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Small Modular Reactors

—Technological Trends in Molten Salt Reactors and High-Temperature Gas Reactors—

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Why This Technology?

Small Modular Reactors (SMRs) are attracting attention due to their compact size and various advantages compared to conventional large-scale nuclear reactors. Non-utility companies, such as Amazon (US), are considering adopting SMRs, and in 2024, Google (US) signed a contract to purchase electricity from an SMR operated by Kairos Power (US), raising expectations for commercial use. Such developments are accelerating SMR technology advancement and market adoption, potentially positioning it as a key clean energy option in the future. While SMR projects continue to advance worldwide, this report focuses on the United States, where many innovative projects are underway, detailing notable trends and future prospects.

Summary

- Kairos Power's Hermes demonstration reactor, a molten salt reactor, is scheduled to begin operation in 2027. In the field of high-temperature gas reactors, X-energy (US) plans to start construction of its Xe-100 reactor in 2026.
- As the number of SMRs increases globally, a wide variety of reactor designs are under development. However, only a limited number of reactor types can leverage economies of scale through the construction of multiple units, and many designs are likely to be phased out based on economic viability.

1. What is a Small Modular Reactor (SMR)?

A Small Modular Reactor (SMR) refers to a nuclear reactor with an output of 350 MW or less, compared to conventional reactors of 1,000 MW or more[1]. Nuclear energy has garnered attention as a means of decarbonization, and a “Declaration to Triple Nuclear Energy[2]” was announced at COP28. SMR development is accelerating alongside traditional large reactors in many countries due to its enhanced safety, greater site flexibility, and cost reductions through modular construction. The Draghi Report[3], published in Europe in September 2024, stated the need to establish a supply chain for nuclear reactors, including SMRs, in the mid-term[4]. As shown in Figure 1, a variety of SMRs are under development, broadly classified based on coolant type. (1) Light water reactors use pressurized or boiling water, similar to existing commercial reactors[5]. (2) Liquid metal-cooled reactors

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[1] In the United Kingdom, liquid metal-cooled reactors, molten salt reactors, and high-temperature gas reactors are classified as advanced modular reactors regardless of their size. In some cases, reactors with an output of 300 MW or less are defined as SMRs.

[2] At the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) in 2023, a declaration was made to triple global nuclear power generation capacity from 2020 levels by 2050. According to estimates by the Japan Atomic Industrial Forum, Inc., achieving this goal would result in a total nuclear power capacity of over 1,200 GW. As of November 2024, 31 countries have signed the declaration.

[3] The official title of the report is “The Future of European Competitiveness,” and it was authored by Mario Draghi.

[4] In “The Future of European Competitiveness Part B, In-depth Analysis and Recommendations,” defines “new nuclear” as including advanced modular reactors and SMRs.

[5] Water that contains deuterium is referred to as heavy water.

utilize sodium or other liquid metals as coolant. (3) Molten salt reactors use chloride-based molten salts. (4) High-temperature gas reactors use gas as the cooling medium.

However, miniaturization reduces scalability, leading to higher power generation costs compared to conventional nuclear reactors[6,7]. This report focuses on (3) Molten salt reactors and (4) High-temperature gas reactors, which offer higher power generation efficiency through high-temperature operation in order to address the issue of power generation costs. Additionally, these reactors can directly supply high-temperature heat, making them suitable for applications where decarbonization is difficult, such as chemical manufacturing. Section 2-1 examines the trends in molten salt reactors and high-temperature gas reactors being advanced by two leading US-based companies. Section 2-2 covers trends in SMR fuel production, while Section 2-3 provides an overview of SMR heat utilization technologies.

Figure 1: Typical SMR specifications and operation start date

Reactor type	Model name	Manufacturer	Core coolant	Single unit output [MWe]	Core outlet temperature [°C]	Heat supply temperature [°C]	Operation start date
Pressurized water reactors	VOYGR	(US) NuScale Power	Light water	77	321	300	2029
Boiling water reactors	BWRX-300	(US) GE Hitachi Nuclear Energy (Japan) Hitachi-GE Nuclear Energy	Light water	300	288	-	2029
Liquid-metal cooled reactors	Natrium	(US) TerraPower	Sodium	345	500	-	2030
Molten salt reactors	KP-FHR	(US) Kairos Power	Molten salt	75	650	-	2030 or later
High-temperature gas reactors	Xe-100	(US) X-energy	Helium	80	750	565	2030

MWe: Electrical output

Source: Compiled by MGSSI based on various data

2. Notable Trends

2-1. Trends in Molten Salt Reactors and High-Temperature Gas Reactors

A leader in the field of molten salt reactors is the Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)[8]. With support from the US Department of Energy (DOE), construction of the Hermes demonstration reactor began in Tennessee, US, in July 2024, with operations planned to commence in 2027[9]. Molten salt reactors face technical challenges, particularly concerning corrosion of structural materials. To address this issue, past reactors have used corrosion-resistant Hastelloy-based alloys[10]. However, Hermes has adopted 316H stainless steel[11], a lower-cost alternative, and has received construction approval from the US Nuclear Regulatory Commission (NRC).

A representative example of a high-temperature gas reactor is the Xe-100, a helium gas-cooled reactor

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[6] NuScale Power (US) had planned to construct the VOYGR SMR in Idaho, US, but the project was abandoned due to rising construction costs and higher-than-expected power generation costs.

[7] In general, the cost of SMR power generation is estimated to be approximately twice that of conventional light water reactors.

[8] The KP-FHR uses a molten salt mixture of lithium fluoride and beryllium fluoride as a coolant. Construction of a high-purity molten salt production facility began in 2024, ensuring a stable supply of materials.

[9] Hermes is not designed for power generation but will instead verify 35 MW thermal energy output.

[10] Hastelloy-N was used as the structural material in the molten-salt reactor experiment at Oak Ridge National Laboratory, US.

[11] 316H stainless steel, which has been used in existing nuclear reactors, is recognized as a high-temperature material under ASME Section III Division 5.

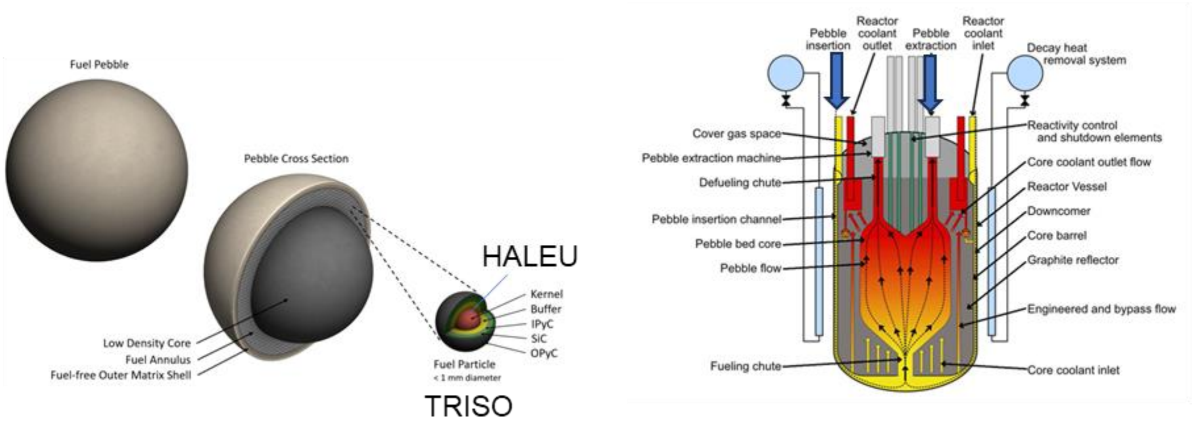
developed by X-energy. The company has signed a contract with the chemical manufacturer Dow (US)[12] to begin construction of a commercial reactor in Texas in 2026, with plans to supply low-carbon electricity and steam starting in 2030. Many high-temperature gas reactors are designed to operate at temperatures exceeding 950°C, which has led to higher structural material costs. There is also a risk of damage to the fuel particle coatings[13]. To address these challenges, the Xe-100 lowers the operating temperature to 750°C, enabling the use of a wider range of materials.

2-2. Trends in SMR Fuel Production

The SMRs mentioned above operate at high temperatures, requiring heat-resistant fuel to enhance safety. However, these advanced fuels necessitate the construction of new manufacturing facilities, making production infrastructure an important consideration. The SMRs developed by the two companies discussed above utilize spherical fuel pebble embedded with many fuel particles (TRISO[14]), each approximately 1 mm in diameter, made from triple-layered High-Assay Low-Enriched Uranium (HALEU[15]). This system is designed to enable continuous refueling during reactor operation (Figure 2).

HALEU is a fuel under consideration for use in various SMRs, and with the increasing demand for SMRs, potential supply shortages have become a concern[16]. Most recently, Centrus Energy (US) began manufacturing HALEU in October 2023. BWX Technologies (US) has started manufacturing of TRISO in Virginia, while X-energy plans to begin manufacturing in Tennessee in 2025. With these companies expanding their manufacturing capabilities, a stable fuel supply is expected to be secured by the time commercial reactors begin operations.

Figure 2: Conceptual fuel diagram and fuel supply system diagram



Fuel pebble overview

Reactor overview

Source: Compiled by MGSSI based on US NRC data

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[12] Dow plans to introduce an SMR at its UCC Seadrift Operations site, replacing the existing steam system while also supplying electric power.

[13] The AVR reactor (Germany) faced challenges regarding the high-temperature durability of its Bi-structural Isotropic (BISO) particle fuel.

[14] The uranium fuel is first coated with inner pyrolytic carbon, followed by a silicon carbide layer, and then outer pyrolytic carbon. This multi-layered coating structure does not melt even at temperatures up to 1600°C and prevents the release of fission products, making it very safe and enabling the further enhancement of SMR safety.

[15] HALEU refers to uranium-235 enriched between 5% and 20%.

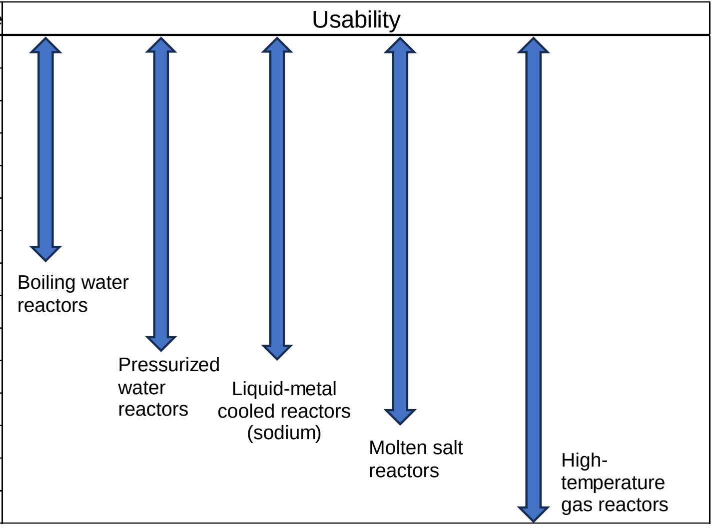
[16] In 2022, companies under Rosatom (Russia) accounted for 100% of the global market supply of HALEU. To reduce dependence on Russia, the US is supporting efforts to establish a domestic HALEU supply chain through the Inflation Reduction Act (IRA).

2-3. SMR Heat Utilization Technologies

The SMRs discussed above are capable of high-temperature heat supply, making them suitable for providing thermal energy to industrial sectors that are difficult to decarbonize, such as chemical plants. Intellectual property analysis has identified patent applications related to heat supply to methanol production systems, etc. Figure 3 summarizes the process temperatures of various industrial sectors and the corresponding SMR types that can be applied[17]. Additionally, the X-energy SMR is being considered for seawater desalination using high-temperature steam.

Figure 3: Process temperatures in industrial sectors and applicable SMRs

Industry	Process temperature
Seawater desalination	70~130℃
District heating	80~150℃
Aluminum production (alumina hydration)	100~300℃
Pulp and paper manufacturing	100~400℃
Chemical processing	250~600℃
Oil sand (SAGD process)	Approx. 300°C
Soda ash production (Solvay process)	300~400℃
Oil refining	350~550℃
Ammonia production (ammonia synthesis)	400~500℃
Oil shale processing	Approx. 500°C
Petroleum refining (catalytic cracking)	600~800℃
Ammonia production (natural gas reforming)	600~800℃
Hydrogen production (natural gas reforming)	Approx. 750°C
Chemical processing (naphtha cracking)	800~900℃
Aluminum production (alumina sintering)	800~1000℃



Source: Compiled by MGSSI based on data provided by Japan Atomic Industrial Forum, Inc.

3. Future Prospects

SMRs are gaining attention as a new development in nuclear energy, but the market competition is expected to be very intense. According to DOE, achieving cost reductions through economies of scale and learning effects requires the construction of at least 5 to 10 reactor units of the same design[18]. According to the IAEA[19] forecast for nuclear power deployment, in the “expected growth case,” global nuclear power capacity will increase by 578 GW by 2050, with SMRs accounting for 24% of the total[20]. Based on this projection, assuming an average capacity of 350 MW per unit, approximately 390 SMRs are expected to be deployed worldwide.

Eighty different designs of SMR are under development[21] in 18 countries worldwide. However, some SMRs currently in development are likely to lose market competitiveness and be phased out due to several challenges[22]. These include unsustainable development costs due to longer-than-expected approval processes by the US Nuclear Regulatory Commission (NRC), rising construction costs exceeding initial estimates during detailed design

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[17] Some liquid metal-cooled reactors are designed for higher operating temperatures, but the temperatures indicated are for typical liquid metal-cooled reactors.

[18] Based on the US Department of Energy report, “Pathways to Commercial Liftoff: Advanced Nuclear.”

[19] International Atomic Energy Agency.

[20] According to the IAEA “Energy, Electricity and Nuclear Power Estimates for the Period up to 2050,” global nuclear power capacity at the end of 2023 was 372 GW. By 2050, the high-case scenario estimates an increase to 950 GW, while the low-case scenario projects 514 GW. The share of SMRs is estimated to range from 6% to 24%.

[21] From “The Future of European Competitiveness,” Part B, Section 1, Chapter 1

[22] In November, Ultra Safe Nuclear Corporation (US), which had been planning a micro-reactor smaller than an SMR, filed for bankruptcy. It was clear that the company had struggled to secure anchor investors.

stages, and the inability to achieve anticipated cost reductions through the introduction of new technologies.

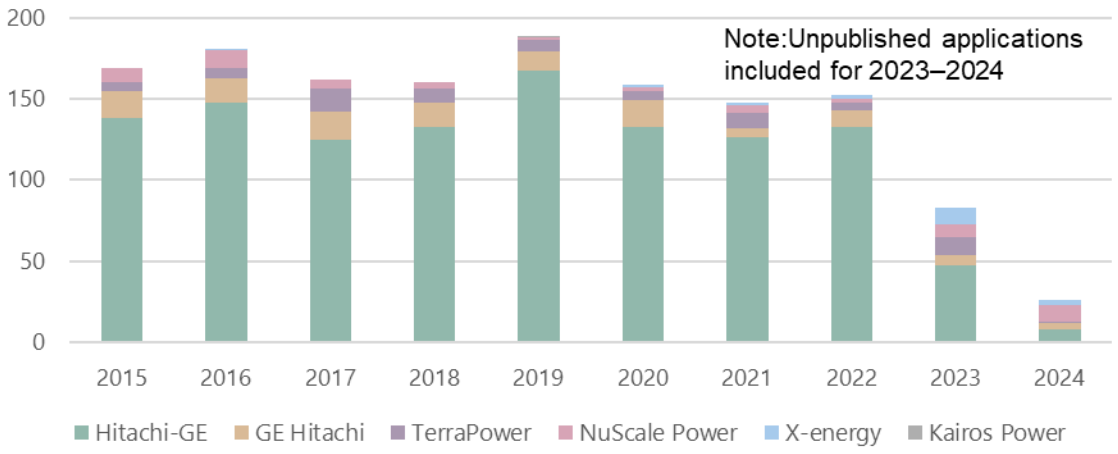
The first SMRs will be constructed by 2030, allowing for comparisons in terms of safety and cost. In the 2030s, commercial molten salt reactors and high-temperature gas reactors will commence operations. At that stage, the key factors driving the competitiveness of SMR manufacturers will include not only (1) fundamental safety assurance and (2) low costs, but also (3) reliable cost estimates, (4) high-temperature heat supply and expertise in its utilization, (5) partnerships with companies experienced in nuclear power plant construction (as the number of manufacturers has declined due to past phases of nuclear phase-out), and (6) the establishment of a highly reliable supply chain.

Despite the technical and economic challenges associated with SMRs, their ability to provide a stable supply of electricity and heat makes them an important option in the transition to a decarbonized society.

IP Analysis of Small Modular Reactors

For the intellectual property analysis of Small Modular Reactors (SMRs), patent data from six major developers listed in Figure 1 was extracted and analyzed to assess the technological landscape. The analysis covered 1,431 patent families filed between 2015 and 2024, identified using the global patent search tool PatSnap.

Figure 4: Annual patent applications by six SMR developers

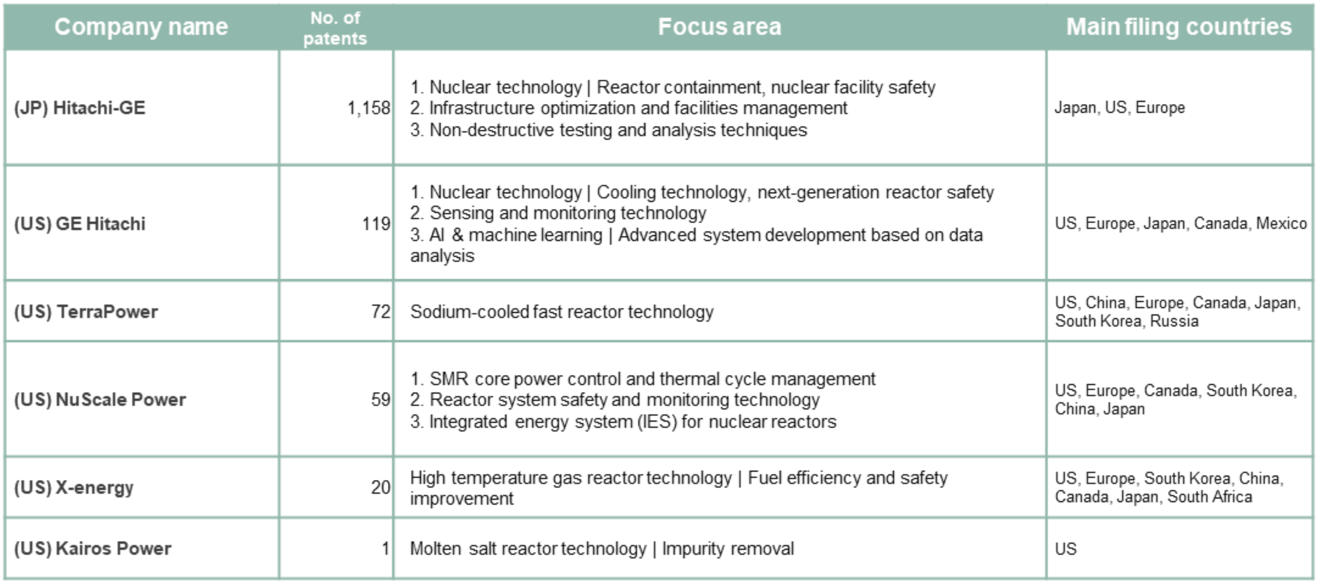


Note:Unpublished applications included for 2023–2024

Source: Compiled by MGSSI

As shown in Figure 4, while the number of patent filings varies by company, technology development has continued at a constant level. Among the companies analyzed, Hitachi-GE Nuclear Energy (Japan) had the highest number of filings over the entire period, averaging 138 patents per year. This was followed by GE Hitachi Nuclear Energy (US) with an average of 14 patents per year, TerraPower with 8 patents per year, and NuScale Power with 5 patents per year. X-energy has consistently filed patents since 2020, with a sharp increase to 10 filings in 2023. In contrast, Kairos Power has only one recorded patent filing in 2019.

Figure 5: Key focus areas and main filing countries by manufacturer (2015–2024)



Company name	No. of patents	Focus area	Main filing countries
(JP) Hitachi-GE	1,158	1. Nuclear technology | Reactor containment, nuclear facility safety 2. Infrastructure optimization and facilities management 3. Non-destructive testing and analysis techniques	Japan, US, Europe
(US) GE Hitachi	119	1. Nuclear technology | Cooling technology, next-generation reactor safety 2. Sensing and monitoring technology 3. AI & machine learning | Advanced system development based on data analysis	US, Europe, Japan, Canada, Mexico
(US) TerraPower	72	Sodium-cooled fast reactor technology	US, China, Europe, Canada, Japan, South Korea, Russia
(US) NuScale Power	59	1. SMR core power control and thermal cycle management 2. Reactor system safety and monitoring technology 3. Integrated energy system (IES) for nuclear reactors	US, Europe, Canada, South Korea, China, Japan
(US) X-energy	20	High temperature gas reactor technology | Fuel efficiency and safety improvement	US, Europe, South Korea, China, Canada, Japan, South Africa
(US) Kairos Power	1	Molten salt reactor technology | Impurity removal	US

Source: Compiled by MGSSI

Figure 5 summarizes the number of patent filings, key focus areas, and main filing countries for each manufacturer. Hitachi-GE had the highest number of filings, but approximately 85% of its patents were filed only in Japan. GE Hitachi is focusing on developing technologies to improve the safety and efficiency of next-generation reactors, including new designs for modular reactors. Additionally, AI-based failure prediction and operation management systems are expected to become important technological fields in the future. TerraPower is prioritizing sodium-cooled fast reactors, while X-energy is focusing on high-temperature gas reactors. While the patent filings of these companies are not exclusively for SMRs, they include technologies that can be applied to SMRs.

NuScale Power, in contrast, has filed patents explicitly mentioning “Small Modular Reactors” in their names, indicating a dedicated focus on SMR development. Furthermore, NuScale Power is notable for its patent filings related to Integrated Energy Systems (IES) for nuclear reactors, which aim to reduce environmental impact and carbon emissions. Patent filings related to IES include systems that utilize reactor-generated heat and electricity to capture CO_2 and utilize it for methanol production, as well as plants that produce hydrogen (H_2) from nuclear-generated steam and subsequently use it to synthesize nitric acid (HNO_3).

These patent data indicate that each manufacturer is strategically focusing on specific areas to realize next-generation nuclear technologies. Understanding future technological trends will be particularly interesting from the perspective of how nuclear technology evolves in response to environmental challenges and the need for efficient energy utilization.