Advanced Reactors Global Market and Technology Overview

NOVEMBER 2024

Table of Contents

FOREWORD

As will be discussed in Section I, the global demand for clean, reliable energy is increasing rapidly. This demand is driven by various factors, including population growth, economic development, and reducing greenhouse gas emissions. Nuclear energy, which currently provides approximately 10% of the world's electricity, is poised to play a crucial role in meeting this growing demand while supporting the transition to a low-carbon future. Advanced reactors, which encompass a wide range of designs and capabilities, have the potential to not only provide clean electricity but also support various non-electric applications, such as district heating, water desalination, hydrogen production, and industrial process heat.

Section II of this report provides an overview of 15 advanced reactor designs, including both light water SMRs and non-light water reactor concepts. The information presented in Section II is based on publicly available sources and reflects the current state of development as of May 31, 2024. It is important to note that the advanced reactor landscape is dynamic and constantly evolving, with new designs, partnerships, and deployment opportunities emerging regularly. As such, the information provided in this report should be considered a snapshot of the industry at a specific point in time and may not reflect the most recent developments. By examining the global demand for clean energy, potential applications for advanced nuclear technologies, and the specific designs currently under development, this report aims to provide an overview of the role that advanced reactors can play in addressing the world's increasing energy demand.

This report provides an overview of 15 advanced reactor designs, including summaries of their key design features, licensing, deployment, and operational status, as well as any known commitments as of May 31, 2024. These 15 designs were selected for the initial version of this report through discussions between EPRI and one of its member organizations. It is important to note that no specific criteria were used to choose these particular designs over others. The selection was based on the interest and input provided by the participating EPRI members during the selection of the potential projects for collaboration. Other designs may be potentially added for the next revision of the document planned for 2026.

EPRI recognizes that there are many other advanced reactor designs in various stages of development worldwide, as evidenced by the Nuclear Energy Agency's (NEA) Small Modular Reactor Dashboard, which features a more extensive list of designs. As an independent, non-profit organization, EPRI maintains an unbiased perspective on all technologies and does not intend to show preference or favor toward any particular design by its inclusion or exclusion in this report.

Lastly, please note that the nuclear industry is rapidly evolving, and this report leveraged the best available information as of Spring 2024. EPRI intends to update this report periodically as new information becomes available.

Section I

Advanced Nuclear Outlook

There are multiple different definitions for *advanced nuclear* currently in use by industry. While these definitions vary, it is important to define *advanced nuclear* for this summary. The Gateway for Accelerated Innovation in Nuclear (GAIN), in conjunction with the Electric Power Research Institute (EPRI) and Nuclear Energy Institute (NEI), proposed the following definitions for *advanced nuclear* (Reference 1):

- **Definition 1 (Suggested):** The term *advanced nuclear reactor* means a nuclear fission reactor with significant improvements, including additional inherent safety features, compared to reactors operating on December 27, 2020, in the U.S.
- **Definition 2 (Alternate):** An advanced reactor is a nuclear fission reactor consistent with the definition of *advanced nuclear reactor* in 42 U.S. Code of Federal Regulations (USC) 16271 (Nuclear Energy).

This report, and subsequent technology assessments for different technologies, will use Definition 1 when referring to advanced nuclear and this group of technology's potential to meet future energy demands.

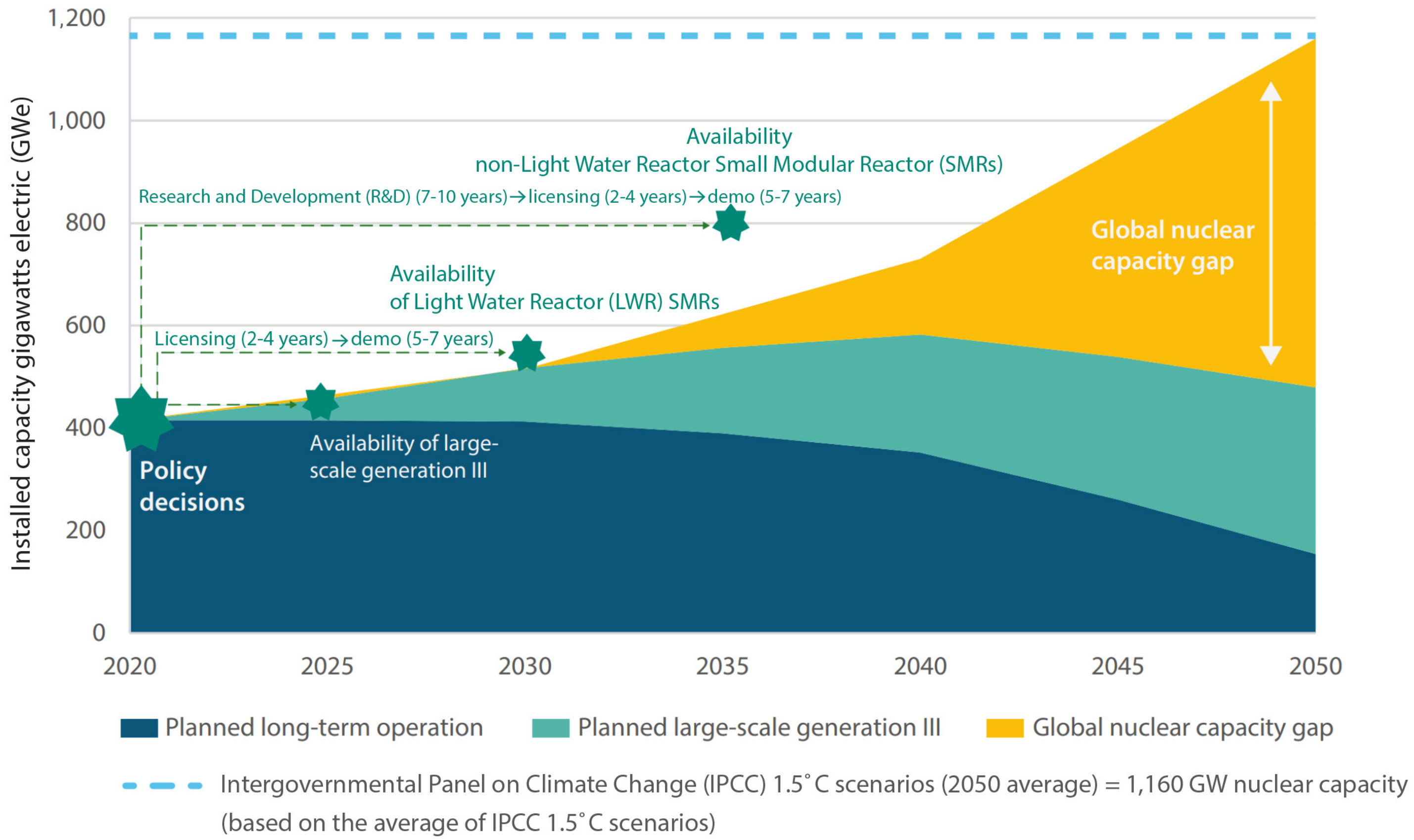
GLOBAL DEMAND FOR CLEAN ENERGY

As of late 2022, nuclear energy supplied 10% of global electricity from 444 nuclear power reactors, providing 394 gigawatts (GW) of capacity. This makes nuclear energy the second largest carbon-free electricity generation source in the world (after hydropower) and the largest source in Organization for Economic Co-operation and Development (OECD) countries. This existing nuclear capacity displaces 1.6 gigatonnes of carbon dioxide emissions annually (Reference 2).

"... late 2022, nuclear energy supplied 10% of global electricity from 444 nuclear power reactors, providing 394 GW of capacity."

Global energy demands and a desire for carbon-free energy production have pushed the need for nuclear energy as part of an integrated energy portfolio. The Paris Agreement is an international treaty on climate change adopted by 196 parties at the United Nations (UN) Climate Change Conference of the Parties 2021 (COP21) that was put into effect in 2016. This treaty's goal is to limit average global warming to less than 1.5°C, with this goal being met by reducing emissions by 45% by 2030 and reaching net zero by 2050. There will be a review of each COP21 signatory country's progress on cutting emissions every 5 years. To meet carbon reduction goals, it is estimated that installed nuclear capacity must reach 1,160 gigawatts by 2050. However, conventional large-scale, non-advanced nuclear reactor capacity is only expected to reach 479 gigawatts by 2050 (Reference 2). This means that advanced nuclear reactors will likely have an important role in closing this nuclear capacity gap, as shown in Figure 1.

Figure 1 | Global Installed Nuclear Capacity (Reference 3)



In addition to the commitments to the Paris Treaty, global interest in nuclear energy has risen due to the increased need for delivering power to underpowered areas, supporting the integration of renewables to the grid, the need for flexibility and resilience of the energy grid, and the need for secondary application support to achieve deep decarbonization (i.e., decarbonization outside of the electricity market) (Reference 4). Electricity demand forecasts are expected to increase, as the extent of electricity-intensive applications, such as electric vehicle (EV) charging stations and data center load demands, are expected to increase overall electricity demand.

Advanced nuclear technologies can enable these goals to be met. These reactors are reliable energy sources that can be flexible to energy needs, tying in well with variable renewables. Advanced nuclear reactors are an option for both power and non-power applications that can support other industries to become carbon-free.

Regional Advanced Nuclear Electricity Forecast

Nuclear output is expected to grow globally by 3.6% per year on average between 2023 and 2025. Low-carbon generation sources, renewables and nuclear together, are expected to meet more than 90% of the additional electricity demand by 2025 (Reference 5). Table 1 provides a breakdown by region of predicted electricity demand and nuclear and renewable supply growth rates from 2023 to 2025, and Figure 2 shows how much each region contributes to the overall global energy demand. Currently, new reactor projects actively under construction account for approximately 62 GW of new capacity from nuclear, with most of the new nuclear capacity coming from Asian Pacific countries (e.g., China, India, and South Korea), as shown in Table 2.

Table 1 | Regional Demand and Supply Annual Growth Rates, 2023–2025 Predictions (Reference 5)

REGION[1]	ELECTRICITY DEMAND ANNUAL GROWTH RATE	NUCLEAR ELECTRICITY SUPPLY ANNUAL GROWTH RATE	RENEWABLES ELECTRICITY SUPPLY ANNUAL GROWTH RATE
Africa	4.1%	6.6%	11.6%
Americas	1.0%	0.6%	5.0%
Asia Pacific	4.6%	2.3%	9.5%
Eurasia	0.4%	0.6%	1.4%
Europe	1.5%	4.2%	9.4%
Middle East	2.1%	24.5%	15.3%

Notes:

1. See Reference 5 for countries included in each region.

Figure 2 | Global Electricity Demand by Region (left) and Regional Shares (right), 1990–2025 (Reference 5)

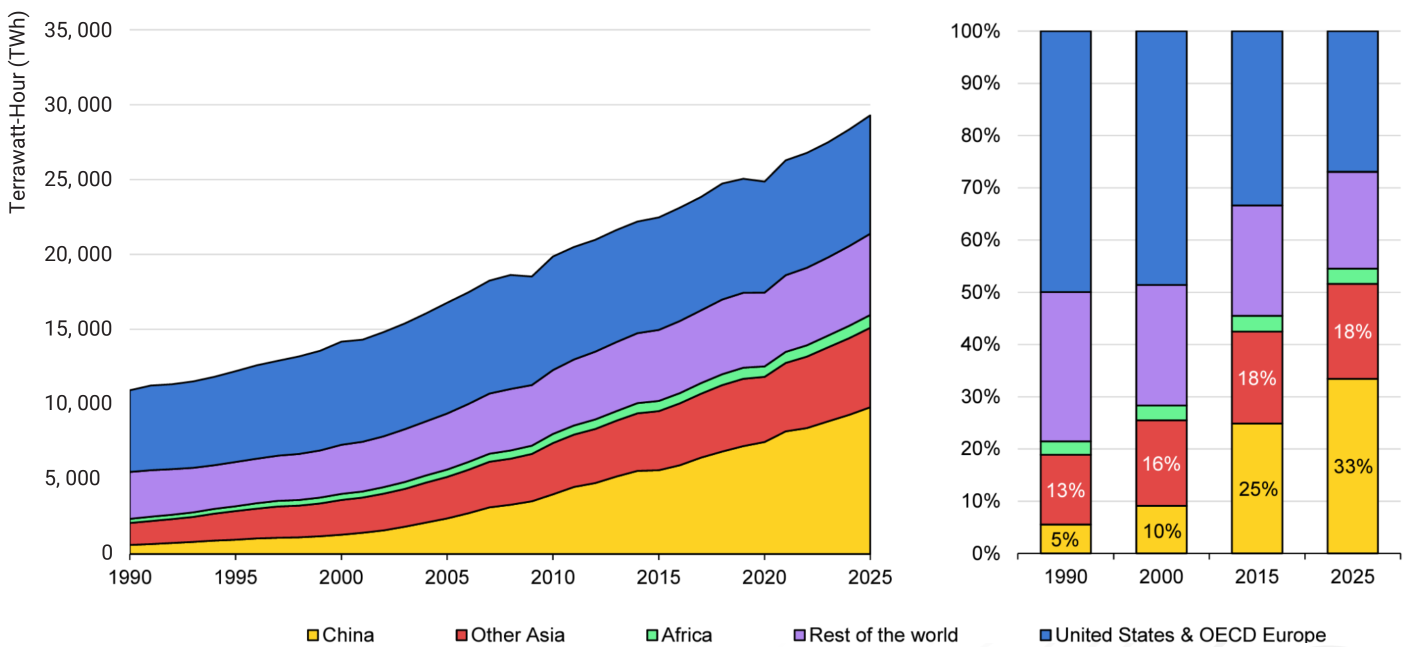


Table 2 | New Nuclear Capacity Under Construction by Country Through 2030 (Reference 6)

COUNTRY	NEW CAPACITY UNDER CONSTRUCTION MEGAWATTS - ELECTRIC (MW_e)
China	27,231
India	6,600
Turkey	4,800
Korea	4,200
Egypt	3,600
United Kingdom (UK)	3,440
Russia	2,810
Bangladesh	2,400
France	1,650
Brazil	1,405
United Arab Emirates (UAE)	1,400
United States (US)	1,250
Iran	1,057
Slovakia	471
Argentina	29
Total	**62,343**

Asia Pacific

By 2025, Asia is set to account for half of the world's electricity consumption with one-third of global electricity demand coming from China, as seen in Figure 2. In 2022, 57% of this demand was generated by coal and 32% came from low carbon sources, like nuclear and renewables (Reference 5).

China is the largest energy consumer in the region. This supply is provided primarily with coal, which supplied 62% of the country's power generation in 2022 (Reference 7). Under China's 14th Five-Year Plan (2021–2025), China hopes to maintain a steady pace of new nuclear deployment with a goal of 70 GW of nuclear supplied power, versus the 53 GW currently supplied at the beginning of 2022 (Reference 8).

India's currently installed electricity generation capacity is 410 GW, 236 GW of which is from fossil-fired power plants. India has a goal of reaching 500 GW of non-fossil capacity by 2030 (renewables and nuclear, Reference 5). As of 2022, India has 22 operating reactors providing 3.2% of its electricity generation (Reference 7). In addition, India is expected to start construction of a new 10 reactor fleet between 2023 and 2025 for a total of 9 GW of additional generation (Reference 8).

In 2022, Japan's nuclear power generation saw a 15% decline due to the shutdown of nuclear power plants for routine or special inspections. Japan is expecting to see a continuous increase in nuclear electricity generation to reduce the reliance on liquefied natural gas (LNG) and enhance energy security in the country. This is supported by a government push to restart the nuclear fleet, which could further boost nuclear generation (Reference 5).

South Korea had 29% of its electricity generation provided by nuclear in 2022 and an additional 8% provided by renewables. South Korea recently released its working draft of the 10th Basic Plan for Electricity Supply and Demand (BLPE) in August 2022, which plans to increase the nuclear and renewable contribution to the energy supply and, therefore, reduce the use of coal. This results in the share of nuclear in the power generation mix to exceed 30% and renewable energy's share to reach 12% by 2025 (Reference 5).

Americas

As of 2022, the United States (US) has 92 operating reactors that make up 19.6% of the electricity generation share (Reference 7). The US has invested in the nuclear industry to support its decarbonization goals. The 2022 Civil Nuclear Credit Program and the Advanced Reactor Demonstration Program have both invested billions of US dollars (USD) into preserving the existing reactor fleet and advanced nuclear, respectively (Reference 9). Additionally, the Inflation Reduction Act includes a targeted grant and loan program for clean energy investments, including nuclear and renewables (Reference 5).

There is also a handful of advanced nuclear power projects that are being planned or actively being built in the US and Canada.

In 2022, Canada had 19 operating reactors, supplying 14.3% of the electricity generation in the country (Reference 7). Canada has similar support from the government with proposed refundable tax credits for clean energy investments, including solar Photo-Voltaic (PV), wind, storage, and advanced nuclear (Reference 5).

Europe

The UK saw a decline in coal-fired power of 20% in 2022, an increase in nuclear power generation of 2%, and a renewable generation increase of 6%. The UK's nuclear capacity, as of 2022, consists of 10 operating reactors that supply 14.8% of the UK's electricity generation needs (Reference 7). As part of the UK's 2022 Energy Security Strategy, there are plans for the addition of advanced nuclear into the UK's grid to achieve a nuclear generation capacity of 24 GW by 2050 (25% of the forecasted electricity demand). The UK has supported the development of advanced nuclear technology with a 210 million Great British Pounds (GBP) investment (Reference 8) in line with its national goal of having a decarbonized power supply by 2035 (Reference 5).

France has 56 operating reactors, capable of supplying 69% of its electricity generation (Reference 7). France experienced low nuclear electricity generation due to maintenance and outages in 2022, but nuclear output is expected to reach 326 TWh in 2023, allowing power generation from fossil-fired sources to decrease by more than 40% (Reference 5). France announced plans to build 6 new large reactors starting in 2028 and a 1 million Euro (EUR) investment in advanced nuclear (Reference 8).

Middle East

In the Middle East, nuclear generation is expected to reach 3.5% of total power generation by 2025, nearly doubling from 2022. This is due largely to the ramp-up of the UAE's Barakah nuclear plant to full capacity. Renewable generation is expected to account for more than 5% of total generation by 2025; the biggest increases are expected in Saudi Arabia, Israel, Oman, and the UAE (Reference 5).

Demand for Additional Resources and Capabilities

Beyond electricity generation, there is a need for carbon-free power sources to achieve deep decarbonization. For example, the *hydrogen economy* is likely to increase in the near future due to its potential for use in the transportation industry. Creating hydrogen is a new process and, therefore, would only have limited benefit if the energy needed for hydrogen production is sourced from carbon-intensive resources. Additionally, humanitarian challenges such as water scarcity can be addressed in an environmentally equitable manner when desalination is powered with carbon-free energy sources. Not only is the demand for electricity increasing but also demand for these additional resources.

Global water use is likely to increase 20% to 50% above current levels by 2050. As of 2020, in many parts of the world, populations already face water insecurity, including about 2.1 billion people worldwide who lack access to safe drinking water or reliable water service. In many places, groundwater is the primary source of water, but these sources have been severely degraded due to overexploitation and pollution (Reference 10). With only 2.5% of the total water on earth being freshwater and demand increasing, the need for more desalination plants will only grow. Desalination plants are expensive, with one of the highest costs being the energy required for the process. This highlights a future energy demand where if global interest is to reduce carbon, desalination plants must be powered with carbon-free sources, such as nuclear.

Currently, hydrogen production is almost exclusively from fossil fuels resulting in high carbon emissions. There are currently around 390 projects, in various stages of development, to increase global capacity of hydrogen production through electrolyzers by 2030 and beyond. Hydrogen is a key pillar of decarbonization for industries, especially transportation, that hope to utilize hydrogen-based fuels to meet the zero-carbon emission goals. Further, there is potential for using hydrogen as a form of energy storage in lieu of other energy storage/production options such as battery storage and diesel generators. Hydrogen and hydrogen-based fuels offer decarbonization opportunities, especially in hard to electrify transport segments like long-haul, shipping, and aviation. While hydrogen is a possible carbon-free fuel source in the transportation industry, it is also in demand for industrial processes like steel manufacturing and chemical production (predominantly ammonia and methanol). This demand for hydrogen is expected to increase 30% by 2030 and double by 2050, mainly due to the increase in demand for ammonia and methanol production. For overall decarbonization of industry, the production of hydrogen needs to shift to become a zero-carbon process (Reference 11).

Black Start refers to a process of restoring an electric power station or part of an electric grid to operation without relying on external power from the grid. Typically, if off-site power is lost, on-site diesel generators are used to power the house loads (i.e., power needed to run pumps, systems) until the plant is capable of producing enough power to operate on its own and subsequently supply power back to the grid. Some power stations do not have enough power on site to start up without power from the grid. These black start capabilities are becoming more sought after, especially with the increased push for grid resiliency across the globe. There are different possible threats to the grid and power reliability, including outages due to climate change and weather-related events, that challenge the grid and the ability for utilities to offer reliable power. Black start capabilities help reduce outage time and can kickstart the process to start adding load back onto the system and getting the power on for more people, more quickly (Reference 3).

ADVANCED NUCLEAR USE CASES

This section outlines some of the main, potential use cases for advanced nuclear and potential technology characteristics an owner/operator may place an emphasis on depending on the envisioned use case of the reactor. EPRI's Advanced Nuclear Technology (ANT) program is leading the R&D effort to enable new nuclear deployment and has numerous publications available to EPRI members that outline key strategies for owners/operators to de-risk nuclear deployment at every stage (e.g., siting, licensing, construction, startup, and initial operations). The ANT program also encompasses EPRI's research conducted on the Nuclear Beyond Electricity (NBE) initiative, which is developing resources to enable existing and future nuclear technologies to participate in energy markets beyond electricity generation for the grid. Owners/operators interested in deploying new nuclear assets should leverage existing ANT resources.

For more information on the ANT program and to view publications, please visit https://www.epri.com/portfolio/programs/065093.

Electricity

Advanced nuclear can be used as an alternative to fossil fuel electricity generation, supporting the drive for emissions-free power generation. This can either be baseload generation or flexible variable power. The reliability of advanced nuclear electrical generation will help with the overall stability and resilience of the grid. Some advanced nuclear reactors can operate on significantly smaller footprints with less of an exclusion area. This feature can help advanced nuclear reactors be incorporated into the grid at ideal locations, rather than limited sites due to large land requirements. Further, smaller nuclear power plants are ideal in markets where baseload power demand increases slowly (e.g., developed countries), where smaller increments of carbon-free baseload power are required as opposed to large, stepwise increases in power.

Most, if not all, advanced nuclear technologies can support electricity generation, but this function is better supported by some concepts than others. Owner/operators who are primarily interested in electricity generation may elect to put less emphasis on a design's outlet temperature and ability to provide process heat and more emphasis on designs that offer high reliability and availability. Additionally, some modular concepts for advanced nuclear reactors provide greater flexibility to meet power needs and the capability to load follow or store energy to complement intermittent renewable power sources.

Off-Grid/Black Start Applications

Remote areas, including mining and resource extraction sites, many times don't have the ability to connect to the grid for electricity. In some cases, diesel generators are used as an alternative connection to the grid; advanced nuclear reactors can replace the need for diesel generators. Additionally, diesel generators are often used for black start capabilities. Some advanced nuclear designs include this black start functionality, where external power is not required to start the plant and could replace the need for diesel generators.

Advanced nuclear reactors that have black start capabilities are well suited for remote areas, where additional power would not be required to get the advanced nuclear reactor electricity generation started. Additionally, an advanced nuclear reactor with a smaller plant footprint would be advantageous to accommodate more types of locations and applications. Advanced nuclear reactors with lower power output would be well suited to these off-grid applications, including replacing the need for diesel generators.

Process Heat and Hydrogen Production

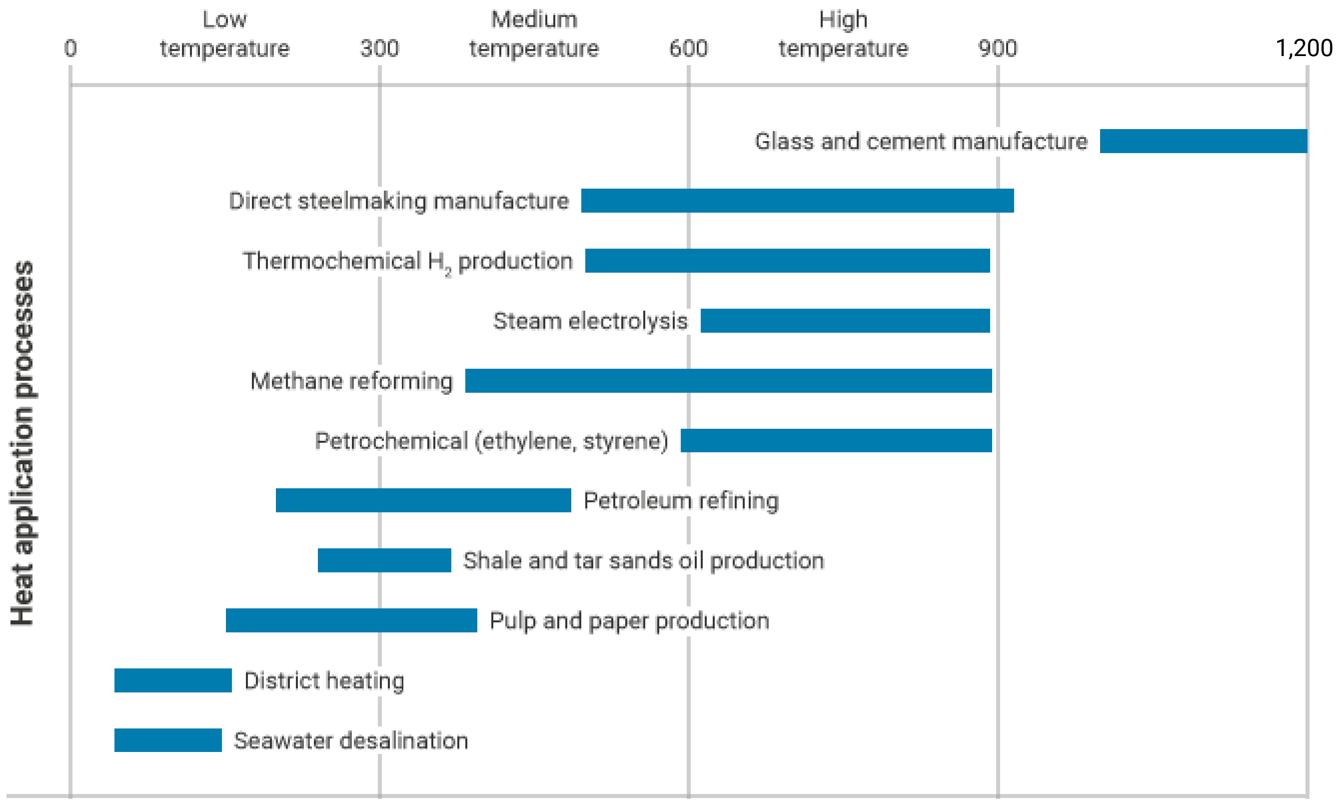
Many industrial processes require a large amount of heat, which a nuclear plant can provide with carbon-free energy. Some designs can be more tailored for heat production as opposed to electricity generation; therefore, potential owner/operators may place more emphasis on a design that can provide temperatures needed for the envisioned end use application. For example, the chemical industry, ammonia, and refinery industries require temperatures near 550°C, whereas the aluminum and steam-methane reforming industries require temperatures near 800°C (Reference 2). High temperature reactors are best suited to these applications, where some advanced nuclear reactors operate at 700°C or higher and others only operate at 550°C (Reference 2).

In terms of hydrogen production, there are currently two main methods of producing hydrogen: steam-methane reforming and electrolysis. In steam-methane reforming, high-temperature steam (700˚C-980°C) at between 3 bar and 25 bar pressure reacts with methane in the presence of a catalyst to produce hydrogen. Byproducts of this process include carbon monoxide and some amount of carbon dioxide. Natural gas and landfill gas/biogas are typical methane sources for this process (Reference 12). *Electrolysis* is a process that splits hydrogen from water using an electric current. Electrolysis itself does not produce any byproducts or emissions other than the hydrogen and oxygen (Reference 12). The high resource needed for this process is the electricity. Advanced nuclear reactors could be integrated into either of these forms of hydrogen production, utilizing either pressurized and high temperature steam from the advanced nuclear plant or the advanced nuclear reactor as a carbon-free electricity generator.

Figure 3 shows temperature requirements (°C) for various industrial applications and hydrogen production processes.

For more information regarding nuclear for hydrogen production applications, please consult *Conceptual Design Guide for Developing a Nuclear-Integrated Hydrogen Facility*, EPRI Report No. 3002026514.

Figure 3 | Temperature Requirements for Various Industrial Processes (Reference 13)



Cogeneration and District Heating

Currently, most co-generation plants (typically electricity and heat) rely heavily on fossil fuels. These co-generation plants could be modified to utilize an advanced nuclear technology as the energy source to run the plant. One specific application of co-generation plants is for district heating. Current district heating relies heavily on fossil fuel co-generation plants that can supply electricity and heating to support building-level boilers and furnaces. This energy need, both residential and commercial, could be supplied by advanced nuclear electricity and heat. Advanced nuclear reactors with smaller footprints may have an advantage over larger facilities as they can be sited closer to the energy need to reduce energy losses for transport (Reference 2). Additionally, some advanced nuclear reactors may have designs more easily adaptable to support a co-generation plant.

Desalination of Water

Currently, reverse osmosis is the typical technology used for desalination, but there are other less common technologies, including thermal processes that advanced nuclear reactors could support with electricity or heat generation. This is very energy-intensive, especially for the pumps needed to achieve the high pressures for the process. The energy required for the pumps alone account for approximately 25% to 40% of the overall cost of the water (Reference 14). There are two primary markets for desalination: large-scale to provide tens of millions of gallons for desalinated water a day and small-scale to provide anywhere from hundreds to thousands of gallons of water per day. Large-scale plants require tens of megawatts to run, whereas small-scale plants only need tens to hundreds of kilowatts to operate. The ability to reduce the energy costs will be critical for future plant development and wide scale desalination deployment (Reference 14). Advanced nuclear reactors can be integrated into this process and provide the electricity needed.

Merchant Shipping

Emissions from maritime transport are a significant source of marine atmospheric pollution. Nuclear energy rather than fossil fuels for propulsion of these merchant ships is one option to transition the maritime industry toward decarbonization. Some militaries operate nuclear powered ships, but few civilian ships have been nuclear powered (Reference 15). Due to the need for an on-ship power source, advanced nuclear reactors with very minimal exclusion area are required. Some vendors are developing specialty designs specifically for maritime applications. Additionally, advanced nuclear can extend the distance merchant ships can travel due to the long spans before refueling is needed.

Coal Station Repowering

Many utilities that currently own coal-fired assets are evaluating nuclear power as a potential carbon-free replacement option. Because coal-fired power stations have existing site infrastructure, such as a grid interconnection, cooling water pumping infrastructure, and an available workforce, advanced nuclear power is a viable option for replacing retiring coal stations.

Section II

Advanced Reactor Concepts ARC-100

OVERVIEW

The ARC-100, designed by Advanced Reactor Concepts, LLC, and General Electric Hitachi, is a Liquid Metal Cooled Reactor (LMCR) based on technology used in the Experimental Breeder Reactor (EBR) II Reactor, built by the Argonne National Laboratory (ANL) under the U.S. Department of Energy (DOE). This non-Light Water Reactor leverages past operational experience to deliver a versatile reactor that can provide electricity , process heat, medical isotope production, load following with other sustainable energy sources, and many other applications. Further, this design leverages a 20-year refueling cycle, significantly reducing the amount of waste generated (Reference 16).

DESIGN DESCRIPTION

The ARC-100 is a fast neutron, pool-type reactor, with liquid sodium cooling that produces 286 MW_{th} and 100 MW_e. Liquid sodium removes heat generated in the core to an intermediate heat exchanger and loop that is also filled with liquid sodium. The intermediate loop then transfers heat to a steam generator, where the steam is taken to the turbine to generate electricity.

The ARC-100 is a fast-spectrum reactor that utilizes High-Assay Low-Enriched Uranium (HALEU) metallic fuel, specifically a Uranium-Zirconium alloy, with an average fuel enrichment of 13.1%. The reactor requires refueling every 20 years, with an ultimate design lifespan of 60 years. The ARC-100 has the capability to reprocess spent fuel but would need regulatory approval in the host country before utilizing this capability. The spent fuel will be pyro-processed, as developed by the ANL, and can then be reused by the reactor (Reference 17).

> "The ARC-100 is a fast neutron, pool-type reactor, with liquid sodium cooling that produces 100 MW_e."

The site footprint stands at approximately 54,000 m^2 (~13.3 acres)[1]. The overall construction time for the ARC-100 is estimated to be 34 months (Reference 16).

Table 3 provides a summary of key ARC-100 design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide.

[1] Depending on the deployment location/additional structures, more land may be required than the ~13.3-acre estimate. Additionally, this does not include any land required for construction activities.

Table 3 | End User Considerations for the ARC-100 (Reference 16)

END USER CONSIDERATION	ARC-100 VALUE
Neutron Spectrum	Fast
Moderator	N/A
Coolant	Liquid Sodium
Fuel State	Solid
Mission [(1)]	Electricity Generation - Flexible
Thermal Output	286 MW_{th}
Electrical Output	100 MW_e
Size	Small [(2)]
Technology Generation	Advanced Reactor [(3)]

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. EPRI defines reactors with power outputs of less than 300 MW_e as small reactors (Reference 4).
3. EPRI defines an advanced reactor as “any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors” (Reference 4).

KEY SAFETY FEATURES

The ARC-100 uses two main shutdown systems. The first system is the reactor protection system, which will drop control rods into the core should the operational safety envelopes be exceeded during operation. The second shutdown system consists of the inherent reactivity feedback system. This inherent safety system adds negative reactivity to the core as the core temperature increases quickly, causing the core to become subcritical. The ARC-100 also consists of two independent passive core cooling systems: the Direct Reactor Auxiliary Cooling System (DRACS) and the Reactor Vessel Auxiliary Cooling System (RVACS). This reactor uses the DRACS and RVACS systems to keep the core and reactor vessel cool during abnormal events. A containment system is utilized to ensure any radiological release is below regulatory limits. These systems remove the need for personnel intervention for safe shutdown while employing redundancy to allow the plant to operate safely (Reference 16).

The safety-related shutdown instrumentation and controls system consists of a Distributed Control and Information System (DCIS), which is a three-division control and monitoring module with separate and independent electric power supply systems. Divisions support an automatic shutdown of the reactor and decay heat removal through DRACS and RVACS (Reference 17).

CURRENT STATUS

The following section provides an overview of ARC-100 deployment status as of Spring 2024. Table 4 provides a summary of various ARC-100 deployment activities.

The ARC-100 has successfully completed Phase I of the pre-licensing Vendor Design Review (VDR) under the Canadian Nuclear Security Commission (CNSC) (Reference 17). The reactor is currently in Phase II of the pre-licensing process (Reference 2).

New Brunswick Power (NB) applied for a License to Prepare Site (LTPS) at the Point Lepreau Nuclear Generating Station in June 2023 to assess the feasibility of hosting an ARC-100 at the site (Reference 18). Additionally, the ARC-100 has been shortlisted for heat and power generation at the Green Energy Hub by the Canadian Belledune Port Authority (Reference 2).

The ARC-100 was granted funding of more than 50 million USD from the DOE and the Government of New Brunswick. The University of New Brunswick allocated funding and resources for the ARC-100 research and early-stage development. Additionally, in 2022, ARC Clean Technology obtained 30 million USD via public and private entities (Reference 2).

Beginning in 2018, NB Power signed a Memorandum of Understanding (MOU) with ARC Clean Technology. In December 2020, ARC Clean Technology signed a new MOU with the Government of New Brunswick and NB to deploy the ARC-100 at the Point Lepreau Nuclear Generating Station (PLNGS) (Reference 19). In May 2024, ARC signed a trilateral Collaboration Agreement with Korea Hydro and Nuclear Power and New Brunswick Power for this project (Reference 20). ARC Clean Technology has existing agreements with AECOM, Hatch, and GE Hitachi to support deployment of the ARC-100. The Government of New Brunswick has continued to support the deployment of the ARC-100 via partnership with Canadian Manufacturers and Exporters and Opportunities New Brunswick on supply chain preparation (Reference 2).

Table 4 | ARC-100 Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	Preliminary Design Phase
Licensing	CNSC: VDR: In Phase II NRC: Pre-Application
Supply Chain	Currently no commercial fuel supply from the Organizations for Economic Co-operation and Development countries Commitments: • Canadian Nuclear Laboratory: Develop Fuel Manufacturing Process • AECOM (U.S.), Hatch (Canada), and GE Hitachi (U.S.): Deployment • OARO (Canada): Digital Security Solutions • Canadian Manufactures & Exporters and Opportunities New Brunswick (Canada) Letter of Intent (LOI): Centrus: HALEU Supply
Lead Demonstration Project	PLNGS: • Anticipated Deployment: 2030 • Application for LTPS for Point Lepreau submitted by NB Power: 6/30/2023
Interested Parties[1] and Level of Interest	MOU: • NB Power (Canada) • Government of New Brunswick (Canada) • Province of Saskatchewan (Canada) • Korea Hydro and Nuclear Power, Collaboration Agreement

Notes:

1. Interested parties include utility and non-utility entities that have publicly stated interest, either through a signed contract MOU or other cooperation agreement.

GE-Hitachi BWRX-300

OVERVIEW

The GE-Hitachi (GEH) BWRX-300 is a boiling water reactor (BWR) design. The design builds upon previous BWR generations, including the Advanced Boiling Water Reactor (ABWR) and Economically Simplified Boiling Water Reactor (ESBWR) (Reference 21). The BWRX-300 design simplifies or eliminates many systems, structures, and components (e.g., safety relief valves and recirculation system) of traditional BWRs with the intention to reduce deployment and operational risk.

DESIGN DESCRIPTION

The BWRX-300 is a natural circulation, light water-cooled and moderated BWR that produces 870 MW_{th} and 300 MW_e.

As the Original Equipment Manufacturer (OEM) for the existing BWR fleet, GEH's design of the BWRX-300 intends to make use of many existing BWR technologies and features. This includes the use of Global Nuclear Fuel - 2 (GNF-2) fuel assemblies, which are currently used in approximately 80% of traditional BWRs. In addition, the reactor pressure vessel is constructed of standard SA-508 reactor pressure vessel steel. This is the material currently used in most existing light water reactors, avoiding the need to use less traditional reactor materials (Reference 21).

Refueling outages are expected to occur every 12–24 months and are anticipated to last between 10 and 20 days. In addition, there are 25-day outages that occur every 120 months (10 years) for major inspections, including the turbine and reactor vessel and internals. The total design life for the plant is 60 years (Reference 21).

> "The BWRX-300 is a natural circulation light water reactor that can produce 300 MW_e."

The plant footprint (including the power block, protected area, and all owner's facilities) is approximately 50 acres (the exact value is site specific). Approximately 70 personnel are anticipated and required during normal operations, and construction time for the 9th-of-a-kind BWRX-300 is projected to be less than 30 months (Reference 21).

Table 5 provides a summary of key BWRX-300 design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide (Reference 4).

Table 5 | End User Considerations for the BWRX-300 (Reference 12)

END USER CONSIDERATION	BWRX-300 VALUE
Neutron Spectrum	Thermal
Moderator	H_2O
Coolant	H_2O
Fuel State	Solid
Mission [(1)]	Electricity (Baseload with load following)
Thermal Output	870 MW_{th}
Electrical Output	300 MW_e
Size	Medium [(2)]
Technology Generation	Advanced Reactor [(3)]

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. EPRI defines reactors with power outputs of 300 MW_e–600 MW_e as medium-sized reactors (Reference 4).
3. EPRI defines an advanced reactor as “any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors” (Reference 4).

KEY SAFETY FEATURES

The BWRX-300 is designed and analyzed using International Atomic Energy Agency (IAEA) guidelines to be more efficiently licensed internationally. The safety approach leverages the inherent safety margins within the design and defense-in-depth principles. Using this approach, the BWRX-300 has both a core damage frequency and a large release frequency of less than 10^{-7} per year (Reference 17).

The shutdown cooling (SDC) system removes decay heat from the core during normal shutdowns. This system consists of two parallel pump and heat exchanger trains. The isolation condenser system (ICS) provides core cooling during emergency conditions, replacing the emergency core cooling system found in traditional BWRs. This system has three independent loops that are each capable of removing 33 megawatts (MW) from the core. The BWRX-300 can cool itself without power or operator action for a minimum of seven days (Reference 17).

The primary containment vessel (PCV) completely encloses the reactor pressure vessel and acts as a barrier to prevent radiological release. This vessel is integral to the reactor building and is located mostly below grade (Reference 17).

The BWRX-300 instrumentation and control (I&C) system is completely integrated into the plant and is divided into three subsystems: safety class 1, safety class 2/3, and non-safety (Reference 17).

CURRENT STATUS

The following section provides an overview of BWRX global deployment status as of October 2023. Table 6 provides a summary of various BWRX deployment activities.

GEH is engaging with the CNSC and has completed Phase 2 of the VDR process. In October 2022, GEH also submitted a construction application to build a BWRX-300 at the Darlington site, owned by Ontario Power Generation (OPG) (Reference 17). In July 2023, this application was updated to include four BWRX-300 reactors (Reference 23). Commercial operations are projected to begin in 2029 (Reference 24). There is another potential Canadian deployment of the BWRX-300 with SaskPower in Saskatchewan, Canada (Reference 2). In January 2024, OPG and Capital Power Corp. signed an agreement to examine the feasibility of developing SMRs in Alberta, Canada.

In addition, GEH is engaging with the United States Nuclear Regulatory Commission (USNRC) on pre-application activities, including the review of several licensing topical reports (Reference 2). The Tennessee Valley Authority (TVA) has partnered with GEH for a construction permit application at the Clinch River Site in Oak Ridge, Tennessee (Reference 24).

The BWRX-300 has also been shortlisted by Fermi Energia as it explores potential options for an SMR deployment in Estonia with additional MOUs for deployments with Synthos Green Energy in Poland, ČEZ in the Czech Republic, and Kärnfull Next in Sweden (Reference 2).

To support the projected BWRX-300 deployments, GEH has both public and private funding. This includes approximately CAD 1 billion for the Darlington deployment from the Canadian federal government and additional funding from the US Department of Energy (Reference 2).

As OEM for the existing BWR fleet, GEH intends to leverage aspects of its existing supply chain and the General Electric parent company, including the GNF-2 fuel assemblies, to support the BWRX-300 (Reference 21). In addition, GEH has signed an MOU with the Canadian mining company Cameco to supply uranium for the planned BWRX-300 fleet (Reference 2). In April 2024, GEH formed a group of qualified supply chain companies to help ensure the deployment of the BWRX-300. The first company to join the supplier group is BWXT Canada, who designs and manufactures large and heavy nuclear components (Reference 22).

Table 6 | BWRX-300 Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	Site specific for Darlington to be completed 2024
Licensing	USNRC: Pre-Application Engagement CNSC VDR Phase 1 and 2 complete
Supply Chain	• Plan to leverage existing BWR supply chain • Fuel Assemblies—Global Nuclear Fuel (a GEH and Toshiba venture) • Uranium Supplier—Cameco • BWXT Canada
Lead Demonstration Project	Darlington Nuclear Power Plant • Approximate Construction Start: 2024 • Approximate Commercial Operations: 2029
Interested Parties[1] and Level of Interest	Commitments: • OPG (Canada)—Construction application submitted to CNSC • TVA (US)—Intends to submit a Construction Permit for Clinch River MOU: • Fermi Energia (Estonia) • Synthos Green Energy (Poland) • ČEZ (Czechia) • Kärnfull (Sweden) • Capital Power Corp (Canada)

Holtec International SMR-300

OVERVIEW

The SMR-300 is a pressurized water reactor (PWR). The reactor components are assembled in a factory-style environment and are shipped out in segments, making it effective for scaling. The SMR-300 is intended to provide safe and reliable electricity for grid-scale markets, including remote locations. It has capabilities for autonomous startup (i.e., "black start"), allowing the reactor to be used in off-grid locations. Additionally, the SMR-300 is configurable in water-scarce locations and can leverage Holtec's air-cooled technology for the reactor's condenser. The SMR-300 has optional capabilities in cogeneration equipment, including district heating and hydrogen generation (Reference 17).

It should be noted that the SMR-160 was uprated to the SMR-300 during the drafting of this report. Values reported in this section that reference previous SMR-160 information are assumed to carry over to the SMR-300 design, but should be confirmed with Holtec directly.

DESIGN DESCRIPTION

The SMR-300 is a thermal neutron, natural circulation reactor, with light water cooling. The reactor produces 1050 MW$_{th}$ and 300 MW$_{e}$ (Reference 17).

The reactor coolant system (RCS) primary loop is naturally circulating. The reactor has an offset configuration of the reactor pressure vessel (RPV) and the steam generator (SG) with an attached pressurizer. This connects the hot and cold leg together in parallel ducts, significantly reducing the risk of a Large Break Loss of Coolant Accident (LBLOCA). Additionally, the RCS operates without any reactor coolant pumps within the system. The RCS is a combined vessel consisting of the RPV, the SG, and the integrated pressurizer, eliminating the need for any intermediary looping (Reference 17).

The SMR-300 utilizes Low Enrichment Uranium (LEU), with an average enrichment of 4.0%. The reactor requires refueling every 24 months, with an ultimate design life cycle of 80 years (Reference 17).

> "The SMR-300 is a thermal neutron, natural circulation reactor, with light water cooling. The reactor produces 160 MW$_{e}$."

The installation area for the SMR-300 is anticipated to take up to approximately 7.5 acres (Reference 25). Overall construction time for an nth-of-a-kind unit is projected to be 24 months (Reference 26).

Table 7 provides a summary of key SMR-300 design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide.

Table 7 | End User Considerations for the SMR-300 (Reference 17)

END USER CONSIDERATION	SMR-300 VALUE
Neutron Spectrum	Thermal
Moderator	H_2O
Coolant	H_2O
Fuel State	Solid
Mission [(1)]	Electricity Generation - Flexible
Thermal Output	1050 MW_{th}
Electrical Output	300 MW_e
Size	Medium [(2)]
Technology Generation	Advanced Reactor [(3)]

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. EPRI defines reactors with power outputs of 300 MW_e–600 MW_e as medium-sized reactors.
3. EPRI defines an advanced reactor as "any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors" (Reference 4).

KEY SAFETY FEATURES

All critical components of the reactor are in an underground steel containment structure (CS), enclosed within a reinforced concrete enclosure system (CES). All safety systems and makeup water in the case of a Loss of Coolant Accident (LOCA) are encapsulated within the CS (Reference 17).

This design employs both passive and redundant safety systems. The Passive Containment Cooling System utilizes natural circulation, gas expansion, and gravity injection as means to regulate flow. The reactor also provides emergency cooling for the spent fuel pool, all contained below grade (Reference 17). The plant is designed to utilize Holtec's HI-STORM UMAX subterranean dry storage casks for spent fuel storage, which have already been licensed by the U.S. Nuclear Regulatory Commission (USNRC) (Reference 27). The Passive Containment Heat Removal (PCHR) system redirects heat from containment without any actuation requirements (Reference 17).

The reliance on a passive safety system removes the need for human intervention, resulting in a safe response to the reactor during postulated events. The core damage frequency is estimated to be 10^{-8} per year (Reference 17). Additionally, no Emergency Planning Zone (EPZ) is required beyond the site fence (Reference 25).

The SMR-300 uses the Mitsubishi Electrical Total Advanced Controller (MELTAC), a unique digital system that allows all integral I&C to be conducted on a single platform (Reference 17).

CURRENT STATUS

The following section provides an overview of SMR-300 deployment status as of Spring 2024. Table 8 provides a summary of various SMR-300 deployment activities.

In late 2023, Holtec uprated the design of the SMR-160 to SMR-300, with a corresponding increase in power output. Holtec had made several status announcements with the SMR-160 as discussed below, but it is unclear as of writing if these status announcements carry over to the SMR-300. Prior to this change, Holtec had successfully completed Phase I of the pre-licensing Vendor Design Review (VDR) with the Canadian Nuclear Safety Commission (CNSC) (Reference 28), and was in pre-application activities with the NRC for the SMR-160 and SMR-300 (Reference 114). Holtec submitted the SMR-160 design to the UK Generic Design Assessment (GDA) Entry Process in early 2023 (Reference 29).

Additionally, before the design change, Korea's two national financial institutions, the Korean Trade Insurance Corporation (K-SURE) and the Export-Import Bank of Korea (KEXIM), entered agreements with Holtec and Hyundai Engineering and Construction to provide finances for the deployment of SMR-160s around the world (Reference 31). Holtec International has 116 million USD from the DOE under its Advanced Reactor Demonstration Program (ARDP) to support the engineering and licensing of the SMR-160. In addition, the DOE approved a loan application for Holtec to expand its manufacturing facility in Camden, New Jersey (Reference 28).

Holtec holds several contracts with third-party vendors for the development and construction activities of the reactor. They have existing contracts with Kiewit Power Constructors, Mitsubishi Electric, and Idaho National Laboratories (Reference 28). In December of 2023, Holtec announced it is planning on deploying the first SMR-300 units at the Palisades Nuclear Power Station in Michigan. Holtec intends to submit a construction permit application with the NRC in 2026 and commission the first SMR-300 unit by the mid 2030s (Reference 115).

Table 8 | SMR-300 Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	Detailed Design by 2025
Licensing	USNRC: Pre-application activities
Supply Chain	• Kiewit Power Construction (US): Construction • Mitsubishi Electric (Japan): Digital I&C • INL (US): Plant Simulator • K-SURE and KEXIM (Korea): Finance
Lead Demonstration Project	Palisades Nuclear Power Station
Interested Parties[1] and Level of Interest	TBD
Notes: 1. Interested parties include utility and non-utility entities that have publicly stated interest, either through a signed contract, MOU, or other cooperation agreement.	

INET HTR-PM

OVERVIEW

The INET High Temperature Reactor – Pebble bed Module (HTR-PM) is a modular pebble bed high-temperature gas-cooled reactor (HTGR) design. The HTR-PM is the world's first demonstrator of an HTGR pebble-bed GEN IV reactor based on the HTR-10, a 10 MW_{th} test reactor. The HTR-PM is a commercial demonstration unit for electricity production to demonstrate feasibility of twin reactor modules driving a single turbine configuration (Reference 17). In December 2022, the HTR-PM project reached "initial full power," and on December 6, 2023, HTR-PM has entered commercial operation (Reference 32).

DESIGN DESCRIPTION

The HTR-PM is a helium-cooled, graphite-moderated pebble bed reactor that produces 500 MW_{th} (2 x 250 MW_{th}) and 210 MW_e (Reference 17).

The HTR-PM consists of two reactor/Nuclear Steam Supply System (NSSS) modules coupled with a single 210 MW_e turbine. Each NSSS module contains a reactor pressure vessel, graphite, carbon, metallic reactor internals, a steam generator, a helium circulator, and a hot gas duct. Each reactor module can produce 250 MW_{th} (Reference 17).

The fuel elements are spherical, graphite pebbles. The inner core, enriched to 8.5% of 235U, consists of uranium kernels coated by three layers of pyro-carbon and one layer of silicon carbon (Reference 17).

> "The HTR-PM is a helium-cooled pebble bed reactor that when two reactors drive a single turbine, can produce 210 MWe."

The primary pressure boundary includes the RPV, the steam generator pressure vessel (SGPV), and the hot gas duct pressure vessel (HDPV), which are all enclosed by a concrete shielding cavity. The material used in the pressure vessel consists of SA533-B steel as the plate material and 508-3 steel as the forging material (Reference 17).

The HTR-PM can be refueled online through continuous fuel loading and discharging. The fuel handling system inspects the fuel pebbles for burnup which are either reloaded back into the core or directed to spent fuel storage. This refueling methodology limits core excess reactivity, meaning no burnable poisons are necessary to keep the reactor reactivity within safe shutdown limits (Reference 17).

Once the HTR-PM demonstration plant is successful (full power operation in 2022), the commercial deployment of different varieties of the HTR-PM, such as the HTR-PM600 (six reactor modules coupled to a singular steam turbine), is planned. The standard design of the HTR-PM600 has been finished and is capable of producing ~650 MW_e.

Each module has the same design as the HTR-PM demonstration plant, with independent safety systems and shared non-safety auxiliary systems (Reference 17).

The plant footprint (including the power block, protected area, and all owner's facilities) is approximately 65 acres (the exact value is site specific). The start of construction to grid connection of the first HTR-PM took approximately 9 years. The total design life for the plant is 40 years (Reference 17).

Table 9 provides a summary of key HTR-PM design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide (Reference 4).

Table 9 | End User Considerations for the HTR-PM (Reference 17)

END USER CONSIDERATION	HTR-PM VALUE
Neutron Spectrum	Thermal
Moderator	Graphite
Coolant	Helium
Fuel State	Solid
Mission (1)	Electricity (Flexible)
Thermal Output	500 MW_{th} (2 x 250 MW_{th})
Electrical Output (2)	210 MW_e
Size	Small (3)
Technology Generation	Advanced Reactor (4)

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. HTR-PM module output is 210 MWe, which comes from 2 reactors feeding a single turbine.
3. EPRI defines reactors with power outputs of 50 MW_e–300 MW_e as "small" sized reactors (Reference 4).
4. EPRI defines an advanced reactor as "any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors" (Reference 4).

KEY SAFETY FEATURES

The HTR-PM has two independent shutdown systems: a control rod system and a small absorber sphere (SAS) system. A total of 24 control rod assemblies control reactivity while six SAS shutdown systems serve as a reserve shutdown system. The control rods are used to control power during normal plant operation and can be dropped during an emergency shutdown to achieve long-term shutdown. The SAS system reduces the shutdown temperature to allow for in-service inspection and maintenance. Absorber material of the control rods and SAS is B_4C (Reference 17).

The HTR-PM is designed to have a large negative temperature coefficient, large temperature margin, low excess reactivity (due to online refueling), and control rods that will contribute to safe operation and will limit accident temperatures. Under designed accident conditions, the core's decay heat is passively removed through natural mechanisms such as heat conduction, convection, and radiation. This ensures that the maximum fuel temperature is kept below 1,620°C where the fuel elements are capable of retaining fission products within the coated particles. The fuel elements and graphite internal structures have a large heat capacity, allowing for a long time period (days) before the fuel elements reach maximum temperature, even with a complete loss of coolant (Reference 17).

CURRENT STATUS

The following section provides an overview of HTR-PM global deployment status as of Spring 2024. Table 10 provides a summary of various HTR-PM deployment activities. The HTR-PM is fully licensed and is under full power operation at the Shidaowan Nuclear Power Plant in Shandong province as of 2022 (References 2 and 17) and entered commercial operation on December 6, 2023 (Reference 32).

The HTR-PM is owned by a consortium composed of China Huaneng, China Nuclear Engineering Corporation, and Tsinghua University's INET. The consortium collaborated with the China National Nuclear Corporation (CNNC) to provide Engineering, Procurement, and Construction (EPC) services to manufacture fuel elements and for construction of the HTR-PM. The HTR-PM fuel is licensed for operation (Reference 2). The consortium is currently evaluating additional demand for high-temperature steam supply from the HTR-PM/HTR-PM600 in China (Reference 17).

Table 10 | HTR-PM Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	In Operation (2022)
Licensing	(In China Only) HTR-PM is fully licensed HTR-PM fuel is licensed for operation
Supply Chain	• CNNC provided EPC Services • Up to 93.4% of equipment was manufactured domestically in China
Lead Demonstration Project	Shidaowan Nuclear Power Plant • Construction Start: 2012 • Full Power Operation: 2022 • Commercial Operation: Dec 2023
Interested Parties[1] and Level of Interest	TBD

Notes:

1. Interested parties include utility and non-utility entities that have publicly stated interest, either through a signed contract, MOU, or other cooperation agreement.

Kairos Power FHR

OVERVIEW

The KP-FHR is a Tri-structural ISOtropic (TRISO)-fueled, molten fluoride salt-cooled pebble bed reactor. This technology is designed for high availability and performance and low maintenance and life-cycle costs (Reference 17). Kairos is utilizing a rapid iterative approach that leverages multiple design, build, and test cycles with both nuclear and non-nuclear demonstration projects prior to the first commercial reactor. The purpose of this demonstration model is to de-risk eventual full-scale deployment and incorporate lessons learned quickly along the way.

DESIGN DESCRIPTION

The KP-FHR is a high-temperature, pebble bed, molten fluoride-salt cooled SMR that produces 320 MW_{th} and 140 MW_e.

This reactor utilizes 19.75% enriched uranium TRISO fuel pebbles in a graphite-moderated core. Molten salt removes heat from the core and transfers this heat to another intermediary salt loop in the intermediate heat exchanger. The intermediary salt loop then carries this heat to a steam generator, where the steam produced is transported to the turbine. A high-level plant systems overview can be seen in Figure 4.

The KP-FHR uses a combination of TRISO particles in a graphite pebble matrix in conjunction with a molten salt mixture (2LiF: BeF_2 also known as FLiBe). The combination of TRISO particles and molten salt results in a higher thermal efficiency reactor that operates at higher temperatures and lower pressures. This design reduces its reliance on high-cost, nuclear-grade structures and components and/or leveraging commercially ready technologies. This includes the RPV, which will use 316 stainless steel that complies with American Society of Mechanical Engineers (ASME) Section III, Division 5 requirements (Reference 17).

> "The KP-FHR is a high temperature, pebble bed, molten fluoride-salt cooled reactor capable of producing 140 MW_e."

The KP-FHR supports online refueling with a system that inspects the fuel pebbles for burnup and integrity where the fuel pebbles can either be inserted back into the core or directed to spent fuel storage. An average fuel pebble passes through the core six times. The KP-FHR has a design life of 80 years (Reference 17).

At the time of writing, no information was publicly available relative to the overall plant size.

Table 11 provides a summary of key KP-FHR design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide (Reference 4).

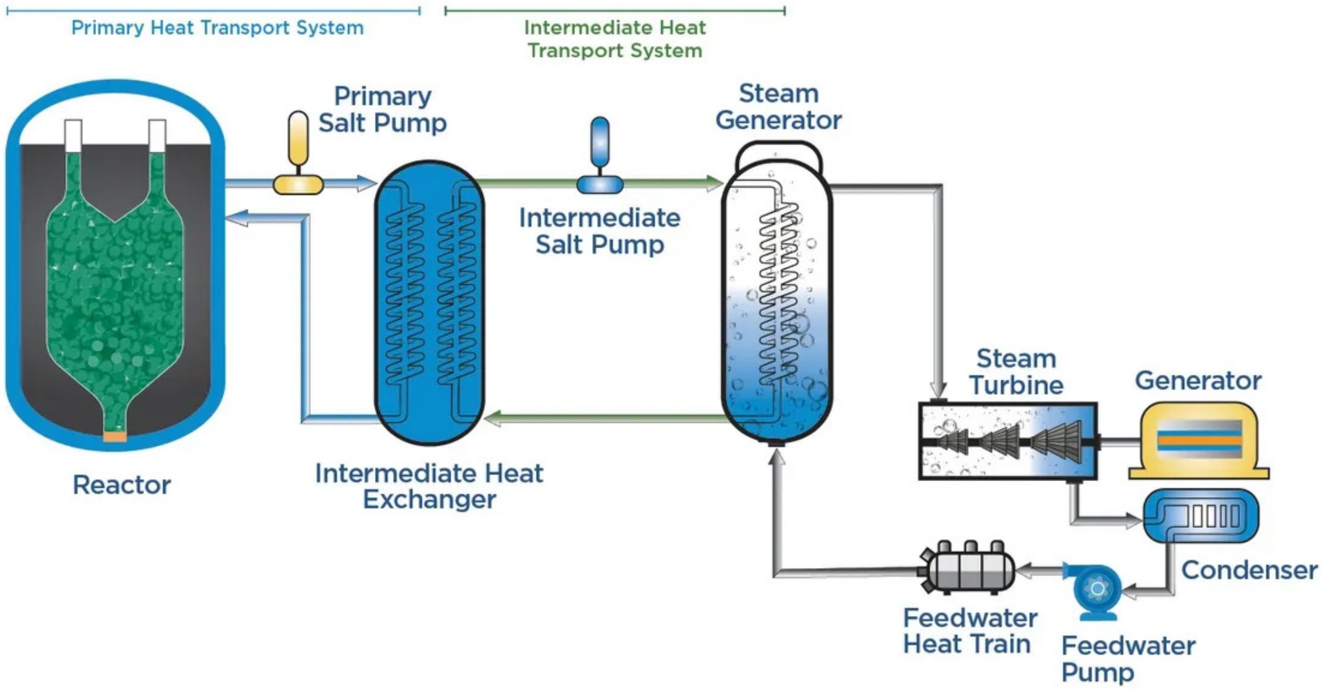
Table 11 | End User Considerations for the KP-FHR

END USER CONSIDERATION	KP-FHR VALUE
Neutron Spectrum	Thermal
Moderator	Graphite
Coolant	Fluoride Salt
Fuel State	Solid (TRISO Particles)
Mission [1]	Electricity
Thermal Output	320 MW_{th}
Electrical Output	140 MW_e
Size	Small [2]
Technology Generation	Advanced Reactor [3]

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. EPRI defines reactors with power outputs of 50 MWe–300 MWe as “small” sized reactors (Reference 4).
3. EPRI defines an advanced reactor as “any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors” (Reference 4).

Figure 4 | Plant Systems Overview (Reference 33)



KEY SAFETY FEATURES

The reactor design takes advantage of the inherent safety of the TRISO fuel and passive safety systems including the RVACS, which provides decay heat removal. This system can operate for 72 hours without coolant inventory makeup or operator action, including valves that do not rely on safety-related electrical power or operator action (Reference 17). The KP-FHR has automatic safe shutdown capabilities and passive cooling upon a loss of power event (Reference 33).

Functional containment is provided in a defense-in-depth strategy, taking advantage of the intrinsic safety of the TRISO fuel and low-pressure fluoride-salt coolant. The KP-FHR also has wide safety margins based on the selected fuel and coolant; therefore, emergency cooling is provided by fundamental physics rather than an engineered safety system (i.e., an Emergency Core Cooling System [ECCS]). Functional containment is provided by characteristics of the TRISO fuel and FLiBe salt. This combination of fuel and coolant also eliminates several fuel damage scenarios (Reference 17).

The KP plant control system operates within an established operating envelope, maximizing automation and continuous health monitoring of the plant. A separate instrumentation and control system, the reactor protection system (RPS), provides protection with the capability to manually or automatically activate the RVACS (Reference 17).

CURRENT STATUS

Kairos Power plans to use multiple experiments to support its design, build, test philosophy, and mature the KP-FHR design. The non-nuclear Engineering Test Unit (ETU) program comprises a series of non-fueled KP-FHR mockups that will test mechanical designs, establish manufacturing infrastructure, and yield operational experience with large-scale molten salt systems. The first ETU iteration — ETU 1.0 — was loaded with 12 Metric Tons (MT) of molten FLiBe in the fall of 2023 and successfully completed 2,000+ hours of pumped salt operations in early 2024.

Following the ETU series, the Hermes reactor will be a 35 MW_{th} fueled, non-power reactor demonstration project, set to be operational in 2026. The construction permit application (CPA) for Hermes was submitted for NRC review in October 2021 (Reference 2). The NRC issued a Final Environmental Impact Statement (FEIS) in August of 2023 (Reference 2) and conducted its mandatory hearing for the Hermes CPA in October 2023 (Reference 2). The USNRC voted to issue a construction permit to KP for Hermes on December 12, 2023. Hermes is the first non-water-cooled reactor to receive a US construction permit in over 50 years.

In July of 2023, KP announced Hermes 2, a dual-unit demonstration plant co-located next to the Hermes demonstration reactor. The purpose of Hermes 2 is to demonstrate complete KP-FHR plant architecture at a smaller scale and supply a small amount of electricity to the grid (Reference 34). The NRC is expected to issue a Final Safety Evaluation and Final Environmental Assessment in 2024 (Reference 35).

In April of 2022, KP established the Kairos Power Operations, Manufacturing, and Development Alliance (KP-OMADA) to advance the development of the KP-FHR technology, licensing, manufacturing, construction, and commercialization. Alliance members include Bruce Power, Constellation, Southern Company, and TVA (Reference 33). Through its engagement with KP-OMADA, KP is planning the deployment of two new facilities, the U-facility and the KP-X. The U-facility will be another non-nuclear demonstration to test the manufacturing and construction of the primary reactor systems. It will serve as a training center and reduce Operations and Maintenance (O&M) cost uncertainty. KP-X will be the first-of-a-kind (FOAK) 140 MW_e commercial reactor at grid-scale (Reference 17).

KP is actively working to set up the necessary supply chain, including for molten salt coolant production. KP partnered with Materion Corp. to commission a molten salt purification plant (MSPP) in Elmore, Ohio, in July 2022 (Reference 33). Additionally, KP is manufacturing pressure vessels in-house at its Albuquerque, New Mexico, location, which has been certified by ASME to manufacture U-stamped pressure vessels (Reference 2). The TRISO fuel will be produced by KP through a partnership with Los Alamos National Lab (LANL) at New Mexico's Low Enriched Fuel Fabrication Facility (LEFFF, Reference 2).

KP has been selected for an ARDP Risk Reduction Award to support the development of the Hermes reactor. The ARDP is a partnership between the DOE and industry to mature advanced nuclear technology. Hermes is a collaborative effort with Oak Ridge National Laboratory, Idaho National Laboratory (INL), EPRI, and Materion Corporation. Hermes leverages proven technologies that originated in Oak Ridge with the Molten-Salt Reactor Experiment (MSRE) in the 1960s (Reference 33). The construction of the Hermes reactor in Oak Ridge, Tennessee, is planned to start in 2024. The Hermes project will receive up to $303 million USD from the DOE through the ARDP risk reduction funding award following a performance-based fixed-price milestone payment approach (Reference 36).

Table 12 | KP-FHR Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	Conceptual Design
Licensing	Construction permit application for Hermes test reactor submitted to the USNRC for review in October 2021
Supply Chain	Fuel Production: • Partnership with LANL at LEFFF In-house Pressure Vessel Manufacturing Molten Salt Coolant: • Partnership with Materion Corporation at MSPP
Lead Demonstration Project	Hermes • Oak Ridge, Tennessee • Expected Construction Start: 2024 • Expected Operations: 2026
Interested Parties[1] and Level of Interest	KP-OMADA • Bruce Power • Southern • TVA • Constellation

Notes:

1. Interested parties include utility and non-utility entities that have publicly stated interest, either through a memorandum of intent (MOI), MOU, or other cooperation agreement.

KHNP i-SMR

OVERVIEW

The KHNP innovative small modular reactor (i-SMR) is an integral PWR design. The i-SMR integrates the primary coolant system and passive safety systems without the need for external safety water injection while reducing the need for operator action due to high-level autonomous control (Reference 17). The design can produce electricity, supply heat for industries, and produce hydrogen.

DESIGN DESCRIPTION

The i-SMR is a forced circulation, light water-cooled and moderated PWR that produces 520 MW_{th} and 170 MW_e (Reference 17). Overviews of the reactor and site are shown in Figure 5 and Figure 6, respectively.

The i-SMR design contains an integral RCS configuration, eliminating a LBLOCA from the design base's events while also eliminating the need for large pipes to connect major components. The major components, consisting of 69 fuel assemblies, eight Reactor Coolant Pumps (RCPs), an SG, a Pressurizer, are equipped in a single RPV and enclosed by a steel Containment Vessel (CV) (Reference 17).

> "The i-SMR is a forced circulation, light water reactor capable of producing 170 MW_e."

The reactor core, SG, RCPs, Control Element Drive Mechanisms (CEDMs), and reactor internals make up the NSSS. The primary cooling system consists of RCPs providing forced circulation of coolant during normal operation. With the absence of Alternating Current / Direct Current (AC/DC) power, the i-SMR can maintain core cooling for 72 hours without operator intervention. If the water source is depleted, an unlimited long-term cooling capability is available through air cooling, allowing for decay heat removal (Reference 17).

The fuel contains gadolinia mixed with uranium dioxide with an enrichment of less than 5%. The refueling cycle is 24 months with a two-batch application (Reference 17).

Publicly available details regarding site footprint, operations, staffing requirements, and construction timeline are limited as of this writing. Table 13 provides a summary of key i-SMR design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide (Reference 4).

Table 13 | End User Considerations for the i-SMR (Reference 17)

END USER CONSIDERATION	i-SMR VALUE
Neutron Spectrum	Thermal
Moderator	H_2O
Coolant	H_2O
Fuel State	Solid
Mission [(1)]	• Electricity • Process Heat • Hydrogen Production
Thermal Output	520 MW_{th}
Electrical Output	170 MW_e
Size	Small [(2)]
Technology Generation	Advanced Reactor [(3)]

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. EPRI defines reactors with power outputs of 50 MW_e–300 MW_e as “small” sized reactors (Reference 4).
3. EPRI defines an advanced reactor as “any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors” (Reference 4).

Figure 5 | i-SMR Reactor Overview (Reference 37)

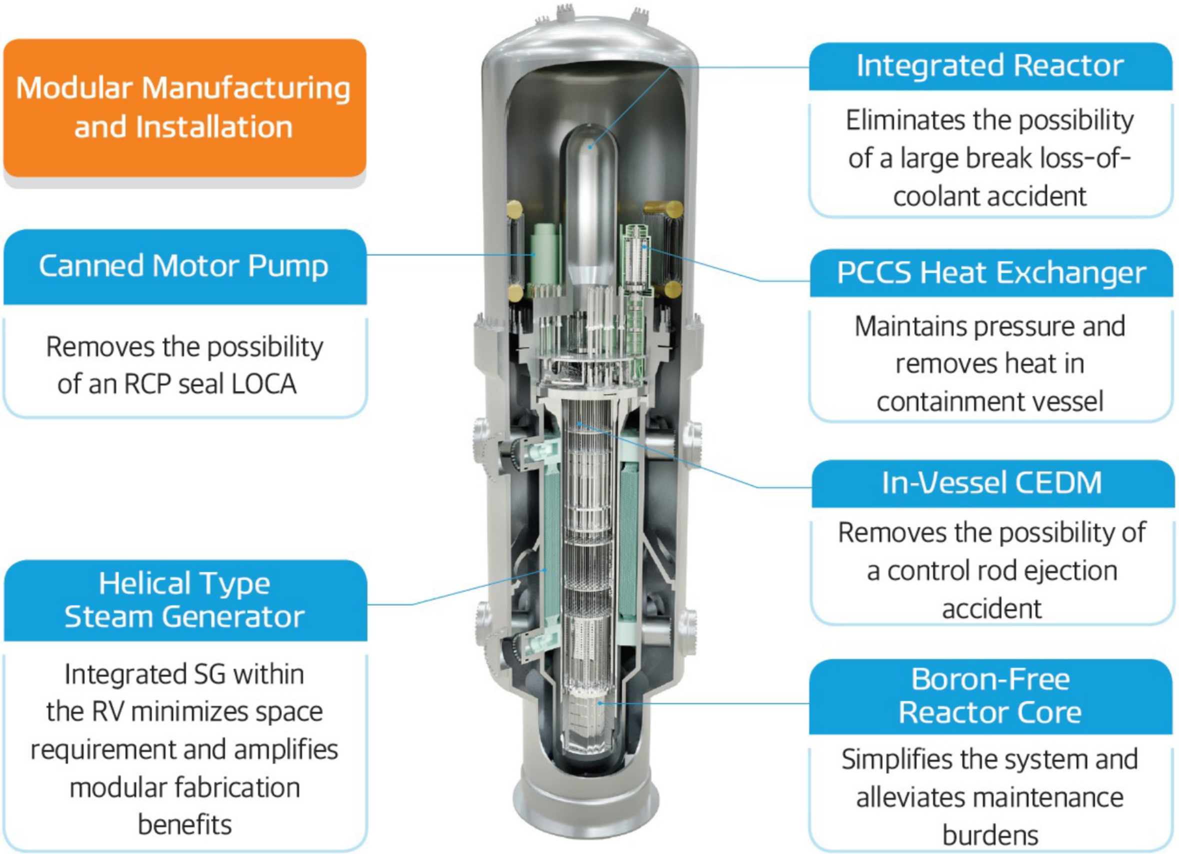


Figure 6 | i-SMR Site Overview (Reference 37)

KEY SAFETY FEATURES

The i-SMR's primary method of reactivity control is using control rods and moderator temperature. The control rods are boron-free, which reduces the number of operational considerations related to boron concentration control. The i-SMR also uses burnable poisons to maintain a flat power profile in the core, increasing thermal safety margins and fuel utilization (Reference 17). The i-SMR has a core damage frequency and a large release frequency of less than 10^{-9} and 10^{-10} per year, respectively (Reference 17).

The i-SMR has multiple barriers to prevent radioactive release to the environment including the fuel pellet, cladding, RPV, and CV. The safety systems of the i-SMR are based on proven technologies with advanced design features that can operate automatically without critical operator action. For postulated design basis accidents, the safety systems cool the RCS below the safe shutdown condition within 36 hours and keep the core undamaged for 72 hours without any corrective actions by the operators (Reference 17).

The ECCS consists of Emergency Depressurization Valves (EDVs) and Emergency Recirculation Valves (ERVs). During LOCA, the EDVs open, allowing the coolant to be released to the CV annulus between the RV and the CV. The ERVs allow water to flow into the RCS and form a natural recirculation path. A Passive Auxiliary Feedwater System (PAFS) will remove decay heat during non-LOCA scenarios while a Passive Containment Cooling System (PCCS) will remove decay heat during a LOCA scenario (Reference 17).

The I&C system contains a Human-Machine Interface System (HMIS) that consists of an advanced control room with digital control systems. The HMIS is integrated with human factor engineering to decrease the probability of operator error, which will enable a better capability to protect, control, and monitor nuclear power plants. The Integrated Main Control Room (IMCR) incorporates Human-Machine Interface (HMI) devices, allowing operators to take control and operate safely during all operating conditions (Reference 17).

CURRENT STATUS

The following section provides an overview of i-SMR global deployment status as of November 2023. Table 14 provides a summary of various i-SMR deployment activities. Publicly available details regarding deployment status, licensing, supply chain, and interested parties are limited as of this writing.

KHNP plans to receive standard design approval of the i-SMR by 2028 in collaboration with the Korean government and introduce the i-SMR to the overseas market once the licensing process is complete. In May 2021, KHNP announced the company was expediting the i-SMR development and investing 350 million USD to design a plant in five years and obtain licenses in three years (Reference 38).

KHNP and Vietnam Atomic Energy Institute signed an MOU on June 22, 2023. The MOU will allow for nuclear and SMR collaboration between the two parties with a portion of the focus on SMR licensing and legal and regulatory systems (Reference 39).

Table 14 | i-SMR Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	Conceptual Design completed (2023) Detailed design in progress
Licensing	TBD
Supply Chain	Plan to leverage existing PWR supply chain
Lead Demonstration Project	TBD
Interested Parties[1] and Level of Interest	MOU: • Vietnam Atomic Energy Institute (Vietnam) • Nusantara Power, a power generation subsidiary of Indonesian Electric Power Corporation (PLN NP) • Jordan Atomic Energy Commission (JAEC) • TerraPower

Notes:

1. Interested parties include utility and non-utility entities that have publicly stated interest, either through a signed contract, MOU, or other cooperation agreement.

NuScale VOYGR

OVERVIEW

The NuScale VOYGR™ is an advancement of traditional PWRs. This design leverages similar systems, structures, and components of traditional PWRs on a smaller scale for an individual NuScale Power Module™ (NPM™), where multiple NPMs can be co-located and scaled to meet the electricity generation needs of the owner. On February 21, 2023, the USNRC issued its final rule in the Federal Register to certify NuScale's 50 MW_e design, becoming the first and currently only SMR design certified by the USNRC and the seventh reactor design ever certified for use in the USA. In January 2023, NuScale submitted a Standard Design Approval (SDA) application for an uprated 77 MW_e design, which is expected to be approved in early 2025 (Reference 40).

DESIGN DESCRIPTION

The NuScale VOYGR™ is a natural circulation light water-cooled and moderated PWR that produces 250 MW_{th} and nominally 77 MW_e.

The reactor core, pressurizer, and SG are all contained within the same vessel, referred to as the NPM™. The VOYGR™ is intended to be deployed in groups of 4, 6, or 12 NPM™s, which allows for some auxiliary systems to be shared between reactors (Reference 40). An overview of a single VOYGR module is shown in Figure 7 and an overview of a VOYGR™-12 plant is shown in Figure 8. Figure 9 shows an illustration of the VOYGR™-12 plant footprint.

NPM™s are designed around passive safety features, including the Decay Heat Removal System (DHRS) and ECCS. The power modules are designed to shut down and self-cool indefinitely without AC or DC electrical power or operator action (Reference 40).

To minimize the risk associated with technology maturity, the VOYGR™ uses many features from the existing PWR fleet. According to NuScale, as of February 2024, 88% of the VOYGR's systems, subsystems, and components have a Technology Readiness Level (TRL) of 7 or higher, on a scale from 1 to 9. NuScale has also developed a robust technology maturation program, including a series of testing facilities, to increase the technology readiness of the VOYGR™ (Reference 38).

> "The NuScale VOYGR™ is a natural circulation light water reactor, consisting of NuScale Power Modules that are capable of producing 77 MWe of power each."

Refueling cycles are currently expected to occur at 18-month intervals per module; however, this can be increased to 20 months or even 24 months with greater than 5% enriched fuel. During refueling, only one NPM™ will be taken offline, and the refueling period is expected to last 10 days. The VOYGR™ plants will have a 60-year design life (Reference 37). The site area of the VOYGR™-12 plant is dependent on the design options selected by the customer, such as wet versus dry cooling.

Table 15 provides a summary of key VOYGR™ design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide (Reference 4). For more specific design details, please see the accompanying EPRI technology design table.

Figure 7 | Overview of a Single NuScale VOYGR™ Module (Reference 40)

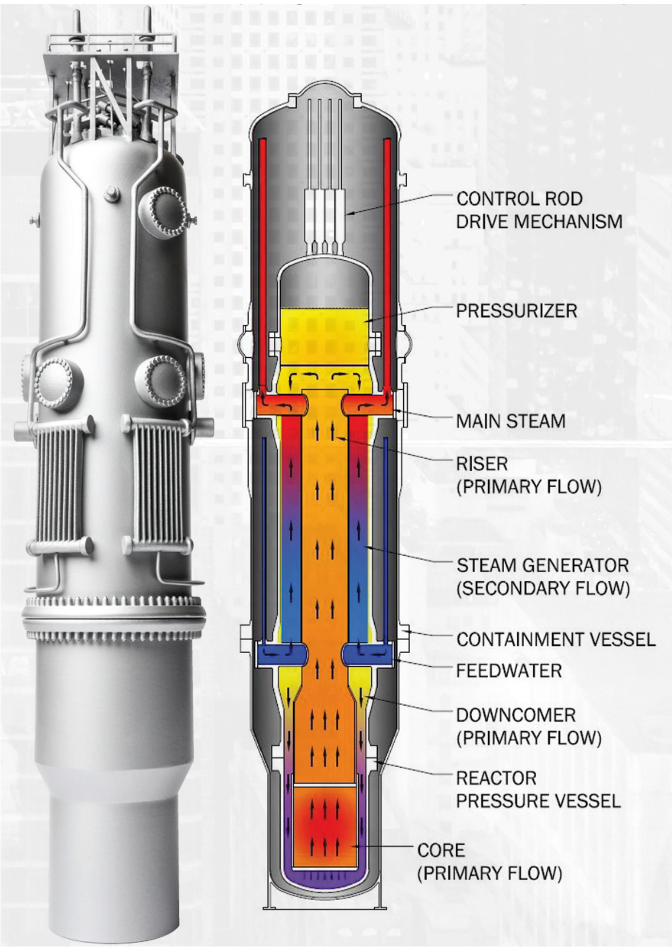


Table 15 | End User Considerations for the VOYGR™ (References 42 and 43)

END USER CONSIDERATION	VOYGR™ VALUE
Neutron Spectrum	Thermal
Moderator	H_2O
Coolant	H_2O
Fuel State	Solid
Mission (1)	Electricity (Baseload with load following)
Thermal Output per Module (2)	250 MW_{th}
Electrical Output per Module (2)	77 MW_e
Size (3)	Small (3)
Technology Generation	Advanced Reactor (4)

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. These values represent a single NPM™. The VOYGR™ is configured in groups of four (308 MW_e/1,000 MW_{th}), six (462 MW_e/1,500 MW_{th}), and 12 (924 MW_e/3,000 MW_{th}) NPMs.
3. EPRI defines reactors with power outputs of 10 MW_e–300 MW_e as "small" sized reactors (Reference 4).
4. EPRI defines an advanced reactor as "any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors" (Reference 4).

Figure 8 | Overview of a NuScale VOYGR™-12 and Surrounding Facilities (Reference 41)

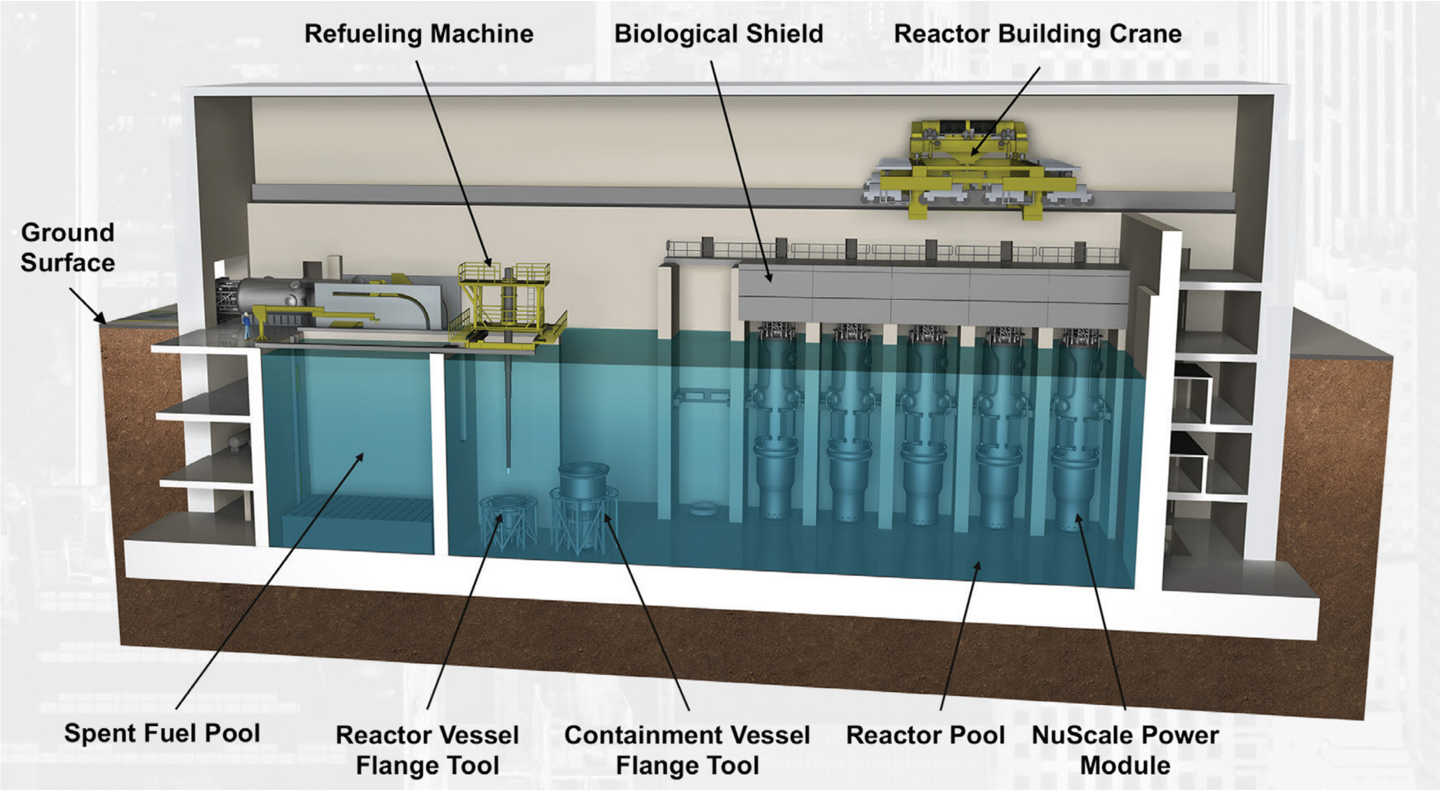
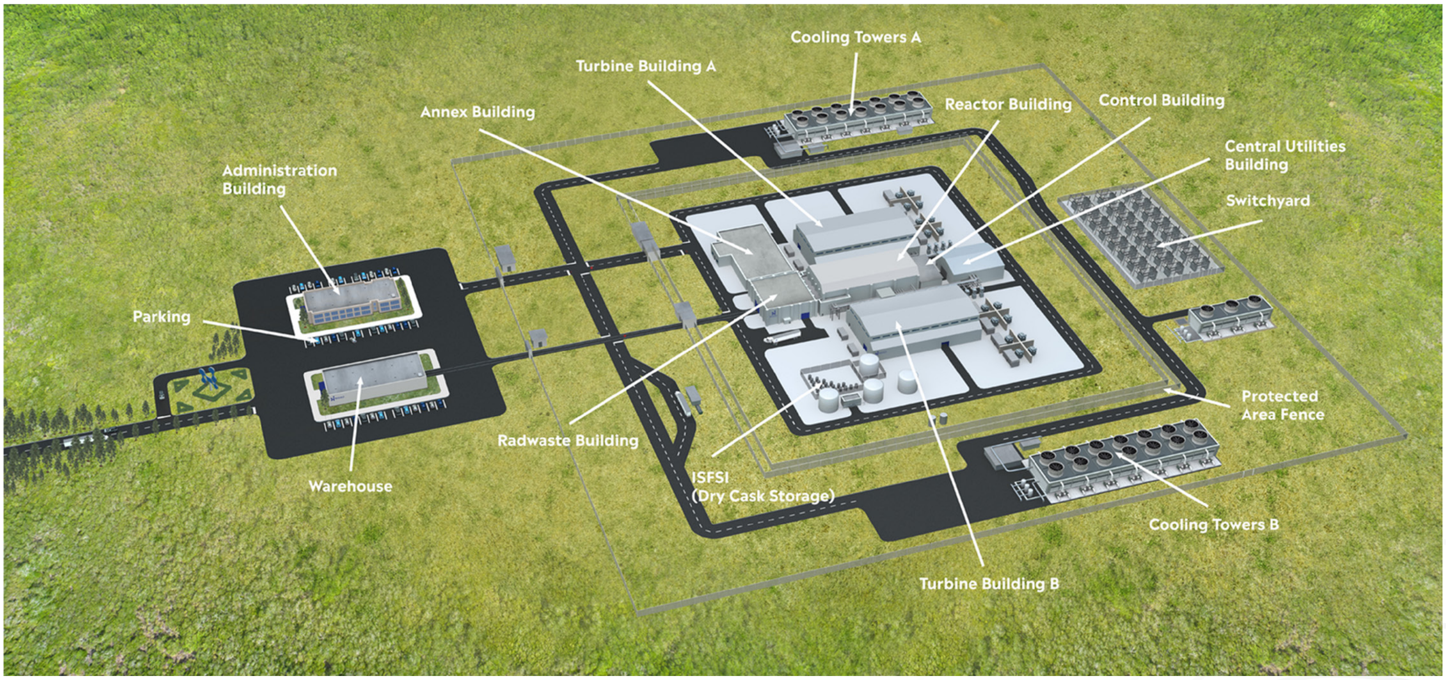


Figure 9 | NuScale VOYGR™-12 Site Layout (Reference 41)



KEY SAFETY FEATURES

The NPM™ is designed around many engineered safety systems, including a fully integral primary system and passive heat removal systems. The DHRS is a closed, natural circulation loop that provides cooling to the secondary side when normal feedwater is unavailable. The ECCS consists of two vent valves and two recirculation valves that provide cooling to the core if normal feedwater and both DHRS trains fail. These systems, along with many others, referred to as the "NuScale Triple Crown for Nuclear Plant Safety™," allow the reactor to self-cool indefinitely without external power or operator action. NuScale estimates that the core damage frequency of the VOYGR™ plant is 6×10^{-9} per reactor year (Reference 42).

The primary system is encapsulated within the containment vessel (CNV) and is credited with containing radiological release as well as protecting the reactor pressure vessel from external hazards. This CNV is then immersed in the reactor pool, which serves as a heat sink under some emergency situations (Reference 17).

The VOYGR™ I&C systems are fully digital. This system is based on field programmable gate array technology, which is not vulnerable to cyberattacks. This system is designed on the principles of independence, redundancy, predictability, repeatability, and diversity. As discussed more in Current Status, this system has been certified by the USNRC (Reference 17).

CURRENT STATUS

The VOYGR™-12 with 50 MW_e NPM™s received design certification from the USNRC in 2020. The Utah Associated Municipal Power Systems (UAMPS) selected NuScale to construct a VOYGR™-6 plant at the INL test site by 2029 (References 2 and 17), with the DOE granting additional funds of 1.355 billion USD through the Carbon Free Power Project (CFPP) in 2020. However, on November 8, 2023, a joint statement announced the mutual termination of the CFPP by UAMPS and NuScale (Reference 43). Despite this, NuScale has redirected its efforts toward other leading projects for deploying the VOYGR™ technology. NuScale recently announced that it has partnered with Standard Power, an infrastructure-as-a-service provider, to use the VOYGR™-12 technology to power data centers in Pennsylvania and Ohio (Reference 44).

In the United States, NuScale received a design certification for a 50 MW_e version of its NPM™ from the NRC in 2020. NuScale is in the process of obtaining USNRC SDA for its uprated 77 MW_e design (Reference 40).

Outside of the United States, NuScale has engaged with the regulatory agencies of Romania, Poland, Ukraine, and Canada to various degrees. In Romania, NuScale has an MOU with Nuclearelectrica for licensing and permitting of a VOYGR™ at the Doicesti Power Station. As part of this effort, NuScale has a contract with RoPower Nuclear S.A. to characterize the site (Reference 2).

NuScale has received financing to support the development of the VOYGR™ on multiple occasions. In 2013, NuScale received 226 million USD to support design and USNRC certification from the DOE. In 2020, the DOE granted an additional 1.355 billion USD in cost matching to support the deployment of the VOYGR™ through the CFPP. In 2021, the US Trade and Development Agency granted Nuclearelectrica, NuScale's partner in Romania, 1.2 million USD to support siting activities. In addition, NuScale has received many smaller grants from the US government. The majority of financing has come from private investment, with Fluor as the lead investor. To date, 1.8 billion USD has been invested in NuScale (Reference 2). NuScale is a publicly traded company on the New York Stock Exchange with the ticker symbol "SMR."

NuScale has agreements and partnerships to establish the supply chain to support the VOYGR™. These partnerships include but are not limited to Framatome, Ultra Electronics, Samsung, Doosan Enerbility, Nucor, and Fluor (Reference 2).

Table 16 provides an overview of NuScale's VOYGR™ deployment status.

Table 16 | VOYGR™ Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	Design certification received by USNRC in 2020 for 550 MW_e module SDA in progress with USNRC for 77 MW_e version, expected 2025
Licensing	Design certification received by USNRC in 2020 Pre-licensing activities ongoing in: • Romania • Poland • Ukraine • Canada
Supply Chain	• Numerous partnerships for supply chain, procurement, and construction (see Current Status)
Lead Demonstration Project	CFPP/UAMPS at INL
Interested Parties[1] and Level of Interest	Commitments: • UAMPS (US) • Standard Power (US) MOU: • Nuclearelectrica (Romania) • Dairyland Power Cooperative (US) • KGHM/PBE (Poland) • Associated Electric Cooperative (US)

Notes:

1. Interested parties include utility and non-utility entities that have publicly stated interest, either through a signed contract, MOU, or other cooperation agreement.

Rolls-Royce SMR

OVERVIEW

Rolls-Royce is developing an advanced PWR SMR design using its experience as the primary nuclear supplier to the UK Royal Navy. The design is based on proven technologies and adapted to maximize modularity and standardization. This SMR will be factory built utilizing as many off-the-shelf components as possible, facilitating rapid and cost-effective production.

DESIGN DESCRIPTION

The Rolls-Royce SMR is a 3-loop PWR with a 60-year design life. The SMR produces 1,358 MW_{th} and 470 MW_e.

Operations will include 18-month cycles between shutdowns for refueling, with each outage targeted to last 15 days, to achieve at least 90% availability over the lifespan of the reactor (Reference 17).

The site footprint for the standard plant is approximately 40,000 m² (~10 acres). This footprint encompasses all structures, including the reactor and turbine islands and supporting buildings and auxiliary services (Reference 17).

This SMR leverages existing PWR technology. UO_2 fuel enriched up to 4.95% will be used, taking advantage of the existing PWR fuel supply chain. Rolls-Royce aims to maintain control of its supply chain by developing and owning factories to build the SMR modules (Reference 2). Additionally, a vertical U-tube SG design has been selected as a mature and readily deployable technology (Reference 17).

> "The Rolls-Royce SMR is a 3-loop PWR that can produce 470 MW_e."

Table 17 provides a summary of key Rolls-Royce SMR design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide (Reference 4).

[1] Rolls-Royce is targeting initial deployment in the UK and, therefore, the standard plant design and accompanying footprint appears to meet UK requirements. Depending on deployment location, larger/additional structures (e.g., Interim Spent Fuel Storage and Isolation (ISFSI), air-cooling) may be required, and, therefore, require more land than the ~10-acre estimate.

Table 17 | End User Considerations for the Rolls-Royce SMR

END USER CONSIDERATION	ROLLS-ROYCE SMR VALUE
Neutron Spectrum	Thermal
Moderator	H_2O
Coolant	H_2O
Fuel State	Solid
Mission [(1)]	Electricity (Baseload)
Thermal Output	1,358 MW_{th}
Electrical Output	470 MW_e
Size	Medium [(2)]
Technology Generation	Advanced Reactor [(3)]

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. EPRI defines reactors with power outputs of 300 MW_e–600 MW_e as "medium" sized reactors (Reference 4).
3. EPRI defines an advanced reactor as "any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors" (Reference 4).

KEY SAFETY FEATURES

The Rolls-Royce SMR design provides defense-in-depth by utilizing independent and diverse active and passive safety systems. This safety informed design demonstrates risk to be acceptable and as low as reasonably possible with a frequency of core damage from plant faults at less than 10^{-7} per year (Reference 17). The passive safety systems are designed to deliver their safety functionality autonomously and without power for 72 hours, minimizing the demand for human actions and electrical power (Reference 17).

This reactor design utilizes both active and passive DHRSs, with heat rejection performed with either pumped or natural circulation flow. These DHRSs use the SGs and normal heat flow path to cool the primary plant. Additionally, the ECCS provides decay heat removal through depressurization of the reactor coolant system and sustained supply of injected coolant by gravity feed. Reactivity control is provided using geometric spacing and solid neutron poison racks in a soluble boron-free environment (Reference 17).

The Rolls-Royce SMR plant has many I&C control systems. The reactor plant control system uses mixed analog and non-programmable digital sensors and hardwired networks. Opportunities to use smart devices are also being pursued. The RPS provides shutdown in response to a fault, and post-accident management systems provide clear plant status displays following a postulated accident (Reference 17).

CURRENT STATUS

In 2022, Rolls-Royce submitted a design certification application to the UK's Office for Nuclear Regulation (ONR) as the first step (of three) in ONR's GDA process. In April of 2023, Rolls-Royce's SMR design moved into step 2 of the process (Reference 45). The GDA is the official regulatory review of the design and step 2 begins the detailed technical assessment. Once the GDA is completed, construction of the FOAK facility will begin, with a planned FOAK commercial operation in 2030.

Rolls-Royce has shortlisted four potential sites owned by the UK Nuclear Decommissioning Authority (NDA) (Reference 2). The NDA is actively exploring opportunities to support the UK government's energy security strategy, including the possible siting of an SMR on NDA land.

NDA is also selecting a site for the first factory for the production of the SMR, with three sites in the UK on the shortlist. There are many agreements in place for products and services relevant to the development of the SMR, including a 3.7 million GBP (~5.1 million USD) contract with Sheffield Forgemasters signed in December 2021. Rolls-Royce launched a supply chain portal to help UK companies become part of the Rolls-Royce SMR supply chain in September 2023 (Reference 45).

Rolls-Royce is funded with 490 million GBP (~600 million USD), including funding from the following groups (Reference 45):

- Qatar Investment Authority (QIA): 85 million GBP (~104 million USD)
- BNF Resources UK limited and Exelon Generation limited: 195 million GBP (~238 million USD)
- UK Research and Innovation (UKRI) grant: 210 million GBP (~258 million USD)

Table 18 | Rolls-Royce SMR Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	Detailed Design Phase
Licensing	ONR: Detailed Technical Review (GDA Process Step 2 of 3)
Supply Chain	Plan to leverage existing LWR supply chain, with focus on UK companies
Lead Demonstration Project	Specific Site: TBD Construction Start: 2026 Commercial Operations: 2030
Interested Parties[1] and Level of Interest	MOU: • Exelon Generation • Skoda JS (Czech Republic) • ČEZ (Czech Republic) • Energoatom (Ukraine) • Fermi Energia (Estonia) • EUAS International ICC (Turkey) • JAEC (Jordan) MOI: • Industria (Poland) Preferred Provider: • Solway Community Power Company (West Cumbria, UK) • ULC-Energy (Netherlands)

Notes:

1. Interested parties include utility and non-utility entities that have publicly stated interest, either through an MOI, MOU, or other cooperation agreement (References 2 and 45).

Seaborg CMSR Power Barge

OVERVIEW

The Compact Molten Salt Reactor (CMSR) developed by Seaborg Technologies, is an advanced, modular, and compact molten salt reactor that will be installed on Power Barges (Reference 17). The CMSR Power Barge comes as a turn-key product, assembled and commissioned at the shipyard, and ready to be moored at an industrial harbor (Reference 4). The CMSR can be used to deliver heat or electricity into the grid, for Power-to-X (PtX) applications such as the production of hydrogen and ammonia, and deliver high-temperature steam for process applications (References 48 and 49).

The CMSR is a liquid fluoride fuel, salt-cooled, graphite-moderated compact reactor that produces 250 MW_{th} and 100 MW_e per CMSR.

Each CMSR has an operating life of 12 years, during which no refueling is required, and is replaced by new CMSR units (Reference 17). The standardized non-self-propelled Power Barges have an operating life of 24 years and are scalable to deliver 200 MW_e to 800 MW_e, enabling configurations with two, four, six, or eight CMSRs on a single Power Barge (Reference 45). Reference 4 provides an overview of the CMSR.

The CMSR liquid fuel fluoride molten salt loop transfers heat generated in the core to a secondary liquid heat-transfer fluoride salt via the primary heat exchanger. The secondary salt circuit then transfers heat to the power conversion system via an SG. Two SGs from separate reactor modules are coupled to drive a single condensing steam turbine. The connected Power Module delivers 200 MW_e to a high-voltage onshore electrical transmission grid (Reference 17).

> "The CMSR is a liquid fluoride, salt-cooled, graphite-moderated reactor that can produce 100 MW_e per CMSR."

The Power Modules are connected to an aft end module (accommodation, offices, conference rooms, main control room, supplementary control room, emergency power, and barge utilities) and a fore end module, where the high-voltage substation is positioned. The complete double hull protects the safety enclosure, the CMSR auxiliary system, emergency diesel generators, diesel tanks, and switchboards. The Power Barge is equipped with suitable towing and mooring facilities (Reference 17). Reference 50 shows a cross-sectional view and overview of a 200 MW_e Power Barge configuration.

The CMSR originally planned to use HALEU fuel for the CMSR. However, given availability concerns surrounding the HALEU supply chain, the company announced in July 2023 that the CMSR will use LEU as the fuel type, which is mixed into a molten fluoride salt that also acts as the coolant (Reference 28). As of this writing, it is unclear what effect on operating parameters (e.g., power output, refueling cycle) this will have on the CMSR (Reference 49).

The total plant footprint ranges from 1.25 acres to 3.5 acres for 200 MW_e to 800 MW_e Power Barge configurations, respectively (Reference 17).

Table 19 provides a summary of key CMSR Power Barge design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide (Reference 4).

Table 19 | End User Considerations for the CMSR Power Barge (Reference 17)

END USER CONSIDERATION	CMSR VALUE
Neutron Spectrum	Thermal
Moderator	Graphite
Coolant	LEU-based Fluoride Fuel Salt
Fuel State	Liquid
Mission [(1)]	Electricity (Flexible), Process Heat (Industrial Processes)
Thermal Output	500 MW_{th} (2 x 250 MW_{th} per Power Module)
Electrical Output	200 MW_e (2 x 100 MW_e per Power Module)
Size	Small [(2)]
Technology Generation	Advanced Reactor [(3)]

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. EPRI defines reactors with power outputs of 50 MW_e–300 MW_e as "small" sized reactors (Reference 4).
3. EPRI defines an advanced reactor as "any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors" (Reference 4).

KEY SAFETY FEATURES

The CMSR incorporates a defense-in-depth approach that focuses on three fundamental safety functions: control of reactivity, heat removal, and confinement of radioactive material (Reference 17).

Reactivity control is achieved through regulating rods to compensate for short-term reactivity changes and through safety rods for prompt nuclear chain reaction control. The CMSR also has inherent reactivity control features such as gravity-driven subcritical configuration and a negative temperature coefficient (Reference 17).

The CMSR contains a reliable and redundant DHRS through draining of the fuel salt from the reactor to a fuel salt drain tank. This system enables cooling for 72 hours without active systems. The fuel salt is allowed to solidify in the salt drain tanks, and passive means of decay heat removal are employed in a similar fashion as dry cask storage for conventional nuclear spent fuel (Reference 17).

The containment enclosure system prevents releases to the atmosphere. The containment enclosure is a leak-tight structure and comprises non-accessible (reactor and drain tank compartments) and accessible compartments (equipment compartments) (Reference 17).

CURRENT STATUS

The following section provides an overview of CMSR Power Barge global deployment status as of December 2023. Table 20 provides a summary of various CMSR Power Barge deployment activities.

The CMSR is in a conceptual design stage with focus on an R&D approach through the development of test facilities to support licensing of a FOAK CMSR. Preliminary engagement is being evaluated with several national regulators in parallel to support international deployment of the CMSR (Reference 17). The receipt of the CMSR Feasibility Statement and Approval in Principle from the American Bureau of Shipping (ABS) in 2020 and 2022, respectively, is the first milestone in the ABS New Technology Qualification (NTQ) process (References 17 and 49).

KHNP, Samsung Heavy Industries (SHI), and Seaborg have formed a consortium to develop Power Barges with CMSR technology, with the first project expected to be a 200 MW_e Power Barge (Reference 50). Seaborg has signed an MOU with South Korean nuclear regulatory consulting company Best Engineering in Energy Solutions (BEES) to identify and fulfill Korean regulatory requirements for global export of fully tested floating nuclear power plants (Reference 51). The partnership agreement between Seaborg and SHI includes the development of hydrogen production plants and ammonia plants powered by the CMSR, optimized for efficient serial construction at SHI's shipyards (Reference 52). The low enriched fluoride fuel salt used in the CMSR is not yet commercially available, and the feasibility of developing a LEU fuel salt production facility in South Korea is currently being investigated by Seaborg, KEPCO Nuclear Fuel (KNF), and GS Engineering & Construction. While they were initially considering HALEU fuel, in July 2023, Seaborg made the decision to use LEU fuel in its CMSRs due to risks associated with developing a sufficient supply of HALEU (Reference 53).

Seaborg, with Norwegian Nuclear Power, has signed an LOI to investigate establishing the CMSR in Norway, with the aim to complete the first plant by the end of the decade (Reference 54). PT Pertamina Power Indonesia (Pertamina NRE) and Seaborg have signed an MOU to assess the potential deployment of the CMSR Power Barge in Indonesia (Reference 55). Seaborg and Terra Praxis have agreed to assess the CMSR as a potential heat source as a method of repurposing existing coal-fired power plants with nuclear reactors (Reference 56). Global Power Synergy Public Company Limited (GPSC), a Thai company, has also signed an MOU with Seaborg (Reference 57).

Table 20 | CMSR Power Barge Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	Conceptual
Licensing	ABS: New Technology Qualification Process South Korea: Identification of Korean regulatory requirements for global export of fully tested floating nuclear power plants
Supply Chain	LEU: • Investigating LEU fuel salt fabrication facility feasiblity in South Korea • KNF (MOU) • GS Engineering & Construction (MOU) HALEU: • Urenco Limited
Lead Demonstration Project	TBD
Interested Parties[1] and Level of Interest	KHNP: • Consortium to export the CMSR Power Barge worldwide SHI: • Consortium to export the CMSR Power Barge worldwide • Partnership to develop the CMSR Power Barge and hydrogen and ammonia plants Norsk Kjernekraft AS: • LOI to establish CMSR technology in Norway Pertamina NRE: • MOU to explore CMSR Power Barge deployment in Indonesia Terra Praxis: • Agreement to assess the CMSR as a potential heat source for coal plant repurposing

Notes:

1. Interested parties include utility and non-utility entities that have publicly stated interest, either through a signed contract, MOU, or other cooperation agreement.

TerraPower & GEH Natrium™ Reactor

OVERVIEW

The Natrium reactor, developed by TerraPower and GEH, is a sodium-cooled fast reactor coupled with a gigawatt-scale energy storage system, designed to increase compatibility in grids with a high share of intermittent generation. Its integrated energy storage system allows it to provide peaking power during periods of high power demand and re-energize during periods of low power demand.

DESIGN DESCRIPTION

The Natrium reactor is a GEN IV, pool-type, sodium-cooled fast reactor (SFR) with a power output of 840 MW_{th} and baseline electrical output of 345 MW_e, with the ability to scale up to 500 MW_e for 5.5 hours by drawing heat from the integrated energy storage system (References 2 and 60).

This makes it a flexible power source capable of providing power to complement intermittent energy sources. Natrium technology was developed by TerraPower and GEH. The Natrium reactor leverages elements of TerraPower's Traveling Wave Reactor and GEH's Power Reactor Innovative Small Module (PRISM) technology (References 60 and 61).

The Natrium reactor operates at atmospheric pressure (because of coolant selection) with a high safety margin, reducing the need for large, high pressure components. The heat produced by the reactor can be used to directly generate electricity, process heat, or be transferred to a thermal storage salt tank with a capacity of 5.5 GWh during periods of high renewable generation (Reference 2). The ability to transfer heat to the thermal storage tank insulates the system from brief anomalies and transients in the grid or generator, which can cause the reactor to shut down in a standard plant design (Reference 34). With growing renewable penetration, gigawatt-scale storage is an increasingly useful capability. Figure 10 shows an overview of the reactor building, and Figure 11 shows an overview of the Natrium reactor plant.

> "The TerraPower Natrium is a sodium-cooled fast reactor capable of producing a baseline power output of 345 MW_e."

The Natrium reactor uses a metallic, hexagonal, pin-type fuel element (Reference 60). The design uses HALEU fuel enriched to 5%–19.75%. Fuel enrichment level varies throughout the core but remains lower than 19.75% (References 63 and 64). Refueling outages, the duration of which is not yet publicly known, are expected to occur every 24 months (Reference 34).

The overall Natrium reactor plant site footprint is approximately 44 acres, with the nuclear island taking up about 16 acres. TerraPower estimates that construction staffing will peak at about 1,600 workers, and 200–250 workers will be required for day-to-day plant operations. TerraPower's lead deployment in Kemmerer, Wyoming, is set to begin nuclear island construction in 2026 and aims to be completed by 2030 (Reference 63). The Natrium reactor plant aims to reduce costs and will use 80% less nuclear-grade concrete per MW_e (Reference 58).

Table 21 provides a summary of key Natrium reactor design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide (Reference 4).

Table 21 | End User Considerations for the Natrium Reactor

END USER CONSIDERATION	NATRIUM REACTOR VALUE
Neutron Spectrum	Fast
Moderator	N/A
Coolant	Liquid Sodium
Fuel State	Solid
Mission (1)	• Electricity Generation - Flexible • Energy Storage • Process Heat
Thermal Output	840 MW_{th}
Electrical Output	• Minimum: 100 MW_e • Baseline reactor power: 345 MW_e • Max (with storage system): 500 MW_e
Size	Medium (2)
Technology Generation	Advanced Reactor (3)

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. EPRI defines reactors with power outputs of 300 MW_e–600 MW_e as "medium" sized reactors (Reference 4). Natrium reactor's wide range of power operations can classify this reactor as either "small" or "medium." For this report, a value of "medium" is used.
3. EPRI defines an advanced reactor as "any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors" (Reference 4).

Figure 10 | Natrium Reactor Overview (Reference 64)

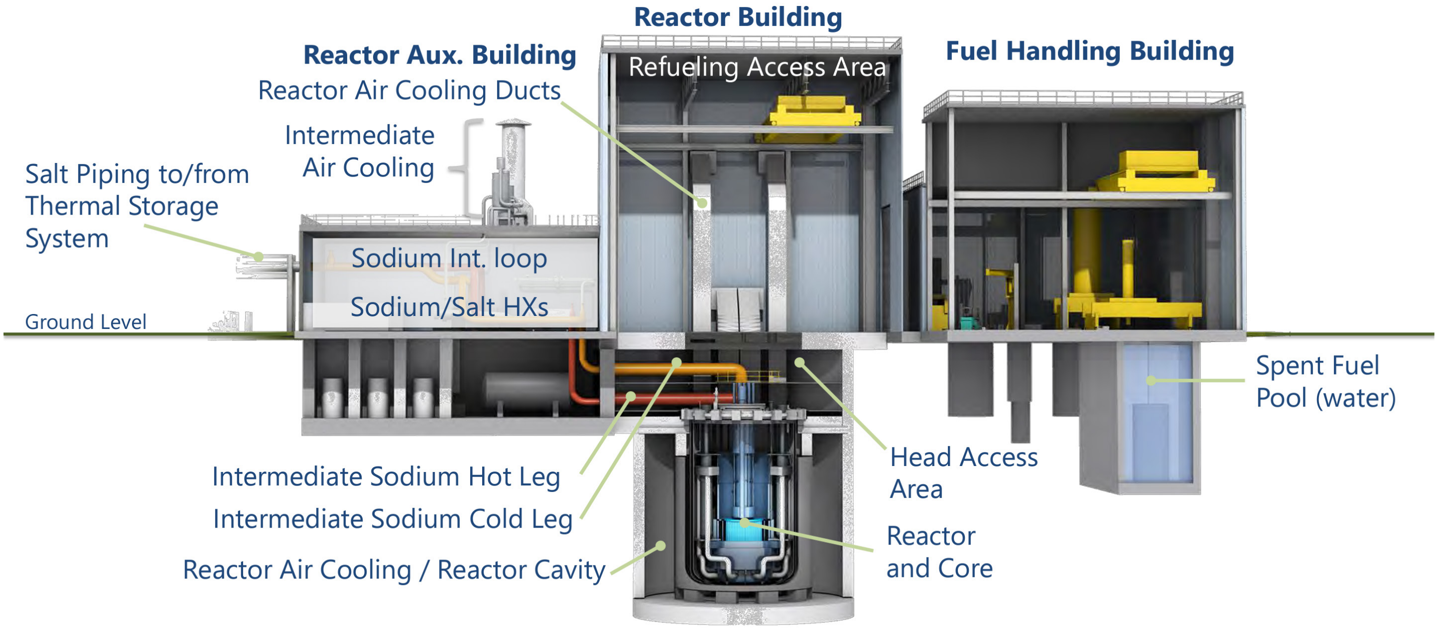
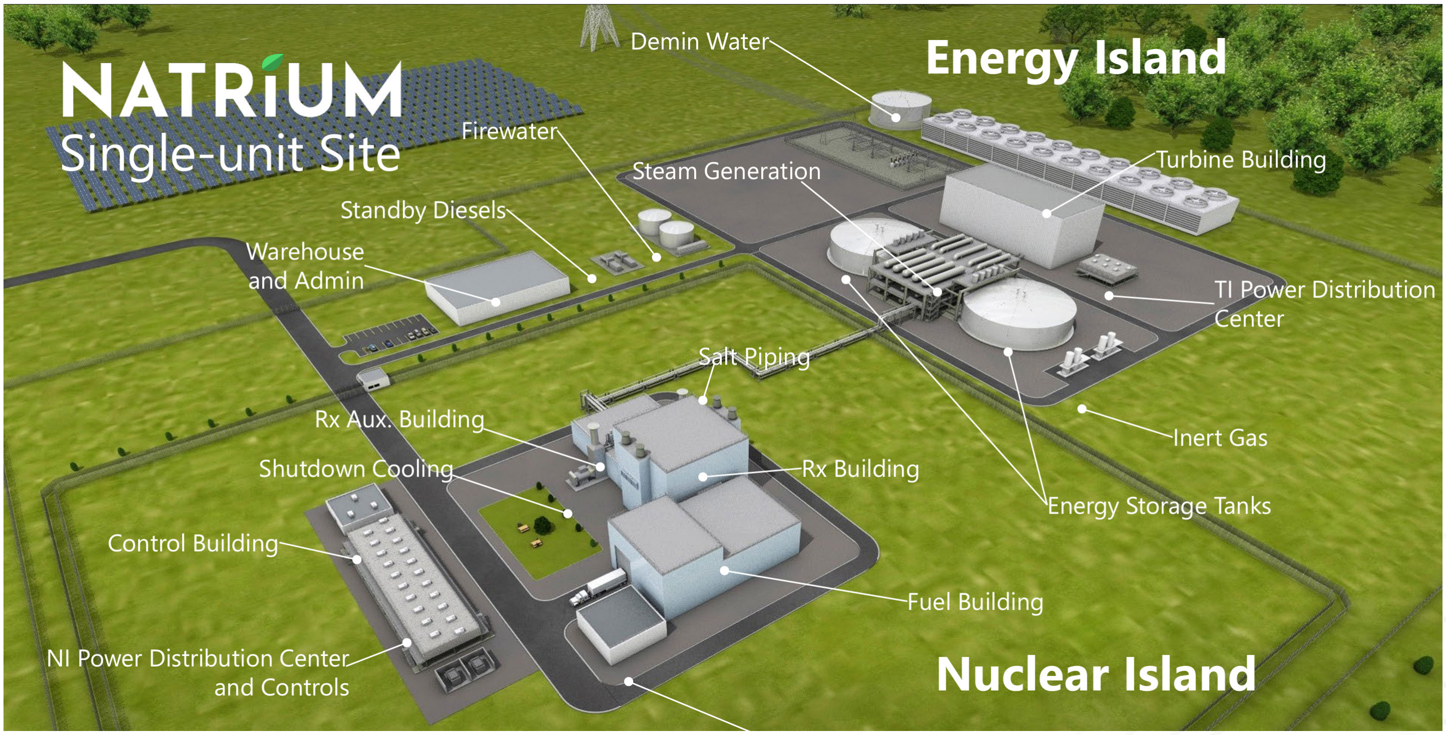


Figure 11 | Conceptual Rendering of Natrium Reactor and Storage System Site Layout (Reference 65)



KEY SAFETY FEATURES

The Natrium reactor leverages inherent and passive safety features using defense-in-depth principles. The Natrium reactor operates at a temperature 350°C below the boiling point of the molten sodium coolant, providing a safety margin during transients and allowing the reactor to operate near atmospheric pressures (Reference 63). Operating at atmospheric pressure removes the need for high-pressure retaining components, such as those found in light water reactors.

The Natrium reactor uses natural air circulation for decay heat removal during design basis events to allow for indefinite passive emergency decay heat removal. The reactor does not require any safety-related operator actions or AC power to safely shut down. The core also uses gravity-driven control rods in an emergency shutdown. Inherent safety characteristics, such as resilience during anticipated transients, were demonstrated in similar previous DOE reactors such as the EBR-II and Fast Flux Test Facility (FFTF) (Reference 66).

CURRENT STATUS

The following section provides an overview of the Natrium reactor deployment status as of Spring 2024. Table 22 provides a summary of various Natrium deployment activities.

TerraPower and GEH are engaged in pre-application activities with the USNRC (Reference 67). TerraPower plans to pursue the 10 CFR Part 50 licensing pathway for the Natrium reactor lead deployment with PacifiCorp, which is located near Kemmerer, Wyoming. In March of 2024, TerraPower submitted its Construction Permit Application to the USNRC (Reference 68). The operating license application submittal is expected in 2027 (Reference 63).

TerraPower plans to start nuclear island construction at the Kemmerer site in 2025, with non-nuclear construction beginning in 2024. To meet ARDP requirements, TerraPower estimates the Natrium reactor demonstration project will be operational by the end of the decade (Reference 63).

In March 2023, PacifiCorp, the utility working with TerraPower on the lead deployment in Kemmerer, released an Integrated Resource Plan (IRP) that identified two additional Natrium reactors to be added into the utility's energy portfolio by 2033. PacifiCorp is also working with TerraPower on a feasibility study for up to five additional units (including those suggested by PacifiCorp's IRP), to be added by 2035 (Reference 69).

TerraPower and GEH's Global Nuclear Fuel announced that they will construct a new fuel fabrication facility in North Carolina to provide HALEU fuel for the Natrium reactor (Reference 59). Additionally, TerraPower signed an MOU with Centrus Energy Corp to expand collaboration in establishing a reliable fuel source for the deployment of the Natrium reactor in Wyoming by 2030.

Table 22 | Natrium Reactor Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	CPA for Kemmerer site to be submitted March 2024 (Reference 70)
Licensing	USNRC: Pre-Application Engagement
Supply Chain	Suppliers: (References 74, 75) • Bechtel Corporation (Reference 71) • Western Service Corporation • James Fisher Technologies • BWXT Canada Ltd • Curtiss-Wright Flow Control Service LLC • GERB Vibration Control Systems Inc • Thermal Engineering International (USA) Inc • Hayward Tyler, Inc • Framatome US Government Solutions LLC • Teledyne Brown Engineering Fuel: • Constructing fuel fabrication facility in North Carolina • Centrus Energy Corp (MOU)
Lead Demonstration Project	Kemmerer, Wyoming: • Approximate Nuclear Island (NI) Construction Start: 2025 • Approximate Commercial Operations: by 2030
Interested Parties[1] and Level of Interest	Commitments: • PacifiCorp – potential for additional deployment
Notes: 1. Interested parties include utility and non-utility entities that have publicly stated interest, either through a signed contract, MOU, or other cooperation agreement.	

TerraPower MCFR

OVERVIEW

The TerraPower Molten Chloride Fast Reactor (MCFR) is a molten salt reactor (MSR). TerraPower's MCFR design can be used for multiple applications (e.g., electricity generation, process heat, and thermal storage). The plant design allows for scaling based on different market needs without redesigning the reactor (Reference 75). The MCFR is designed to operate at high temperatures, allowing for an increase in plant efficiency while also producing high-grade heat that can be used in new industrial applications (Reference 76).

DESIGN DESCRIPTION

The MCFR is an MSR utilizing molten chloride as both the reactor's coolant and fuel. The reactor is capable of producing at a baseline either 300 MW_e or 780 MW_e depending on the size needed for the application (Reference 34).

In addition to using molten salt for heat transfer, MCFR is also expected to be paired with a molten salt energy storage system, similar to TerraPower's Natrium reactor (Reference 34).

The MCFR design uses liquid chloride salt as coolant and fuel that flows through the reactor core and allows for fission to directly heat the salts. The mixture is then circulated through a heat exchanger to a coolant chloride salt loop that can be used for process heat, thermal storage, or electricity generation (Reference 77).

> "The MCFR is an MSR that can produce either 300 MW_e or 780 MW_e, depending on the design."

The MCFR operates using a fast neutron spectrum, which when coupled with other reactor features, allows for continuous refueling and reduces the amount of fission products present in the fuel (Reference 76).

Publicly available details regarding site footprint, operations, staffing requirements, and construction timeline are limited.

Table 23 provides a summary of key MCFR design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide (Reference 4).

Table 23 | End User Considerations for the MCFR (Reference 6)

END USER CONSIDERATION	MCFR VALUE
Neutron Spectrum	Fast
Moderator	N/A
Coolant	Molten Chloride
Fuel State	Liquid
Mission [(1)]	Electricity (Flexible), Process Heat (Industrial Processes)
Thermal Output	TBD
Electrical Output	300 MW_e/780 MW_e
Size	Medium/Large [(2)]
Technology Generation	Advanced Reactor [(3)]

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. EPRI defines reactors with power outputs of 300 MW_e–600 MW_e as “medium” sized reactors and 600 MW_e–1,500 MW_e as “large” sized reactors (Reference 4).
3. EPRI defines an advanced reactor as “any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors” (Reference 4).

KEY SAFETY FEATURES

The MCFR's molten fuel systems include passive safety features involving inherent temperature feedback mechanisms. The fuel density is temperature dependent and expands upon increase in temperature. Due to this expansion of fuel, the systems become subcritical through negative reactivity feedback as fuel temperature increases. Given this safety feature, no heat removal or temperature control function is required during the in-vessel shutdown (Reference 79).

The fuel drain tank system is required to provide a natural circulation heat removal using air cooling, a high surface-area-to-volume ratio, and a subcritical configuration for the fuel that is drained. This provides an indefinite cold shutdown scenario that requires no further action (Reference 79).

CURRENT STATUS

The following section provides an overview of TerraPower's MCFR global deployment status as of December 2023. Table 24 provides a summary of various MCFR deployment activities.

In January 2016, the DOE awarded a five-year, 40 million USD cost-share award for continued R&D into TerraPower's MCFR project. This award creates a new MCFR project development partnership consisting of TerraPower, Southern Company, Oak Ridge National Laboratory, EPRI, and Vanderbilt University (Reference 76).

In December 2020, the DOE selected the Molten Chloride Reactor Experiment (MCRE) proposal, with Southern Company as the Prime, as a winner of the ARDP risk-reduction pathway. The MCRE is a uranium chloride salt-fueled concept relevant to TerraPower's MCFR design. In February 2022, TerraPower and Southern Company finalized an agreement to design, construct, and operate the MCRE at INL under the DOE's ARDP. The project will demonstrate the world's first fast spectrum salt reactor and provide crucial operational data for fast-spectrum salt reactors (Reference 76).

TerraPower and Southern Company are working together to create an Integrated Effects Test (IET) with hopes of learning how the MCFR technology will scale and behave at larger, commercially relevant sizes. The IET was installed at TerraPower's Everett, Washington, facility in October 2022 (Reference 76).

TerraPower is a member company of the MSR Technology Working Group (TWG). The MSR TWG's goal is to accelerate the development and market deployment of MSR technologies. TerraPower's collaboration with TWG will aid in determining licensing approaches, establish unique test facilities, and result in the development of liquid-fueled reactors in the United States (Reference 76).

Table 24 | MCFR Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	TBD
Licensing	USNRC: Pre-Application interactions are being planned
Supply Chain	TBD
Lead Demonstration Project [1]	Molten Chloride Reactor Experiment at INL Construction and Operation Date: TBD
Interested Parties and Level of Interest [2]	Commitments: Partnership with Southern Company, Oak Ridge National Laboratory, INL, EPRI, and Vanderbilt University

Notes:

1. These lead projects are smaller scale, demonstrations of the MCFR concept. A full-scale lead demonstration of the MCFR is TBD.
2. Interested parties include utility and non-utility entities that have publicly stated interest, either through a signed contract, MOU, or other cooperation agreement.

USNC MMR

OVERVIEW

The Micro Modular™ Reactor (MMR) is an HTGR designed by Ultra Safe Nuclear Corporation (USNC). The MMR energy systems are manufactured in USNC's large-scale facilities as individual modules such that multiple modules can be assembled to meet rising energy demands. The MMR is intended for energy generation in both remote and grid-scale applications with additional capabilities in process heat, district heating, and desalination (Reference 80). USNC leverages its Fully Ceramic Micro-encapsulated (FCM) fuel, which encases TRISO fuel particles in a fully dense silicon carbide matrix (Reference 80).

DESIGN DESCRIPTION

The MMR is a thermal neutron, helium-cooled, graphite-moderated, prismatic HTGR that produces up to 45 MW_{th} and 15 MW_e (Reference 2).

An MMR facility generates electricity via two plants: a Nuclear Plant and an Adjacent Plant. The Nuclear Plant consists of an MMR module, where heat from the core is transported to the Adjacent Plant. The Adjacent Plant contains the infrastructure necessary to extract and store the heat generated from the reactor and directly convert energy from the Nuclear Plant to electricity for customer applications (Reference 17).

The FCM Fuel, developed by USNC, is a distinguishing feature of the MMR. The reactor utilizes TRISO particles in its fuel pellets. These particles contain a protective layer of SiC over the uranium to isolate the fuel. The TRISO particles are embedded in a (SiC) matrix. The structure of TRISO particles embedded in a SiC matrix offers exceptional fission product retention and high-temperature resistance. The design requires no fuel cladding and increases the maximum allowable temperature to around 1600 °C (Reference 80).

> "The USNC MMR is a high temperature gas reactor that can produce 15 MW_e."

The SiC pellets are created through an additive manufacturing process, developed by USNC, allowing for extremely tight tolerances to be met and the ability to create a variety of shapes (Reference 80). The reactor is compatible with both HALEU with a 19.75% enrichment and LEU+ with an enrichment of 9.9% (Reference 81).

The plant footprint of just the reactor and its associated Nuclear Heat Supply System stands at approximately 1.58 acres (Reference 17). A standard MMR Energy System, which includes all nuclear and adjacent plant systems, structures, and components, requires less than 5 acres[1] of land, where a single MMR site can host either one or two MMRs. Multiple MMR units can be linked together to provide as much power as needed (Reference 82).

Table 25 provides a summary of key MMR design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide (Reference 4).

Table 25 | End User Considerations for the MMR (Reference 17 and 83)

END USER CONSIDERATION	MMR VALUE
Neutron Spectrum	Thermal
Moderator	Graphite
Coolant	Helium
Fuel State	Solid
Mission (1)	• Energy Generation - Flexible • Process Heat
Thermal Output	10 MW_e to 45 MW_{th}
Electrical Output	3.3 MW_e to 15 MW_e
Size	Micro (2)
Technology Generation	Advanced (3)

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. EPRI defines reactors with power outputs of less than 50 MW_e as “micro” reactors (Reference 4).
3. EPRI defines an advanced reactor as “any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors” (Reference 4).

[1] Depending on the deployment location/additional structures, more land may be required than the above estimate.

KEY SAFETY FEATURES

The MMR reactor leverages inherent and passive safety systems, resulting from the careful selection of materials for the reactor's fuel, core, moderator, and coolant. The use of the FCM fuel decreases radioactive waste and protects against unexpected chemical attacks by containing the fission products safely within the SiC pellet (Reference 17).

The design is walk-away safe with built-in inherent and passive features for heat dissipation. The MMR is stored deep below grade and dissipates all heat from the reactor directly into the environment. The plant does not need any additional services or active systems for heat removal (Reference 82).

The MMR design specifically is notable for its inherent safety features to control potential radiological hazards. Apart from the FCM, the reactor does not require any other containment structure. The MMR cannot reach above critical temperatures, due to the passive cooling systems it employs. The primary cycle is pressurized to reduce the exposure to air within containment (Reference 17).

Helium acts as a benign medium to cool down the reactor core safely and effectively. The pellet shape can be changed to allow for more efficient heat transfer, while maintaining the fission products safely within the FCM (Reference 82).

CURRENT STATUS

The following section provides an overview of the MMR deployment status as of Spring 2024. Table 26 provides a summary of various MMR deployment activities.

USNC has successfully completed Phase I of the CNSC's Pre-Licensing VDR and is currently in Phase II. This project is led by Global First Power (GFP), which is jointly owned by USNC and OPG. GFP submitted a license to the CNSC for the construction of the MMR at Canadian Nuclear Lab's Chalk River Laboratory (CRL) (References 2 and 85). Further, USNC and GFP signed an MOU with McMaster University in Ontario with the intent to deploy an MMR on campus (Reference 2).

In May 2021, the University of Illinois Urbana-Champaign (UIUC), in collaboration with USNC, submitted an LOI to the USNRC for a construction permit to build a research reactor on the UIUC campus (Reference 84).

There are ongoing plans for the construction of test facilities for the MMR as well. In March 2023, Grupa Azoty Police in Poland, USNC, and West Pomeranian University of Technology signed an agreement to construct, test, and maintain an MMR at Grupa Azoty Police's plant. The reactor will be examined for future use in powering chemical processes to generate steam and hydrogen (Reference 85). In Finland, USNC and Lappeenranta-Lahti University of Technology signed an MOU to examine the feasibility of deploying the MMR within the city or campus. The reactor would operate as a training, research, and test reactor and provide district heating to the university and local community (Reference 86). In June 2023, USNC announced plans to locate a highly automated MMR assembly plant in Gadsden, Alabama (Reference 87).

USNC has received funding from the UK Government's Advanced Modular Reactor Research, Development, and Demonstration Program to develop a design that has been tailored for industry needs in the UK, including higher power and higher temperature operations. USNC's efforts in the UK have included bringing in personnel from the U-Battery team. (References 90 and 91).

Through investment in USNC, Hyundai Engineering owns exclusive rights to the EPC business of the MMR (Reference 2).

USNC has a cooperative agreement with Meralco, the Philippines' largest electric distribution utility, to study the potential deployment of one or more MMR Energy Systems in the Philippines. USNC will complete a pre-feasibility study to familiarize Meralco with MMR systems and how these can be effectively utilized in the Philippines (Reference 90).

USNC maintains in-house capabilities for its additive manufacturing techniques and has opened fuel testing and development facilities in Salt Lake City, Utah, and Oak Ridge, Tennessee. The University of Illinois plans to acquire fuel for the MMR through the DOE's existing Research Reactor Infrastructure Program (Reference 2). In June 2023, USNC announced plans to locate a highly automated MMR assembly plant in Gadsden, Alabama (Reference 87).

USNC has signed agreements to support the supply chain necessary to produce FCM fuel for its commercial deployments. USNC has an agreement with Urenco to supply Enriched Uranium Product (EUP) (Reference 91). USNC has a Joint Venture (JV) with Framatome to manufacture TRISO particles and FCM fuel (Reference 92).

Table 26 | USNC MMR Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	Basic Design
Licensing	CNSC: • VDR: In Phase 2 NRC: • LOI for construction application at UIUC • Pre-application engagement
Supply Chain	Commitments: • Hyundai Engineering: EPC • MMR Assembly Plant in Gadsden, AL • Urenco: EUP supply • JV with Framatome: Fuel manufacturing • DOE: Fuel for UIUC
Lead Demonstration Project	Chalk River, Ontario
Interested Parties[1] and Level of Interest	MOU: • McMaster University (Canada) • Lappeenranta-Lahti University of Technology (Finland) • Grupa Azoty Police and West Pomeranian University of Technology (Poland) • Meralco (Philippines) Commitments: • UIUC (US)

Notes:

1. Interested parties include utility and non-utility entities that have publicly stated interest, either through a signed contract, MOU, or other cooperation agreement.

Westinghouse AP300

OVERVIEW

The Westinghouse AP300 SMR is a 330 MW_e, single-loop PWR based on Westinghouse's AP1000® reactor (Reference 93). The AP300 SMR is promoted as a scaled-down version of the AP1000 reactor, allowing Westinghouse to leverage similar components, an established supply chain, and lessons learned from the deployment of previous AP1000 reactors. Westinghouse markets that the proven experience from AP1000 reactor deployments can be directly applied to the AP300 SMR.

DESIGN DESCRIPTION

The AP300 is a light-water cooled and moderated PWR that produces 900 MW_{th} and 300 MW_e with an 80-year design life.

The AP300 SMR is described as a scaled-down version of the AP1000 reactor, with similar technology and components. The AP300 SMR leverages a single primary loop, as opposed to the AP1000 two-loop reactor design. The AP300 SMR design can accept ramp load changes of 5%/minute operating in the range of 25% to 100% percent of full power.

The reactor uses Westinghouse's Advanced Doped Pellet Technology (ADOPT) fuel (Reference 94). ADOPT pellets are UO_2 fuel doped with additional additives (chromia and alumina) that enable higher burnup and increase corrosion resistance (Reference 95). The Westinghouse AP300 SMR reference fuel cycle is 3 years, with design considerations to accommodate a 2-year and 4-year cycle length.

> "The AP300 is a PWR that is capable of producing 300 MW_e."

As of writing, publicly available details regarding site footprint, operations, staffing requirements, and construction timeline are limited.

Potential use cases for the AP300 SMR include electricity generation (baseload and load-following), hydrogen production, process and district heating, and water desalination. Table 27 provides a summary of key AP300 SMR design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide (Reference 4).

Table 27 | End User Considerations for the AP300 SMR

END USER CONSIDERATION	AP300 SMR VALUE
Neutron Spectrum	Thermal
Moderator	H_2O
Coolant	H_2O
Fuel State	Solid
Mission [1]	• Electricity Generation - Flexible • Process Heat • Product Generation
Thermal Output	900 MW_{th}
Electrical Output	300 MW_e
Size	Medium [2]
Technology Generation	Advanced [3]

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. EPRI defines reactors with power outputs of 300 MW_e–600 MW_e as "medium" sized reactors (Reference 4).
3. EPRI defines an advanced reactor as "any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors" (Reference 4).

Figure 12 | AP300 Reactor Overview (Reference 96)

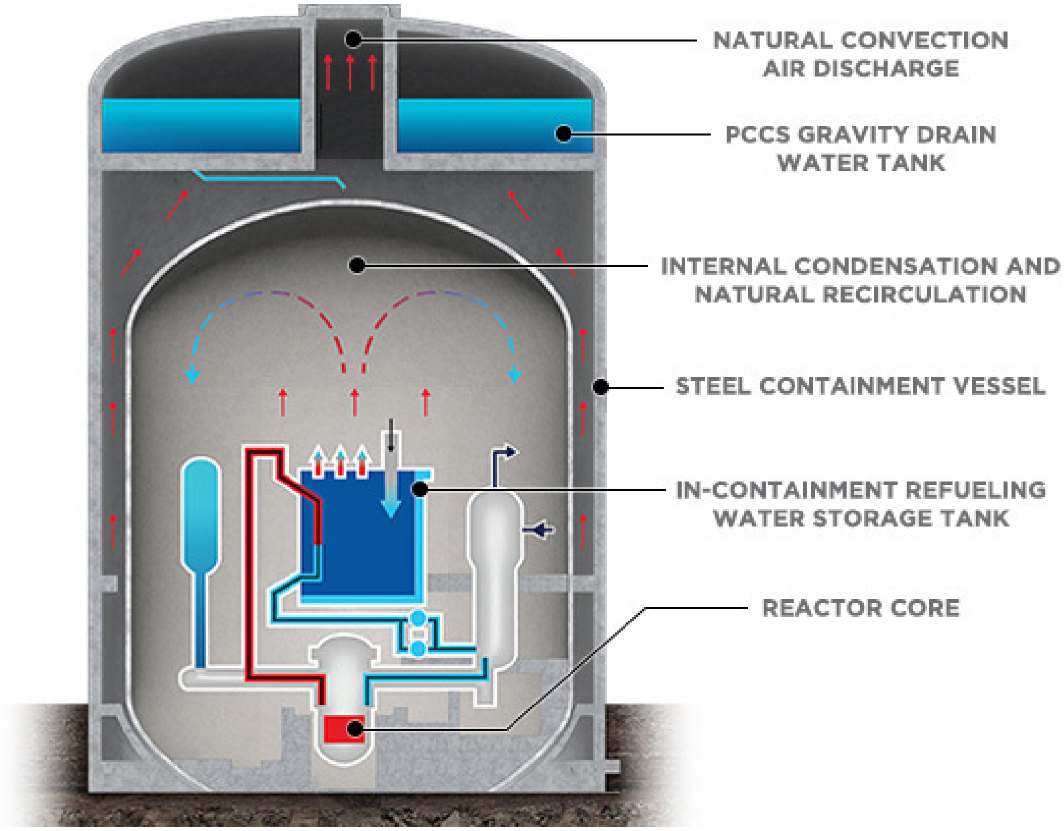


Figure 13 | AP300 Site Overview (Reference 97)

KEY SAFETY FEATURES

The AP300 SMR leverages similar safety systems to the AP1000, which has already received regulatory approval in multiple jurisdictions (Reference 96). The reactor is designed with passive safety features to maintain safe shutdown condition without operator intervention, backup power, or pumps (Reference 97). As shown in Figure 12, the AP300 will utilize a large steel containment vessel to facilitate internal condensation and recirculation in the event of a LOCA. Figure 12 also shows a PCCS, which will remove the heat released from the reactor to the environment via natural convection.

A pre-application regulatory engagement plan states that the AP300 will not require support systems after safety system actuation and that operator action will not be required to mitigate design basis accidents (DBAs) (Reference 98).

Due to the novelty of the AP300 SMR public announcement, limited technical details are available.

CURRENT STATUS

The following section provides an overview of Westinghouse's recent new nuclear power plant deployment activities as of Spring 2024.

Westinghouse announced the AP300 SMR in May of 2023 and submitted a pre-application regulatory engagement plan to the USNRC that same month (Reference 98). Westinghouse expects the AP300 to be licensed by U.S. nuclear regulators by 2027 and built and producing power by 2033 (Reference 99). In February 2023, Westinghouse submitted an application to the UK Department of Energy Security and Net Zero (DESNZ) for approval to enter the General Design Assessment process (Reference 100). Westinghouse has also noted that a similar supply chain that supported past AP1000 PWR deployment will be used and that construction and startup lessons learned in AP1000 PWR projects will be incorporated in AP300 SMR deployment. No lead deployments have been identified for the AP300 SMR. Table 27 provides a summary of the current AP300 SMR deployment status.

Table 27 | AP300 SMR Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	Conceptual
Licensing	USNRC: Pre-Application Engagement UK Department of Energy Security and Net Zero: Applied to Enter General Design Assessment
Supply Chain	Plan to leverage existing AP1000/ PWR supply chain
Lead Demonstration Project	TBD
Interested Parties[1] and Level of Interest	Agreement between WEC and Community Nuclear Power, Ltd signed Feb 8, 2024

Notes:

1. Interested parties include utility and non-utility entities that have publicly stated interest, either through a signed contract, MOU, or other cooperation agreement.

Westinghouse eVinci Microreactor

OVERVIEW

The eVinci Microreactor is a 5 MW_e microreactor designed by Westinghouse Electric Company. The reactor is manufactured and assembled in a factory and is transportable via land or water. The eVinci is intended to provide safe and reliable energy and for decentralized, remote locations. It also has additional capabilities in providing district heating, hydrogen generation, and integration with other sustainable energy sources. The reactor operates for at least 8 years. Westinghouse leverages heat pipe technology to passively transfer heat from the reactor core, removing the need for a water-based cooling system. The site layout is just over 2 acres. (Reference 102).

DESIGN DESCRIPTION

The eVinci Microreactor is a thermal neutron, heat pipe reactor that is estimated to produce up to 5 MW_e or 13 MW_{th} of high grade heat (Reference 102).

An overview of the major plant systems is shown in Figure 14. Figure 15 shows an illustration of the eVinci microreactor.

The eVinci module itself is fully fabricated off site and shipped to the site in a fueled subcritical state. Very little on-site construction and installation is required for the module itself. The eVinci module is brought to a critical, powered, and then controlled state by rotating radial control drums around the core. Sodium heat pipes are used to transfer heat from the core to the heat exchanger and associated power conversion system, where the heat can be used for secondary operations or in an open-air Brayton cycle to produce power. The use of heat pipes removes the need for coolant pumps in the primary loop. This high-speed engine is capable of black startup and utilizes power electronics to efficiently load follow based on grid demand. An autonomous load-following system is integrated with the power conversion and heat delivery system to enable the reactor to meet varying grid demands (Reference 17).

> "The eVinci Microreactor is a thermal neutron reactor that is capable of producing up to 5 MW_e of power."

The eVinci will be designed to use an encapsulated fuel. The reactor will utilize HALEU – Uranium Oxycarbide (UCO) in a TRISO fuel element (Reference 17).

The reactor core is to be fueled to operate for 8 or more years with no interim refueling. Toward end of life, a new reactor is brought on site and the spent reactor is removed in its entirety from the site for refueling at factory and potentially redeployment (Reference 102). The reactor is not refueled on the customer site.

The plant footprint is expected to take up approximately an acre of land[2] (Reference 17). The above ground installation is anticipated to be less than 2 acres of lands (Reference 102). Nearly all the assembly for the reactor is done in a factory. Once on site, the installation of the container only requires a connection between the electrical power conduits or pipe connections if both process heat and power are requested (Reference 17).

Table 28 provides a summary of key eVinci design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide (Reference 4).

Table 28 | End User Considerations for the eVinci

END USER CONSIDERATION	eVINCI VALUE
Neutron Spectrum	Thermal
Moderator	Graphite
Coolant	Heat Pipes, Liquid Sodium
Fuel State	Solid
Mission (1)	• Electricity Generation - Flexible • Process Heat
Thermal Output	13 MW_{th}
Electrical Output	5 MW_e
Size	Micro (2)
Technology Generation	Advanced (3)

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. EPRI defines reactors with power outputs of less than 50 MW_e as “micro” reactors (Reference 4).
3. EPRI defines an advanced reactor as “any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors” (Reference 4).

[2] Depending on the deployment location/additional structures, more land may be required than the above estimate.

Figure 14 | Major Systems in the eVinci Microreactor (Reference 102)

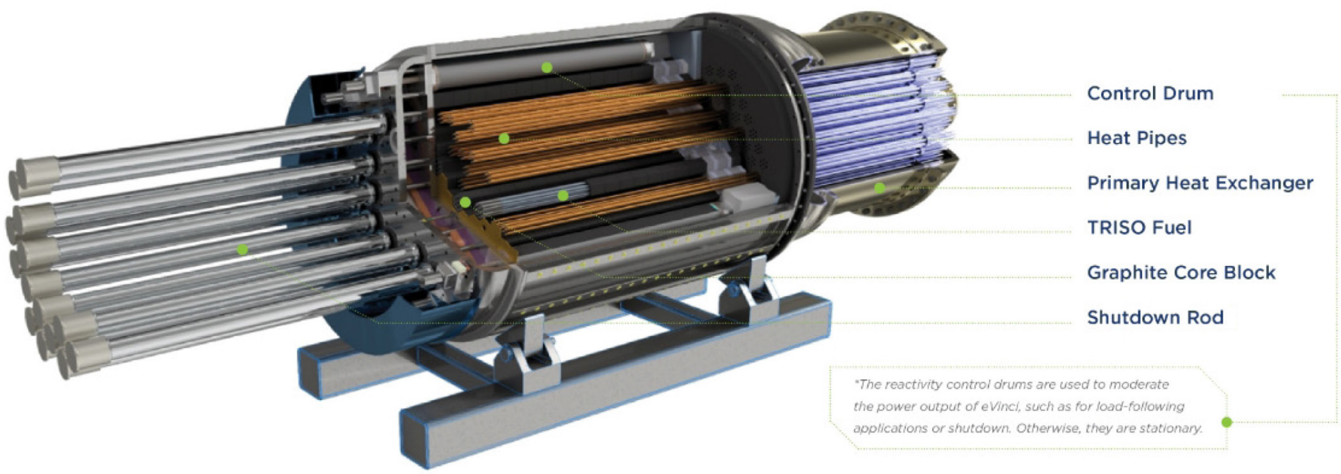
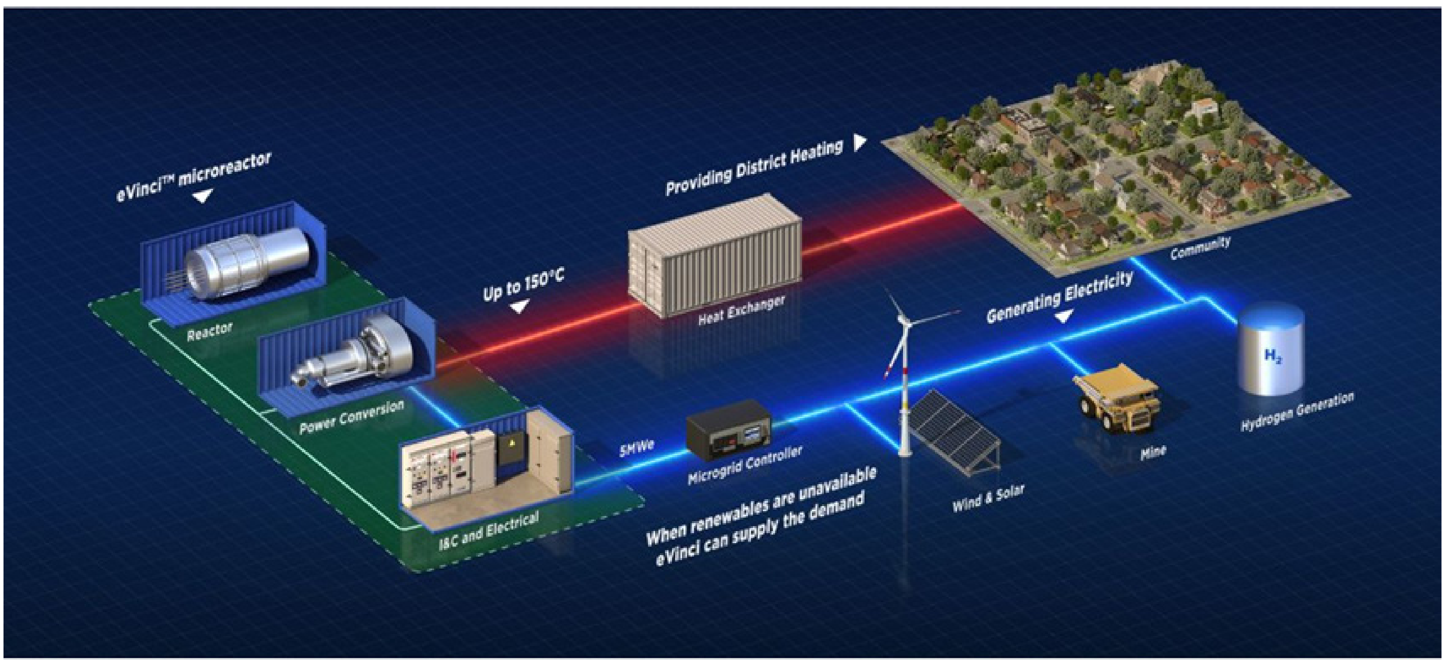


Figure 15 | eVinci Microreactor Illustration (Reference 102)



KEY SAFETY FEATURES

The eVinci Microreactor leverages inherent and passive safety systems for cooling, heat removal, and shutdown activities. The reactor utilizes Westinghouse's advanced heat pipe technology to employ passive heat transfer without the need for a cooling medium, which reduces the risk from high pressure systems and LOCA (Reference 102).

The reactor has inherent safety features built into its design. Control drums are located radially along the core. These drums automatically rotate and bring the reactor to safe shutdown during the event of a trip. The reactor also has shutdown rods that are inserted into the core to terminate operation as well as during transport, providing defense-in-depth shutdown capabilities (Reference 17). The Passive Heat Removal System (PHS) rejects heat to the atmosphere through natural convection and radiation, without the need for operator action or active components (Reference 102).

The Autonomous Control System (ACS) is implemented within the eVinci Microreactor. This I&C can determine trip decisions and load-following blueprints with high-fidelity sensors and hardware. Additionally, this system can modulate the position of the control drums based on its sophisticated feedback network. The use of an ACS eliminates the need for operator intervention to moderate the reactor or bring it down to a safe shutdown state (Reference 17).

CURRENT STATUS

The following section provides an overview of the eVinci deployment status as of Spring 2024. Table 29 provides a summary of various eVinci deployment activities.

In February 2023, a Notice of Intent (NOI) was filed by Westinghouse for joint licensing review by the CNSC and the United States Nuclear Regulatory Commission (NRC) (Reference 103). Westinghouse submitted the first of three planned joint submissions for CNSC and USNRC review in November 2023. In July 2023, Westinghouse announced the eVinci has begun the VDR with the CNSC and is currently in Phase 2 of the VDR (Reference 104). To meet the intent of a Phase 1 review, 21 reports were submitted for CNSC review in three packages over the course of 2023.

Westinghouse has signed an MOU with Canadian Saskatchewan Research Council and Pennsylvania State University for potential deployment activities for the eVinci (Reference 28). In June 2023, Astrobotic and Westinghouse signed an MOU for the development of the eVinci for space power applications (Reference 105). In October 2023, Westinghouse announced the launch of their heat pipe manufacturing facility and dedicated eVinci Technologies LLC office space in the Pittsburgh area (Reference 103). Additionally, Urenco and Westinghouse are working together to study TRISO fuel for use in the eVinci (Reference 5).

The DOE awarded the eVinci a Front-End Engineering and Experiment Design (FEEED) Contract in funding support for commercialization and deployment of the reactor at INL. This involves the demonstration of a one-fifth power scale eVinci reactor at the National Reactor Innovation Center (NRIC) by the end of 2025 (Reference 106). Additionally, the DOE, in tandem with the Canadian Federal Government and the Government of Saskatchewan has granted over 100 million USD for the eVinci under several different development programs (Reference 28).

Table 29 | Westinghouse eVinci Microreactor Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	Conceptual Design/Testing
Licensing	CNSC: • Begun VDR, currently in Phase 2 USNRC: • Pre-licensing activities
Supply Chain	• Brayton Energy (US) • Urenco (US): TRISO Fuel • DOE (US) & Canadian Federal Government (Canada): Funding
Lead Demonstration Project	INL/NRIC – One-fifth scale test of eVinci (end of 2026)
Interested Parties[1] and Level of Interest	MOU: • Canadian Saskatchewan Research Council (Canada) • Pennsylvania State University (US) • Astrobotic (US)

Notes:

1. Interested parties include utility and non-utility entities that have publicly stated interest, either through a signed contract, MOU, or other cooperation agreement.

X-energy Xe-100

OVERVIEW

The X-energy Xe-100 is a pebble bed HTGR with capabilities in process heat, desalination, electricity, and co-generation applications (Reference 2). The Xe-100 design builds upon proven high-temperature pebble bed reactor technology, derived from over 50 years of design and development (Reference 107). The Xe-100 design aims to improve economics by simplifying systems, modularizing components, reducing construction time, and having high plant availability.

DESIGN DESCRIPTION

The Xe-100 is a helium-cooled, graphite-moderated pebble-bed reactor that produces 200 MW_{th} and 80 MW_e (Reference 17).

Xe-100 uses TRISO particles embedded in a graphite matrix pebble (Reference 17). The particles consist of coated uranium oxide and carbide kernels with an enrichment at 15.5 weight percent (wt%). The maximum fuel temperature during normal operations is 1,100°C, which is far less than the melting temperature of graphite (3,920°C), which provides a significant thermal safety margin.

> "The X-energy Xe-100 is a helium-cooled, pebble-bed reactor capable of producing 80 MW_e."

The Xe-100 can be refueled online, with a system that inspects the fuel pebbles for burnup and integrity where the fuel pebbles can either be reloaded back into the core or directed to spent fuel storage. This refueling methodology limits core excess reactivity to 2%, meaning no burnable poisons are necessary to keep the reactor reactivity within safe shutdown limits (Reference 17). An average fuel pebble passes through the core six times.

The plant footprint is approximately 35 acres[3] for four reactor modules with four turbines (the exact value is site-specific) (Reference 17). Construction time for the Xe-100 is projected to be between 2.5 years and 4 years for a 320 MW_e plant (Reference 108). The total design life for the plant is 60 years (Reference 1).

[3] Depending on the deployment location/additional structures, more land may be required than the above estimate.

Table 30 provides a summary of key Xe-100 design features that align with end user considerations provided in Section 1.5 of the EPRI Owner/Operator Reactor Technology Assessment Guide (Reference 4). For more specific design details, please see the accompanying EPRI technology design table.

Table 30 | End User Considerations for the Xe-100

END USER CONSIDERATION	XE-100 VALUE
Neutron Spectrum	Thermal
Moderator	Graphite
Coolant	Helium
Fuel State	Solid
Mission [1]	Electricity Generation - Flexible
Thermal Output	200 MW_{th}
Electrical Output	80 MW_e
Size	Small [2]
Technology Generation	Advanced Reactor [3]

Notes:

1. See Appendix A in Reference 4 for a complete description of reactor technology primary missions.
2. EPRI defines reactors with power outputs of 50 MW_e–300 MW_e as "small" sized reactors (Reference 4).
3. EPRI defines an advanced reactor as "any (fission) reactor concept or design beyond GEN III/III+ technologies and includes non-light water designs, lwSMRs, and microreactors" (Reference 14).

KEY SAFETY FEATURES

The primary source of reactivity control relies on a strong negative temperature coefficient to ensure nuclear stability throughout the reactor's lifetime. A safe shutdown condition can be achieved with the negative temperature coefficient and without the use of active reactivity control systems (e.g., control rods, neutron poisons). The reactor is also equipped with a Reactivity Control & Shutdown System (RCSS) that contains a bank of nine control rods with B_4C as the control rod material for operational reactivity control. There is a second bank of nine rods with the purpose of a reserve shutdown system mainly for maintenance shutdown. Each of these systems is capable of completely shutting down the reactor to safe conditions (Reference 17).

X-energy optimized the core geometry, power density, and enrichment level to allow for decay heat to be removed during the most severe accident scenarios, such as a total loss of power along with the loss of the helium heat transfer fluid. The UCO TRISO particles allow for retention of fission product at the source. The pressure boundary provides another physical barrier to retain the small amount of fission products that may be in the graphite dust particles or circulating in the helium. In the event of a break in the pressure boundary, the helium will be filtered through a release vent that will remove the radionuclides and be released to the atmosphere (Reference 17).

The I&C system consists of three layers: distributed control system, investment protection system, and reactor protection system (Reference 17). X-energy configured the human machine interface in a particular way to ensure that no operator action is needed to guarantee a safe shutdown of the reactor during all events.

CURRENT STATUS

The following section provides an overview of Xe-100 global deployment status as of November 2023. Table 31 provides a summary of various Xe-100 deployment activities.

X-energy is in the pre-licensing review process by the USNRC and completed the Vendor Design Review licensing process for the Canadian Nuclear Safety Commission on January 17, 2024 (Reference 109).

Energy Northwest shortlisted the Xe-100 design for its nuclear-licensed site in Richland, Washington. Other opportunities for the Xe-100 reactor are with the Maryland Energy Association to supply power to its Maryland coal site along with supplying heat and power to one of Dow Chemical's industrial plants. X-energy and Dow Chemical agreed to an equity stake deal in August 2022. Dow and X-energy are in the process of preparing and submitting a Construction Permit application to the USNRC (Reference 2). The construction of this four-reactor project is expected to begin in 2026 and to be finished by 2030 (Reference 110). Furthermore, Grant County Public Utility District (PUD) selected the Xe-100 as the SMR of choice for further assessment of potential development (Reference 2).

In October 2020, X-energy was awarded 80 million USD in funding by the DOE ARDP. A total of 1.23 billion USD is currently approved by the ARDP across 7 years for X-energy nuclear reactor demonstration. In April 2022, X-energy selected and applied for Oak Ridge, Tennessee, to be the location of its TRISO-X Fuel Fabrication Facility (Reference 2). In October 2022, X-energy broke ground and began construction activities on this fuel facility (Reference 111).

In addition to the lead demonstration project at Dow Chemical's Seadrift site, X-energy is in conversations with other interested parties, including outfits in the UK and Canada (References 114 and 115).

Table 31 | X-energy Xe-100 Deployment Status Summary

DEPLOYMENT CATEGORY	STATUS
Design	Basic Design Phase
Licensing	• USNRC: Pre-Application Engagement • CNSC: Phase 2 of VDR
Supply Chain	• Construction Support: Zachry Group, Day & Zimmerman, and Burns & McDonnell • Design Studies: Doosan • Xe-100 Deployment: OPG, Southern Nuclear, Cavendish Nuclear, and Kinectrics • Fuel: TRISO-X Fuel Fabrication Facility is scheduled for commissioning and startup in 2025 • Graphite: Amsted Graphite • Fuel Fabrication Facility (US): Submitted a Construction Permit for TRISO-X Fuel Fabrication Facility
Lead Demonstration Project	Dow Seadrift Facility • Approximate Construction Start: 2026 • Approximate Commercial Operations: 2030
Interested Parties[1] and Level of Interest	MOU: • Energy Northwest (US) • Invest Alberta Corporation (Canada) • Kier and Cavendish Nuclear (UK) • Grant County PUD (US) Other Interested Parties: • Maryland Energy Association • TransAlta (Alberta)

Notes:

1. Interested parties include utility and non-utility entities that have publicly stated interest, either through a signed contract, MOU, or other cooperation agreement.

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