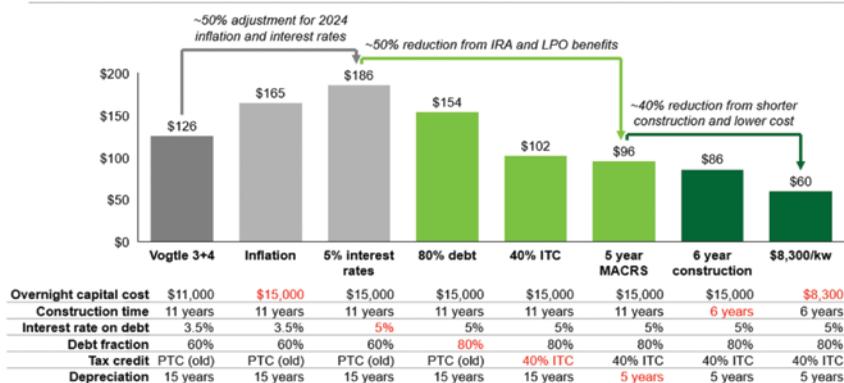


1. The International Atomic Energy Agency (IAEA) projects that while total power capacity could increase by about 12% by 2030 and more than double by 2050, nuclear capacity could increase 2.5 times the 2023 capacity by 2050 in the high case and by about 24% by 2050 in the low case. Courtesy: IAEA

Economic Realities, Financing, and Emerging Business Models

As Stein explained to *POWER*, a critical vision of the nuclear industry must be focused on achieving large-scale, sustained growth that will have a real impact on decarbonization and energy security goals. To do that, the industry must forge a pathway that can achieve “scale”—a massive gigawatt-level buildout and orders of magnitude beyond that. And to do that, it must overcome a lengthy list of formidable, persistent technical, regu-

LCOE using NREL model, 2024 \$/MWh



2. Levelized cost of energy (LCOE) values are shown here calculated using the National Renewable Energy Laboratory (NREL) model, which includes such things as Inflation Reduction Act (IRA) and Loan Programs Office (LPO) benefits, and production tax credit (PTC) and investment tax credit (ITC) incentives. Even assuming Vogtle 3 and 4 costs inflated to 2024, “the next AP1000s could be under \$100/MWh with IRA benefits and closer to ~\$60/MWh with cost reductions,” suggests the U.S. Department of Energy (DOE). MACRS = modified accelerated cost recovery system. Source: Pathways to Commercial Liff: Advanced Nuclear (DOE, September 2024)

numerous standardized units—which allows greater predictability and reduced timelines for the development of additional plants.” In addition, capital costs—the total cost to build a plant and bring it to operation—can be significantly reduced by learning-through-replication, scaling up unit capacities, simplifying designs, maintaining consistent licensing, and minimizing construction delays to accelerate revenue generation, it says.

Financing costs—typically comprising interest accruing during construction and for project debt and equity remuneration—of a project’s costs can also pose a steep (up to 80%) impact on total investment cost. In deregulated markets, these costs can be exacerbated by revenue uncertainty, as wholesale prices can fluctuate significantly. But here, too, new models are emerging that use frameworks like special purpose vehicles (SPV) and regulated asset bases (RAB) to share risk and provide more predictable returns. RAB models proposed for the UK’s Sizewell C project, for example, permit revenue collection during the construction phase, offsetting financing costs.

In the U.S., the DOE’s Loan Programs Office (LPO) is implementing an “equity-first” approach that reduces early high-risk exposure by requiring developers to raise private investment before accessing federal loans. The method, as a senior DOE official explained, ensures projects are “financially sound and com-

mercially validated” before committing taxpayer dollars.

A landmark example is the \$1.52 billion loan guarantee finalized in September 2024 to support Holtec International’s restart of the 800-MW Palisades nuclear plant in Michigan. The transaction marked the first loan guarantee through the Energy Infrastructure Reinvestment (EIR) program, established by the Inflation Reduction Act (IRA) Section 1706, which allows projects to leverage existing infrastructure. The framework notably also requires developers to achieve significant milestones upfront, reducing the likelihood of cost overruns or construction delays, he said.

Managing Substantial New Risks

Still, according to Stephen Greene, senior fellow at the Nuclear Innovation Alliance (NIA), while the government’s support will be crucial in jumpstarting nuclear development, over the long run—and to sustain the envisioned buildout—the nuclear industry will need to reconfigure its existing development model to mitigate financial risks that make independent development of new nuclear more challenging than other types of energy projects. At the crux of the issue is that the nuclear industry has historically proven to be notoriously slow, expensive, and risk-averse, and it requires considerable nuclear project development skillsets.

Along with large capital requirements, new nuclear projects require longer pre-construction timeframes with greater costs. And, due to the “limited commercial maturity of advanced nuclear technologies and the dearth of recent construction experience, supply chains, and construction capabilities are limited, and it is more difficult to allocate risks efficiently for a nuclear energy project today than it is for projects using more established energy technologies,” Greene explained.

“In our view, risk management is the key issue hindering the development of nuclear energy projects today. A key question is: Which parties have the motivation and the resources to take on that risk for the next few advanced nuclear energy projects?” Greene said. “Integrated electric utilities have discussed nuclear energy as an attractive option, but so far, U.S. utilities have not proposed specific projects despite recent



3. TerraPower celebrated the start of construction on the Natrium reactor demonstration project during a groundbreaking ceremony in Wyoming on June 10, 2024. The beginning of construction activities marked the first advanced nuclear reactor project under construction in the Western Hemisphere. Courtesy: TerraPower

Data Centers—Nuclear Energy’s New Frontier?

Major deals recently unveiled by tech giants with nuclear developers over the past few months underscore considerable market signal from the energy-hungry digital sector. In September 2024, Microsoft and Constellation Energy committed \$1.6 billion to restart the Unit 1 reactor of the shuttered Three Mile Island plant in Pennsylvania by 2028, now known as the Crane Clean Energy Center (Figure 4). Then, in October, Google signed a Master Plant Development Agreement to facilitate the development of a 500-MW fleet of Kairos Power molten salt nuclear reactors by 2035 to power Google’s data centers. That same week, Amazon said it would back the deployment of 5 GW of new X-energy small modular reactors projects, starting with an initial four-unit 320-MWe Xe-100 plant with regional utility Energy Northwest in central Washington. It also signed an agreement with Dominion Energy to explore a 300-MW SMR near Virginia’s North Anna Power Station.

These deals could just be the beginning. McKinsey reports that data center power demand in the U.S. could rise by 400 TWh by 2030, with a 23% compound annual growth rate. The consulting group also boldly predicts that while data centers may soon represent 30%–40% of all new demand, “hyperscalers” may be best poised to take on nuclear’s higher initial risks, given the long-term payoff in stability and low-carbon output.

Still, challenges loom large. Nuclear’s high capital costs and decade-long build timelines make rapid scale-up difficult, McKinsey warns. In addition,

nuclear’s cost competitiveness with other energy options is uncertain, and while modular reactors promise efficiency gains, achieving economies of scale remains elusive. Transmission and interconnection delays pose another substantial barrier. Even co-located, islanded systems for data centers may face grid integration complexities.

In November, the Federal Energy Regulatory Commission (FERC) rejected a request to increase the amount of power that Talen Energy’s Susquehanna nuclear plant can dispatch to an Amazon data center campus. While the order has posed new uncertainties about the regulatory landscape for behind-the-meter configurations, specifically for large co-located data center loads, legal experts generally suggest they expect that FERC will use a recent co-location technical conference to initiate a generic rulemaking proceeding, an action that could provide more clarity on behind-the-meter arrangements.

For now, key nuclear players remain mostly optimistic. Constellation CEO Joe Dominguez, during an earnings call in November, underscored that the 2–1 FERC ruling “is not the final word” on co-location. “Co-location in competitive markets remains one of the best ways for the U.S. to quickly build the large data centers that are necessary to lead on AI [artificial intelligence]. As Chairman Phillips explained, our nation’s entire economy and national security is at stake if we do not lead in AI.”

Dominguez said Constellation, the nation’s largest nuclear generator, remained bullish on data center



4. Constellation in September signed a landmark 20-year agreement with Microsoft to restart Three Mile Island Unit 1 in Pennsylvania as the Crane Clean Energy Center, named after former Exelon CEO Chris Crane. The project will add 835 MW of carbon-free power to the grid, with operations expected by 2028. Courtesy: Constellation

prospects. “We are seeing a wave of interest from customers who are interested in these opportunities and in our relicensing, and we are making significant progress on contracting. The intensity of our negotiations with hyperscalers and others keeps going up and up,” he said.

But he also noted data center demand was just one part of the value proposition to restart the Crane Clean Energy Center (formerly Three Mile Island)—which he hailed as a “powerful symbol of the rebirth of nuclear energy,” he said. “Second, it confirms our thesis that the most valuable energy commodity in the world today is clean and reliable electricity. And third, it underscores the growing demand for 24/7 clean energy, driven by the data economy, onshoring, and electrification. All of these macro points benefit our owners.” Given optimism for the market, Constellation is also exploring at least 1 GW of additional nuclear generation through updates, Dominguez said.

forecasts of more rapid electricity demand growth than we’ve experienced in decades. Some users have expressed interest in purchasing power from nuclear energy projects, but most have indicated they want to be customers of such projects, not developers,” he said.

Meanwhile, “The reality is that for early-stage nuclear projects, project developers are not in a position to absorb the potential cost risk of early-stage nuclear energy,” Greene added. The entities involved—such as constructors, major equipment suppliers, and even some technology developers—don’t yet have the experience with new nuclear energy technologies to make them comfortable taking on those risks, and many don’t have the fi-

ancial resources to backstop that risk. Green suggested more subsidies, like an investment tax credit, may be necessary to help offset risks and enable more private investment.

To address the challenge, some advanced technology developers—traditionally tasked with maturing their technologies—have stepped up to spearhead project development. TerraPower, for example, is developing its first Sodium power plant, Kemmerer 1, in Wyoming (Figure 3), a fast reactor and energy storage hybrid project that is furnished with up to \$2 billion in authorized funding under the DOE’s Advanced Reactor Demonstration Program (ARDP) and set to begin commercial operation in the early

2030s. The company, which has so far secured offtake from PacifiCorp and contracted Bechtel as its engineering, procurement, and construction (EPC) contractor, has adopted a strategy of “equity-only funding for first-of-a-kind (FOAK) projects” to avoid debt burdens and manage financial exposure, said Jeff Miller, TerraPower’s director of Business Development.

Oklo, meanwhile, is spearheading a “full value chain” approach, which involves managing the design, build, and operation of smaller reactors through power purchase agreements (PPAs)—essentially allowing Oklo to maintain greater control over costs and risk management. “Instead of starting with large, capital-intensive projects, we opted to

begin with smaller reactors” based on Oklo’s liquid metal sodium fast reactor design, said Craig Bealmear, Oklo’s Chief Financial Officer. “We have found a sweet spot at the 15-MW to 50-MW reactor size, with the potential for 100 MW as we scale. This approach makes sense as our reactors are more accessible to a wide range of customers and markets, and drastically reduce upfront capital requirements, which helps accelerate deployment,” he said.

The Prospect of Leveraging Existing Coal or Nuclear Sites

As one specific potentially impactful approach to slash risks, governments around the world are facilitating the utilization of existing energy infrastructure. Site repurposing projects typically exhibit community acceptance and have regulatory background. The ability to utilize such things as existing transmission connections can help minimize costs and reduce timelines associated with new builds. Challenges exist, of course, which include environmental and physical constraints—for example, population density, seismic risks, water availability, and local policies could pose problems.

In an August 2024 report, the DOE suggested the nation’s 54 existing nuclear plant sites (which already host 94 commercial reactors) and 11 retired nuclear sites could backfit 60 GWe or 54 large-scale nuclear plants (sized like AP1000s, at 1,117-MWe), and 95 GWe from 158 smaller reactors, sized at 600 MWe. A larger array of 145 coal power sites, meanwhile, could host another 128 GWe to 174 GWe. The report identified at least 27 coal sites retired before 2020 in 16 states that could be used as new sites for new nuclear plants.

Idaho National Laboratory (INL) has separately suggested at least 18 sites are promising for near-term AP1000 deployment, and at least nine sites qualify if state policy is considered. These include the restarts already announced at Palisades and Three Mile Island Unit 1, as well as at Duane Arnold (where a feasibility study is underway) and V.C. Summer (where an AP1000 project was abandoned).

For now, however, the focus on new builds appears firmly entrenched on small modular reactor (SMR) prospects, Stein has suggested. “First, unless there are already AP1000 reactors on the site, as is the case at the Vogtle site in Georgia, no one is going to build



5. Oklo Inc. announced on Nov. 7, 2024, that the DOE and the Idaho National Laboratory (INL) have completed the environmental compliance process addressing the DOE requirements for site characterization at Oklo’s first commercial advanced fission power plant site at INL. This image shows Oklo’s preferred site, with INL’s Materials and Fuels Complex, and Transient Reactor Test Facility, visible in the background. Courtesy: Oklo

a single large reactor. Single-unit sites simply cost more than multi-unit sites and won’t reach the low-cost estimates that have created the recent wave of enthusiasm for large LWRs [light-water reactors],” he said.

SMRs are also more feasible in liberalized markets, given they demand lower initial capital and shorter deployment timelines, aligning with market demand and corporate needs for urgent, firm power solutions. “SMRs offer the potential for lowering the absolute dollar risk bands for construction,” the DOE underscores. “As an example, a \$4 billion SMR with a 50% cost overrun would result in a completed FOAK cost of \$6 billion; a \$10 billion reactor with the same 50% cost overrun will result in a completed FOAK cost of \$15 billion.”

New Market Entrants, Industrial Demand, and Expanding Applications

As several nuclear entities have told *POWER*, the most forceful impetus currently driving nuclear forward is market signal. Developers are fielding substantial interest from tech giants looking to urgently feed data centers (see sidebar “Data Centers—Nuclear Energy’s New Frontier?”), but also from customers who want to secure reliable, clean, and affordable power for other industrial and commercial uses.

Oklo’s Bealmear, for example, noted his company’s partnerships (Figure 5) had expanded rapidly from 700 MW since May 2024, when it completed a business combination with AltC Acquisition Corp., to include 1.4-GW in deals across multiple sectors—including with data

center providers Equinix and Wyoming Hyperscale, and Texas-based oil and gas company Diamondback Energy. “I think the biggest question we all get is, ‘Can you move faster?’ And I think we’re all starting to get questions of ‘What can we do to help you move faster,’ which I think is a great place for the industry to be,” he said.

So far, 65 operational reactors around the world already supply heat for non-electric applications, including district heating, desalination, and industrial heat applications. Interest is now cropping up, in Finland, for example, to explore nuclear power to replace aging heat plants. Finnish nuclear startup Steady Energy’s LDR-50, a 50-MW pressurized water reactor, has garnered substantial interest for its design, which produces heat of up to 150C for district heating, industrial steam production, and desalination projects.

Cogeneration also poses a growth opportunity. Industry is already exploring value in high-temperature applications, particularly for processes requiring heat above 500C, such as hydrogen production, and the oil and gas sector. In China, nuclear-driven cogeneration projects that combine electricity and process heat for industrial complexes have reportedly yielded “significant cost savings in fuel and emissions reduction,” the IAEA notes. Haiyang nuclear plant, which began providing district heat in 2020 to replace coal-fired boilers, is now also planning a large-scale desalination plant coupled to its AP1000 reactors.

Stein told *POWER* that the nuclear industry’s potential to supply industrial process heat may be its biggest overlooked value proposition. “If we just talk about low-grade heat for industrial processes in the U.S., that’s the thermal output of 70 AP1000s—“a massive market that is almost entirely served by fossil fuels right now,” he underscored. The thermal energy application has broader implications for decarbonization goals beyond just electricity generation, he noted, and it should more prominently be part of nuclear’s “bigger picture,” he said.

The Risk of Regulatory Bottlenecks

Finally, and with emphasis, sources told *POWER*, the most insidious risk facing nuclear are outdated and stringent regulatory practices that delay its potential. Despite Congressional pressure to modernize, the Nuclear Regulatory Commission (NRC) has just begun to grapple

A Compelling Case for the Rapid, High-Volume Deployment of Microreactors

The Nuclear Energy Institute (NEI), a North American trade group that works to shape nuclear policy, is fiercely pushing the Nuclear Regulatory Commission (NRC) to drastically streamline its regulatory process so that it will be supportive of an emerging brand of microreactors that could be potentially deployed in less than six months.

“Rapid high-volume deployable reactors are unlike current operating nuclear plants or other advanced small modular reactors,” wrote Marcus Nichol, executive director, NEI New Nuclear, in a recent concept paper. More akin to non-power or research reactors than commercial reactors, these 2-MWth to 50-MWth technologies are “very small in size and source term,” he explained. They enable innovative business models by allowing for extensive factory construction, appealing to customers who only want to use energy (not sell it). In addition, they reduce costs enough so that vendors can build reactors pre-emptively without specific customer orders, require minimal onsite construction, and, in some cases, can be transported fully assembled. The reactors are envisioned for remote deployment for a range of power and heat applications, including oil and gas production and development, mining and extraction, and chemical processing.

At least one company—Shepherd Power—is actively exploring the concept and has called for “sufficient clarity by the end of 2024 on a licensing pathway supporting scale microreactor deployment.” In a letter to the NRC, the subsidiary owned by oil and gas technology firm NOV said the imperative is driven by market demand. “In the Permian Basin alone, electrical demand is expected to jump from 4 GWe in 2022 to over 17 GWe in 2032, driven by electrification of oil and gas operations to reduce emissions. We led an in-depth evaluation, with participation from several major oil and gas companies, that identified a substantial number of potential upstream power and heat applications that can be served by microreactors, including

water treatment, hydrogen production, and enhanced carbon capture and storage. These applications were selected because microreactors present the best technical option for achieving their decarbonization, and aggregated together, imply a very large and immediate domestic market,” it said.

NEI’s 180-day rapid-deployment concept essentially envisions five stages after site selection: mobilization and site characterization (1 month); site preparation (1 month); site assembly (2 months); delivery and emplacement (1 month); and commissioning and startup (1 month). The concept of deployment, however, is “dependent upon several milestones in the NRC process for the site license,” Nichols noted. “Currently, the NRC licensing process is complex, including many steps and features that would not be necessary for a rapid high-volume deployable reactor.”

NEI proposes a more pragmatic and efficient regulatory approach that would align with the ADVANCE Act’s Section 208, which explicitly calls for the NRC to establish a regulatory framework for microreactors. For one, it advocates for a specialized framework tailored to microreactors. NEI stresses that because these smaller reactors operate with fundamentally different source terms and simpler operational models than large-scale plants, they would need minimized safety concerns and oversight. In addition, NEI urges the NRC to drastically streamline the licensing process to aim for essentially a four-month review process: a month each for application preparation and engagement, an acceptance review, two months for the NRC’s verification review, and one for its final approval.

The NEI report stresses the need for NRC regulatory costs to remain below 1% of total project costs to keep microreactor deployment economically viable, supporting rapid, high-volume deployment models without compromising safety. By minimizing overhead, this approach ensures nuclear technologies can compete in cost-sensitive, remote, and industrial applications, it says.

“the challenge is actual implementation,” Stein noted (see sidebar “A Compelling Case for the Rapid, High-Volume Deployment of Microreactors”).

In October, the NRC published a proposed rule for a Part 53 licensing pathway, an alternative to two existing licensing

options (focused heavily on LWR-specific requirements), which seeks to establish risk-informed, performance-based techniques. Part 53, designed to accommodate multiple technologies, must be finalized by 2027.

“It does have a lot of things that potentially could help expedite the licensing process for advanced reactors and really just make the process more efficient without sacrificing the NRC’s independent review of safety,” said Patrick White, NIA research director. However, he said the bigger question remains: “When will this or how can this rule potentially bring benefits to applicants and have it be kind of a more predictable, efficient, and effective process?” Congress actually recognized “hesitancy to use the new rule,” so as part of the ADVANCE Act, it included a set of licensing prizes that will provide a 100% fee refund for any applicant that makes it through certain NRC licensing pathways, he noted. “The federal government is willing to essentially pay those costs for you to be that first mover,” he said.

Stein suggested many more opportunities exist for efficiency at the regulatory body, particularly for its “risk-averse regulatory paradigm,” which he said is stricter than what Congress has said is “ample margin of safety.” Its overly conservative approach “slows the process down without providing meaningful additional safety to the public,” he said.

As just one critical measure, the NRC must move away from treating each application as “entirely new” and instead “reference more easily from past decisions,” Stein said. Meanwhile, further complicating matters is that the agency is losing experienced senior staff to industry, including “change makers” in its middle ranks. That “hollowing out of the middle” is further hampering the NRC’s ability to streamline its processes as the institutional knowledge is being drained, he said.

Ultimately, for all its recent successes, alignment across the nuclear sector is emerging as the industry’s next crucial imperative. As White observed, nuclear deployment relies heavily on “lining up all the different stakeholders”—from developers, operators, and end users to state and federal officials and, crucially, a strong regulatory body, he said. For years, the industry struggled with one or more of these pieces missing, he said. “We still have work to do, but I think we’ve really got that process started.” ■

—**Sonal Patel** is a **POWER** senior editor.

How Nuclear O&M Is Evolving for the Emerging Power Paradigm

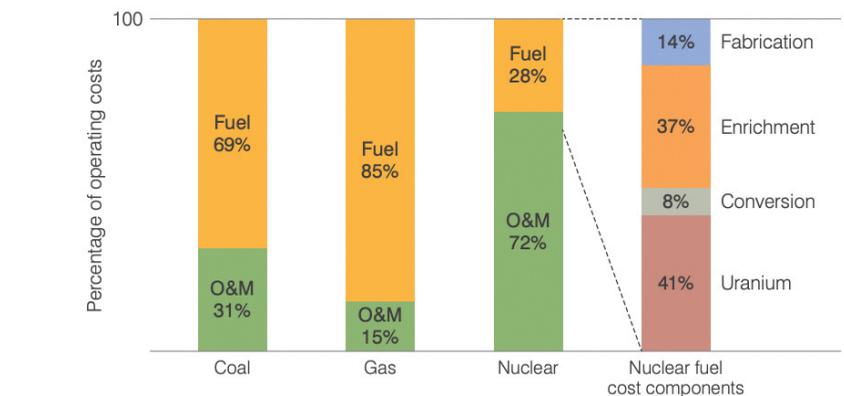
In its quest to drive down costs while boosting safety, the nuclear industry has ramped up efforts to streamline operations and maintenance (O&M). New approaches target efficiency and resilience.

Sonal Patel

If there is an underreported trend in nuclear, it has been the global sector's dramatic reduction in generating costs over the past decade. In 2022, the average total generating cost for U.S. nuclear energy hovered at \$30.92/MWh—0.8% lower than in 2021 but as much as 40% below 2012 costs, according to the Nuclear Energy Institute (NEI). Cost reductions have been driven by “a 41.4% decrease in fuel costs, a 50.9% decrease in capital expenditures, and a 33.4% decrease in operating costs,” the trade group said. “Prior to the 2012 peak, nuclear total generating costs had increased steadily over the previous decade,” it noted. The recent figures are the lowest since the Electric Utility Cost Group (EUCG) Nuclear Committee, a cooperating group of nuclear plant representatives, started collecting industry-wide detailed data in 2002.

In the U.S., at least, the sharp cost reductions over the past decade can be pegged to a concerted effort, “Delivering the Nuclear Promise,” a strategic, multi-year, industry-wide collaboration kicked off in 2016. The initiative rolled out a comprehensive suite of targeted efficiency measures to transform nuclear operations and maintenance (O&M). Efforts focused, for example, on the standardization of design processes to streamline upgrades across plants, the integration of machine-learning diagnostics to predict equipment maintenance needs, and the implementation of online monitoring systems that allowed real-time operational adjustments. The program has also focused heavily on workforce improvement, spearheading innovations like virtual reality training programs to attract new talent and empower supervisors.

Across the world, nuclear O&M costs remain varied, with significant regional differences driven by factors such as la-



1. Ratio of fuel costs to operating and maintenance (O&M) costs for nuclear, coal, and gas generation. Courtesy: World Nuclear Association, *Nuclear Power Economics and Structuring (2024 Edition)*

bor costs, material availability, and regulatory requirements. A 2024 analysis for the Net Zero World Initiative estimates that variable O&M costs—expenses directly tied to a plant's operational output—range between \$9.25/MWh and \$17/MWh. In contrast, fixed O&M costs—expenses necessary to maintain a plant's readiness regardless of output—span from \$4/kWe to as high as \$223/kWe annually, depending on the country and economic conditions.

Generally, “nuclear fuel costs have fallen over time due to lower uranium and enrichment prices together with new fuel designs allowing higher burn-ups, while O&M costs tend to be somewhat higher than for other thermal modes of generation,” notes the World Nuclear Association (WNA) in a report published in April this year (Figure 1). A major component of this has involved a dramatic shortening in the length of refueling outages. While in 1990, these averaged 107 days, the average duration dropped to 40 days in 2000. In 2023, in the U.S., nuclear plant refueling outages averaged 35 days, but plants have reported outages of as short as 16 days.

A Set of New Drivers Emerging for Nuclear O&M

Despite regional cost variations and persistent challenges, nuclear plants globally have also achieved remarkable performance improvements over the past few decades. Since the 1990s, global nuclear capacity factors—a key measure of operational efficiency—have surged from 70% to 82%, driven largely by advances in operational practices and plant upgrades. In some countries, the improvement is even more dramatic—for example, in the U.S., from 66% to 90%. Levels greater than 90% have also been achieved by plants in Europe and Asia, the WNA reports. As Sama Bilbao y Leon, WNA director general, underscored, these achievements are playing an overlooked part in bolstering the current energy system. “Nuclear reactors helped avoid 2.1 billion tonnes of carbon dioxide emissions in 2023 from equivalent coal generation—that’s more than the annual emissions of almost every individual country, with only China, India, and the USA having higher national CO₂ emissions,” she said.

However, the future of nuclear de-

mands even more boosts to performance, cost-efficiency, and reliability. “We see several trends reshaping nuclear O&M,” global nuclear O&M services leader Trillium told *POWER*. “The primary trend, or more specifically, objective, is achieving net zero by 2050. According to the International Energy Agency (IEA), global nuclear capacity would need to increase to 916 GWe by 2050 to limit global temperature increase to the 1.5C target. This is more than twice the current global capacity,” it noted.

Currently, however, only about 66 GWe worth of projects are under construction, with 84 GWe planned. And while there are 365 GW of proposed projects, several are advanced nuclear or small modular reactor (SMR) designs, Trillium said. “Very few are at a mature stage. The ramp-up in resource levels and skills required to operate these plants will be significant, and there will also be a demand for the same resources and skills to extend the lifetimes of the current operating fleet.”

Addressing Aging Infrastructure

The most urgent initiative facing the world’s nuclear industry, for now, is to sustain stellar operations (Figure 2) at its 415 nuclear reactors across 31 countries. As the International Atomic Energy Agency (IAEA) noted in its September 2024–released Nuclear Technology Review, 295 reactors, or about 67% of global operational reactor capacity (261.8 GWe), have been in operation for more than 30 years, and 142 of those (29%) are over 40 years. “The aging fleet highlights the need for new or updated operating nuclear capacity to offset planned retirements and contribute to sustainability and global

energy security and climate change objectives,” the report notes. So far, governments, utilities, and other stakeholders are investing in long-term operation (LTO) and aging management programs for an increasing number of reactors to ensure sustainable operation and a smooth transition to new capacity.

Modernization and life-extension strategies embraced by nuclear plant operators around the world are so far showing immense gains, leveraging new approaches, digital tools, and advanced diagnostics. Finland’s Olkiluoto plant recently achieved a 30 MW power uprate through targeted turbine and generator upgrades, while in Canada, Bruce Power’s Major Component Replacement project is expected to add approximately 2,400 MW to Ontario’s grid while supporting safe operations for another 30 years. In France, EDF’s 900-MW reactors have seen consistent 40 MW boosts per reactor following control system and turbine upgrades, all while meeting modern safety standards.

In the U.S., initiatives like the Inflation Reduction Act, along with actions at the state level, have encouraged several utilities to seek licenses to extend plant lifetimes to up to 80 years. Constellation is investing \$800 million to increase the output at its Braidwood and Byron nuclear plants in Illinois by 135 MW—part of planned upgrades that could add up to 1,000 MW of additional capacity to its 21-reactor nuclear fleet—alongside recommissioning a shuttered reactor at Three Mile Island and seeking lifetime extensions for its Dresden units.

Long-term operation, however, presents critical technical and operational challenges mainly linked to materials ag-

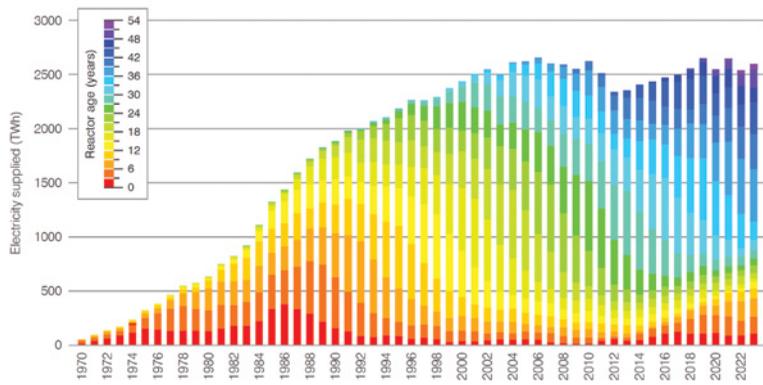
ing, replacement of critical components, and modernization needs. Because their replacement can be unfeasible and costly, key life-limiting components, such as reactor pressure vessels and containment structures, require focused aging management. Often posing more complexity is component obsolescence, extended lead times for components, and sub-suppliers no longer operating, Trillium noted. “These challenges often require a revised or modified safety case, leading to a lengthy process, additional delays, and increased costs.” To address these issues, Trillium aims to proactively manage lifetime spares/repair demands and adopt a full lifecycle approach.

Digital Transformation and Automation in Nuclear O&M

As in other power industries, the nuclear sector has also embraced digitalization to provide new options to slash O&M costs. A focus has been on automation—which the Electric Power Research Institute (EPRI) describes as a technology that “performs a task or part of a task that was previously carried out manually.” Automation, EPRI notes, promises to streamline nuclear operations by reducing labor hours, minimizing safety risks, enabling continuous online monitoring, improving data quality, reducing human error, and enhancing scheduling flexibility for personnel.

While nuclear “is rarely the first adopter of contemporary technologies,” most “have taken at least initial steps to implement digital online monitoring,” the research organization says. Plants are using advanced sensors, including ultrasonic and vibration sensors, to support continuous online monitoring of critical components like pumps, turbines, and condensers. “Data generated by online monitoring is processed in recently established monitoring and diagnostic (M&D) centers, where [nuclear plants] have also been able to start automating real-time data analysis,” it says.

These and other tools are also poised to revolutionize non-destructive evaluation (NDE), a set of techniques used to inspect and assess the condition of materials and components without damaging them. NDE is advancing from basic radiography and manual ultrasonic testing to leverage techniques such as phased array ultrasonic testing (PAUT) and automated data analysis. For example, recent trials by EPRI have demonstrated how artificial intelligence tools can drastically reduce inspection time by quickly flagging areas



Source: World Nuclear Association, IAEA PRIS

2. As of December 2023, the world’s nuclear fleet’s capacity was 371.5 GWe, provided by 413 reactors across 31 countries. About 67% of global operational reactor capacity (261.8 GWe, 295 reactors) has been in operation for more than 30 years, while about 29% (112.2 GWe, 142 reactors) has been in operation for over 40 years, and 4% (17.5 GWe, 28 reactors) for over 50 years. Courtesy: World Nuclear Association



3. Talen Energy has tested “Spot” in high-radiation areas at the Susquehanna nuclear power plant. Spot can conduct visual and thermal inspections safely and effectively, without the need for costly derates or shut downs. Courtesy: Boston Dynamics

of concern, cutting analysis time from days to hours, while drones and permanent sensors provide continuous, real-time monitoring in high-risk areas.

The use of robotic tools for inspections, particularly in hazardous areas to limit personnel exposure, also appears to be gaining prominence. The Krsko Nuclear Power Plant in Slovenia offers one example of camera-based monitoring to conduct visual inspections and as a predictive diagnostic method. But several other plants are using robotic platforms, such as single-purpose robots, to navigate and inspect various components. These include static or semi-fixed arms, diggers and rollers, submersibles, and light detection and ranging (LIDAR)-equipped drones.

Robots like Boston Dynamics’ “Spot” are actively enhancing operations at facilities such as Talen Energy’s Susquehanna plant in Pennsylvania (Figure 3), Duke Energy’s Oconee Nuclear Station in South Carolina, and Ontario Power Generation’s Pickering Nuclear Generating Station in Canada. At Oconee, Spot assists in inspecting hard-to-reach areas, including underground piping and containment buildings. According to EPRI, future advancements in AI could allow robots to perform more autonomous tasks, such as identifying issues in real time and possibly even executing corrective actions, which could more substantially reduce manual intervention.

As an especially bright spot for nuclear O&M, over recent years, digital instrumentation and controls (I&C) upgrades have also proven transformative, including to enhance precision, enable further automation, and improve safety. Although costly and complex to install, digital systems promise lasting benefits, including, for example, rapid, precise adjustments to reactor or steam generator water levels—crucial attributes that

What’s AI’s Value for Nuclear O&M?

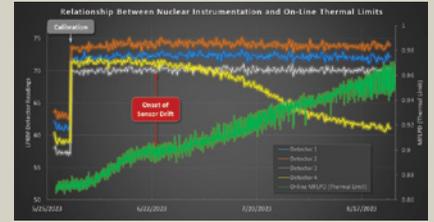
Like other power sectors, the nuclear industry has begun to embrace artificial intelligence’s (AI’s) potential to enhance efficiency, automation, safety, predictive maintenance, and process optimization. So far, machine learning (ML), a subset of AI, is already being used extensively for monitoring and predictive maintenance across the world, enhancing precision, reducing costs, and allowing operators to focus on high-value tasks. A recent report authored by several U.S. national labs highlights several more potential use cases, including for AI-driven digital twins for real-time monitoring, automated anomaly detection, and remote operations and maintenance (O&M) management to support workforce challenges. The report also explores the potential of large language models (LLMs) as “virtual subject matter experts” that could help with complex regulatory reviews, compliance documentation, and risk assessment, providing critical support for both nuclear plant operators and regulators.

However, the report stresses that extensive validation will be essential to ensure reliability to meet nuclear regulators’ stringent safety standards, especially as AI evolves toward more autonomous functions. Regulators in the U.S., UK, and Canada have begun assessing how AI applications can be safely integrated into nuclear operations. Several regulatory bodies have convened workshops in recent months to explore frameworks to address the unique risks AI poses, including those that anticipate future, more advanced uses, particularly around cybersecurity, data integrity, and transparency in AI decision-making processes.

In one particularly illustrative triumph for an AI use case, Indiana-based BlueWave AI Labs recently deployed ML tools at Constellation’s Peach Bottom and Limerick boiling water reactor (BWR) plants. Backed with a U.S. De-

partment of Energy \$6 million grant, the three-year initiative tested its advanced ML tools at the plants starting in 2022 leveraging vast amounts of historical plant data to analyze and improve sensor measurements within the reactor core. In 2023, BlueWave’s system identified out-of-calibration sensors at Limerick 2, which allowed operators to recalibrate without power output—an intervention that preserved operational efficiency and avoided costly downtime (Figure 4). BlueWave estimates that its AI tools can be deployed across all 32 of the nation’s BWRs within three years, potentially saving the industry up to \$80 million by optimizing sensor accuracy, improving fuel management, and reducing manual inspection time. It is also working to adapt the AI algorithms to pressurized water reactors, which make up most of the American nuclear fleet.

“Constellation’s collaboration with Blue Wave AI Labs has allowed us to use powerful machine learning tools to complement traditional engineering practices when designing innovative nuclear fuel products for our operating fleet,” said Jason Murphy, vice president for nuclear fuels at Constellation. “Widespread adoption of these new tools will benefit nuclear reliability and cost-effectiveness.”



4. This graph shows a drifting sensor reading (yellow) at Limerick Generating Station in 2023. Constellation used Blue Wave AI Labs’ technology to take the malfunctioning sensor offline, avoiding other remedial actions that would result in lost energy generation. The company intends to expand artificial intelligence (AI) applications to additional reactors in its boiling water reactor fleet. Courtesy: Blue Wave AI Labs

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them to reduce equipment footprint and improve monitoring capabilities, says Curtiss-Wright (which partnered with RadICS in 2019 to bring the RadICS digital I&C platform to the U.S. nuclear fleet).

Finally, as in other power sectors, nuclear plants have homed in on digital twin technologies, and AI and machine learning (ML), to enhance predictive maintenance (see sidebar “What’s AI’s

Value for Nuclear O&M?”). Digital twins (DTs), virtual models that replicate nuclear systems throughout their lifecycle, are using real-time data to enhance design, licensing, construction, and O&M processes. By leveraging decades of operational knowledge, DTs also improve plant availability, reduce operational risks and costs, and support the feasibility of operating advanced reactor designs, including SMRs.

Despite these benefits, the nuclear industry faces several formidable challenges and risks when integrating digital solutions into aging nuclear infrastructure, as EPRI notes. Initially designed with analog systems, modernization requires diligent assessment to consider technical and logistical hurdles.

Cybersecurity is another critical consideration, especially given that civil nuclear infrastructure is a high-value target. Technical, personnel, and sector-wide vulnerabilities in nuclear cybersecurity include reliance on outdated, unsupported software; “security by obscurity” assumptions in rare control systems; insufficient cybersecurity personnel; and cultural overconfidence, according to a recent Chatham House report. Digital O&M technologies also introduce new dependencies for both highly skilled labor and resilient supply chains, which could affect maintenance costs and operational efficiency.

New Considerations for the Coming Wave of SMRs

The next evolution of the nuclear sector is, meanwhile, poised to introduce a new wave of SMRs and advanced reac-



5. Akademik Lomonosov, the world's first floating nuclear power plant, underwent its first full refueling operation in Pevek, Chukotka, in 2023. The comprehensive procedure involved replacing the entire reactor core for each of its KLT-40S reactors to ensure uninterrupted power. Managed by Rosatom's specialized teams, the procedure was the most extensive maintenance campaign since the novel plant's commissioning in 2019. Courtesy: Rosatom

On the Prospect of Load Following

While existing nuclear plants and new designs are technically capable of performing frequency control and load-following operations, most nuclear generators worldwide prioritize operating at full capacity for as long as maintenance and refueling schedules permit, mainly for economic and regulatory reasons.

But as power intelligence firm Kpler Power posits in a recent paper, new power paradigms that support the heavy integration of renewables are driving nuclear “modulation”—whereby generation follows not just residual demand (purely, “load following”) but is also influenced by “market price signals, which act as proxies for residual demand and cross-border flows.” When residual demand and price decouple amid low prices, nuclear generation is more responsive to price movements, it contends. Nuclear power plants modulate their output for different reasons: fuel savings, efficient resource allocation, and cooling constraints,” it notes. The increasing trend is driven by increased renewable energy installed capacity and market price volatility.

The 56-reactor French fleet is a prime example, the firm says. “Today, the fleet continuously shows its ability to ramp down to 12 GW in under a day, a 20% flexible output of its total operational capacity. A single reactor is able to reduce output by as much as 1 GW, as seen in the case of Cattenom 2 and 3. Moreover, the age at which nuclear plants modulate does not look like an issue: the Tricastin nuclear site example shows that plants built as far back as the 1970s can still adapt to modern modulation practices.”

Kpler's data suggests a generally positive correlation between cumulative ramp-down intensity and capture rates—the ratio between a generator's average revenue from electricity produced and the average spot price. “This suggests that as reactors become more flexible and modulate their output to adapt to grid demands, they can take advantage of market grid volatility, which often rewards flexibility, particularly during periods of peak pricing.”

Still, this type of flexible operation

can pose new operation and maintenance (O&M) challenges, Kpler acknowledges. Thermal cycling can lead to significant wear on reactor components, and temperature fluctuations could affect materials like steel and zirconium alloys used in the reactor pressure vessel, fuel cladding, steam generators, and piping. It also causes steam turbine erosion due to condensation, and it demands intricate control of reactor kinetics, particularly in adjusting neutron flux and reaction rates, with degradation impacts to control rods. It may even affect the uniformity of fuel burnup, leading to “suboptimal fuel use.”

The emerging fleet of small modular reactors (SMRs), which are being marketed with load-following capabilities, may face a different set of challenges, as two experts from the University of Western Ontario suggest in a paper recently published in the journal *Progress in Nuclear Energy*. “Since an SMR can be considered as a combination of the reactor and the balance-of-the-plant, its power output can be regulated at the reactor power output or from the balance-of-the-plant,” experts explain. Load-following can generally be implemented through direct techniques (involving reactivity control and turbine control) or indirectly, leveraging energy storage systems (as Kemmerer 1, the first Sodium plant, will demonstrate).

The experts, however, highlight several issues that aren't usually encountered during existing baseload nuclear operations. These include the risk of uneven core power distribution leading to localized overheating, flow-induced vibrations that stress components, excessive production during peak demand, heightened risk of fission product leaks due to fuel cladding strain, and flow-accelerated corrosion in piping, which can compromise structural integrity over time. The experts recommend further investigation into optimal component sizing, combining direct and indirect load-following methods, assessing long-term wear effects, and refining operational strategies to manage dynamic changes and avoid adverse conditions unique to load-following in SMRs.

tors. According to EPRI, which is spearheading a dedicated Advanced Nuclear Technology (ANT) program, SMRs are designed for modularity, which simplifies scalability and reduces construc-

tion costs but could require specialized O&M strategies tailored to their potential remote (Figure 5) or off-grid applications. Advanced reactors, including Gen IV technologies—spanning fast reac-

tors to molten salt reactors and high-temperature gas-cooled reactor (HTGR) designs—typically incorporate passive safety features and alternative coolants. While these designs reduce reliance on active safety systems, they will require tailored maintenance protocols and distinct O&M practices.

Advanced reactors, notably, will also bolster new applications beyond power generation, including heat production, desalination, and hydrogen production. These applications introduce new operational demands, but also present opportunities, for example, to integrate automated chemistry control systems that could reduce corrosion and extend the lifespan of components.

For now, research and development efforts are notably focused heavily on how advanced reactors can minimize O&M costs. Several notable projects are underway under the U.S. Department of Energy's (DOE's) Generating Electricity Managed by Intelligent Nuclear Assets (GEMINA) program. Argonne National Laboratory is spearheading the Maintenance of Advanced Reactor Sensors and Components (MARS) project, which is looking to slash O&M costs from \$23/MWh—the minimum considered for nuclear energy cost competitiveness—to \$2/MWh.

The project, focused on Kairos Power's molten salt HTGR, is working to enhance sensor diversity and functionality, and enable simultaneous measurement of multiple variables while using ML for automated fault detection and diagnostics. GEMINA is also fostering Framatome's digital twin diagnostics for HTGR cooling systems, GE's AI-powered predictive maintenance for advanced reactors, high-fidelity digital twins for BWRX-300 systems, and irradiation data for molten salt reactors. Moltex Energy is exploring fully automated and digitized stable salt reactor (SSR) plants, while the University of Michigan is developing its SAFARI project for secure automation for advanced reactors. X-energy is also exploring digital twin-enhanced O&M techniques in the Xe-100 to lower fixed costs.

Some approaches propose a “fresh think” strategy, deviating from traditional O&M (see sidebar “On the Prospect of Load Following”). EPRI recently wrapped up a project that sought to rethink O&M for advanced reactors through a “Build-to-Replace” model. The approach proposed shorter, planned lifespans for structures, systems, and components

(SSCs), and critical reactor components, shifting from the traditional “monitor and repair” strategy to a “replace and refurbish” model. The project assumed that by designing components with predictable lifetimes—similar to practices in the airline industry—the model could potentially lower O&M costs to below \$5/MWh for advanced reactors.

For now, nuclear service firms are readying for new demands from advanced nuclear. Trillium told *POWER* it is “engaging in structured and in-depth discussions with current and potential customers in the SMR space, encompassing both Gen III and Gen IV types, with a central function to manage trends and inform the innovation activities.” The company said: “It's important to note that while SMRs share similarities with existing GW-scale water-cooled nuclear programs, there are also significant differences that define SMRs as a distinct market sector with unique requirements, which the industry needs to tune in. Next-generation nuclear technology challenges conventional thinking, and Trillium encourages its employees to embrace this mindset.”

The Workforce Question

Among the industry's most prominent challenges as it grapples with emerging O&M demands is retaining its specialized skillset and talent. During France's 2022 nuclear outage crisis—prompted by a series of overlapping issues that dropped its operational capacity to about 40% at its lowest point—workforce shortages featured prominently as a debilitating factor. While routine inspections revealed corrosion-related cracks in critical reactor piping, requiring time-consuming repairs, the thin labor force left EDF struggling to keep pace with maintenance needs. EDF and French labor unions pointed to the declining nuclear workforce as a critical factor, emphasizing that “wavering government support and lack of policy clarity” had discouraged young engineers and skilled trades personnel from pursuing careers in nuclear.

Given prospects for tripling nuclear capacity globally, Europe's nuclear trade group Euronuclear suggests the industry is bound to face skills shortages in certain disciplines, technical areas, or locations. “There are some skills like [instrumentation and control], licensing, or major project management that are difficult to find, either because the skills are rare or because competition with other

sectors is strong,” said Callum Thomas, CEO of Thomas Thor. “The problem that nuclear industry has, certainly in Western Europe and North America, is that it did not hire from the late 1980s until the early 2000s. During these 15 years, we saw a significant immobilism, and a lack of investment, which has led to a generation-sized gap in experienced staff and leaders. On the one hand, we have a vibrant, nuclear young generation, while on the other hand, we have a very talented older generation, which often decides to postpone retirement. This kind of postponement of retirement is among the factors that saved the nuclear industry facing severe skill shortages in the Western world.”

In the U.S., the DOE “predicts that by 2035, we will need hundreds of thousands of additional workers in the workforce,” noted Erin Hultman, NEI's vice president of Human Resources & Finance, and Chief Financial Officer. “A typical nuclear energy plant employs 500 to 800 individuals. So, that's a lot of different types of skills that we need. The skilled trades are of critical importance. We need mechanics, electricians, carpenters, welders. We need IT [information technology] and cybersecurity professionals. And just like any business, we need accountants, human resource professionals, and administrative support. There's room for everyone.”

To address growing workforce needs, the nuclear industry is placing a strong focus on knowledge transfer and training. Programs that promote mentorship are helping bridge the skills gap by ensuring experienced workers can pass down essential expertise. EPRI also emphasizes the role of digital tools in capturing critical procedural knowledge, including through AI, which supports real-time decision-making and smooth transitions for new staff. Additionally, automation is poised to streamline routine tasks.

The commercial industry is already playing its part. “In some cases, when operators have a shortage of trained staff in certain areas, Trillium has stepped in and become embedded within customer organizations,” the company noted. “We then redeploy when those roles are filled, supporting the upskilling efforts in some cases. Additionally, in the UK, for instance, Trillium is actively developing a concept for country-wide training academies and has a regular annual intake of apprentices and school leavers.” ■

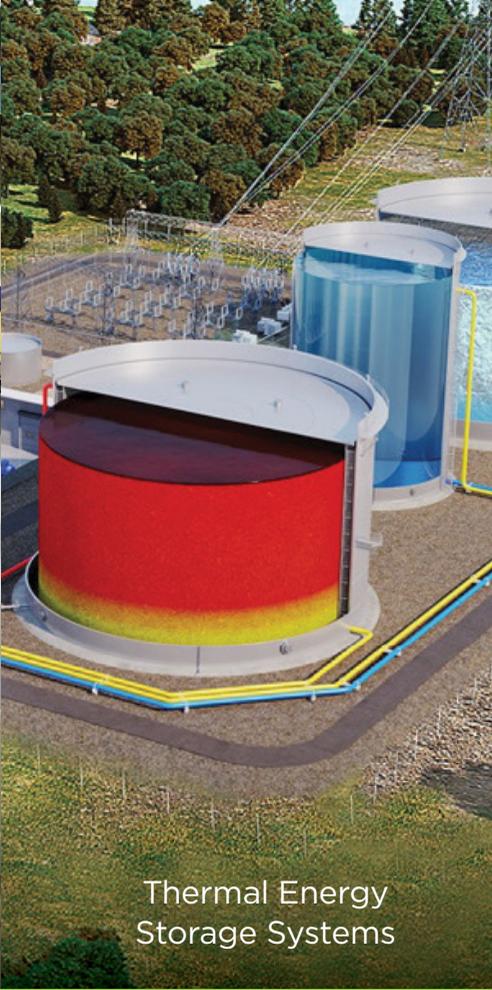
—**Sonal Patel** is a *POWER* senior editor.



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AP300 SMR

Mobility, Flexibility, Scalability: SMRs Forging Nuclear's Future

The need for emissions-free power generation, along with the ability to provide more power when and where it's needed, is driving research and development of smaller nuclear reactors.

Darrell Proctor

Energy industry analysts have said nuclear power will be important as part of the move toward zero-emissions electricity generation. They also agree that finding scalable nuclear solutions is key for providing the needed energy in a faster, lower-cost fashion.

Small modular reactors (SMRs), generally considered those with a generation capacity of 300 MW or less, and smaller microreactors are touted as a way to support a more rapid buildout of nuclear power. Countries around the world are looking at projects to install SMRs, particularly as scientists and engineers continue to work on the technology and investors pour money into research and development (R&D).

The goal is to prove the viability of SMR technology, and enable large-scale production of units that can provide power when and where it's needed, at less expense—and in less time—than building utility-scale reactors.

"SMRs represent a serious next step in nuclear technology developments designed to give a far more flexible, cost-effective, and inherently safer answer to nuclear power," said Brandon Young, CEO at Utilities Now, a Texas-based retail electricity provider. "As of now, Russia and China are leading the charge in SMR deployment. Both countries have successfully brought four SMRs into operation. Russia, with its floating nuclear power plant *Akademik Lomonosov* [Figure 1], has been a pioneer in this field, demonstrating not just the feasibility but also the commercial viability of SMRs in remote regions. China, too, has capitalized on its robust manufacturing and regulatory environment to deploy SMRs quickly."

Young told *POWER*, "In contrast, the U.S. and Canada, despite being home to some of the most advanced nuclear technology companies, have lagged behind in terms of deployment. The reasons for this delay are multifaceted. Both countries have stringent regula-



1. The *Akademik Lomonosov* floating nuclear power plant, equipped with two KLT-40S reactors, was fully commissioned in 2020. Courtesy: Rosatom

tory frameworks designed to ensure the highest safety standards, which, while crucial, have also slowed the pace of deployment. Moreover, the emphasis on 'getting it right' means that U.S. and Canadian companies often engage in extended periods of design refinement, testing, and public consultations before moving forward."

The Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy (ADVANCE) Act, enacted in July, followed the U.S. Department of Energy's (DOE's) announcement in June of as much as \$900 million in funding for SMR deployments. The money comes from the Bipartisan Infrastructure Law signed by President Biden in 2021.

Mission-critical sites such as military bases and data centers are increasingly considering the potential of nuclear power to supply baseload, flexible, and carbon-free power for operations. Companies such as Microsoft, Google, and Amazon Web Services are working on SMR deals for future facilities to provide power for technology around artificial intelligence (AI).

A report from BMI, a unit of Fitch Solutions, earlier this year said the group "anticipate[s] that Small Modular Reactors will become key in transforming the global nuclear landscape. Gaining international support, SMRs are set to be vital for low-carbon baseload in markets pursuing cleaner energy sources." The report added, "SMRs in our Key Projects

Database (KPD) are set for completion within the next decade, accounting for just under 4% of all nuclear projects in the planning or construction phase, with a combined capacity of 10.85 GW."

The BMI report said four countries, led by Canada and Poland, are leading the market for SMRs, with the U.S. and France also showing commitments to the technology. BMI also noted that "markets such as China and Russia are leading the charge in SMR development. China is making significant strides with its HTR-PM pebble bed modular reactor, while Russia has advanced with the deployment of its floating nuclear power plant, the *Akademik Lomonosov*."

Debate About Economics

Not everyone agrees with the promise of SMRs. The Institute for Energy Economics and Financial Analysis (IEEFA), a group that examines issues related to energy markets, trends, and policies, in a report earlier this year said SMRs are still too expensive, too slow to build, and too risky to play a significant role in transitioning away from fossil fuels.

"A key argument from SMR proponents is that the new reactors will be economically competitive. But the on-the-ground experience with the initial SMRs that have been built or that are currently under construction shows that this simply is not true," said David Schlissel, IEEFA director of resource planning analysis and co-author of the report, published in May and titled, "Small Modular Reactors: Still Too Expensive, Too Slow and Too Risky."

The IEEFA in the report wrote, "The experience of other reactor projects has repeatedly shown that further significant cost increases and substantial schedule delays should be anticipated at future stages of project development. Finally, IEEFA questions the assertion by SMR advocates that costs will decline as more reactors of a given design are brought online, leading to what is known as a positive learning curve. The U.S. nucle-

ar industry has never shown a positive learning curve. Instead, it has repeatedly shown a negative learning curve where the cost of new reactors continued to rise, even as more were built." The report continued, "And any positive learning curve achieved in building SMRs will depend heavily on how many of each design are built. The International Atomic Energy Agency estimates that there are about 80 SMR designs currently being proposed and marketed worldwide, making it highly uncertain how many of each design will be constructed. Too few, and there may not be any cost savings over time, and there may also be no economic justification for modular construction in a factory."

The folks making financial decisions, though, appear to see the promise of SMR deployment. Several well-known energy companies, such as Westinghouse, GE Hitachi Nuclear Energy, and Russia's state-owned Rosatom, along with national laboratories in both the U.S. and Canada, are heavily involved in R&D of SMR technology. Allied Market Research earlier this year released a forecast that said the SMR market could grow up to 9% annually, and be worth at least \$13.4 billion by 2032.

Jigar Shah, director of the Loan Programs Office at the DOE, told *POWER* recently that the agency is "very excited about small modular reactors." Shah, whose office makes loans and loan guarantees available to help deploy a wide variety of energy and other projects in the U.S., said SMRs are attractive because "bite sizes are more affordable for the utilities," as opposed to the cost of a utility-scale nuclear plant. Shah said, though, his office and the DOE are involved in supporting large-scale nuclear projects as well as smaller ones, saying, "We want to support what it takes to build these projects, whether it's a nuclear power plant or producing stable

aviation fuel."

Shah said SMRs could be a faster and more cost-effective solution at many sites, including where transmission infrastructure already exists—such as at retired coal-fired power plants.

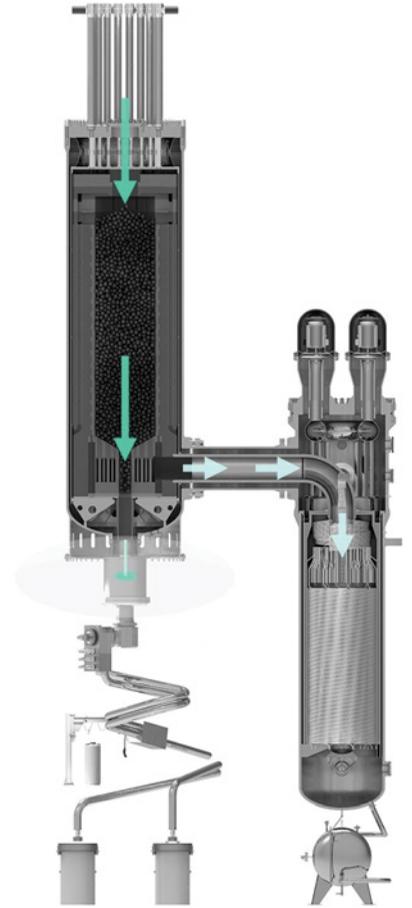
"We definitely need to look at putting nuclear power plants at these existing coal plants," said Shah. "It's very clear that we need to [take advantage of existing infrastructure] in the constraints of our system." Shah added, "We're looking for solutions to how we meet load growth on the distribution grid. We can handle 65,000 new megawatts at those [decommissioned] sites."

Shah also noted the rise of AI and data centers, and their impact on power demand, which has led to tech companies inking deals with SMR developers to provide electricity for their energy-intensive operations. "There's a hunger to find people who are willing to pay a premium for 24/7 clean, firm power," said Shah.

Varied Technologies

Several companies are involved with developing SMR technology, including established nuclear power developers such as Westinghouse. The company calls its AP300 "the most advanced, proven and readily deployable SMR solution."

Westinghouse said the 300-MW AP300 (Figure 2) "is based on the licensed and operating AP1000 pressurized light water technology that has demonstrated industry leading reliability." The AP1000 technology is used in two reactors that came online at Plant Vogtle in Georgia over the past several months, representing the first utility-scale new-build nuclear power plant in the U.S. in decades. Westinghouse has said, "The AP300 SMR is the backbone of a community clean energy system. Flexible performance provides a proven capability to stabilize modern renewable heavy electric grids, including fast load



3. This graphic shows the inner workings of X-energy's Xe-100 small modular reactor (SMR). Courtesy: X-energy

change capabilities to support variations in demand. Includes additional capability to support district heating, desalination, and hydrogen production."

Westinghouse also is developing the eVinci microreactor, which the company said "can produce 5 MWe with a 15-MWth core design. The reactor core is designed to run for eight or more full-power years before refueling." It has said the eVinci is "fully factory-assembled and transportable in shipping containers via rail, barge, and truck. Above-ground installation requires minimum ground disruption with less than a 2-acre footprint."

X-energy is developing its Xe-100 (Figure 3) advanced SMR along with TRISO-X fuel. Each reactor unit is engineered to provide 80 MW of electricity, according to X-energy, which said the design "is optimized in multi-unit plants ranging from 320 MW to 960 MW. The innovative and simplified modular design is road-shippable and intended to drive geographic scalability, accelerate construction timelines, and create more predictable and manageable construction costs."



2. The Westinghouse AP300 reactor is based on the company's AP1000 pressurized light water technology. Courtesy: Westinghouse



4. This rendering shows a power station with Kairos Power's FHR reactor technology. The company is building a demonstration reactor at a technology park in Oak Ridge, Tennessee. Courtesy: Kairos Power

Tech company Amazon in October announced it had led a \$500 million financing round for X-energy. The groups said the investment "will help meet growing energy demands by funding the completion of X-energy's reactor design and licensing as well as the first phase of its TRISO-X fuel fabrication facility in Oak Ridge, Tennessee," adding that "the funding will support future carbon-free projects that will use X-energy's Xe-100 advanced small modular nuclear reactors."

Kam Ghaffarian, founder and executive chairman of X-energy, said, "The investments from Amazon, our Series C-1 funders, and valued partners like Dow and the U.S. Department of Energy underscore X-energy's leadership in commercializing SMR technology and delivering the clean, safe, affordable, and reliable power our world needs now. Reaching this milestone is a testament to the dedication of the X-energy team and the essential energy solutions we've built. We remain focused on bringing our advanced reactor technology to market, enabling a future powered by sustainable, zero-carbon energy."

Kairos Power, headquartered in California and with offices in other cities including Oak Ridge, Tennessee, in October signed corporate purchase agreements to provide energy for tech giant Google. The group said it would purchase nuclear energy "from multiple small modular reactors to be developed by Kairos Power. The initial phase of work is intended to bring Kairos Power's first SMR [Figure 4] online quickly and safely by 2030, followed by additional reactor deployments through 2035. Overall, this deal will enable up to 500 MW of new 24/7 carbon-free power to U.S. electricity grids and help more communities benefit from clean and affordable nuclear power."

Kairos Power said its "FHR (KP-FHR) is a novel advanced reactor technology that leverages TRISO fuel in pebble form

combined with a low-pressure fluoride salt coolant. The technology uses an efficient and flexible steam cycle to convert heat from fission into electricity and to complement renewable energy sources." Kairos' demonstration reactor, known as Hermes, is sited at the East Tennessee Technology Park in Oak Ridge. The company said, "Hermes will be designed to achieve a thermal power level of 35 MWth, compared to 320 MWth for Kairos Power's future commercial reactors."

NuScale's VOYGR SMR plants (Figure 5), powered by the NuScale Power Module, were the first SMR to receive design approval from the U.S. Nuclear Regulatory Commission (NRC). The NuScale Power Module design is based on proven pressurized water-cooled reactor technology, and was developed to supply energy for electrical generation, district heating, desalination, commercial-scale hydrogen production, and other process heat applications.

Fluor Corp. in July announced the company had signed a contract with RoPower Nuclear for Phase 2 front-end engineering and design (FEED) work at an SMR facility in Doicești, Romania. Fluor completed Phase 1 FEED work late last year.

The project will utilize NuScale Power's SMR technology. A contract signing ceremony took place during the Partnership for Transatlantic Energy and Climate Cooperation summit in Bucharest, Romania, on July 24. The event included representatives from Fluor and NuScale, as well as Romanian Minister of Energy Sebastian Burduja and Energy Secretary Jennifer Granholm. The project has received substantial support from both the Romanian and U.S. governments.

"We are pleased to continue our role in supporting this important project to deploy the next generation of nuclear power to produce clean and reliable

baseload electricity for Romania and Europe," said Pierre Bechelany, president of Fluor's combined liquefied natural gas (LNG) and Power business line. "When completed, this facility will be the first of its kind in Europe." Fluor's Phase 2 FEED work will customize a six-reactor SMR power plant with NuScale technology, capable of producing up to 462 MW of power. Fluor is the majority investor in NuScale.

The Romania project is among nine chosen in October for support by the European Industrial Alliance on Small Modular Reactors. The alliance said it will support research as part of its project working groups, or PWGs, a first step toward the alliance's goal of deploying SMR technologies across Europe by the early 2030s. The alliance is a public-private platform launched by the European Commission in February of this year. It picked the projects from a pool of 22 applications. The group said the nine projects are: EU-SMR-LFR project (Ansaldo Nucleare, SCK-CEN, ENEA, RATEN); CityHeat project (Calogena, Steady Energy); Project Quantum (Last Energy); European LFR AS Project (newcleo); Nuward (EDF); European BWRX-300 SMR (OSGE); Rolls-Royce SMR (Rolls-Royce SMR Ltd.); NuScale VOYGR SMR (RoPower Nuclear S.A.); and Thorizon One project (Thorizon).

Design and Construction

Louis Shoukas, chief nuclear officer for PCL Construction, a group that works on a variety of projects, told *POWER* his company "is engaged with Ultra Safe Nuclear Corporation [USNC] for module fabrication, reactor vessel fabrication, and site construction and installation of the nuclear and conventional power plants." He said PCL also is working with X-energy in support of policies around emissions reduction in Canada, along with the "Reshaping Energy Systems grant



5. NuScale's VOYGR small modular reactor was the first SMR to receive design approval from the U.S. Nuclear Regulatory Commission. Courtesy: NuScale

[a Canadian program] that X-energy was awarded to evaluate their technology from a cost, schedule, and construction perspective for a site in Alberta, Canada.”

Shoukas noted that USNC, which filed for bankruptcy in late October, has a project deploying its technology at the Chalk River Canadian Nuclear Laboratories site in Ontario, and is in the regulatory process to obtain a license to prepare the site with a target of full operation in 2028. USNC executives said the company “will maintain full operational continuity across its projects,” so the bankruptcy may not impact Chalk River.

Shoukas added that while X-energy does not presently have a project to deploy a reactor in Canada, the company is working with Dow Chemical as part of the DOE’s Advanced Reactor Deployment Program to deploy a first commercial application in Seadrift, Texas, by the end of the decade.

Shoukas told *POWER* that R&D of SMRs has many challenges, including financial considerations. “New reactor technologies will have FOAK [first-of-a-kind] cost challenges. To create a path for commercialized deployments, it is critical that FOAK nuclear projects receive financial support from various sources, including the government.” He said PCL is a partner with X-energy and USNC “in the early stages of design to provide construction input to ensure our construction knowledge is incorporated such that it leads to a design that is low cost and easily constructible.”

Shoukas said the USNC project “fits on two acres and produces 15 MWe per reactor for a two-unit site. X-energy’s Xe-100 fits on three to four acres and produces 80 MWe. The standard design is commonly a four-pack, which is 320 MWe.” Shoukas said both reactors use TRISO fuel. “Both designs, USNC and Xe, can produce high-pressure and high-temperature steam, making them great candidates for industrial companies that use steam in their processes.” In addition to conventional electrical generation, other uses include inside-the-fence electrical generation to feed industrial companies, such as data centers, desalination plants, and so on. Their distributed generation ability makes them easily deployable to any market.

“These new advanced reactors are based on TRISO fuel (Figure 6), which is not readily available at the higher uranium contents required,” said Shoukas. “This is a major development that has to be ready for the unit to go online. USNC



6. *TRi-structural ISOtropic particle fuel, or TRISO fuel, is a small, robust nuclear fuel made for use in advanced reactors, including SMRs and microreactors. Source: U.S. Department of Energy*

is producing TRISO under its patent, and X-energy is also developing its own fuel. Reactors like GE Hitachi’s BWRX-300 and ARC Clean Energy’s ARC-100 already have an established fuel supply. Terrestrial also has to perform a fuel qualification process.”

Shoukas added, “These advanced reactor vessels are built to new codes and standards. There is a significant investment from the supply chain, like PCL, to become qualified for these new standards, which are costly and take at least a year or more to establish. Aside from that, there are a limited number of suppliers around the world that supply and fabricate vessels under these new codes. With the resulting increase in demand, there will be a bottleneck in the supply chain’s manufacturing, delivery, and installation portions in the coming years.” Shoukas also noted that “The licensing process is a significant cost and a four- to five-year process that must be completed prior to construction permits being awarded and the plant can begin to operate.”

Jag Singh, regional sector lead for Clean Generation at Stantec, an engineering, architecture, and environmental consulting company, told *POWER*, “Stantec is engaged with several vendor and utilities within the SMR arena. The basic premise around effective SMR deployment is implementing a ‘standard design’ into a specified site. Stantec’s role within the SMR industry is to execute the site-specific design and engineering.”

Singh listed nearly two dozen cost considerations for SMRs, including upfront R&D, site works and building construction, equipment manufacturing and testing, and off-site modular factory acceptance testing. Other costs include securing the fuel supply, its route to the site, the electrical switchyard, and waste management.

Said Singh, “I believe that SMRs will

be a part of the future as a clean energy source for grid supply and industrial applications providing stable baseload electricity and heat. For the technology to be rapidly deployed and truly successful, it is imperative that nuclear regulatory approvals are expedited, and public funding sources are secured, to propel the industry onwards. Once the first-of-a-kind SMR plants have been deployed successfully, the Nth-of-a-kind will become significantly more attractive and cost-effective.”

Use Cases

Oklo, a California-based nuclear technology group, in a financial update in August of this year said its customer pipeline has grown 93% to 1.35 GW year-over-year, as of July. The company said most of the agreements have been non-binding letters of intent and term sheets that Oklo hopes to turn into new power purchase agreements (PPAs). The company said most of the new customer demand is coming from the data center sector.

Oklo, which wants to commission a commercial-scale version of the company’s Aurora reactor (Figure 7) at Idaho National Laboratory in the next few years, has said that project would represent the first advanced nuclear reactor completed in the U.S. The company has been working on microreactors ranging from 15 MW to more than 50 MW in generation capacity. It is still waiting on approval for a combined license from the U.S. Nuclear Regulatory Commission (NRC), in which the NRC would combine its review of “the applicant’s qualifications, design safety, environmental impacts, operational programs, site safety, and verification of construction” into a single process. Oklo in a shareholder letter earlier this year said the company has engaged with the NRC since 2016, longer than any other non-water-cooled advanced reactor company. The agency in 2022 denied Oklo’s application for a



7. Oklo has said its Aurora reactor, notable for its distinct architecture that some compare to a ski chalet, would represent the first advanced nuclear reactor completed in the U.S. Courtesy: Oklo

smaller 1.5-MWe reactor design.

Oklo has a signed PPA deal with Diamondback Energy to electrify that company's Permian Basin oil and gas operations; oil and gas exploration companies in recent years have discussed using SMRs to power field operations, in much the same way some sites use renewable energy resources to power drilling rigs and compressor stations. The company in a recent shareholder presentation said its technology's levelized electricity costs would range from \$40/MWh to \$90/MWh, which would be competitive—and in some cases less—than other DOE-estimated per-MWh costs for generation from sources such as natural gas, other advanced nuclear, and renewable energy plus storage.

NANO Nuclear Energy, a microreactor developer, purchased land around Oak Ridge in eastern Tennessee earlier this year, a site where the company plans to build its technical headquarters. James Walker, the company's CEO, has said NANO wants to build deconversion and fuel fabrication facilities as well as develop its SMR technology.

Walker told *POWER*: "We're pioneering a new approach to small modular reactors with our proprietary reactor design. Our focus is on the ZEUS [Figure 8], a micro modular reactor that is designed to be versatile, scalable, and deployable in remote locations. ZEUS represents a significant leap forward in nuclear technology, emphasizing safety, efficiency, and adaptability. We're incorporating advanced materials and cutting-edge nuclear fuel technology to ensure that our reactors are not only compact but also

capable of running efficiently in a variety of environments."

Walker, originally from the UK and working in both Canada and the U.S., said his company is "targeting the early 2030s for the commercial operation of our reactors. Currently, we're deep into the R&D phase, and have started physical test work to begin collecting the data for the licensing process and ensure our technology meets all safety and operational standards. The timeline includes rigorous testing and validation phases, which are critical to delivering a product that our customers can trust. Our goal is to have a fully functional product by the early 2030s."

Walker said his company's reactor will use high-assay low-enriched uranium (HALEU, see sidebar) as fuel, which offers a higher energy density compared to traditional nuclear fuels. "HALEU is particularly well-suited for SMRs due to its efficiency and the smaller volume of

waste it produces. Additionally, the use of HALEU allows for longer intervals between refueling, which enhances the overall operational efficiency and lowers costs over the reactor's lifespan," Walker said.

NANO's ZEUS reactor is designed to be incredibly compact, making it ideal for deployment in confined or remote locations, according to the company. Despite its small size, ZEUS and ODIN are engineered to deliver a generation capacity of up to 5 MWth, which is substantial for a micro modular reactor. "This makes it versatile enough to power small communities, industrial sites, or even support disaster recovery efforts," the company said.

Walker told *POWER*, "The practical applications for our ODIN and ZEUS reactors are extensive. It's designed to provide reliable, off-grid power for remote and island communities, military bases, and industrial operations such as mining and oil extraction."

Putting SMRs at Palisades

Holtec International, involved in restarting the Palisades nuclear power station in Michigan, also is talking about putting SMRs at that site to provide even more energy. Dr. Kris Singh, Holtec's CEO, said, "Siting the first two SMR-300 units at Palisades eliminates the delays associated with erecting the plant at an undeveloped property and confers the many benefits of synergy that accrue from the presence of a co-located operating plant—including shared infrastructure and operational expertise, enhancements to grid stability, and resource optimization. By building at our own site with our own credit and our own at-risk funds, we hope to deliver the dual-unit SMR-300 plant within schedule and budget—an outcome that has eluded our industry



8. The ZEUS micro modular reactor, developed by NANO Nuclear Energy, is designed for use in rural areas among other locations. Courtesy: NANO Nuclear Energy

Fueling the Growth of SMRs

Several companies are working on the design and development of small modular nuclear reactors (SMRs). Part of that work involves the production of fuels necessary to operate those units.

One of the groups working in the fuels space is ASP Isotopes (ASPI), a company with its roots in South Africa's uranium enrichment program in the 1980s. The group today works in the medical and semiconductor fields, and is involved in the development and production of advanced nuclear fuels.

Viktor Petkov, the company's vice president of funding and business development, provided *POWER* with insight about his company's operations and how ASPI works with SMR designers and developers.

POWER: What current technology is your company working on with regard to supporting the market for SMRs?

Petkov: ASP Isotopes (ASPI) is focusing on producing critical nuclear fuels necessary for the operation of small modular reactors. These include HALEU (High-Assay Low-Enriched Uranium), Lithium-6 and Lithium-7, Chlorine-37, and Thorium Fluoride. Currently, there is no Western producer of HALEU, which poses a significant risk to the deployment and viability of SMRs. By developing a reliable supply chain for these fuels, ASPI aims to address this challenge and support the growth of SMR technology in the energy sector.

POWER: Do you have a timeline for commercial operation of your technology?

Petkov: Our technology is fully prepared for deployment, pending the necessary approvals to operate an isotope enrichment facility. We are targeting 2025/2026 for the production of Lithium-6 and Lithium-7. ASPI is actively engaged in discussions with multiple governments to secure authorization for the construction of a uranium enrichment plant, which will produce HALEU. Once the required

permits are obtained, we anticipate that the facility could be operational within 12 to 18 months.

POWER: What financial considerations must be accounted for prior to, and during, the development process?

Petkov: In nuclear fuel production, the key financial considerations revolve around capital expenditures for the procurement, manufacturing, and assembly of specialized equipment. At ASPI, we handle the in-house fabrication of certain components, such as separators, while sourcing other essential parts like compressors, heat exchangers, and valves from the broader market. Once operational, the primary ongoing costs include electricity, feedstock, labor, and facility rental.

POWER: Is your company working with partners on development of your fuels for SMRs?

Petkov: We are working in a close partnership with several SMR developers for establishing a reliable supply chain for the nuclear fuels of the future. ASPI will be capable of producing a range of fuels for use in SMRs and molten salt reactors such as HALEU, Lithium-6 and Lithium-7, Chlorine-37, and Thorium Fluoride.

POWER: What do you see as the practical applications of the SMRs that will use your company's fuels?

Petkov: ASPI is collaborating with multiple SMR manufacturers, each offering reactors of varying sizes and generation capacities. Some of these reactors are designed to power large communities and contribute to the broader energy grid, while others are better suited for more specialized applications, such as data centers, factories, and other commercial and industrial facilities. We aim to build a reliable and cost-effective supply chain for the nuclear fuels essential to SMR manufacturers, positioning ourselves as an indispensable partner in their success.

POWER: What safety features are you incorporating into your technology?

Petkov: Our isotope enrichment technology is classified as dual-use, meaning it is subject to protection and oversight by the Non-Proliferation Council and the International Atomic Energy Agency (IAEA). We strictly adhere to the highest safety standards, and our facilities undergo regular inspections by the nuclear regulatory authorities to ensure full compliance.

POWER: How will your company address environmental radiation and nuclear waste? Are there regulatory hurdles for your technology?

Petkov: The use of our technology does not generate radiation or nuclear waste. In fact, we aim to repurpose nuclear waste, such as depleted uranium tails, as feedstock for the production of HALEU. We are currently awaiting government approval to establish a uranium enrichment facility at one of the selected sites we have identified.

POWER: What is your opinion of the future market for SMRs?

Petkov: We are confident that SMRs will play a pivotal role in the future energy landscape. SMRs have the potential to provide reliable, cost-effective, and low-carbon energy, making them essential for supporting the electricity grid as we transition toward a net-zero future. Their scalability and flexibility make them particularly well-suited for integrating into renewable energy systems, offering consistent power generation to complement intermittent renewable sources like wind and solar.

Additionally, SMRs will be crucial in meeting the increasing energy demands of industries such as large data centers, especially with the growing needs of AI and quantum computing. These reactors can ensure these energy-intensive operations have a dependable and sustainable power supply.

for a long time."

Holtec officials said the company's SMR (Figure 9) has been in development since 2011. The company said, "The SMR-300 reactor is intended to be deployable in virtually any terrain, including those with significant seismic loadings.

The plant is also readily adaptable for diverting all or some of its cycle steam for other purposes such as hydrogen production and industrial thermal needs."

Holtec wants to restart the Palisades nuclear station by the end of next year. The company said it hopes to have the

SMRs approved by regulators, built, and in commercial operation by 2030 or 2031. Holtec also is considering deployment of an SMR at its Oyster Creek site in New Jersey, where the company is decommissioning a nuclear power plant that closed in 2018. DOE officials have said



9. Holtec International wants to put SMRs of the company's design adjacent to the Palisades nuclear plant in Michigan. The company has said it could restart Palisades, which was closed in 2022, by the end of 2025. Courtesy: Holtec International

SMRs at that site could support clean hydrogen generation as part of the Mid-Atlantic Clean Hydrogen Hub.

Steady Energy, a Finnish technology company, in October said its LDR-50 SMR can be operational within seven years, complete with all necessary permits, for under €100 million (\$108 million). The company said its reactor could be used for district heating, and "is also suitable for producing industrial steam and desalinating seawater in regions affected by drought." Steady Energy said it has letters of intent and preliminary investment agreements to build 15 to 20 reactors to provide district heating in Kuopio, Helsinki, and Kerava in Finland, and to sell reactors to Sweden.

The company, which plans to begin building a pilot plant in Finland in 2025, in October announced an agreement with Finnish utility Keravan Energia to develop nuclear-powered district heating. Steady Energy said construction of the SMR could begin as soon as 2029, with commercial operation beginning in 2032.

"Think of district heating as a large system of hot water pipes, where heat flows to radiators from a giant boiler, where the heat source now is biomass and peat. While green electricity is a good backup, we need more stable solutions to counter electricity price volatility. A dedicated nuclear heat source, like Steady Energy's reactor, is a very viable option," Keravan Energia CEO Jussi Lehto said.

Steady Energy said its LDR-50 is a 50-MW SMR, specifically designed to produce heat up to 150C (302F). "Heating water to 150 degrees accounts for 10% of global emissions. Our reactor focuses solely on this task, making it possibly the world's simplest commercial nuclear reactor. This design ensures that SMR-produced heat is cost-competitive com-

pared to other alternatives," said Steady Energy CEO Tommi Nyman. Officials said the LDR-50 is the size of a standard shipping container and can be constructed underground.

'Safe, Reliable, and Widely Accepted'

SMR developers know they must address the questions that always surround nuclear power, such as safety and cost. They say the pros outweigh any cons.

"Looking forward, the global market for SMRs is poised for significant growth," said Young of Utilities Now. "The flexibility and reduced upfront capital costs of SMRs make them an attractive option for both developed and developing nations seeking to reduce carbon emissions and meet growing energy demands. In the U.S. and Canada, the focus remains on getting it right rather than getting there first. Companies are working closely with regulators to ensure that once SMRs are deployed, they will be safe, reliable, and widely accepted by the public. This cautious approach could pay off in the long run, as a well-regulated, safe, and efficient SMR technology might become the gold standard worldwide."

Proponents of SMRs tout their safety features, while opponents argue any type of nuclear power is unsafe. It's a debate that's not likely to end soon, if ever, though SMR developers say their technology will prove its viability and be able to ease concerns.

"What makes these reactors safe is the advanced fuel development that prevents uranium in the fuel from reaching its melting point. [These] reactor types don't have any design basis accident scenarios that can melt the fuel," said Shoukas. "As such all the safety systems that are typically present on traditional

reactors are not required. During events, these reactors don't have any operator intervention for at least 72 hours because of the ability to passively cool themselves in the most extreme events."

Those who spoke with *POWER* agreed it's important for Western nations, including the U.S. and Canada, to have lead roles in SMR development. That's of particular importance as rising demand for power, particularly emissions-free generation, puts a premium on clean energy.

Said Young, "The aggressive pace set by Russia and China cannot be ignored. These countries are likely to continue capitalizing on their head start, expanding their SMR fleets and possibly exporting their technology to other nations. This could create a competitive market where countries are faced with choosing between faster-to-deploy but potentially less-regulated technology from Russia and China or the more meticulously vetted SMRs from North America."

Mike Naughton, CEO of Ohio-based energy broker Integrity Energy, said, "While I believe the adoption of SMRs will be a bit slow to start, the future of SMR applications is bright. A modern and reliable electrical grid needs distributed energy resources. Solar and wind power have been great for reducing our carbon footprint, however, SMR technology has the potential to create a carbon-neutral energy system."

Naughton told *POWER*, "While the upfront investment is considerable, nuclear power is inexpensive for consumers and highly reliable. It's an ideal complement to intermittent renewable power and can greatly improve energy access in remote or rural communities. It also offers a quicker path to addressing the growing energy demands from the tech industry. Ultimately, it will take public education and a final pivot in public opinion to foster greater SMR adoption."

Said Shoukas: "As a constructor who has executed heavy industrial work across all major sectors, PCL is well-positioned to deliver energy transition projects. This includes projects where nuclear technology is leveraged for alternative uses such as hydrogen production and desalination. There is a place for these technologies to provide clean, safe, reliable electricity to the industrial sector. There are no greenhouse gas emissions, making it one of the most cost-effective generation [types]." ■

—Darrell Proctor is a senior editor for *POWER*.

Tear It Down or Start It Back Up? Plant Owners Weigh Options Around Retired Reactors

Nuclear power plants are still being dismantled, and the business of decommissioning remains strong, but the need for more baseload power and emissions-free generation has some companies ready to restart idled units.

Darrell Proctor

Policymakers and those involved in the energy industry recognize that demand for electricity is increasing, as are concerns about power generation's impact on climate. Nuclear power is touted as a way to help on both fronts, providing a reliable source of energy and also doing it without harmful emissions.

Decommissioning of nuclear power plants, at times a decades-long process, has long marked the final chapter for atomic facilities. The energy industry has worked to refine the process, one that brings the challenge of safely dismantling a complex structure while also addressing environmental concerns. The need for effective decommissioning also speaks to why plant owners develop a plan for a reactor's end of life even before a unit enters commercial operation.

The International Atomic Energy Agency (IAEA) has said, "Decommissioning refers to the administrative and technical actions taken to remove all or some of the regulatory controls from an authorized facility so the facility and its site can be reused. Decommissioning includes activities such as planning, physical and radiological characterization, facility and site decontamination, dismantling, and materials management." The group adds, "Decommissioning is a normal part of a nuclear facility's lifetime and needs to be considered at the earliest stages of its development."

Today, though, there's another discussion. Why tear down a nuclear power plant when its units could be restarted, at a time when more electricity—particularly emissions-free power—is sorely needed?

At least three U.S. plants have been mentioned as restart candidates, and Ali Zaidi, the White House climate adviser, last month said the Biden administration is working on plans to bring additional re-



1. The Palisades nuclear power plant on the shore of Lake Michigan was closed in 2022. Holtec International was preparing to decommission the facility, but instead now plans to restart operations sometime in 2025. Courtesy: Energy

actors back online to help meet soaring demand for emissions-free electricity.

The Palisades nuclear plant in Michigan (Figure 1) could restart as soon as next year. Constellation Energy is working toward a restart of a unit at Pennsylvania's Three Mile Island as part of a deal with Microsoft. And NextEra Energy has discussed bringing the Duane Arnold plant in Iowa back online. Zaidi, speaking at conference in New York on Oct. 7, and asked whether more closed plants could be restarted, said, "We're working on it in a very concrete way. There are two that I can think of," although he would not identify the facilities.

Dissecting Decommissioning

There are many steps that must be taken to decommission and dismantle a nuclear power plant, all with significant costs (which also may factor into restart decisions). Those who spoke with *POWER* about the process agreed it's a time-con-

suming task, and safety must be a priority.

A company in charge of decommissioning will develop a plan that outlines the process, along with a timeline, which usually involves years of work. In the U.S., the Nuclear Regulatory Commission (NRC) oversees the entire process.

Power plant operators today are weighing the costs, and the timelines, as they look at whether tearing down a closed facility makes sense.

"The decommissioning of nuclear plants is a complex and expensive process that can take decades. It's safety-related, but there's the challenge of storing and adequately recycling radioactive waste, reusing the land on which these power plants sit, and otherwise dealing with the spent [fuel and equipment]," said Andrei Marveaux, an energy analyst involved with optimizing electricity use, and managing director at Solartech Solutions/The Home Upgrade. "As more nuclear plants reach

Zion Nuclear Power Station

It's been a year since the U.S. Nuclear Regulatory Commission (NRC) released for "unrestricted use" most of the land on and around where the Zion Nuclear Power Station operated in northern Illinois, along the shore of Lake Michigan. The plant, located about 40 miles north of Chicago and 42 miles south of Milwaukee, Wisconsin, served the Chicago area. The plant's decommissioning has served as one of the more high-profile case studies of a nuclear shutdown project due to the plant's proximity to two major metropolitan areas.

Zion had two pressurized water reactors that were in service from 1973 until 1997. Commonwealth Edison, the plant's operator, permanently shut the plant in 1998. The NRC in November 2023 said any residual radiation is below the NRC's limits, and the agency will no longer put regulatory controls on the property—save for about five acres that are home to the plant's independent spent fuel storage installation, or ISFSI, which will remain under NRC license and oversight.

Zion's licenses in 2010 were transferred from Exelon Generation, now Constellation Energy, to ZionSolutions, which is a subsidiary of radioactive waste disposal company EnergySolutions, headquartered in Salt Lake City, Utah. ZionSolutions completed the majority of Zion's decommissioning work by 2019; the NRC approved the transfer of Zion's licenses back to Constellation that same year, on the condition that the site's final status surveys were completed to the satisfaction of the agen-



2. ZionSolutions, part of Utah-based EnergySolutions, worked on the decommissioning of the Zion nuclear power plant in Illinois. The station operated from 1973 to 1997. Source: U.S. Nuclear Regulatory Commission

cy. The NRC did find some radioactive contamination at the site, which required additional remediation and delayed the final status survey reviews. The NRC said the radiation was found in particles released from Zion's containment buildings (Figure 2), and the fuel handling building, during decommissioning work.

The NRC on Nov. 8, 2023, told ZionSolutions it had completed its review of the survey reports. The agency said it found "reasonable assurance" that the residual radioactivity at the site met the agency's radiation protection standards. The transfer of the ISFSI license to Constellation, just days after the NRC completed its review in November 2023, means Constellation is responsible for the security and protection of the spent fuel at the site, until an off-site storage facility or permanent disposal site becomes available.

James Walker, CEO and head of Reactor Development and a board member at NANO Nuclear Energy, told *POWER*, "Decommissioning is essential to protect public health by removing or safely containing radioactive materials. If not properly managed, residual radioactivity could pose serious health risks to the surrounding community, including potential contamination of air, water, and soil."

Walker noted that "the plant operator must adhere to strict regulatory requirements set by national nuclear safety authorities. This involves submitting a decommissioning plan, which details the approach, timelines, and safety measures."

The IAEA has defined three options for decommissioning. The group said

these definitions have been adopted as international standards.

One option is immediate dismantling, or early site release, often called DECON. The U.S. Energy Information Administration (EIA) calls DECON a "relatively faster method of decommissioning a nuclear reactor and involves removing all fuel and equipment from the power plant. The fuel and equipment represent the bulk of the irradiated material on the site and are removed for separate storage and decontamination. DECON can take at least seven years and allows for the relatively quick return of the land for reuse."

Safe Enclosure, also known as SAFSTOR, is what the NRC defines as a facility "placed and maintained in a condition that allows the facility to be safely stored and subsequently decontaminated [deferred decontamination]." The IAEA has said this option allows a longer period for the final removal of controls at a site, for as much as 40 to 60 years. The EIA said the SAFSTOR timeline "allows for up to 50 years of containment followed by up to 10 years for decontamination." A facility placed in a safe storage configuration is dismantled, and decontaminated, after residual radioactivity has decayed. Industry experts note that this could increase the costs of decommissioning a site, and also have said regulatory changes could impact the process.

A facility also can be "entombed." The IAEA says the ENTOMB option "entails placing the facility into a condition that will allow the remaining on-site radioactive material to remain on-site without ever removing it totally." Entombment—which the EIA said is not used in the U.S.—usually means the size of an area of radioactive material is reduced as much as possible, with the affected area then encased, usually in concrete. Officials said this is done to limit exposure to remaining radioactivity. The Chernobyl site in Ukraine is an example of a reactor that has been entombed.

'No Easy Process'

Stantec is among the companies involved in the decommissioning of energy sites, along with their remediation and restoration.

"Decommissioning a nuclear plant is no easy process. Irradiation and contamination of plant and equipment makes the operation extremely challenging," said Jag Singh, regional sector lead of Clean Generation for Stantec. "Furthermore, the lack of historic data-keeping

the end of their life cycles, decommissioning will become an increasingly relevant issue."

As part of decommissioning, a nuclear facility must be decontaminated to reduce residual radioactivity. That's work that continues as buildings are torn down and other infrastructure is dismantled, with any contaminated materials removed for proper disposal. Used nuclear fuel is removed from each reactor and placed into storage, often onsite and in containers specifically made for that purpose. Some used fuel may be transported off-site to an interim storage facility or reprocessing plant. Once the NRC determines the site is safe, it can be "released" for other uses (see sidebar "Zion Nuclear Power Station").

on older plants makes the spent fuel and waste forms problematic to manage and handle. The essential first step is the decommissioning plan that will outline the process, stakeholders, timelines, strategies, finances, supply chain, and resources.”

Singh told *POWER*, “The environmental and safety assessments are paramount before initiating the actual decommissioning, and feeds into the overall planned shutdown. It’s critically important to plan for the waste management routes as orphan waste forms can be detrimental to the decommissioning of the site. Also, decontamination giving rise to secondary and tertiary waste streams needs to be considered. In fact, these are just a few topics that need to be addressed before the granting of a license to decommission.”

Singh added: “Stakeholder management is key, from the country’s regulator to the local public. A decommissioning project is a very high-profile endeavor that requires meticulous planning and communication.” Singh reiterated that full decommissioning of a nuclear power plant or other nuclear facility can take years. Industry officials have said a nuclear reactor decommissioning typically takes 15 to 20 years, and can cost hundreds of millions or even billions of dollars. A large fuel cycle facility can take even longer, at an even larger cost.

Smaller Reactors

The decommissioning of a research reactor, such as at a laboratory or military base (see sidebar “Fort Greely in Alaska”), also can take several years and cost several million dollars. Officials have said the cost depends on the reactor’s size, purpose, and operational history.

The IAEA has said, “The management approach to the decommissioning of nuclear power plants and other large facilities is broadly applicable to smaller projects,” but also notes, “The decommissioning of small facilities should not be underestimated. Under certain conditions, a small project may face a range of issues as challenging to the licensee or operator as the decommissioning of power reactors is to other licensees. Additionally, since the design intent was often to conduct research or to use radioactive material for medical or industrial applications, decommissioning was rarely a consideration in design or during operation.”

Singh said that in any case, “Timelines are important and decommissioning pro-

Fort Greely in Alaska

Demolition work is proceeding on a reactor facility at the Fort Greely military base in Alaska. Louisiana-based Aptim Federal Services (APTIM) in October 2023 said it was awarded a contract from the U.S. Army Corps of Engineers (USACE)-Baltimore District to decommission and dismantle the 20.2-MW SM-1A Reactor Facility located at Fort Greely, about 175 miles south of the Arctic Circle, near Delta Junction.

The SM-1A (Stationary, Medium Size) is the last remaining nuclear reactor built as part of the Army Nuclear Power Program, which operated from 1954 to 1978. Government officials in 1954 assigned the Army responsibility for “developing nuclear power plants to supply heat and electricity at remote and relatively inaccessible military installations,” according to a memo from the Department of Defense.

The reactor at Fort Greely (Figure 3) was among nine built to serve the Army, Navy, and Air Force. The decommissioning work is part of the USACE Deactivated Nuclear Power Plant Program. Among its most recent projects prior to Fort Greely were the decommissioning and dismantling of the historic 10-MW MH-1A STURGIS barge, the first floating nuclear power station (Mobile High Power Nuclear Reactor 1A). The project was deemed complete when the final section of the STURGIS barge was brought ashore for processing and recycling at the International Shipbreaking facility at the Port of Brownsville, Texas, in 2019.

Decommissioning and dismantling of the 2-MW SM-1 reactor was completed at the end of last year, when the USACE said all large reactor components had been removed from the vapor container structure of the SM-1 on the western shore of the Potomac River at Fort Belvoir, Virginia. The group also said all above-grade demolition was complete.

APTIM said its team will manage the Fort Greely project, and “will integrate and utilize mature, proven innovations to dispose of both hazardous and radioactive soil and debris from the remote Alaskan installation,” transporting it to the U.S. mainland. Initial work involves construction of a weather enclosure to support working



3. Officials with the U.S. Army Corps of Engineers (USACE) meet with prospective decommissioning contractors and others during a site visit in 2019. The SM-1A reactor at the site, which came online in 1962, was Alaska’s only nuclear power plant. Source: Rebecca Nappi/USACE

conditions at the site. APTIM has said it expects to complete the decommissioning project by 2029.

The decommissioning contract was awarded to APTIM-Amentum Alaska Decommissioning LLC (A3D), which is a joint venture led by APTIM and Amentum Technical Services LLC. APTIM said the contract “has an estimated value of \$95.5 million, over a six-year ordering period. The work to be performed under this contract includes planning, permitting, and engineering; site preparation; demolition and disposal of facilities, including components from the deactivated and defueled nuclear reactor, related wells and utility corridors, plus other ancillary facilities. The contract also includes remediation of contaminated soils, a final status survey, and site restoration.”

David Lowe, senior vice president of APTIM’s Nuclear Decommissioning business unit, said at the time of the contract award: “APTIM and our heritage companies have a long history of supporting USACE and the Army Reactor Office (ARO) and have managed numerous Decontamination and Decommissioning projects across the federal complex. Our extensive experience performing reactor decommissioning projects for USACE and the ARO enables us to bring advanced innovations and solutions to complete the work safely and effectively at Fort Greely. We will partner with USACE, regulators, and community stakeholders to eliminate the environmental liabilities of this legacy, aging nuclear facility.”

grams are notoriously long.” It is imperative that the front-end of the program is loaded so that the feed and strategies

are defined and the design activities and plans can progress smoothly.

“In certain cases, the nuclear safety



4. Dry cask storage of spent nuclear fuel is a common practice at decommissioned nuclear power plant sites. Source: U.S. Nuclear Regulatory Commission

case of a plant may limit the amount of time that nuclear material may be able to be contained or handled in the specific medium," said Singh. "And the decommissioning plan must address what must be done to safely secure that medium for the long term."

Singh said Stantec builds "entire specific plants for nuclear decommissioning. This is everything from retrievals to characterization labs to gloveboxes and hot cells. There should be a pre-defined route and waste management strategy for all solids, effluents, and off-gas waste streams. The equipment and plants will be designed and built to facilitate these processes."

Singh said safe decontamination of materials in a nuclear power plant is paramount. "The use of hot cells and gloveboxes with remotely operated equipment is essential," said Singh. "Decontamination may give rise to secondary and tertiary waste routes."

Systematic Dismantling

Walker in his outline of the decommissioning process noted it "involves the systematic dismantling of reactor components, such as the reactor vessel, steam generators, and piping systems. Specialized techniques, including remote-controlled machinery, are often used due to high radiation levels." He said waste segregation is important, with materials "categorized as radioactive or non-radioactive. Radioactive materials are further classified based on their level of radioactivity, guiding their disposal method." A power plant operator also may establish a decommissioning fund to ensure the finances of the process are properly managed and costs are controlled.

Walker told *POWER* that the removal

of spent nuclear fuel "is one of the first steps. Fuel assemblies are typically transferred to onsite spent fuel pools or dry cask storage (Figure 4) until they can be permanently disposed of or reprocessed. All radioactive materials, including contaminated structures and soil, must be safely managed."

Remediation and environmental restoration of a site involves several measures. The site must be "characterized" to identify contamination levels, with that assessment guiding the cleanup process, according to Walker. Soil and groundwater remediation is another step. Said Walker: "Contaminated soil and groundwater are treated or removed to meet regulatory standards for site reuse. The goal is to restore the site to a condition that allows for safe future use, which may include unrestricted use, industrial use, or greenfield status."

Radiation protection programs also are part of a decommissioning, with programs implemented to monitor and minimize radiation exposure for workers. Those onsite will wear personal pro-

TECTIVE equipment, or PPE, and utilize dosimeters, a device that measures radiation. Workers also will undergo regular health monitoring.

Stantec's Singh said it's also important to keep the surrounding community informed of what's happening at a site. "Public engagement is extremely important. The success of these programs is tied to the socioeconomic benefits to, and positive perceptions of, the public," said Singh. "The impact to the local economies is profound and community outreach is essential, from education of the younger generations to the benefits of clean energy and engineering."

Walker agreed with Singh that public outreach is a critical step, telling *POWER*, "The public's safety is prioritized. This involves clear communication about risks, progress, and safety measures, and ensuring that all activities comply with environmental and public health regulations."

A final survey of a decommissioned site is conducted before the NRC will release the property, with the agency ensuring it meets the regulatory criteria for decontamination. The NRC also handles any licensing issues. The agency said about "100 materials licenses are terminated each year. Most of these license terminations are routine, and the sites require little, if any, remediation to meet the NRC's criteria for unrestricted release." Some long-term surveillance of a site, along with monitoring, may be required if radioactive material remains onsite, such as in the case of entombment.

Walker noted another part of the decommissioning process, which he said "can significantly impact the local economy, especially in communities where the plant is a major employer. Planning for economic transition, job retraining, and site reuse is often a critical component."



5. NextEra Energy is exploring a possible restart of the Duane Arnold nuclear power station in Iowa. The plant was taken out of service in 2020. Courtesy: NextEra Energy

Dismantle? How About Restart?

Talk of decommissioning nuclear power stations, at least in the U.S., has turned to restarting closed facilities. Holtec International, which acquired the shuttered 800-MW Palisades nuclear plant in Michigan after Entergy—citing poor economics—closed the power station in 2022, could be the first U.S. nuclear power plant to restart after decommissioning. Holtec has said Palisades could return to service as soon as late next year.

NextEra has said it is exploring the restart of the 615-MW Duane Arnold nuclear plant in Iowa (Figure 5), which was taken out of service in 2020. Constellation Energy has said it could restart a reactor at the Three Mile Island (TMI) site in Pennsylvania, famously the location of a partial meltdown of Unit 2 at the site in 1979. Unit 1 at TMI, which came online in 1974 and remained in operation after Unit 2 was closed, was taken offline in 2019. Constellation and Microsoft in September of this year signed an agreement in which the tech giant would use the electricity from a restarted 835-MW Unit 1 to power its data center operations.

Jeffrey Jakubiak, partner of Energy Regulation at Vinson & Elkins law group, told *POWER*: “The restarting of nuclear facilities is precisely what needs to get done to meet the rapidly growing energy demand in the face of carbon reduction goals. Wind and solar generating facilities are increasingly difficult to site and connect to the grid. So, the best and fastest path to increasing carbon-free generation at this point is restarting nuclear facilities.”

With the U.S. government helping fund restarts, and also supporting a buildout of new nuclear power resources, plant owners are reconsidering their options. Steve Everley, senior managing director in FTI Consulting’s Energy and Natural Resources practice, told *POWER* restarts make sense in the current energy landscape.

“What’s driving this? For one, rapid load growth from data centers, AI [artificial intelligence], and advanced manufacturing, as well as electrification efforts. Major grid managers are warning of price spikes in the years ahead because of growing demand and limited supply,” said Everley. “It’s not a simple process in an absolute sense, but shifting from decommissioning to restart for nuclear power plants may be the best option in some areas, since no other power source can provide the same volume of reliable power (i.e. 92% capacity factor) as nuclear.”

Everley added, “The other factor is climate policy, specifically aggressive emissions reductions targets. The deployment of wind and solar has been accelerating but is by no means at a pace consistent with meeting climate goals. There has been a dramatic reversal of opinion about nuclear in recent years, given it emits zero CO₂ and can provide baseload power.”

Mike Capone, CEO of Qlik, a Pennsylvania-based software company and AI platform, told *POWER*: “Amazon, Google, and Microsoft’s investments in nuclear energy highlight how the future of AI depends on building sustainable, reliable infrastructure. These long-term investments signal confidence in AI’s enduring role in the market.”

“There’s also a win-win here—AI can drive efficiencies that help reduce waste, optimize energy use, and accelerate breakthroughs in sustainability. It’s a strategic loop: clean energy powers AI, and AI, in turn, finds smarter ways to manage and reduce energy consumption. This is where the intersection of technology and sustainability can truly shine, leading to a future where innovation and responsibility go hand in hand.”

Both Amazon and Google are looking at small modular reactors to power data centers, and Amazon Web Services earlier this year acquired a data center campus in Pennsylvania that receives its power from the nearby Susquehanna nuclear power plant.

Palisades, Duane Arnold, or TMI would not be the first U.S. nuclear power plant to return to service after a lengthy closure. Three reactors at the Browns Ferry plant in Alabama were restarted after being shut down in 1985 due to operational

and management concerns. Unit 2 at Browns Ferry was returned to service in 1991, with Unit 3 restarted in 1995. Unit 1 was offline for 22 years before being restarted by the Tennessee Valley Authority in 2007.

DOE Financial Support

The DOE in March of this year announced a \$1.52 billion conditional loan commitment to support the recommissioning of Palisades, and the DOE’s Loan Programs Office announced closure of the loan on Sept. 30. State officials in Michigan also have committed \$300 million to the effort. The U.S. Department of Agriculture in September awarded Michigan-based Wolverine Power Cooperative, along with Indiana-based Hoosier Energy, money from the Empowering Rural America program, a \$9.7 billion fund established by the Inflation Reduction Act, to support buying power from Palisades. The fund is designed to help rural U.S. electric cooperatives transition to clean energy. A Wolverine spokesperson told the Bridge Michigan news service the utility received more than \$600 million from the fund.

Michigan Gov. Gretchen Whitmer has said that by restarting Palisades, “We are showing the world that Michigan will continue to lead the future of clean energy.”

“This loan funding is not only a critical financial milestone but a bellwether for the vital role that nuclear energy will play in securing our clean energy future,” said Dr. Kris Singh, founder and CEO of Holtec International. “The repowering of Palisades is a testament to our dedication to revitalizing the nuclear industry and ensuring a sustainable, carbon-free energy source for



6. Microsoft has a 20-year power purchase agreement with Constellation Energy for electricity from Unit 1 at Three Mile Island in Pennsylvania. Constellation has a plan to restart the reactor, which was shut down in 2019. Source: U.S. Department of Energy

generations to come. It is also a tremendous credit to the strong backing we have received from our partners in the federal government, State of Michigan, local community, and throughout the nuclear industry.”

Several groups have pushed back against a Palisades restart, citing the plant’s history of safety violations, including its designation as one of five commercial facilities with the most “high-level” safety violations, according to a 2013 report from the NRC. The NRC in November of last year established the Palisades Nuclear Plant Restart Panel (PRP), a group whose “primary objective is to proactively identify and promptly resolve any licensing, inspection, or regulatory challenges that concern the Palisades restart. To accomplish this objective, the PRP provides high-level assessments, coordination, oversight, and management direction of NRC activities associated with the licensing, inspection, testing, and operation of Palisades.”

John Ketchum, CEO of NextEra Energy, in June of this year during an investors meeting said, “I think there would be opportunities and a lot of demand from the market if we were able to do something with Duane Arnold.” He said a restart of the plant located in Palo, Iowa, would require examination. “Obviously, bringing back a nuclear plant is ... not something you can do without a lot of thought,” he said. Ketchum noted the company would need to weigh the risks of such a move.

Said Ketchum: “So sure, we’re looking at it, but we would only do it if we could do it in a way that is essentially risk-free with plenty of mitigants around the approach. There are a few things that we would have to work through, but yes, we are. We are looking at it.”

Microsoft has a 20-year power purchase agreement with Constellation for electricity from Unit 1 at TMI (Figure 6). Constellation in a statement said “significant investments will be made to restore” the unit, “including the turbine, generator, main power transformer, and cooling and control systems.” The property will be renamed the Crane Clean Energy Center, with the restart expected in 2028.

Constellation noted, “Restarting a nuclear reactor requires NRC approval following a comprehensive safety and environmental review, as well as permits from relevant state and local agencies. Additionally, through a separate request,

The Situation at Fukushima

Much attention about the cleanup of nuclear power sites in recent years has focused on the Fukushima Daiichi site in Japan. A major earthquake on March 11, 2011, followed by a massive tsunami, knocked out the power supply at the plant, which disabled the cooling of three reactors, with all three cores melting within three days. Japan took its entire nuclear power fleet offline after the disaster, and has only restarted about a dozen facilities in recent years as it has worked to improve safety standards at its atomic power plants.

Decommissioning work at Fukushima (Figure 7) has been ongoing; officials provided an update at the International Atomic Energy Agency (IAEA) General Conference in Vienna, Austria, in September. The Japanese government, the Nuclear Damage Compensation and Decommissioning Facilitation Corp. (NDF), and Tokyo Electric Power Co. (TEPCO), the plant’s operator, are all involved in the work. Officials said the decommissioning of the site and its surroundings is scheduled to be completed by 2051, or 40 years after the cold shutdown of the plant.

Nuclear fuel began being removed from the site in November 2013, with officials noting the process for each reactor is different. Fuel removal from used fuel pools was completed for Unit 4 in December 2014, and for Unit 3 in 2021. Another phase of the process began in September of this year, with the start of trial fuel debris removal in Unit 2, with a goal to start removing fuel from Unit 2 this year, and from Unit 1 sometime in 2027 or 2028.

Officials said some technological innovations will be needed at the site, including ways to accomplish



7. Decommissioning of the damaged Fukushima nuclear power plant in Japan is scheduled to be completed in 2051, or 40 years after cold shutdown of the facility after a devastating earthquake and tsunami in March 2011. Courtesy: Tokyo Electric Power Co.

removal of fuel debris from the reactors. Officials said there is uncertainty about the fuel distribution in each of the reactors. Yoshitomo Mori, an official from Japan’s Environment Ministry, in the Vienna presentation said that since 2014 about 13.76 million cubic meters of soil and waste had been removed from Fukushima and transported to an interim storage facility set up to take materials after decontamination.

Officials said contaminated water from Fukushima is being treated by an Advanced Liquid Processing System (ALPS), which removes most of the radioactive contamination, with the exception of tritium. This treated water is currently stored in tanks onsite. Japanese officials in April 2021 said the country would discharge ALPS-treated water into the sea over about a 30-year period, and releases began in August of last year. Officials said there have been nine releases as of the end of September.

TEPCO has prepared an interactive video guide to the decommissioning process at Fukushima. TEPCO also provides cameras with live images of the site.

Constellation will pursue license renewal that will extend plant operations to at least 2054.”

Bobby Hollis, vice president of energy for Microsoft, in a statement said, “This agreement is a major milestone in Microsoft’s efforts to help decarbonize the grid in support of our commitment to become carbon negative. Microsoft continues to collaborate with energy providers to develop carbon-free energy sources to help meet the grids’ capacity and reliability needs.”

Constellation in a September presentation to investors said the com-

pany plans to spend about \$1.6 billion to restart TMI. The company said the work would require “significant investments” in major systems at the facility, along with a three-year relicensing engagement with the NRC. The group also would need to go through a three-year interconnection application and study process with PJM Interconnection (the regional grid operator) and the Federal Energy Regulatory Commission.

Constellation in the presentation said it already has inspected key power system components of Unit 1, and started work to restore its training simulator. It



8. The Kewaunee nuclear station in Wisconsin was closed in 2013. Dominion Power, the plant's operator, said decommissioning will likely continue until 2073, at a cost of about \$1 billion. Courtesy: EnergySolutions

also said it has begun the process for a supply of nuclear fuel and long-lead materials and equipment. The group in the presentation said it still would need to conduct more inspections, along with restoration work and testing. Installation of a main power transformer, along with workforce training and development, also would be needed. The Reuters news service on Oct. 16 reported Constellation has ordered a \$100 million transformer, which would likely be the largest single piece of equipment needed for a restart.

Reuters was part of a tour of the facility on Oct. 16 that included Constellation executives. The news service quoted Bryan Hanson, Constellation's vice president of Generation, as saying, "I have walked the facility top to bottom, every floor. The plant is in great condition."

Recent Decommissioning Work

The experts who spoke with *POWER* noted that each power plant operator creates a fund to pay for decommissioning work as part of the upfront cost of building a reactor. The World Nuclear Association said about two-thirds of the total estimated cost of decommissioning all U.S. nuclear reactors—more than 90 are operating—already has been collected. There could be additional expenses, though, when units are retired earlier than planned (see sidebar "The Situation at Fukushima").

Recent projects in the U.S., in addition to those mentioned earlier, include the 619-MW Haddam Neck plant in Connecticut, which was taken offline in 1997. The plant was decommissioned using the DECON method, with work completed in 2007 at a total cost of \$893 million, according to the EIA.

The 556-MW Kewaunee Nuclear

Power Plant in Wisconsin (Figure 8) was closed in 2013. Dominion Power, the plant's operator, has said it anticipates a total cost to decommission the plant at nearly \$1 billion. The plant is being decommissioned using the SAFSTOR method, and Dominion Power has said it estimates work will not be complete until 2073.

Orano Decommissioning Services completed its project at the Vermont Yankee Nuclear Power Station in late 2022. The company said work included the full segmentation, packaging, and disposal of the reactor vessel (RV) and other components at the 620-MW plant, which was shut down by Entergy in late December 2014. Orano said its work at the site was accomplished in less than four years.

Orano wrote that the Vermont Yankee (VY) project "represented the first full



9. A barge with four packages containing the remnants of the Crystal River nuclear power plant arrives on the Texas coast after crossing the Gulf of Mexico from the power station's former home in Citrus County, Florida. Courtesy: Orano USA

segmentation decommissioning of a commercial-scale boiling water reactor in the U.S. and presented the opportunity to demonstrate several first-of-a-kind technologies. The VY decommissioning project execution involved the full segmentation of the RV and RVI [reactor vessel internal] components as opposed to removal of the vessel while relatively intact. The full segmentation method was chosen early in project planning due primarily to the size of the RV and the limited locally accessible transportation infrastructure."

The company also said that high-activity low-level radioactive waste, "including Class B/C and high-activity Class A, was packaged and shipped using the new Orano Transnuclear (OTN) Radioactive Waste Canister (RWC) system." The group said, "OTN had designed and fabricated an MP197HB dual-purpose transport cask for commercial use prior to work starting at Vermont Yankee. This was the first time this transport cask had been used, and it transported seven loaded RWCs from Vermont to WCS [Waste Control Specialists] in West Texas via railway safely and efficiently."

Orano in October of this year said it also completed a segmentation project that included transportation and disposal of the dismantled Crystal River Unit 3 (CR3) reactor, a facility that operated in Crystal River, Florida. Orano said the project, which included segmentation, packaging, and removal of the 35-foot nuclear reactor vessel and its internal components, was completed in less than two years. The company said its work, involving removal of the large cooling system components, and the off-site shipment (Figure 9) and final disposal of all generated low-level waste, was completed in less than four years.

The Crystal River decommissioning included transport of equipment, placed in four packages, on a single barge across the Gulf of Mexico from the nuclear plant's site on Florida's Gulf Coast in Citrus County to Texas. The packages were then separately transported via truck hundreds of miles to the WCS disposal site in Andrews County in West Texas. Orano said the company also "conducted 10 disposal shipments by rail of the CR3 reactor coolant system, including a pressurizer, four reactor coolant pumps, and four motors, plus the reactor vessel's integrated head assembly containing the control rod drives and service structure." ■

—Darrell Proctor is a senior editor for *POWER*.

Nuclear Fuel: The Unseen Barrier Ahead

As global nuclear ambitions surge, the industry's fuel supply chain faces critical gaps. Can advanced fuels like HALEU (high-assay low-enriched uranium) and TRISO (TRi-structural ISOtropic particle fuel) bridge the demand for next-gen reactors or will supply limits hold back nuclear's potential?

Sonal Patel

For nearly six decades, the nuclear industry's fuel landscape has marked a relatively stable trajectory. The world's commercial nuclear power plants, 95% of which are water-cooled, have generally relied on a mature front-end supply chain for low-enriched uranium oxide (UO₂) pellet fuel. "Demand was more or less stable," keeping pace with an expansion of the nuclear fleet in the 1970s and 1980s, explained Jacopo Buongiorno, director of the Center for Advanced Nuclear Energy Systems (CANES) at the Massachusetts Institute of Technology (MIT). Since the speculative "nuclear renaissance" bubble in the late 2000s, uranium prices have been in flux, driven in part by "an imbalance between projected demand and capacity for enrichment, conversion, and fabrication," he said.

Between 2020 and 2024, all three components saw a surge "by a factor of three," Buongiorno noted. While exacerbated in part by a pushback against Russian fuel in light of its aggression in Ukraine, the market's unprecedented volatility is caught between ambitious global decarbonization targets and supply limitations. At the 2023 U.N. Climate Change Conference (COP28), a coalition of 22 nations set an aspirational goal to triple nuclear power capacity by 2050—a vision that could skyrocket uranium demand, with projections for 2040 ranging from 63,000 tonnes of uranium (tU) in a low-demand scenario to a staggering 184,000 tU if small modular reactors (SMRs) become widely adopted.

The implications could be stark, Buongiorno suggested. "Don't get me wrong, I think, honestly, this community is in the best position it has been in decades. There is a lot to be excited about. The opportunities are massive, but there are also many challenges."

New Needs to Accommodate Advanced Nuclear

Buongiorno's blunt assessment came as an introduction to a symposium MIT hosted at the end of October aptly titled "No Fuel? No Party." The event brought together industry leaders, nuclear technology developers, research scientists, and fuel cycle specialists who laid out how integral a reliable and diversified fuel supply chain will be to the nuclear industry's aspirations.

A central takeaway from the symposium was clear: the nuclear industry must urgently scale up its technical and production capabilities for advanced fuels to power the reactors of tomorrow. "Virtually all advanced reactors require higher-enrichment fuel, for which, at the moment, we don't have facilities at commercial scale," Buongiorno underscored.

The diversity of fuels is significant. High-temperature gas-cooled reactors often rely on TRi-structural ISOtropic (TRISO) particle fuel for their enhanced safety properties, while fast reactors may use metallic fuels or mixed oxide fuels (MOX) to achieve high burnup and efficient transmutation of long-lived isotopes. Innovative fuel types, such as

uranium nitride and uranium silicide, are also being explored for their higher uranium density and thermal conductivity, which could improve fuel performance under extreme conditions.

So far, more than 20 advanced reactor designs are actively pursuing high-assay low-enriched uranium (HALEU), a specialized fuel enriched to levels between 5% and 20%. However, while HALEU could enable extended fuel cycles, improve reactor safety, and more efficient utilization of uranium resources, currently, "there is no market," Jonathan Hinze, president of nuclear fuel market intelligence firm UxC, said bluntly. "We have concepts of a market, but we don't have the actual market."

For now, the advanced fuel cycle will need to rely on the low-enriched uranium (LEU) supply chain. But, that supply chain is already under stress. "We're moving away from 100% Russian supply in the U.S., and other markets are similarly moving away," he said. "That's a huge supply source, and there are going to be implications of that that are still not felt for years to come." Meanwhile, compounding that challenge is that the advanced fuel cycle will require



1. Urenco USA in October 2024 won a 10-year Indefinite Delivery/Indefinite Quantity contract from the U.S. Department of Energy to produce high-assay low-enriched uranium (HALEU) from new domestic capacity at its New Mexico facility. Currently meeting one-third of U.S. utilities' enrichment needs, Urenco USA is already expanding and in the licensing process to enrich up to 10% for LEU+. Courtesy: Urenco

Innovation in Action: Accident-Tolerant Fuels

An especially notable triumph for the nuclear industry over the past decade has been its development and commercialization of accident-tolerant fuels (ATFs). An industry concept used to describe new technologies in the form of new cladding and/or fuel pellet designs, ATFs are thought to increase efficiency, improve performance, and reduce operating costs. They essentially leverage new materials that improve fission product retention and are structurally more resistant to radiations, corrosion, and high temperatures. And because they could potentially extend the time between refueling from 1.5 to 2 years, ATFs promise to reduce the amount of fuel needed by about 30%, resulting in less waste and used nuclear fuel.

The push for ATF has gained dramatic momentum in recent years, driven by a confluence of policy, regulatory, and market forces. The Nuclear Energy Innovation and Modernization Act (NEIMA) signed in 2019 and the Advanced Nuclear Fuel Availability Act of 2022 have solidified ATF as a key priority, with the goal of enhancing reactor safety and lowering the cost of electricity.

"We're seeing a real shift in the market, with utilities and reactor developers actively pursuing ATF as a critical enabler for their future plans," explained AI Csontos, director of Fuels at the Nuclear Energy Institute (NEI).

A specific development involves the push for LEU+—low-enriched uranium fuels with enrichment levels up to 10% and extended burnup capabilities. "By increasing enrichment and burnup, we can achieve two-year fuel cycles, reducing outages and improving overall plant economics," Csontos said.

The industry faces challenges in this realm, too, however. "The licensing and approval process for these advanced fuels is a critical hurdle we must overcome. Streamlining regulations will be crucial to accelerating deployment," he noted. "These advanced fuels are the key that unlocks the door to a new era of nuclear power—safer, more efficient, and more cost-effective than ever before. It's not going to be easy, but the potential benefits are too great to ignore."

a host of new facilities that don't currently exist, including specialized enrichment plants to deconversion and fuel fabrication processes."

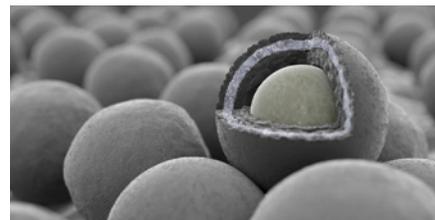
Nuclear fuel suppliers have begun stepping up to the challenge. Enrichment giant Urenco (Figure 1) is investing billions of dollars to deliver HALEU enrichment capabilities in the UK and U.S. by the mid-2020s, as well as developing a dedicated HALEU enrichment plant in the UK, targeting the early 2030s for initial material availability, said Magnus Mori, head of Market Development and Technical Sales at Urenco. "It's a paradigm change, it's a shock to the system." But it poses immense risks, he suggested. "We can take orders, but we don't have the momentum, the critical mass for a private investor to take all the investment risk," he said.

Global Laser Enrichment (GLE), which is working to commercialize laser enrichment as an alternative to the traditional gas centrifuge enrichment process and targeting production by 2030, anticipates a role for government support to kickstart the market. Unlike Centrus Energy, "We don't need the DOE [U.S. Department of Energy] to be a buyer of any product we produce," said Nima Ashkeboussi, GLE vice president of Government Relations. "We see utilities ready to buy that material. But we do think there is a space for DOE to enter in some sort of cost-share or milestone-based awards with us to add capacity to the marketplace."

The DOE has already taken steps to incentivize the HALEU market. In October, it announced awards for both HALEU enrichment and deconversion projects. Incremental progress is also surfacing for spent nuclear fuel (SNF) recycling. As Temi Taiwo, director of the Nuclear Science and Engineering Division at Argonne National Laboratory, suggested, recycling could dramatically improve the sustainability of the fuel cycle. Taiwo acknowledged, however, that demonstrating the feasibility and cost-effectiveness of scaling up recycling technologies poses a key challenge.

The Chicken-Egg Dilemma of Fabricating Novel Fuels

Fabricating fuel to meet emerging demands faces similar challenges. According to Dave Petti, an industry veteran who has been instrumental in advancing high-temperature nuclear reactor fuels, fabricators face the ultimate "chicken-and-egg" problem. "You'd need a sustained demand, kind of like a metric ton



2. BWX Technologies' (BWXT's) Specialty Fuel Facility in Lynchburg, Virginia, is the only U.S. site producing irradiation-tested uranium oxycarbide tri-structural isotropic (TRISO) fuel. TRISO particles cannot melt in a reactor when tested at temperatures of up to 1,800C, exceeding the predicted worst-case accident conditions for high-temperature gas reactors. Courtesy: BWXT

per year, to really support a fuel fabrication facility," he said. Without that consistent, high-volume demand, Petti noted that suppliers are tasked with using highly enriched uranium and blending it down for each individual reactor concept. Petti also underscored that the lack of clarity on how quickly reactors will come online makes it difficult for fuel vendors to properly size their production facilities. Bridging that gap will require strategic investments, both from the private sector and government, Petti suggested.

However, some companies are already preparing to meet demand. BWX Technologies (BWXT), the only company currently producing TRISO in the U.S., is considering a "purpose-built," Category 2 TRISO production facility, noted Andrew Davidson, BWXT project manager of Specialty Fuels Fabrication and Uranium Recovery (Figure 2). However, it would only consider the investment, which could require "several hundreds of millions" of dollars if the company is "confident that the market exists to pay back that investment before we go off and take that step."

Ultimately, the gap could perhaps be resolved by emerging concepts of a shared international fuel cycle infrastructure that could help mitigate risks and costs for individual players. Buongiorno suggested the U.S., European Union, UK, Canada, South Korea, Japan, United Arab Emirates, and perhaps Australia should think about creating joint enrichment facilities, which would add some security on the enrichment side. "Perhaps even a shared LEU reserve in the form of UO_2 ," he said could be worthwhile. "It's not a zero-cost investment, but it's not enormous in the greater scheme of things, and it could actually insulate our countries from big fluctuations in the prices of uranium and uranium enrichment." ■

—**Sonal Patel** is a POWER senior editor.

Artificial Intelligence Has Entered the Nuclear Industry and Its Early Benefits Are Just the Tip of the Iceberg

A collaboration between startup Atomic Canyon and the Oak Ridge National Laboratory allowed construction of a sentence-embedding model using 53 million pages of Nuclear Regulatory Commission documents. Understanding nuclear terminology opens doors for artificial intelligence to revolutionize many processes within the industry.

Aaron Larson

The nuclear power sector is regarded by many onlookers as a slow-moving industry. Strict regulatory frameworks mean extensive testing, documentation, and approval processes are necessary for any modifications to nuclear facilities or procedures. Furthermore, nuclear plants represent massive investments, which makes owners and operators err on the side of caution when it comes to making changes to proven designs. Major upgrades must be thoroughly validated given the complexity of nuclear systems and the potential consequences of failure, and the studies conducted as part of the process can take years. The industry relies heavily on experienced personnel, who are trained to follow detailed procedures, which means they may be resistant to adopting new approaches. So, in the end, things often do change slowly.

However, change does happen, and technology has worked its way into the nuclear industry as the development of advanced reactor designs and small modular reactors have accelerated innovation in the field. Recently, artificial intelligence (AI) even found its way into the nuclear conversation as a startup called Atomic Canyon collaborated with the Department of Energy's Oak Ridge National Laboratory (ORNL) to develop an advanced AI model capable of understanding complex nuclear terminology.

Training AI

"The first thing you need to build artificial intelligence is a data set—you need access to information," Trey Lauderdale, founder and CEO of Atomic Canyon told

POWER. Lauderdale is not a nuclear expert, but he has founded and supported multiple companies over the past 15 years with a focus on utilizing technology to improve processes, which is what Atomic Canyon's AI platform is designed to do for nuclear power plants, manufacturers of next-generation reactors, and government and national laboratories.

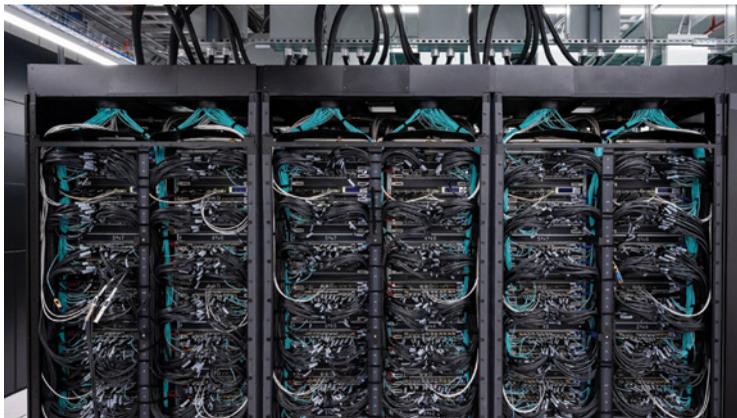
"One thing we quickly realized about nuclear power is there is a tremendous amount of data. The Nuclear Regulatory Commission—the NRC—actually has a database called ADAMS [which stands for Agencywide Documents Access and Management System], where there's all sorts of public information that's available that can be viewed by anyone, and it's all available on their website," Lauderdale said.

As Atomic Canyon's team started building AI models and experimenting with the ADAMS dataset, its experts

quickly discovered a problem: all of the AI models that are generally available would get confused when they ran into "nuclear words." Lauderdale explained, "The nuclear vernacular is very complex. It has all sorts of acronyms and words that these AI models haven't seen enough examples of. So, what ends up happening is the AI hallucinates. That's AI speak for: 'It makes stuff up.' As you can imagine, in an industry like nuclear, making stuff up is very, very bad."

Lauderdale's team realized they didn't necessarily need to create a new large language model (LLM) to solve the problem, they just needed to build sentence-embedding models for AI applications so nuclear terminology could be understood. "To do that, you need access to a lot of what's referred to as GPUs—graphical processing units," Lauderdale said.

A typical start-up might raise millions of dollars and buy a bunch of GPUs to



1. Oak Ridge National Laboratory (ORNL) says its investment in high-performance computing is critical to delivering on the lab's and the Department of Energy's mission. This image shows a side view of the Frontier supercomputer cabinets. Courtesy: Carlos Jones/ORNL, U.S. Department of Energy

do a project like this, but Atomic Canyon had a better option: work with the government. ORNL is home to Frontier (Figure 1), a supercomputer that was touted as the world's fastest when it debuted in May 2022 and has maintained that title through the most recent rankings in May 2024. "It was quickly discovered that this was a project that was worthwhile of the world's fastest supercomputer—the ability to go train AI models on nuclear terminology and then have an output which is basically a more advanced search application that could be used to help find documents," Lauderdale said.

The results were astounding. Within just six months, the team developed an advanced AI model capable of understanding complex nuclear terminology. This specialized open-source AI model has set new benchmarks for accuracy, efficiency, and speed in AI search. Developed to be open source, the model is available to ORNL, the nuclear national lab complex, independent researchers, and nuclear institutions. It will also be integrated into Neutron, Atomic Canyon's AI search platform.

The open-source aspect was important to Lauderdale. "I would argue a big ethos of the nuclear industry is inherently open source in nature," he said. In many industries, there is intense competition, and companies are reluctant to share information that might jeopardize their competitive advantage. But Lauderdale said the nuclear industry is just the opposite. "The statement I've heard over and over is: 'An accident at any plant is an accident at every plant.' As a result, you have so much sharing of data—whether it's with the NRC, with INPO [Institute of Nuclear Power Operations], which is an organization that provides quality metrics to all these nuclear power plants—there is an ethos of openness, transparency, and sharing information back and forth," he explained.

"Transitioning to the technology and the code that we've built, we've used government resources to build this. There was the NRC data. There was Oak Ridge. And it's our view that enabling artificial intelligence to understand nuclear terminology is so foundational to any AI application that's going to be built, we want to open source this code, which is a way of saying, we want to make sure any party, even our competitors—people that might build competitive applications—are able to leverage this tool set as they build their own apps. And all we ask in exchange is that as they make

improvements—as they add different features—that they commit back to the project," he said.

The AI Revolution

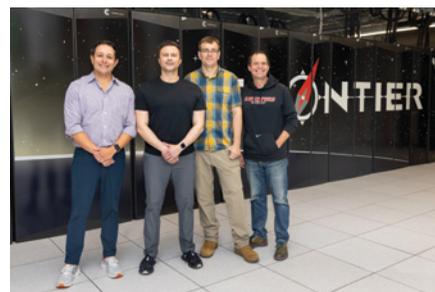
Yet, Lauderdale suggested this is just the beginning. "Everyone hears there's this big AI revolution that's occurring, and we're all as a society starting to realize the energy demands for artificial intelligence are going to be astronomical, to the point that Three Mile Island is going to be reopened for a Microsoft data center," Lauderdale said. "We are at the tip of the iceberg, because all the hyper-scalers are talking about 10x, 20x, crazy growth, and that is going to require reliable energy that's available 24/7, that's safe, and ideally not emitting carbon. So, nuclear is that path."

However, the path is not necessarily straightforward or easy. "It's our view that not only is AI going to need nuclear, nuclear is actually going to need AI," Lauderdale predicted. "I think there's the opportunity to start applying artificial intelligence in very safe manners, in foundational manners."

While Lauderdale doesn't think AI is ready to start running nuclear power plants on its own yet, he does believe it can provide benefits to operators and developers. "The ability to have AI help people search and find documents is a very worthwhile cause," he said. "It's where we started. And then from there, once you have that foundation, you build layer after layer and more advanced applications."

"Where the early wins can really occur is in the licensing process," Tom Evans, leader of the High-Performance Computing (HPC) Methods for Nuclear Applications group in the Nuclear Energy and Fuel Cycles division at ORNL (Figure 2), told *POWER*. "The knowledge-based barriers to understanding and navigating the licensing process are large, and if you can do something to reduce those barriers significantly, you've already, just out of the gate, made a massive, massive improvement to the entire process and to the prospects for actually being able to deploy nuclear power more economically," he said.

Yet, Evans suggested there are multiple vectors through which AI can play a role. One area is in complex design analysis. Evans said ORNL often helps the NRC and other industry stakeholders by doing this type of analysis for them using supercomputer models. He explained that analysts usually start



2. Trey Lauderdale, Atomic Canyon CEO; Kristian Kielhofner, Atomic Canyon CTO; Richard Klaffer, Atomic Canyon Lead Artificial Intelligence (AI) Architect; and Tom Evans, ORNL Research Scientist are pictured here standing near the Frontier supercomputer. Courtesy: Genevieve Martin, ORNL

by searching through previous analysis to find something similar that they can use as a reference. From there, they adjust inputs to account for the differences in the new design and then run simulations.

Evans noted, however, that just identifying the most applicable past analysis to use as a starting point can take a great deal of time. This is where AI could improve the process. Rather than having an analyst search through reams of data, the AI tool, which has literally been trained on 53 million pages from the NRC's ADAMS database, can quickly provide the most relevant files. This would save the analyst a lot of effort.

Atomic Canyon has larger ambitions too. Lauderdale said his team is in discussions with several companies in the nuclear field, who have proprietary datasets they'd like to incorporate AI into. He said his group could install an enterprise version of the software that would ingest the proprietary data, allowing users to search their droves of internal data. "That's kind of the next iteration of where we're going," said Lauderdale.

Beyond his own company's aspirations, Lauderdale suggested the nuclear industry isn't as slow moving as some people may believe, and, in fact, could end up being a leader in the AI revolution. "One of the key ingredients you need to build fantastic world-class AI models is data. And the more data you have, the better the models you can build," he said. "Because the nuclear power space has been documenting so much information, I actually think this space has the opportunity to become really a thought leader and an innovator in the artificial intelligence realm, and that's what gets me really excited." ■

—Aaron Larson is *POWER's* executive editor.

Continued Excellent Nuclear Power Plant Performance Bodes Well for Future Prospects

The carbon-free attributes and consistently high fleet performance have led to increasing momentum behind nuclear power. With ambitious plans to triple global nuclear capacity by 2050, the nuclear industry is poised for expansion, supported by new policies and partnerships across various sectors.

Henry Preston

Each year, World Nuclear Association, the organization advocating for nuclear energy and representing the global nuclear industry, publishes the World Nuclear Performance Report and hosts the World Nuclear Symposium. Both are cornerstones for those inside and outside of the nuclear sector serving as a platform to provide authoritative information, and connect thought-leaders and decision-makers.

World Nuclear Performance Report

World Nuclear Performance Report showed an increase in global nuclear electricity generation (Figure 1) and average capacity factors for 2023, highlighting the continuation of excellent performance of the global nuclear reactor fleet. A variety of lifetime operation extensions, uprates, and restarts are included within the case studies of the 2024 report. Key highlights include:

- Global nuclear electricity generation rose to 2,602 TWh in 2023, up from 2,544 TWh in 2022, providing 9% of the world's electricity—second only to hydropower among clean energy sources.
- The global capacity factor reached 81.5% in 2023, up 1% from 2022, reflecting the consistent strong performance over the past 20 years. Reactor performance remains high regardless of age.
- In 2023, nuclear reactors helped avoid 2.1 billion tonnes of carbon dioxide emissions from equivalent coal generation—that's more than the annual emissions of almost every individual country, with only China, the U.S., and India having higher national CO₂ emissions.
- 64 reactors in 15 countries are currently under construction, while more than 20 new entrant countries, such as Ghana, Poland, and the Philippines,

are at various stages of developing policies to enable construction of their first nuclear plants.

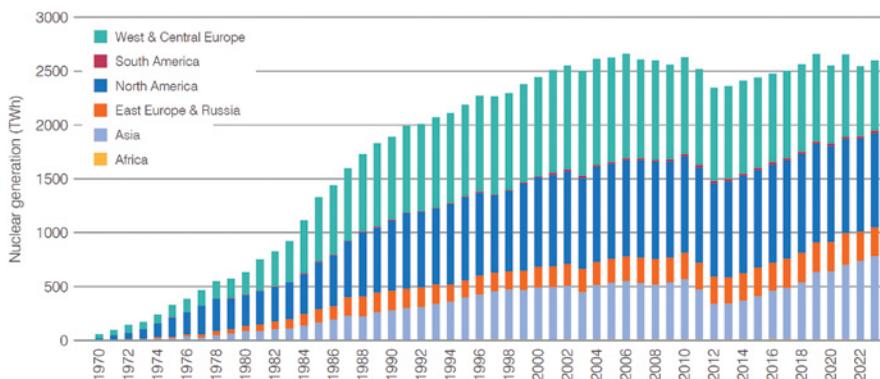
The report also includes data about new grid connections and construction starts. Highlights from that section include:

- In 2023, five reactors were connected to the grid for the first time across a diverse set of countries: one each in China, Slovakia, the U.S., Belarus, and South Korea. Meanwhile, construction starts were mostly confined to China, with five of six new construction starts in 2023 breaking ground there, while work began in Egypt on one unit.
- In Asia, there has been a sustained and significant increase in nuclear generation over the last decade. Of the total 64 reactors under construction today, more than two-thirds are in Asia, with 30 reactors under construction in China alone.
- Eastern Europe and Russia are second to Asia in terms of the number of units under construction. Notably, Africa is ahead

of North and South America, as well as Western and Central Europe, in terms of the share of reactors under construction, due to the El Dabaa project in Egypt.

With five reactors starting up and five closing, global nuclear capacity was down by 1 GW compared to the previous year, reflecting minimal change in global capacity over the last five years. The increase in generation, despite a drop in capacity, highlights the excellent performance and value delivered by nuclear energy to the grid.

Dr. Sama Bilbao y León, director general of World Nuclear Association, commenting on the report and looking ahead, said: "The global nuclear industry is set for a period of major expansion. At COP 28 [the United Nations Climate Change Conference], 25 countries signed the declaration to triple global nuclear capacity by 2050. Excitingly, there are new reactors coming online and plans for new construction in a diverse range of countries. Collaboration and competition in the industry will deliver many new projects over the coming years. Our Performance



Sources: World Nuclear Association and IEA Power Reactor Information Service (PRIS)

1. Nuclear reactors generated a total of 2,602 TWh of electricity in 2023, up 58 TWh from 2022. A key contributor to the uptick was a 42 TWh increase in generation in France, recovering about half of the reduction it saw due to extended outages in 2022. Courtesy: World Nuclear Association



2. Dr. Sama Bilbao y León, Director General, World Nuclear Association; John Gorman, President and CEO, Canadian Nuclear Association; Huang Mingang, Chief Economist, China National Nuclear Corp. (CNNC); and Daniel Westlén, State Secretary to Minister for Climate and the Environment, The Government of Sweden, participated in a high-level opening panel focused on nuclear policy and progress toward net zero at the 2024 World Nuclear Symposium in London, UK. Courtesy: World Nuclear Association

Report indicates that reactors built now will produce dependable, carbon-free energy for decades and decades.”

World Nuclear Symposium

World Nuclear Association welcomed record attendance of more than 800 delegates to its 2024 Symposium, hosted at the Park Plaza Hotel in London, UK, Sept. 4–6, 2024. The Symposium is the premier event for bringing together the nuclear industry from across the globe, addressing developments in nuclear fuel and supply chains, as well as high-level policy (Figure 2) in emerging markets, finance, and for end energy users, as the role of nuclear energy in meeting the world’s decarbonization goals expands.

This year saw a growing number of delegates from outside the nuclear industry. Many of those attending were curious and engaged, seriously considering nuclear for its benefits—clean, reliable, secure, affordable energy, as well as socio-economic development, jobs, and the potential to decarbonise the entire economy. The nuclear sector has known this potential for years, but now other sectors are seeing it too.

Leaders from organizations including BlackRock, Microsoft, Samsung C&T, Shell Global, Urenco, and Westinghouse spoke in the programme around the theme “Turning Momentum into Energy.” The theme highlighted the positive developments being seen for nuclear in the policy space, as well as in aspirations, commitments, and the growing number of countries and other industries interested in what nuclear can do for them. The momentum behind nuclear is significant and growing. The Symposium also



3. The Emirates Nuclear Energy Corp. (ENEC) announced a historic milestone on Sept. 5, 2024, with the fourth unit of the Barakah Nuclear Energy Plant entering commercial operations, marking its full delivery. Courtesy: ENEC

offered an opportunity for members of World Nuclear Association to showcase high-profile announcements, such as:

- Emirates Nuclear Energy Corp. confirming that the United Arab Emirates’ (UAE’s) Barakah Unit 4 had entered commercial operation (Figure 3), thus completing its building programme. The full-fleet operations will enable the generation of up to 25% of the UAE’s electricity demand.
- Orano announcing the selection of Oak Ridge, Tennessee, as a preferred site to build a multi-billion-dollar U.S. uranium enrichment plant.
- Westinghouse launching its Generative Artificial Intelligence (GenAI) System Hive to deliver custom GenAI solutions for its global customer base.

Looking back at the programme, attendees heard governments from across the world speaking about their plans, then heard from the nuclear sector—addressing fuel cycle challenges and supply chain in terms of project delivery, building up the workforce, and harnessing innovation. The finance community was also on stage discussing how to support expansion, while the Power Partners panel looked at the potential applications, including why data centres can benefit from 24/7 clean nuclear electricity.

The Time Is Now

From a policy point of view, nuclear is at its strongest moment in a generation, having gained momentum over the past few years, and now, a growing number of projects with interest from a range of suitors are coming to fruition. The nuclear industry is at a pivotal moment to deliver on its promise, but it fits into a wider world that needs clean, secure, and affordable energy for the entire economy. If nuclear can reach beyond its traditional boundaries to forge new partnerships with sectors essential to expanding nuclear and in

need of clean energy, then it will be easier to realise a clean future for all.

The Net Zero Nuclear initiative was launched, for COP28, in Dubai. Twenty-five countries signed the Declaration to Triple Nuclear, and more than 120 nuclear energy and technology companies signed the Net Zero Nuclear Industry Pledge to at least triple global nuclear energy capacity by 2050. Then, the COP28 global stocktake agreed upon by 199 countries recognised nuclear as a technology to be accelerated.

The COP28 pledges highlighted the commitment of both governments and the nuclear industry to work together to turn aspiration into results. Since then, the powerful commitment in support of nuclear has been repeated and reinforced by the G7 (Group of Seven—Canada, France, Germany, Italy, Japan, UK, and U.S.), and at the International Atomic Energy Agency’s (IAEA’s) Nuclear Energy Summit in Brussels, Belgium. More recently, 14 major financial institutions backed the goal of tripling global nuclear capacity by 2050.

Over the next 18 months leading up to COP30 in Brazil, World Nuclear Association is planning a programme of high-profile Net Zero Nuclear activity across the globe to promote and strengthen the shared commitment of government and industry. The Association is a non-profit, non-governmental organisation, supported by more than 200 members from across 44 countries and comprising more than 70% of utilities powering world nuclear generation. Its mission is to enable the growth of the global nuclear sector by connecting companies and individuals across the nuclear value chain, shaping and representing the industry’s position in major world forums, providing authoritative information, and influencing key audiences, organizations, and media. Learn more at: world-nuclear.org. ■

—Henry Preston is external communication and media manager for World Nuclear Association.

Solid Leadership and Experience Are Keys to Successful Nuclear Plant Construction Projects

One of the biggest challenges the nuclear power industry faces is building plants on time and on budget. Having an experienced project team with the right leaders driving the bus, so to speak, can mean the difference between failure and success.

Aaron Larson

Nuclear power plants are large and complex facilities. Constructing one costs billions of dollars and takes many years to complete. In fact, over the decade 2014–2023, the *World Nuclear Industry Status Report 2024* says the average construction time for a nuclear unit was 9.9 years. Its research looked at 67 reactors completed in 11 different countries. Notably, more than half of the reactors (37) were built in China, which had the second-lowest mean construction time at 6.3 years per unit behind only Pakistan's 5.6 years per unit. The majority of other countries took well over 10 years on average to complete nuclear plants with two clocking in at more than three decades each.

Yet, no project begins with a 10-year timeline as its goal. Of the 18 reactors connected to the grid in 2021–2023, all of them began with an expected construction time between 4.3 years and 6.5 years. Only one of those 18 units—the Chinese-designed and -built Tianwan Unit 6—started up on-time. Several of the other units took more than twice the expected duration.

“These are extremely hard things to build. These are mega projects costing tens of billions of dollars,” Chandu Boli-setti, senior scientist at the Idaho National Laboratory (INL), told *POWER*. “All over the world, mega projects are often delayed. They’re often over budget and over schedule. They’re hard to execute.”

Getting Off to a Good Start

Before a nuclear plant construction project breaks ground and the clock starts ticking, many years are often spent behind the scenes doing preliminary work. Power companies must evaluate electricity supply and demand projections, and if a nuclear plant is deemed necessary, they must consider all the in-

frastructure needed to support a project. Feasibility studies and environmental impact assessments are required. The specific technology and design to be deployed must be evaluated and selected, along with the mode of execution, such as turnkey, EPC (engineering, procurement, and construction), or some other contractual arrangement. All of this takes time and dedicated resources.

The International Atomic Energy Agency (IAEA) has provided guidance in a 139-page document designed to improve project management in nuclear power plant construction. It suggests deploying nuclear technology often requires a parallel social and economic development plan, ensuring a culture of safety and protection of the environment is top-of-mind, and establishing effective working relationships with government institutions.

For companies intending to develop a greenfield location, the site selection and acquisition process can be time-consuming, requiring considerations such as:

- Proximity to large industrial consumers of electricity.
- Availability of skilled and semi-skilled manpower in the vicinity of the proposed plant.
- Adequacy of the approach roads or waterways for the transportation of over-dimensioned equipment typical of nuclear power plants.
- Adequate water and power supply.
- Favorable perception regarding nuclear plants amidst the local population.

Creating an Effective Team

The IAEA pointed to the establishment of a well-defined project management organization as being vital to success. “A written instruction from the organization’s top management announcing the appointment of the project manager should immediately follow the contract

effective date,” it says. “Since large amounts of materials and equipment must be ordered, manufactured and installed during this phase and the human resource profile reaches its peak, this is also when the largest part of the overall cost occurs and the highest degree of coordination is most necessary. It is during this phase that project management has to show its strength and use all the tools at its disposal.”

The contract effective date represents a major milestone in project work. It is at this point that the project ceases to be merely a planning exercise and becomes an actual implementation of construction and installation work in the field. “Clear and well-defined commitments should exist between the project partners and signed at the highest management level, expenditures begin to incur in orders of magnitude higher than before. Each day lost on a critical activity may now affect the schedule and cost,” the IAEA says.

The Organisation for Economic Co-operation and Development’s (OECD’s) Nuclear Energy Agency (NEA) has also published a practical guide for reducing nuclear construction costs. In its 134-page document, the NEA agrees that having a strong and dedicated project team led by an effective project manager is essential to success. “The importance of leadership in managing nuclear new-build projects cannot be overstated,” it says.

“Regardless of the procurement approach chosen, given the scale and complexity of a nuclear new-build project, it is very important to develop a dedicated project team structure with sufficient resources and empowerment to enable competent leadership and ensure timely decision-making,” the NEA guide notes.

The project owner/operator (in most cases, the future utility) is central to the acquisition strategy, according to the NEA,

and its active involvement needs to be maintained throughout the project. “A systematic approach to acquisition especially helps the owner to be prepared to react to changing situations,” the guide says.

The project team is usually responsible for developing the detailed design, securing the safety case, and planning the procurement and construction schedule. It will also collaborate with the supply chain and with external stakeholders, including the local community, to address emerging environmental and social issues, for example. The project team must have a strong team leader reporting directly to the organization’s top-level management.

Contrasting Case Studies

Two relatively recent projects in the U.S.—Plant Vogtle Units 3 and 4, and V.C. Summer Units 2 and 3—demonstrate the importance of experience and sound leadership when it comes to nuclear plant construction. Both projects set out to utilize the Westinghouse AP1000 design and both began with the same main construction contractor—Stone & Webster (S&W), part of The Shaw Group. According to the NEA, S&W originated as an engineering company in the oil sector and had no previous nuclear experience. Consequently, the company’s senior management initially underestimated the challenges of new nuclear construction, particularly the quality requirements, and their lack of experience contributed to recurring quality assurance issues.

In the case of the V.C. Summer project, the NEA said the lack of experience also led to a situation in which the plans and

schedules were not reflective of the actual project situation. A deeper dive into the history of the project suggests fraud also played a role. At least two former executives of SCANA Corp., the majority owner of the project, served prison time for conspiracy to cover up problems at the V.C. Summer site, where Units 2 and 3 were ultimately abandoned (Figure 1).

The Plant Vogtle expansion experienced some of the same schedule and cost overrun issues that the Summer project did, but its leaders managed to avoid criminal wrongdoing. When the Plant Vogtle project owners in 2017 took a close look at project completion estimates and evaluated whether to continue or abandon the job, they chose Bechtel, a global EPC contractor with extensive nuclear experience, to take over day-to-day construction of the new units under the direction of Southern Nuclear, a Southern Co. subsidiary, which operates Units 1 and 2 at the site near Waynesboro, Georgia. While the changes did not completely eliminate schedule delays and cost overruns, they did set a clear path to project completion, and the units were ultimately brought online, with Unit 3 entering commercial operation on July 31, 2023, and Unit 4 following on April 29, 2024 (Figure 2).

Bolisetti said the Vogtle expansion had added complexity because it was essentially a first-of-a-kind mega project. “I’m not surprised that these units were over budget and over schedule,” he said. “The fact that they pulled it off is impressive and proof that we can still build large plants in this country.”

Nonetheless, these projects under-



1. This image of the V.C. Summer Nuclear Station in South Carolina was taken on Sept. 18, 2017, after project owners SCANA Corp. and Santee Cooper ceased construction of Units 2 and 3 earlier that year. The companies said the decision was prompted by analysis of detailed schedule and cost data, and would save customers nearly \$7 billion. Courtesy: High Flyer © 2017



2. Plant Vogtle Units 3 and 4 were completed in 2023 and 2024, respectively. The project won POWER’s 2024 Plant of the Year award in recognition of the achievement. Courtesy: Georgia Power Company

score the need for plant owners to establish an experienced, dedicated, and honest project management organization to ensure that the consortium’s contractors are fulfilling their contractual obligations. The NEA said these two projects’ initial lack of resources in this area contributed to conflict between the EPC consortium, led by Westinghouse, and the plant owners, which hindered rapid and non-litigious adjustments to unanticipated changes in requirements or subcontractor performance. This also amplified contractual challenges that arose within the projects, according to the NEA.

Developing Experience

Yet, Bolisetti suggested that finding experienced people to fill nuclear construction teams won’t be easy, at least for a while. “There has been a huge lull in nuclear construction for the last few decades before they started building these plants in the late 2000s,” he told POWER. “With that kind of a lull—with that kind of loss of expertise and experience, and loss of supply chain—you can’t blame the industry for being the way it is, because that’s just what happens when you have a huge lull and loss of talent.”

Abdalla Abou Jaoude, INL’s deputy director for the System Analysis & Integration Program, suggested the best way to gain experience is to construct plants. “The silver bullet is to build many of them in a consistent fashion, capturing learning from one year to the next, having the same design team, the same EPC firms, the same specifications,” he said. “Everything that you do for the first time is going to be very expensive and very difficult to do. It’s not a question of changing something or innovating anywhere, necessarily, it’s primarily a question of rolling up our sleeves, doing it over and over again, and being consistent.” ■

—Aaron Larson is POWER’s executive editor.

Idaho Digital Twin Project Trailblazing for Nuclear

Courtesy: Idaho National Laboratory

In 2023, Idaho National Laboratory (INL) and Idaho State University unveiled the industry's first near real-time digital twin of a nuclear reactor. The virtual replica of the 5-Wth AGN-201 research reactor uses cloud-based monitoring and advanced machine learning to predict reactor performance dynamically.

Sonal Patel

Digital twins in the nuclear sector—real-time virtual models of reactors—have long-held promises to enhance safety, efficiency, and precision by allowing operators to monitor and predict system behaviors without physical intervention.

According to regulators, digital twins (Figure 1) could offer a real-time, synchronized view of plant conditions, supporting swift, data-driven responses to anomalies and reinforcing operational safety and efficiency. As key benefits to the nuclear industry, digital twins hold the potential to streamline diagnostics



1. According to the U.S. Nuclear Regulatory Commission (NRC), a digital twin, as part of a digital twin system, is a virtual representation of an entity, process, or system synchronized at a frequency and fidelity sufficient to maintain state concurrence. Essentially, it leverages various types of models, data, and frameworks to produce knowledge and insights about the represented entity, process, or system to fulfill an intended purpose. Source: NRC

and preventive measures, furnishing operators with more insights for efficient, informed decision-making. Still, developing effective digital twins has been challenging, owing to the sector's unique demand for secure, reliable data integration, complex sensor networks, and stringent regulatory compliance—all of which require high levels of accuracy and coordination.

Since 2020, Idaho National Laboratory (INL), a hotbed for nuclear innovation, has pursued several digital twin initiatives, exploring models that simulate reactor misuse scenarios, enhance safeguards in advanced reactors like sodium fast reactors and pebble-bed reactors, and other efforts that sought to optimize sensor placement and data flows for real-time monitoring and security compliance in new reactor designs. To add to that foundational research, in 2023, Ryan Stewart, an INL digital engineer, recommended using the Aerojet-General Nucleonics nuclear reactor (AGN-201) for some of the team's planned demonstrations.

A Groundbreaking Replica

Built in the 1960s at Idaho State University's (ISU's) College of Science and Engineering in Pocatello, Idaho, the compact 5-Wth AGN-201 reactor—one of only five still operating around the world—has served as a crucial teaching and research tool for scientists and students.

The reactor's core consists of nine fuel disks made from enriched uranium dioxide mixed with polyethylene, forming a compact 9.45-inch by 10.08-inch reactor core. Safety is central to its design: a polystyrene thermal fuse separates core sections if temperatures rise, halting the reaction safely. The reactor also features control rods and a central irradiation facility. As INL explains, the reactor's simplified structure provided an ideal backdrop for creating a digital model without the complexity and risks associated with larger commercial reactors.

Stewart's recommendation evolved into a full collaboration between INL and ISU, bringing together researchers, engineers, and ISU nuclear engineering students with the intent to create an integrated, cloud-based digital twin. By mid-2023, the team had developed a sophisticated, real-time digital twin that captures reactor data, processes it through advanced machine learning models, and streams it securely via cloud infrastructure. The digital twin has since been put to work in a range of operational scenarios, allowing researchers to monitor and predict reactor performance in real-time continuously.

INL says the digital twin is "a first in the industry." The experiment has served as a "key step in building a digital twin of a larger reactor system and has helped highlight many potential pitfalls and problems that such an endeavor might face," project

researchers added. It has “also shown the great promise that a cloud-first approach has when creating digital twins.”

The Technology Behind the Twin

According to INL, the AGN-201 digital twin is composed of several components. Essentially, it is powered by a robust data architecture that connects the physical reactor to its digital counterpart to allow for real-time, seamless data flow. To replicate the physical AGN-201’s characteristics digitally, the twin includes models of control rods, thermal safety mechanisms, and key temperature points.

At the core of the setup is the Data Acquisition System (DAS), which serves to monitor the physical reactor parameters continuously. That data feeds into Jester, an open-source tool developed by INL with an extensive plugin system, “which allows it to work on a myriad of different systems and with different file types,” the lab explains.

Jester then transfers data from sensor systems to the DeepLynx, the backbone of the digital twin. DeepLynx is an open-source data lake hosted on a Microsoft Azure for Government cloud platform, which allows it to connect all other processes and software developed for the twin. The cloud platform also leverages the Azure Kubernetes system (AKS) to deploy and manage infrastructure.

“Unlike other data warehouses, DeepLynx users can use an ontology [a structured framework] to custom-define how their data will be represented,” INL notes. “DeepLynx enables users to store their data in a graph-like format, ensuring that connections between data can be easily seen and understood. This data lake also allows users to store tabular, or time-series, data such as the data coming in off of sensors and [internet of things].” However, INL adds, “It is important to note that while fast, this process is not considered ‘real-time’ but ‘near real-time’ due to the network latency between each process communicating over the web.”

One of the project’s key achievements is to have developed programs to enable visualization of the digital twin, which allows its operators to monitor and easily identify anomalies and issues in reactor operation. One beta desktop application, OperatorUI, is designed to provide insights into reactor function by incorporating the machine learning data ingested by DeepLynx and then displaying it in an easy-to-digest format. Visualization

tools also leverage Microsoft HoloLens, an augmented reality (AR)/mixed reality (MR) headset with Microsoft positional tracking technology. Paired with Unity’s cross-platform game engine, the AR interactive view of the AGN-201 reactor allows operators to visualize real-time data flows in a fully immersive environment. The interface, notably, also integrates QR code scanning for precise alignment of digital data with physical components, essential for design reviews, ergonomics, and operational pathway testing.

Another core strength of the AGN-201 digital twin is its sophisticated machine learning and artificial intelligence (AI) detection programs, which pull live data from DeepLynx to enable real-time analysis and predictive insights. Tools like Papermill—an open-source utility for executing parameterized Jupyter Notebooks—streamline workflows by allowing automated, efficient processing without manual integration. Meanwhile, DuckDB, an in-process SQL OLAP database management system, serves as a temporary in-memory database to allow fast, columnar data storage optimized for analytics.

Overall, INL notes that two main constraints impacted the digital twin’s implementation. First, given data transmission limits over HTTPS and security firewalls, the digital twin operates in near real-time using batch processing rather than continuous data streaming from the AGN-201 reactor. Second, while INL chose to use Rust, a newer general-purpose programming language, given Rust’s fast runtime and secure memory handling, it required substantial debugging to establish reliable interoperability with Python for managing and analyzing reactor data in DeepLynx. The lessons “will continue to advance the understanding of how digital twins are implemented,” INL says.

Testing and Validation

To validate the digital twin’s (DT’s) security and system integrity, ISU operators have, over the past year, run the AGN-201 reactor under varied conditions while keeping the INL digital twin team in the dark. The approach has given INL’s digital twin team opportunities to independently evaluate the twin’s ability to detect off-normal operations.

The ISU and INL teams have also conducted a “Red versus Blue” test to evaluate the digital twin’s ability to detect and respond to potential misuse or nefarious activity. As part of the exercise, ISU reactor operators (as the red team) simulated

POWER POINTS

Winning Attributes

- ✓ Idaho State University and Idaho National Laboratory collaborated on a novel nuclear reactor digital twin that is “a first in the industry.”
- ✓ The experiment has served as a key step in building a digital twin of a larger reactor system.
- ✓ The digital twin’s machine learning algorithm has successfully flagged simulated anomalies and identified real-time security threats.

potential intrusions by introducing hidden operational changes, like inserting a polyethylene rod or cadmium foil into the central irradiation facility to mimic reactor tampering. The INL digital twin team (the blue team) used the digital twin’s anomaly detection system to monitor these changes and respond accordingly.

INL’s team says that to enhance the digital twin, it implemented an Isolation Forest machine learning algorithm during the test. “This algorithm is particularly good at spotting unusual patterns in data without the need for previously identified examples of such anomalies. The team first standardized the data, then fine-tuned the Isolation Forest model to the specific characteristics of the DT’s data,” it notes. The system successfully flagged each simulated anomaly and, in effect, showcased the digital twin’s reliability in identifying real-time security threats.

More work continues, however. Future development of the AGN-201 digital twin will focus on enhancing the reactor physics surrogate model using the Point Kinetics Equations-Surrogate Model (PKE-SM). That improvement should enable more precise tracking of power changes over time. Other efforts will address refining detection thresholds to identify even minor perturbations to ensure they stand out from normal operational variability, INL says.

For now, the digital twin has proven “a resounding success, despite the difficulties and hurdles in both operations and implementation,” INL says. “This work will lay the foundation for future digital twins in the Idaho National Laboratory’s sphere of influence and has proven that they have the capability to handle larger projects.” ■

—**Sonal Patel** is a **POWER** senior editor.

Belarusian Nuclear Power Plant Cuts Nation's Reliance on Natural Gas-Fired Electricity Generation

Courtesy: ROSATOM

In a strategic move to reduce its heavy dependence on Russian natural gas, Belarus has successfully completed its first nuclear power plant (NPP). The Belarusian NPP, featuring two VVER-1200 reactors, now provides about a third of the nation's electricity needs and represents a major step toward energy diversification, earning it recognition as a 2024 *POWER* Top Plant award winner.

Aaron Larson

The Republic of Belarus is a landlocked country in Eastern Europe. It is bordered by Russia to the north and east, Ukraine to the south, Poland to the west, and Lithuania and Latvia to the northwest. Belarus covers an area of about 207,595 square kilometers (km², about the size of Minnesota), 40% of which is forested. Its population was about 9.156 million as of Jan. 1, 2024, according to the country's official website. Minsk, the largest city and nation's capital, is home to 21.8% of the population; about 78% of the total population is urban, while 22% is rural.

Belarus was not blessed with abundant energy resources. In 2018, only 15% of the country's energy demand was met by domestic production, making Belarus one of the least energy self-sufficient countries in the world. Nearly all electricity generation that year (97% or 39 TWh) came from natural gas, supplied mainly by Russia. Notably, Belarus is an important part of Russia's gas transit corridor to Western Europe, and matters related to natural gas transit, such as infrastructure, system operations, tariff structure, and technical services, are established in a bilateral agreement with Russia's Gazprom.

Diversifying the Energy Mix

Yet, Belarus has long sought to lessen its reliance on Russian natural gas. The World Nuclear Association reports that in mid-2006, the Belarusian government approved a plan for the construction of

an initial 2,000-MWe nuclear power plant (NPP) in the Mogilev region of eastern Belarus. This was expected to provide electricity at half the cost of that from Russian gas and to provide some 30% of the country's electricity by 2020 at a cost of about €4 billion (January 2008 estimate).

After expressions of interest from international reactor vendors were invited, Russia's Atomstroyexport emerged as the most likely partner from a list of four suppliers for the two 1,000-MWe units because the others either did not provide all the information required or could not build the plant according to the desired timeline. Operation of the first unit was initially imagined in 2016 and the second in 2018, and two further units were proposed for operation by 2025.

In November 2007, a presidential decree defined the organizations responsible for preparing for the construction of the country's first NPP, and budgeted money for engineering and site selection. The candidate sites, according to the World Nuclear Association, were Krasnopolyansk and Kukshinovsk (both in the Mogilev region), and Ostrovets in the Grodno region. Ostrovets, 23 km from the Lithuanian border and 55 km from Vilnius, was chosen in December 2008, despite protests from Lithuania.

In June 2009, the Belarusian government announced that Atomstroyexport would be the general contractor, with Russian and Belarusian subcontractors. "On July 18, 2012, the General Contract for the construction of a nuclear power

plant was signed," a spokesperson for the Belarusian NPP told *POWER*. "Several subcontractors worked on the construction of the Belarusian NPP. Five of them—Belenergostroy, Rossem, Trust No. 8, Gomelpromstroy, and Grodno-promstroy—are the main ones."

Gen III+ Technology

The units constructed at Ostrovets are VVER-1200/AES-2006 plant designs. They are specifically the V-491 version, which was developed by St. Petersburg Atomenergoproekt on the basis of the AES-91 design developed for China and successfully deployed at Tianwan. The units each have a design net capacity of 1,110 MWe.

According to ROSATOM, Russia's state atomic energy corporation, the safety philosophy embodied in the VVER-1200/AES-2006 is unique among reactors on the market in deploying a full range of both active and passive systems to provide fundamental safety functions. Its safety systems are reportedly able to handle complicated situations that go beyond traditional design basis accidents. ROSATOM says all new VVER-1200 plants including the Belarusian NPP have design features that fully account for lessons learned from the Fukushima disaster. Notable safety features include having long-term cooling capability of the reactor core without electrical power; long-term decay heat removal that does not rely on primary ultimate heat sinks such as the sea, river, or cooling towers; and protection of reactor containment



1. VVER-1200 units utilize a horizontal steam generator design. One of the Belarusian steam generators is shown here being delivered. Courtesy: ROSATOM

integrity with dedicated systems after a core meltdown accident.

60-Year Service Life

The design service life of the reactor pressure vessel in the VVER-1200/AES-2006 plant is 60 years. Several measures have been taken to achieve that duration, which include limiting nickel content in welds; limiting impurities in base metal and welds; decreasing the ductile-to-brittle transition temperature of the nozzle area shell material to -35°C ; and increasing the vessel diameter, which reduces neutron flux at vessel walls. Notably, ROSATOM says the main coolant piping is designed to meet all necessary conditions of the “leak-before-break” concept, including material properties, stress analysis, in-service inspections, and leak monitoring.

The steam generators employed in the VVER-1200 are horizontal (Figure 1) and use a “corridor” layout for the heat-exchange tubes in the tube bundle. The horizontal design means the steam generators do not face such problems as primary water stress-corrosion cracking, fouling, and denting, according to ROSATOM. It says several VVER-440 plants have had steam generators in operation for more than 35 years with no corrosion of heat exchange tubes requiring tube plugging. The steam generator design, which has had incremental improvements over the years, is expected to match the 60-year service life of the reactor pressure vessel.

The heat transfer surface of the steam generator consists of 10,978 stainless steel tubes with a 16-millimeter (mm) diameter and 1.5-mm wall thickness. ROSATOM says the tubes and their support structures are very robust when compared with those typically used in vertical pressurized water reactor (PWR) steam generators.

The heat exchange tubes are arranged in a U-shaped bundle. The corridor layout of the tubes has 22 mm vertical and 24 mm horizontal spacings. The tube bundle

slopes downward 20 mm over the full length to provide proper drainage of tubes. The tubes are mounted by welding the ends to the inside surfaces of the main coolant inlet and outlet collectors.

VVER reactor plants have always used high-volume pressurizers. ROSATOM says this assures a high level of reactor safety, owing to the large coolant inventory in the primary circuit. In the VVER-1200 design, an additional line of controlled water injection to the steam space is included, which allows even better pressure control under transients.

The reactor core contains 163 fuel assemblies. Reactor output is controlled using 121 control rods, as well as with burnable neutron absorber in the fuel rods and by adjusting the boric acid concentration in the primary circuit water. In the VVER-1200 design, hexagonal fuel assemblies are used with 13 spacer grids (including an anti-vibration support) located with a gap of 340 mm. The height of fuel column 3.73 meters and the fuel is enriched up to 4.95%.

Project Details

At the height of construction of the Belarusian NPP facilities, more than 8,000 people were involved. All of them were qualified and experienced workers, according to the plant spokesperson.

The project went smoothly for the most part. However, in July 2016, while workers were moving the Unit 1 reactor pressure vessel, it slipped out of its sling and hit the ground. Although it was reportedly not damaged, ROSATOM replaced the vessel at the request of project overseers. Asked to elaborate on the event, the plant spokesperson said, “During cargo slinging, the subcontractor made deviations from the instructions, and the load was skewed when lifting it. As a result, the reactor vessel slid along the lines and hung diagonally in contact with the ground. At the moment it touched the ground, the main weight of the reactor vessel—more than two-thirds—was held by the crane. The Interdepartmental Commission for the Construction of a Nuclear Power Plant in the Republic of Belarus decided to change the reactor vessel at the Belarusian NPP.”

Still, the plant was reportedly completed on time and on budget. Unit 1 entered commercial operation on June 10, 2021, and Unit 2 followed on Nov. 1, 2023. “The construction of the Belarusian NPP was completed in full in accordance with the project and schedule of construction and installation work,” the spokesperson said. Today, more than 2,700 people work at the Belarusian NPP. “The staff of the nuclear

POWER POINTS

Winning Attributes

- ✓ The Belarusian Nuclear Power Plant (NPP) provides energy security and significantly diversifies the country's energy mix, reducing dependence on Russian natural gas.
- ✓ The addition of nuclear power reduces greenhouse gas emissions in Belarus.
- ✓ The Belarusian NPP supports the national economy and allows pursuit of other industrial opportunities.

power plant has been formed, trained, and has confirmed its qualifications more than once,” the spokesperson reported.

Game-Changing Results

The Belarusian NPP performed well in 2023. Unit 1 recorded an annual load factor of 78.9% and Unit 2 achieved a load factor of 84.6%, albeit in only two months of commercial operation. “Against the backdrop of the energy crisis, when other states are just starting to implement national nuclear programs, our country has already created its own nuclear infrastructure, the Belarusian NPP is working for the economy and bringing a tangible effect,” the plant spokesperson said. “The operation of two power units of the Belarusian NPP allows us to significantly reduce Belarus’ dependence on hydrocarbon fuels.”

The launch of the nuclear power plant reportedly opened up new opportunities for Belarus and its national economy, and made it possible to more actively develop other areas, such as the production of electric vehicles. “This large-scale project is of historical significance for our country,” the spokesperson said. “Belarus has received a stable, environmentally friendly source of energy, which will cover a third of its domestic electricity needs. Until recently, a significant part of it was produced from natural gas, the reserves of which Belarus does not have. Therefore, the focus is on alternative energy and the most advanced technologies.”

POWER congratulates Belarus and all the people who worked on the Belarusian NPP project. Their efforts are worthy of recognition, specifically, in the form of a 2024 *POWER* Top Plant award. ■

—**Aaron Larson** is *POWER's* executive editor.

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Nuclear Energy Comeback Action Is at the State Level

Todd Abrajano

This is indeed an extraordinary time to be in nuclear energy. Case in point: Over the past few months, we have seen an announcement between Microsoft and Constellation Energy to restart the Three Mile Island nuclear plant, a \$1.5 billion loan guarantee from the Department of Energy (DOE) to restart another reactor in Michigan, and a new DOE liftoff report on how to build new nuclear facilities.

We are witnessing much more demand from data centers and industrial facilities for the reliable, carbon-free power that nuclear plants produce and unprecedented federal government support. In addition, the U.S. government recognizes that we cannot achieve 2050 net-zero decarbonization goals without including new nuclear builds as a significant part of the mix.

But the real action is at the state level, where state governments are looking to encourage nuclear projects—first, to ensure businesses have the clean, reliable power they need at competitive prices, and second, to ensure that the state secures the high-quality jobs that nuclear plants bring.

Several U.S. states have begun to offer incentives or have set aside placeholders in their budgets for the industry. For example, the governor of Virginia recently signed a bill to accelerate the development of small modular reactors (SMRs) in the state, with plans to have at least one built by 2030. There are also plans for new SMRs next to an existing plant in Washington state, with some support from the state legislature.

Meanwhile, officials in Texas are working hard to attract new nuclear projects to the state, with plans under consideration at universities in the state and on other sites. In Tennessee, regulators have issued exemptions that will aid the progress of two high-temperature reactors planned for the Oak Ridge National Laboratory site, which has also been earmarked as the location of a new uranium enrichment facility.

The recent activity at the state level is on top of the strong support from the Federal government, which, through the DOE, is supporting several demonstration projects across the country. These include the TerraPower project in Wyoming, X-energy's project with Dow Chemical in Texas, and several others.

Only a few years ago, in the U.S., we were working just to keep existing reactors on the grid. Today, that danger has passed. Reactors previously under threat of closure are staying open. We are seeing a complete about face with reactors already closed, with some, like Three Mile Island—now slated to reopen. Administration officials acknowledge there are several others under consideration for restart. And there are a growing number of plans to build new nuclear facilities.

As tech companies build new data centers to power AI

and other power-hungry activities, there is new demand for reliable, carbon-free power, which nuclear plants are best at providing. We can all see that the demand from such centers is set to increase further in the future. Meanwhile, major industrial end-users like steel, oil, gas, and chemical companies have begun considering nuclear and have launched demand aggregation to build order books for new nuclear power plants.

Some advanced nuclear technologies operate at high temperatures, making them very good at servicing industrial applications such as producing hydrogen or ammonia. Their high-temperature operation makes them excellent choices to replace coal plants, because they can sometimes use the same turbines as well as other infrastructure such as grid connections.

Of course, new nuclear designs must prove themselves cost-competitive with other energy sources. The U.S. has gained hard-won experience building Vogtle 3 and 4, and estimates are that the next AP1000 could achieve a 25% cost reduction. Evidence from around the world shows us that substantial cost reductions are achievable once we get to an "nth-of-a-kind reactor," and once local workforce supply chains are built out and secure.

DOE's updated version of its liftoff report provides practical advice on how to reduce the cost of building nuclear plants. "Delivering the first projects reasonably on-time and on-budget will be essential for achieving liftoff of the next wave of nuclear in the U.S.; Vogtle provides essential lessons for project delivery," the report notes.

In addition, U.S. nuclear companies are seeing new international opportunities and are looking to complete their first project domestically before pursuing the new projects abroad. While many potential customers are interested in U.S. technology, coupled with the trust they have in the long-established U.S. nuclear sector, they all want to see a project completed before signing on.

Meeting the anticipated demand for new nuclear will require more than construction experience. This growth will also require specialized training and overall workforce development. We need to do more—globally—to ensure we have a suitably skilled extensive workforce to keep up with the demand.

We know that when we build nuclear plants, we don't just build reactors. We build the engines of a cleaner economy. We build supply chains. We build capability. We build sustainable futures.

There is a beautiful irony that the recent news from Three Mile Island—a site once seen as casting a shadow over the nuclear sector in the U.S. and beyond—could, in fact, mark a major turning point in the sector's resurgence. ■

—*Todd Abrajano is president and CEO of the U.S. Nuclear Industry Council.*

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