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SUMMARY

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Advanced Nuclear Reactors: Technology Overview and Current Issues

All nuclear power in the United States is generated by light water reactors (LWRs), which were commercialized in the 1950s and early 1960s and are now used throughout most of the world. LWRs are cooled by ordinary ("light") water, which also slows ("moderates") the neutrons that maintain the nuclear fission chain reaction. High construction costs of large conventional LWRs, concerns about safety raised by the 2011 Fukushima nuclear disaster in Japan, growing volumes of nuclear waste, and other issues have led to increased interest in unconventional, or "advanced," nuclear technologies that proponents say could be less expensive, safer, and more fuel efficient than existing LWRs.

The Energy Act of 2020 (Division Z of P.L. 116-260) defines an "advanced nuclear reactor" as a fission reactor "with significant improvements compared to reactors operating on the date of enactment" or a reactor using nuclear fusion. Such reactors include LWR designs that are far smaller than existing reactors, as well as concepts that would use different moderators, coolants, and types of fuel. Many of these advanced designs are considered to be small modular reactors (SMRs), defined by the International Atomic Energy Agency (IAEA) as reactors with electric generating capacity of 300 megawatts (MW) and below. IAEA classifies reactors with 10 megawatts or less as microreactors.

Advanced reactors are often referred to as "Generation IV" nuclear technologies, with existing commercial reactors constituting "Generation III" or, for the most recently constructed reactors, "Generation III+." Major categories of advanced reactors include advanced water-cooled reactors, which would make safety, efficiency, and other improvements over existing commercial reactors; gas-cooled reactors, which could use graphite as a neutron moderator or have no moderator; liquid-metal-cooled reactors, which would be cooled by liquid sodium or other metals and have no moderator; molten salt reactors, which would use liquid fuel; and fusion reactors, which would release energy through the combination of light atomic nuclei rather than the splitting (fission) of heavy nuclei such as uranium. Most of these concepts have been studied, but relatively few have advanced to commercial-scale demonstration, and such demonstrations in the United States took place decades ago.

To conduct new demonstrations of these technologies, Congress established the Advanced Reactor Demonstration Program (ARDP) in FY2020, with an appropriation of $230 million (P.L. 116-94). In 2021, Congress, through the Infrastructure Investment and Jobs Act (P.L. 117-58), appropriated $2.477 billion through FY2025, in addition to annual appropriations. The Department of Energy (DOE) selected two demonstration projects for funding under ARDP in October 2020. Under the awards, the two projects are to receive a total of $3.2 billion over seven years from DOE, with the project sponsors matching that amount. Five potential future reactor demonstration projects received 80% cost-share awards under ARDP in December 2020, totaling $600 million of DOE funding over seven years. In addition to the ARDP projects, DOE announced a cost-shared award of up to $1.4 billion in October 2020 to demonstrate a water-cooled SMR at Idaho National Laboratory.

Tax credits for advanced nuclear reactors and other new zero-carbon power plants were included in the law commonly referred to as the Inflation Reduction Act (IRA, P.L. 117-169). Qualifying plants can receive a 10-year electricity production tax credit of up to 2.6 cents/kilowatt-hour (adjusted for inflation) or a 30% investment tax credit. IRA also includes $700 million for DOE to develop supplies of high-assay low enriched uranium (HALEU), needed for some reactor designs, including the two non-LWR demonstration plants that DOE is supporting. HALEU, not currently available commercially, is uranium enriched in the fissile isotope U-235 above the 3%-5% level used by existing commercial reactors but below the 20% threshold for highly enriched uranium. DOE's HALEU program was authorized by the Energy Act of 2020.

Fundamental issues involving advanced reactors include the appropriate role of the federal government in developing and deploying advanced nuclear power technologies and whether advanced nuclear power should be a major part of the nation's energy strategy. Major options for federal assistance include cost sharing, loan guarantees, power purchase agreements, purchase of reactor capacity for research uses, and tax credits. Supporters of advanced nuclear technology contend that it will be crucial in reducing emissions of greenhouse gases and bringing carbon-free power to the majority of the world that currently has little access to electricity. However, some observers and interest groups have cast doubt on the potential safety, affordability, and sustainability of advanced reactors. Because many of these technologies are in the conceptual or design phases, the potential advantages of these systems have not yet been established on a commercial scale. Concern has also been raised about the weapons-proliferation risks posed by the potential use of plutonium-based fuel by some advanced reactor technologies.

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Introduction

The nuclear power industry in the United States is the largest in the world, with 92 operating reactors, but its capacity has been nearly flat for the past three decades.[1] High capital costs, low electricity demand growth, and competition from cheaper sources of electricity, such as natural gas and renewables, have dampened the demand for new nuclear power plants and led to the permanent shutdown of existing reactors. Thirteen nuclear reactors have closed in the United States during the past 10 years, although the announced retirements of two more by 2025 have been postponed. As aging reactors reach the end of their operating licenses in 2030 and beyond, the number of retirements is projected to increase. In addition, cost and schedule overruns have hindered recent efforts to build new U.S. nuclear units. The only power reactors currently under construction in the United States—two new units at the Vogtle nuclear plant in Georgia—are six years behind schedule and more than double their original estimated cost of about $14 billion.[2]

All nuclear power in the United States is generated by light water reactors (LWRs), which were commercialized in the 1950s and early 1960s and are now used throughout most of the world. LWRs are cooled by ordinary ("light") water, which also slows ("moderates") the neutrons that maintain the nuclear fission chain reaction (splitting of heavy nuclei) that releases energy. Conventional LWRs are large—typically with 1,000 megawatts of electric generating capacity (MWe) or more—in order to spread their high construction costs among the maximum possible number of kilowatt-hours of electricity generated over their operating lifetime.

At the same time that conventional reactors are facing an uncertain future, some in Congress contend that more nuclear power plants, not fewer, are needed to help reduce U.S. greenhouse gas emissions and bring low-carbon power to the majority of the world that currently has little access to electricity.[3] Proponents of this view argue that the key to increasing the number of nuclear power plants is investment in "advanced" nuclear technologies, which they say could address the economic problems, safety concerns, waste management, and other issues that have stalled the growth of conventional LWRs. Advanced reactors that could run far hotter than today's LWRs could be aimed at wider markets beyond electricity generation, such as production of heat for industrial processes, hydrogen production, desalination, and heating commercial and residential buildings.[4]

The Energy Act of 2020 (Division Z of P.L. 116-260) defines "advanced nuclear reactor" as a fission reactor "with significant improvements compared to reactors operating on the date of

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[1] Energy Information Administration, "Nuclear Explained: U.S. Nuclear Industry," updated April 18, 2022, https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php.

[2] Sonal Patel, "How the Vogtle Nuclear Expansion's Costs Escalated," *Power*, September 24, 2018, https://www.powermag.com/how-the-vogtle-nuclear-expansions-costs-escalated/?pagenum=1; and Darrell Proctor, "Votgle Expansion Cost Jumps Again; In-Service Dates Set for 2023," *Power*, July 28, 2022, https://www.powermag.com/vogtle-expansion-cost-jumps-again-in-service-dates-set-for-2023/.

[3] Some analyses have concluded that the average CO_2 emissions rate of electricity generation must decline to a range of 10-25 grams CO_2/kilowatt-hour (kWh) worldwide by 2050 to meet the internationally agreed-upon target of limiting global temperature rise to 2°C. Some studies suggest there is a significant opportunity cost associated with attempting to meet these goals without the expansion of nuclear energy capacity. See Massachusetts Institute of Technology, "The Future of Nuclear Energy in a Carbon-Constrained World," 2018, http://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world.

[4] Senate Committee on Energy and Natural Resources, *Potential Non-Electric Applications of Civilian Nuclear Energy*, full committee hearing, November 4, 2021, https://www.energy.senate.gov/hearings/2021/11/full-committee-hearing-on-potential-non-electric-applications-of-civilian-nuclear-energy.

enactment" or a fusion reactor (which releases energy by forcing together the nuclei of light isotopes).[5] Examples of fission reactor improvements listed in the act include

- additional inherent safety features;
- lower waste yields;
- improved fuel and material performance;
- greater reliability;
- increased resistance to nuclear weapons proliferation;
- increased thermal efficiency;
- reduced consumption of cooling water and other environmental impacts;
- ability to integrate electricity generation and non-electric applications;
- operational flexibility to change output to match demand and complement intermittent renewable energy output or energy storage; and
- modular sizes to match electricity and other energy requirements.

The definition of advanced reactors encompasses a wide range of technologies, including next-generation water-cooled reactors (e.g., small modular LWRs and supercritical water-cooled reactors), non-water-cooled reactors (e.g., lead or sodium fast reactors, molten salt reactors, and high temperature gas reactors), and fusion reactors. Some advanced reactor concepts are relatively new, while others have been under consideration for decades and used in research, test, and prototype reactors in the United States and around the world. Reactors using any of these technologies that have electric generating capacity of 300 MW or below are classified as small modular reactors (SMRs) by the International Atomic Energy Agency (IAEA).[6] Proponents of SMRs contend that their smaller size would reduce the financing costs and allow for large-scale factory production. Some designs for improved versions of existing large LWRs could also be considered advanced reactors under this definition if they were not in operation on the date of enactment.

The Energy Act of 2020 authorized the Advanced Reactor Demonstration Program (ARDP) within the Department of Energy (DOE), allowing DOE to fund up to 50% of the costs of two commercial demonstration projects and 80% of the costs for possible future demonstration plants. An initial appropriation of $230 million was provided for the program by the Further Consolidated Appropriations Act, 2020 (P.L. 116-94). The Infrastructure Investment and Jobs Act (P.L. 117-58) appropriated $2.477 billion for the program through FY2025, in addition to annual appropriations. In the annual appropriations process, Congress provided $250 million for ARDP in FY2022 (P.L. 117-103), the same as in FY2021, and $85 million in the Consolidated Appropriations Act, 2023 (P.L. 117-328).

Awards for the first two demonstration plants under ARDP were announced on October 13, 2020.[7] One of the award recipients, TerraPower, is proposing to build its demonstration plant on

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[5] P.L. 116-260, Division Z, Section 2002, enacted December 27, 2020, amended the definition of advanced nuclear reactor in the Energy Policy Act of 2005 at 42 U.S.C. §16271(b)(1).

[6] International Atomic Energy Agency, "What Are Small Modular Reactors (SMRs)?," November 4, 2021, https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs.

[7] DOE Office of Nuclear Energy, "U.S. Department of Energy Announces $160 Million in First Awards under Advanced Reactor Demonstration Program," October 13, 2020, https://www.energy.gov/ne/articles/us-department-energy-announces-160-million-first-awards-under-advanced-reactor.

the site of a closing coal-fired power plant in Wyoming.[8] The other recipient, X-energy, plans to build its demonstration plant in Washington.[9]

The Nuclear Regulatory Commission (NRC) is currently reviewing a design certification application for an SMR plant designed by NuScale, to consist of up to a dozen 77 MWe reactors in a large pool of water.[10] In 2020, DOE, through a separate Office of Nuclear Energy program from ARDP, announced a cost-shared award of up to $1.4 billion for a six-unit NuScale demonstration plant to be built at Idaho National Laboratory (INL).[11]

DOE is also authorized under ARDP to provide up to 80% of the funding to develop advanced reactor concepts for possible future demonstrations. In 2020, DOE announced five awards for "risk reduction for future demonstration projects," with the goal of designing and developing advanced reactor technologies that could be licensed and deployed within 10-14 years.[12]

The Department of Defense (DOD) is funding a prototype mobile high-temperature gas-cooled microreactor to provide power for military bases and other defense needs. Under a program called Project Pele, DOD awarded a contract estimated at $300 million in June 2022 to BWX Technologies (BWXT) for the prototype, which is to begin testing at INL in 2024. Because the 1-5 MWe DOD prototype microreactor will not be a commercial power plant, it will not require an NRC license. Instead it is expected to be built and operated under DOE safety oversight with NRC participation.[13] DOE also awarded BWXT up to $85 million from the ARDP risk reduction program to develop a commercially viable transportable high-temperature microreactor.

The CHIPS Act of 2022 (P.L. 117-167, Division A, Section 10781) authorizes a DOE advanced nuclear reactor research, development, and demonstration grant program. In awarding the grants, DOE is to give priority to projects that would be located at closed or closing fossil fuel power plants and that "plan to support non-electric applications" of nuclear energy.

Planned or potential demonstration plants with committed federal funding or NRC licensing or pre-application interactions are shown in **Table 1**.

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[8] TerraPower, "TerraPower Selects Kemmerer, Wyoming as the Preferred Site for Advanced Reactor Demonstration Plant," November 16, 2021, https://www.terrapower.com/natrium-demo-kemmerer-wyoming.

[9] TRi Energy Partnership, "Frequently Asked Questions," https://www.energy-northwest.com/whoweare/news-and-info/Documents/TRi%20Energy%20Partnership%20-%20Frequently%20Asked%20Questions.pdf.

[10] NRC, "Application Review Schedule for the NuScale Design," September 20, 2022, https://www.nrc.gov/reactors/new-reactors/smr/nuscale/review-schedule.html. NuScale has applied to increase each module's electric generating capacity to 77 MW. See NuScale Power, "Technology Overview," https://www.nuscalepower.com/technology/technology-overview.

[11] DOE Office of Nuclear Energy, "DOE Approves Award for Carbon Free Power Project," October 16, 2020, https://www.energy.gov/ne/articles/doe-approves-award-carbon-free-power-project.

[12] DOE, "Energy Department's Advanced Reactor Demonstration Program Awards $30 Million in Initial Funding for Risk Reduction Projects," December 16, 2020, https://www.energy.gov/ne/articles/energy-departments-advanced-reactor-demonstration-program-awards-30-million-initial.

[13] Sonal Patel, "DOD Picks BWXT Design for 'Project Pele' Prototype Nuclear Microreactor," *Power*, June 9, 2022, https://www.powermag.com/dod-picks-bwxt-to-manufacture-project-pele-prototype-nuclear-microreactor.

Table 1. Planned and Potential U.S. Advanced Reactor Demonstration Plants

Reactor Designer	Technology	Reactor Power (Electric)	Plant Owner	DOE Funding	DOE Cost Share	Plant Location	NRC Licensing Status
Demonstrations with ARDP Funding							
Terra Power	Sodium-cooled fast reactor	345 MW	PacifiCorp	Up to $2.0 billion	50%	Kemmerer, WY	Pre-application activities
X-energy	High-temperature gas-cooled reactor	80 MW	Energy Northwest	Up to $1.2 billion	50%	Washington	Pre-application activities
Demonstrations with Other DOE Funding							
NuScale	Light water SMR	77 MW	Utah Associated Municipal Power Systems	Up to $1.4 billion	23%	INL	77 MW standard design application submitted 1/1/2023
Pre-Demonstrations with ARDP Funding							
Westinghouse	Heat pipe micro-reactor	5 MW	Westing-house	Up to $7 million	80%	Unspecified	Pre-application activities
BWX Technologies	Commercial high-temperature gas-cooled micro-reactor	17 MW	BWX Technologies	Up to $85 million	80%	Unspecified	None
Kairos	Fluoride-salt-cooled high-temperature test reactor	35 MW thermal	Kairos	Up to $303 million	48%	Oak Ridge, TN	Construction permit application submitted 9/29/2021
Holtec	Water-cooled SMR	160 MW	Holtec	Up to $116 million	79%	Unspecified	Pre-application activities
Terra Power	Molten chloride fast reactor test facilities	Unspeci-fied	TerraPower	Up to $90 million	80%	Everett, WA	Pre-application activities

Reactor Designer	Technology	Reactor Power (Electric)	Plant Owner	DOE Funding	DOE Cost Share	Plant Location	NRC Licensing Status
Prototype Funded by DOD							
BWX Technologies	Defense high-temperature gas-cooled micro-reactor	1-5 MW	DOD	About $300 million	Funded by DOD	INL	DOE safety oversight
Other Designs with NRC Interactions							
General Atomics	High-temperature gas-cooled fast reactor	50 MW	Unspecified	No demonstration funding	None	Unspecified	Pre-application activities
Terrestrial Energy	Molten salt reactor	392 MW	Unspecified	No demonstration funding	None	Unspecified	Pre-application activities
GE Hitachi	Water-cooled SMR	300 MW	Ontario Power Generation	No demonstration funding	None	Clarington, Ontario	Pre-application activities by NRC and Canadian Nuclear Safety Commission
Ultra Safe Nuclear Corporation	High-temperature gas-cooled micro-reactor	15 MW thermal	University of Illinois	No demonstration funding	None	University of Illinois at Urbana-Champaign	Pre-application activities

Sources: DOE, NRC, Government Accountability Office, company websites, news accounts.

Note: Demonstration projects with announced DOE or DOD funding or with licensing application or pre-application activities listed on the NRC website. INL = Idaho National Laboratory. The planned TerraPower demonstration near Kemmerer, WY, is at the site of closing coal plant.

The Energy Act of 2020 also included several other provisions to support the development and commercialization of advanced reactors. The act requires DOE to provide high-assay low-enriched uranium (HALEU)—uranium enriched in the fissile isotope U-235 between 5% and 20%—that would be required by many advanced reactor designs, including the two ARDP demonstrations. The act authorizes appropriations for major DOE nuclear energy programs, including advanced reactor research; demonstration of nuclear energy systems integrated with non-electricity applications, such as hydrogen production and industrial heat; and nuclear fuel cycle R&D.

Tax credits for advanced nuclear reactors and other new zero-carbon power plants were included in the law commonly referred to as the Inflation Reduction Act (IRA, P.L. 117-169). The owners of qualifying plants can receive a 10-year electricity production tax credit of up to 2.6 cents/kilowatt-hour (adjusted for inflation) or a 30% investment tax credit. IRA also included $700 million for DOE to develop supplies of HALEU.

The Nuclear Energy Innovation Capabilities Act of 2017 (NEICA, P.L. 115-248) required DOE to take several actions to support advanced reactor development, including establishment of the National Reactor Innovation Center to enable testing and demonstration of private-sector reactor concepts at DOE sites. The Nuclear Energy Innovation and Modernization Act (NEIMA, P.L. 115-439), signed January 14, 2019, required NRC to develop a regulatory framework that could be used for advanced nuclear technologies.

Advocates of nuclear power cite a variety of reasons in addition to concern about greenhouse gas emissions for preserving and expanding the U.S. nuclear industry. They contend that a robust domestic nuclear energy industry would contribute to such goals as energy security and diversification, electricity grid resilience and reliability, promotion of a domestic nuclear component manufacturing base and associated exports, clean air, and preservation and enhancement of geopolitical influence. The U.S. Navy uses nuclear energy to power submarines and aircraft carriers. Some observers have suggested that the Navy and other national security organizations benefit from maintaining a strong domestic nuclear energy industry, which provides a post-military career path for many naval reactor personnel, as well as expanding the base of qualified engineers and technicians, and strengthening the infrastructure for training and knowledge transfer.[14] Geopolitical arguments focus particularly on concerns that U.S. influence on the international nuclear weapons nonproliferation regime would diminish without a robust domestic nuclear power industry and technology exports.[15]

Not all observers are optimistic about the potential safety, affordability, proliferation resistance, and sustainability of advanced reactors.[16] Because many of these technologies are in the conceptual or design phases, the potential advantages of these systems are unproven.[17] Testing

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[14] Nuclear Energy Institute, "Navy Leaders Say Commercial Nuclear Industry Benefits National Security, Innovation," Electric Energy Online, October 5, 2018, https://electricenergyonline.com/social/fj1y/article/energy/article/_/0/724534/Navy-Leaders-Say-Commercial-Nuclear-Industry-Benefits-National-Security-Innovation.htm.

[15] Center for Strategic and International Studies, *Restoring U.S. Leadership in Nuclear Energy: A National Security Imperative*, June 2013, https://csis-website-prod.s3.amazonaws.com/s3fs-public/legacy_files/files/publication/130614_RestoringUSLeadershipNuclearEnergy_WEB.pdf.

[16] For example, a report by the Intergovernmental Panel on Climate Change (IPCC) states that nuclear energy, whether derived from existing or advanced technologies, poses a risk for accidents, lacks agreed-upon solutions for long-term waste storage, has negative downstream impacts from uranium mining, poses a constant threat of weapons proliferation, and has been associated by some studies with increased risk of childhood leukemia for populations living near nuclear plants. IPCC, "Global Warming of 1.5°C," 2018, Ch. 5, pp. 52, 57, https://www.ipcc.ch/sr15.

[17] Beginning in the 1950s, the U.S. government built experimental and, in some cases, commercial versions of reactors utilizing some of the same advanced reactor technologies discussed in this report. These demonstrations provided

and demonstration at a commercial scale, and possibly the operation of multiple plants, would be required to determine the validity of advocates' claims, particularly related to costs. Many environmental advocates contend that nuclear power would not be necessary to decarbonize world energy supplies, and that public policy should instead focus on renewable energy and energy efficiency.[18]

The U.S. advanced nuclear industry has expanded in recent years to encompass an array of developers, suppliers, and supporting institutions. By one count, at least 25 U.S. companies were developing advanced nuclear reactor technologies as of July 2021.[19] Some have projected that the first U.S. advanced reactor could be providing electricity to the grid by the late 2020s. For example, the advanced reactor company NuScale has predicted, "The first NuScale Power Module will begin generating power in 2029."[20]

This report discusses the history of advanced reactor technologies, briefly describes major categories of advanced reactors, provides an overview of federal programs on advanced nuclear technology, and discusses current issues and legislation.

Advanced Reactor Technologies

Advanced or unconventional reactor designs seek to use combinations of new and existing technologies and materials to improve upon earlier generations of nuclear reactors in one or more of the following areas: cost, safety, security, waste management, and versatility. To achieve these improvements, advanced designs may incorporate one or more of the following characteristics: inherent or passive safety features, simplified or modular designs, enhanced load-following capabilities, high-temperature stability, fast neutron spectrums, and "closed" fuel cycles (see text box on Fast Reactors). Advanced reactor technologies are often referred to as "Generation IV" nuclear reactors, with existing commercial reactors constituting "Generation III" or, for the most recently constructed reactors, "Generation III+."

Advanced reactor designs may be grouped into three primary categories:

- *Advanced water-cooled reactors*, which provide evolutionary improvements to proven water-based fission technologies through innovations such as simplified design, smaller size, or enhanced efficiency;

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historical data and experience for the development of the current wave of advanced reactor designs. While federal funding for nuclear power research was largely consolidated to relatively few sites (e.g., Oak Ridge and Idaho National Laboratories), federal spending for environmental remediation, decommissioning and decontamination (D&D), and long-term stewardship continues at former nuclear research sites, such as the Energy Technology Engineering Center at the Santa Susana Field Laboratory in California and the Fort St. Vrain Site in Colorado. Part of the costs for carrying out nuclear power research is the D&D and remediation costs for the contaminated facilities resulting from that research.

[18] Heinrich Boll Stiftung, "Energy Transitions Around the World," April 12, 2019, https://us.boell.org/energy-transition-around-world. For a discussion of U.S. electricity options, see CRS Insight IN11065, *An Electric Grid Based on 100% Renewable Energy?*, by Richard J. Campbell.

[19] DOE Gateway for Accelerated Innovation in Nuclear (GAIN), *Advanced Nuclear Directory: Developers, Suppliers and National Laboratories*, July 1, 2021, https://gain.inl.gov/SiteAssets/Funding%20Opportunities/GAINAdvancedNuclearDirectory-Seventh%20Edition_07.01.2021-R1.pdf.

[20] NuScale, "Carbon Free Power Project," company web page, viewed November 12, 2021, https://www.nuscalepower.com/projects/carbon-free-power-project.

- *Non-water-cooled reactors*, which are fission reactors that use materials such as liquid metals (e.g., sodium and lead), gases (e.g., helium and carbon dioxide), or molten salts as coolants instead of water; and
- *Fusion reactors*, which seek to generate energy by joining small atomic nuclei, as opposed to fission reactors, which generate energy by splitting large atomic nuclei.

Fission reactors can also be classified as fast neutron reactors and thermal neutron reactors, as described in the box below. They also may vary in their use of fuels, such as by irradiating thorium to produce the fissile isotope uranium-233.

Small modular reactors, with electric generating capacity of no more than 300 MW,[21] can be in any of those categories. According to DOE, SMRs "employ modular construction techniques, ship major components from factory fabrication locations to the plant site by rail or truck, and include designs that simplify plant site activities required for plant assembly."[22] Microreactors are relatively small-capacity SMRs, defined by DOE as producing 1-20 megawatts of thermal energy (MWt), which could be used directly as heat for industrial processes or to generate electricity. In theory, microreactors could be transported by truck and installed at a remote location or military base, according to DOE.[23]

Many widely differing advanced reactor designs are conceivable, with major variables including the type of coolant, fuel, size, and other examples shown in **Table 2**. An advanced reactor design could use one or more of the features from each column. For example, the planned X-energy demonstration plant in Washington would have these characteristics, among others: helium coolant, thermal neutrons moderated by graphite, HALEU fuel in TRISO pebbles, high burnup, and the size of an SMR.[24]

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[21] Compared with typically 1,000 MW or more for existing conventional LWRs.

[22] U.S. Department of Energy, "Advanced Small Modular Reactors (SMRs)," https://www.energy.gov/ne/nuclear-reactor-technologies/small-modular-nuclear-reactors.

[23] According to DOE, the setup time for a transportable microreactor would range from weeks to months. DOE, "What Is a Nuclear Microreactor?," February 26, 2021, https://www.energy.gov/ne/articles/what-nuclear-microreactor. According to Defense News, the Project Pele microreactor "must be designed to operate within three days of delivery and be safely removed in as few as seven days if needed." Aaron Mehta, Defense News, Portable Nuclear Reactor Project Moves Forward at Pentagon," March 23, 2021, https://www.defensenews.com/smr/energy-and-environment/2021/03/23/portable-nuclear-reactor-project-moves-forward-at-pentagon.

[24] X-energy, "X-energy's Reactor: Xe-100," https://x-energy.com/reactors/xe-100.

Table 2. Major Design Variables for Advanced Nuclear Technologies

Fission reactor designs could use one or more features from each column

Coolant	Neutron Energy	Moderator	Fuel Material	Fuel Form	Fuel Cycle	Reactor Size
Light water	Thermal	Light water	LEU	Oxide, metal clad	Open	Microreactor
Heavy water	Fast	Heavy water	HALEU	TRISO pebble bed	High burnup	SMR
Liquid metal		Graphite	Plutonium	Other TRISO	Closed	Conventional
Molten salt		None	Thorium	Molten salt		
Helium				Metal		
CO_2				Carbide		
				Ceramic matrix		

Source: National Academies of Sciences, Engineering, and Medicine, DOE, IAEA, World Nuclear Association.

Notes: Light water is ordinary water; heavy water has an extra neutron in the hydrogen component. Examples of liquid metal coolants are sodium and lead. A reactor with no moderator is a fast reactor. LEU=low enriched uranium; HALEU=high-assay low enriched uranium (5%-10% enriched in U-235). Thorium in fuel must first be transmuted to uranium-233 to be fissile. In an open fuel cycle, spent nuclear fuel is intended for permanent disposal. In the high-burnup cycle, fuel produces power for a long period before permanent disposal but is not reprocessed. In a closed fuel cycle, spent fuel is reprocessed to separate uranium, plutonium, and other materials that can be used in new fuel.

Advanced reactor concepts may be characterized along a continuum of technological maturity. Light water-cooled SMRs, high-temperature gas-cooled reactors, and sodium-cooled fast reactors are considered to be among the most mature of the unconventional reactor technologies.[25] Molten salt reactors, gas-cooled fast reactors, and fusion reactors are generally considered to be further from commercialization.

Expert estimates of timeframes for commercialization of these technologies range widely, from the late 2020s or early 2030s for the first small modular LWRs to mid-century or later for some advanced reactor concepts, such as molten salt reactors and gas-cooled fast reactors. Companies developing similar reactor technologies may be at different stages of design and manufacturing readiness. Planned demonstrations of molten salt reactors, for example, range from the late 2020s to the 2040s.[26]

Fast Reactors

A large proportion of advanced reactor concepts are fast neutron reactors (FNRs or fast reactors), which have fundamental differences from conventional LWRs. Some of these unique characteristics could provide advantages over conventional nuclear technology, although there are potential drawbacks as well.

Thermal nuclear reactors—the majority of those currently in operation worldwide—rely on a "moderator" to slow the movement of neutrons in the nuclear chain reaction. Slower-moving neutrons, or *thermal neutrons*, have a relatively high likelihood of producing a new fission reaction in the fissile uranium isotope U-235, which makes up about 0.7% of natural uranium. The remaining 99.3% is non-fissile U-238. Nuclear fuel is usually "enriched" to increase the percentage of U-235. Because thermal neutrons readily induce fission, thermal reactors can be fueled by uranium with low levels of enrichment or in some designs by natural (unenriched) uranium.

LWRs are thermal reactors that use ordinary (light) water as a moderator and coolant. Thermal neutrons in LWRs can sustain a nuclear chain reaction with low-enriched uranium (LEU) of between 3% and 5% U-235.

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[25] Massachusetts Institute of Technology, "The Future of Nuclear Energy in a Carbon-Constrained World," p. xxii. Gen IV International Forum, "Technology Systems," November 15, 2018, https://www.gen-4.org/gif/jcms/c_40486/technology-systems.

[26] World Nuclear Association, "Molten Salt Reactors," May 2021, http://www.world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx.

Reactors that are cooled and moderated by heavy water (water whose hydrogen component includes a neutron) can operate on natural uranium, because heavy water absorbs fewer neutrons than light water, freeing additional neutrons to sustain the chain reaction. Reactors using graphite as a moderator can also operate with LEU.

Fast reactors, in contrast, do not use a moderator to slow neutron movement. Fast neutrons have a lower likelihood of inducing fission than thermal neutrons, so to sustain a chain reaction, the fuel must have relatively high concentrations of U-235 or other fissile isotopes. For fast reactor uranium fuel, enrichment in U-235 must at least be near the upper LEU limit of just below 20%. Current reactor designs avoid uranium enrichment of 20% and above, because it is classified as high-enriched uranium (HEU)—a potential weapons material that is subject to additional nonproliferation safeguards. LEU enriched above 5% (the maximum level used by LWRs) is called high-assay low-enriched uranium (HALEU). Production of HALEU for demonstrations of fast reactors and other advanced reactor designs is a DOE priority, as noted above. FNRs also may use plutonium as a primary fuel. Plutonium typically has a high percentage of fissile isotopes (primarily Pu-239) and at high neutron energies produces more neutrons per fission event than uranium.

Fast reactor coolants must have no neutron moderating effect. Possible coolants include molten salts, liquid metals such as sodium, lead, and lead-bismuth, and gases such as helium or carbon dioxide. To date, most experimental FNRs that have been built used sodium as a coolant.

Liquid metal coolants transfer heat from nuclear fuel more efficiently than water and operate at low pressure (because they remain liquid at high temperatures). The physics of fast reactors dampens the nuclear chain reaction when the temperature rises, preventing the fuel from producing more heat than the coolant can safely remove. Proponents of fast reactors contend that those characteristics would greatly reduce the likelihood of accidental fuel damage and any resulting release of radioactive material.

Non-fissile U-238 can be transmuted to fissile Pu-239 through neutron capture, which occurs at a higher rate in fast reactors than in thermal reactors. If a reactor produces more fissile material (such as Pu-239) than it consumes (such as U-235), it is considered to be a "breeder." A reactor that produces less than it consumes is a "burner" or "converter." Most breeder reactors are fast reactors because of their neutron capture efficiency, but fast reactors can be configured as either breeders or burners.

Fast neutrons are also more effective than thermal reactors at fissioning plutonium and actinides, which are converted to relatively short-lived fission products such as cesium 137 and strontium 90. This effectiveness at fissioning a wide variety of isotopes allows fast reactors to operate well with fuel made from the plutonium and uranium separated during the reprocessing (or "recycling") of spent nuclear fuel. Unlike thermal reactors, fast reactors could theoretically re-use their spent fuel indefinitely—disposing only of the highly radioactive fission products. Such a "closed" fuel cycle would be in contrast to the current "open" or "once through" fuel cycle, in which spent fuel would be permanently disposed of in a deep repository without reprocessing.

In theory, the closed fuel cycle (with the re-use of uranium and plutonium) could extend fuel supplies and potentially reduce the duration of the radioactive hazard of nuclear waste from more than a million years to less than 1,000 years. If breeder reactors were employed to maximize the conversion of U-238 to plutonium, the amount of energy released from a given quantity of natural uranium could be increased by a factor of 60.[27]

The closed fuel cycle has major drawbacks that would need to be addressed. One is that the separation of plutonium from spent fuel is widely perceived as a nuclear weapons proliferation risk, because plutonium is a key weapons material. As a result, U.S. policy has been based primarily on the once-through fuel cycle since the mid-1970s. Another drawback is that reprocessing spent fuel to separate uranium, plutonium, and waste products can require large, costly facilities that generate large volumes of low- and high-level waste that, while shorter-lived than spent fuel, still must be treated and disposed of. Potential waste generation by spent fuel reprocessing has been a continuing issue in Congress, which requested a report on the topic from the National Academies of Sciences, Engineering, and Medicine (NASEM) that was released in December 2022.[28]

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[27] Lisa Zyga, "Why Nuclear Power Will Never Supply the World's Energy Needs," *PhysOrg.com*, May 11, 2011, https://phys.org/news/2011-05-nuclear-power-world-energy.html.

[28] National Academies of Sciences, Engineering, and Medicine, *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*, December 2022, https://nap.nationalacademies.org/catalog/26500/merits-and-viability-of-different-nuclear-fuel-cycles-and-technology-options-and-the-waste-aspects-of-advanced-nuclear-reactors. The NASEM study was mandated by the explanatory statements for P.L. 116-94 and P.L. 116-260.

FNRs are not a new concept. The first FNR was built in 1946 in the United States,[29] and the world's first reactor to generate electricity was a U.S.-built fast reactor.[30] Since the 1940s, there have been more than 20 fast reactors built—including 10 in the United States—mostly for either experimental or demonstration purposes.[31] Five fast reactors are currently in operation globally.[32] Despite that experience, the commercial viability of FNRs, as with other types of advanced reactors, remains uncertain.

Advanced Water-Cooled Reactors

Small Modular Light Water Reactors

Small modular reactors are defined by DOE and IAEA as reactors with an electric generating capacity of up to 300 MW, as opposed to the average capacity of existing U.S. commercial reactors of about 1,000 MW. Light water reactor SMR designs are based on existing commercial LWR technology but are generally small enough to allow all major reactor components to be placed in a single pressure vessel. For example, in a pressurized water reactor, such as the NuScale design described below, cooling water is kept under pressure so that it will not boil and circulates through heat exchangers (steam generators) in the reactor pressure vessel. The steam generators transfer heat to a secondary loop of cooling water that is allowed to boil to make steam for power generation.

The reactor vessel and its components are designed to be assembled in a factory and transported to the plant site for installation, potentially reducing construction time and costs from those of large LWRs. If large numbers of identical SMRs were ordered, mass production could further reduce manufacturing costs and construction schedules, according to proponents of the technology.

Shortening the timeframe before a new reactor begins producing revenue could reduce interest payments and shorten payback periods. In addition, each SMR would require a fraction of the capital investment of a large conventional nuclear unit, further reducing the financial risk to plant owners. Some observers have suggested that the smaller size of SMRs would reduce the economies of scale available to larger reactors, potentially negating any SMR cost advantages.[33]

DOE has awarded up to $1.4 billion for a light water SMR demonstration plant at INL that would consist of six 77 MWe reactor modules designed by NuScale Power. The plant, called the Carbon Free Power Project, would be owned and operated by the Utah Associated Municipal Power

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[29] Clementine, a 25 kWt (kilowatts of thermal energy) mercury-cooled experimental fast reactor, was built at Los Alamos to produce plutonium for nuclear weapons.

[30] Experimental Breeder Reactor I (EBR-I), a 1.2 MWt (megawatts of thermal energy) sodium-cooled experimental fast reactor, was built in 1951 in Idaho and produced both plutonium and electrical power. For a history of the U.S. fast breeder reactor program, see Thomas B. Cochran, et al., *Fast Breeder Reactor Programs, History and Status*, International Panel on Fissile Materials, February 2010, https://fissilematerials.org/library/rr08.pdf.

[31] A majority of these were breeder reactors, intended to produce more nuclear fuel than they consumed. The 10 U.S. FNRs were Clementine, S1G, S2G, LAMPRE-I, EBR-I, EBR-II, Fermi I, SEFOR, the Fast Source Reactor, and the Fast Flux Test Facility.

[32] Three are in Russia, one in China, and one in India. All are sodium-cooled (see "Sodium-Cooled Fast Reactor"). Japan has two FNRs that were in operation within the past decade, but are currently inactive. Several others are in various stages of development or construction. (World Nuclear Association, "Fast Neutron Reactors," August 2021, http://www.world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx.)

[33] Ahmed Abdulla et al., "Expert Assessments of the Cost of Light Wter Small Modular Reactors," *PNAS*, vol. 110, no. 24, May 28, 2013, https://www.pnas.org/doi/10.1073/pnas.1300195110.

Systems (UAMPS) and start generating power by 2029.[34] The plant's SMR modules would be co-located in a central pool of water, which serves as a heat sink and passive cooling system. The DOE funding is estimated to cover about 23% of the cost of building the demonstration plant.[35] As with other SMR concepts, the major components of the NuScale plant are designed to be factory-fabricated and shipped to the plant site for installation.[36]

A light water SMR design by GE Hitachi, BWRX-300, is proposed for demonstration by Ontario Power Company at its Darlington Plant in Clarington, Ontario. The BWRX-300 is a 300 MW version of the company's large boiling water reactors, in which cooling water in the reactor vessel is directly allowed to boil (rather than going through a steam generator) to make steam for power generation.[37] The Tennessee Valley Authority is considering construction of a BWRX-300 plant at its Clinch River site in Tennessee.[38] The design is currently undergoing pre-application reviews at NRC and the Canadian Nuclear Safety Commission.[39]

Holtec International has received a DOE ARDP pre-demonstration grant for its SMR-160 design (a 160 MW water-cooled SMR). The design is currently undergoing NRC pre-application review and has completed Phase 1 of the Canadian Nuclear Safety Agency Vendor Design Review. Holtec has announced that it might build the first SMR-160 module at the site of the closed Oyster Creek nuclear power plant, which is owned and being decommissioned by a Holtec subsidiary.[40]

Supercritical Water-Cooled Reactor

The supercritical water-cooled reactor (SCWR) is a high-temperature variant of existing LWR technologies. SCWRs would use supercritical water—water which has been brought to a temperature and pressure at which the liquid and vapor states are indistinguishable—to improve plant efficiency (which may approach 44% in SCWRs, compared with about 33% for current reactors). As in a conventional boiling water reactor (BWR), liquid water would pass upward

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[34] UAMPS, "Carbon Free Power Project," https://www.uamps.com/Carbon-Free.

[35] Government Accountability Office, *Nuclear Energy Projects: DOE Should Institutionalize Oversight Plans for Demonstrations of New Reactor Types*, GAO-22-105394, September 2022, p. 9, https://www.gao.gov/assets/gao-22-105394.pdf. The report notes that, including previous funding, DOE could provide up to $1.9 billion for the demonstration plant.

[36] This does not include civil structures and major site preparation work, which have been identified by an MIT study as the primary contributors to construction costs in conventional nuclear plants built in the United States. (See section on "Cost.")

[37] GE Hitachi, "The BWRX-300 Small Modular Reactor," https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview/bwrx-300.

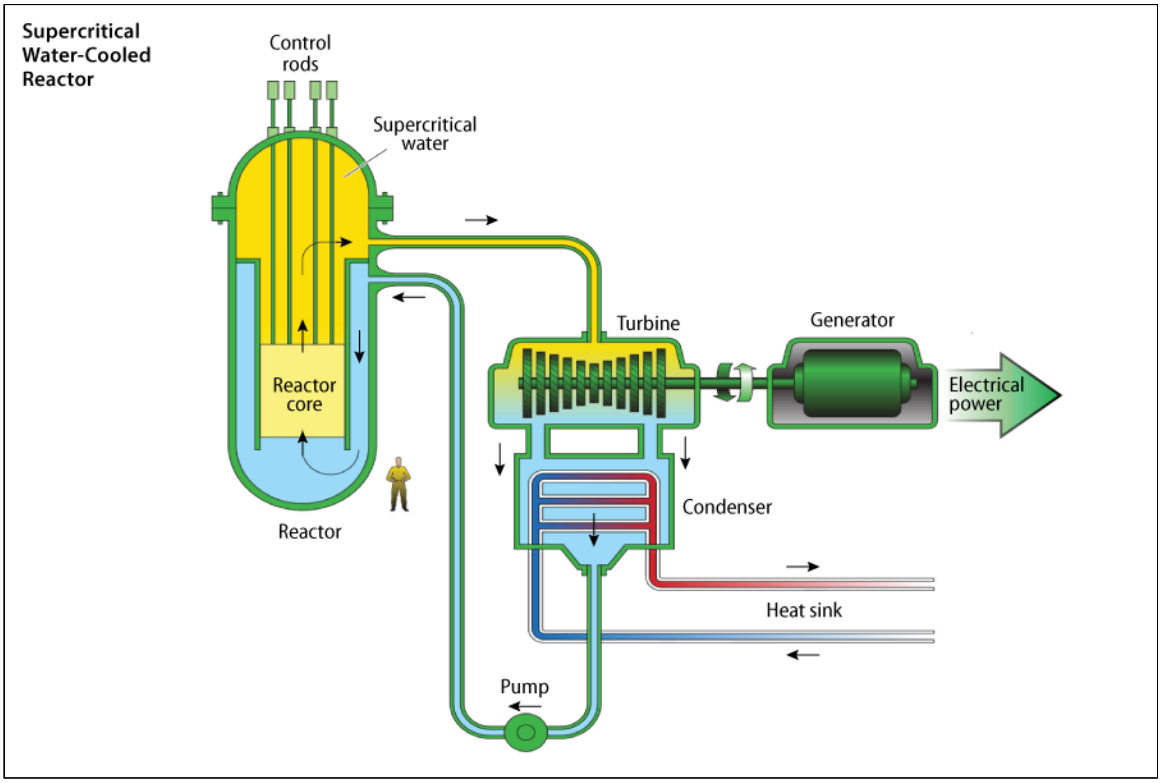
[38] Tennessee Valley Authority, "TVA Board Authorizes New Nuclear Program to Explore Innovative Technology," February 10, 2022, https://www.tva.com/newsroom/press-releases/tva-board-authorizes-new-nuclear-program-to-explore-innovative-technology.

[39] NRC, "GEH BWRX-300," September 21, 2022, https://www.nrc.gov/reactors/new-reactors/smr/licensing-activities/pre-application-activities/bwrx-300.html; Canadian Nuclear Safety Commission, "Charter: Collaboration on GE Hitachi's BWRX-300 Design," September 2022, https://nuclearsafety.gc.ca/eng/resources/international-cooperation/international-agreements/cnsc-usnrc-smr-advanced-reactor-charter.cfm.

[40] Holtec International, "Overview," https://holtecinternational.com/products-and-services/smr/technology/overview; NRC, "SMR-160," October 5, 2022, https://www.nrc.gov/reactors/new-reactors/smr/licensing-activities/pre-application-activities/holtec.html; DOE, "5 Advanced Reactor Designs to Watch in 2030," March 17, 2021, https://www.energy.gov/ne/articles/5-advanced-reactor-designs-watch-2030; Holtec International, "Holtec and Hyundai Engineering and Construction Completed Workshop on SMR-160 Balance of Plant Design," February 22, 2022, https://holtecinternational.com/2022/02/22/holtec-and-hyundai-engineering-and-construction-completed-workshop-on-smr-160-balance-of-plant-design.

through the reactor core and turn directly to steam, which would drive a turbine-generator (**Figure 1**). The superheated conditions would eliminate the need in current BWRs for reactor coolant pumps and steam separators and dryers.[41] Supercritical water has already been used to boost plant efficiency in some advanced coal- and gas-fired power plants. SCWRs could be designed to operate in either the fast or thermal neutron spectrums, and to use either light or heavy water as the coolant and/or moderator. Organizations in Canada, China, the European Union, Japan, and Russia are developing SCWRs.[42]

Figure 1. Supercritical Water-Cooled Reactor



Source: U.S. Department of Energy, modified by CRS.

Non-Water-Cooled Reactors

High Temperature Gas Reactors

High temperature gas reactors (HTGRs), including very high temperature gas reactors (VHTRs), are helium-cooled, graphite-moderated thermal reactors. As their names imply, they would operate at higher coolant outlet temperatures than most existing reactors—700°-1,000°C compared with 330°C for existing LWRs.[43] This higher temperature threshold allows for the

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[41] Gen IV International Forum, "Supercritical-Water-Cooled Reactor (SCWR)," viewed November 9, 2022, https://www.gen-4.org/gif/jcms/c_9360/scwr.

[42] Ibid.

[43] Some sources differentiate between HTGRs and VHTRs based on their outlet temperatures, considering any reactor that achieves a range of 900°-1,000°C to be a VHTR, with the rest being considered HTGRs. Others use these terms interchangeably. The precise outlet temperature of a given reactor determines the types of process heat services the

provision of heat for industrial processes, such as the cogeneration of electricity and hydrogen, and high-temperature processes in the iron, oil, and chemical industries. While previous R&D programs focused on achieving very high outlet temperatures, more recently the focus has shifted to reactor designs with more modest outlet temperatures (700°-850°C), based on the assessment that lower temperature reactors may be more commercially viable in the short term and involve fewer technical risks.[44]

A key feature of these reactors is their fuel, called TRISO fuel, which is composed of poppy seed-sized fuel particles that have been encased in silicon carbide and other highly heat-resistant coatings.[45] Coupled with the high heat capacity of the graphite moderator, the reactor and its fuel are designed to withstand the maximum core heat attainable if core cooling is lost during an accident. Therefore, according to HTGR proponents, the loss of active cooling systems would not result in a core meltdown and radioactive releases to the environment.

Reactors using TRISO fuel are being designed without containment structures to retain radioactive releases, because the fuel coatings are considered to be "functional containments" that serve the same purpose. According to X-energy, "With triple-coated layers, each particle is its own containment system and retains fission products under all reactor conditions and temperatures.[46]

There are two primary design variants: In one, the TRISO fuel particles are formed into cylindrical fuel elements and placed into prismatic graphite blocks (**Figure 2**). In the other variant, the TRISO fuel particles are embedded in billiard ball-sized graphite spheres, or "pebbles," that are loaded into the core to form a "pebble bed." The spheres are steadily removed from the bottom of the reactor, tested for their level of burnup, and returned to the top of the reactor if they are still viable as fuel and replaced if not. In both variants, the graphite serves as a neutron moderator. Many HTGRs have been designed as SMRs.

HTGRs are among the most technologically mature of the advanced reactor concepts. Since the 1960s a number of experimental and commercial HTGRs have been built in multiple countries, including the United States, United Kingdom, Japan, Germany, and China.[47] A 210 MW, two-reactor pebble bed HTGR plant in China was connected to the electric grid on December 20, 2021.[48] A U.S. HTGR demonstration called the Next Generation Nuclear Plant (NGNP) was authorized by the Energy Policy Act of 2005 (P.L. 109-58), although the project was halted in 2011.

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reactor can provide.

[44] Gen IV International Forum, "Very-High-Temperature Reactor (VHTR)," viewed November 9, 2022, https://www.gen-4.org/gif/jcms/c_42153/very-high-temperature-reactor-vhtr.

[45] TRISO fuel is short for tristructural isotropic fuel, in which a kernel of uranium is surrounded by layers of porous carbide, silicon carbide, and pyrolitic carbon. TRISO fuel can be formed into cylindrical fuel pellets for insertion into graphite fuel blocks in a prismatic reactor, or into billiard-ball-sized spheres for a pebble bed reactor. For a diagram, see Idaho National Laboratory, "Fuel Development and Qualification," https://art.inl.gov/trisofuels/SitePages/Home.aspx.

[46] For example, see X-energy, *Xe-100 Principal Design Criteria Licensing Topical Report*, Table 5, July 8, 2022; and X-energy, "US Department of Energy's Advanced Reactor Demonstraton Program," https://x-energy.com/ardp.

[47] Historically, two commercial HTGRs have operated in the United States: The Peach Bottom 1 commercial reactor operated from 1967 to 1988 in Pennsylvania, and the Fort St. Vrain commercial reactor operated from 1979 to 1989 in Colorado. Some gas reactors have used carbon dioxide as a coolant.

[48] World Nuclear News, "Demonstration HTR-PM Connected to Grid," December 21, 2021, https://www.world-nuclear-news.org/Articles/Demonstration-HTR-PM-connected-to-grid.

In 2015, DOE awarded X-energy $40 million over six years to develop a modular pebble bed HTGR design.[49] Under ARDP, the company received a 50% cost-shared award of $1.2 billion to build a commercial scale demonstration plant in Washington.[50] The project includes a TRISO fuel fabrication plant in Oak Ridge, TN.[51]

HTGR microreactor technology is being developed by BWX Technologies (BWXT). In June 2022, DOD awarded BWXT an approximately $300 million contract to build a TRISO-fueled HTGR microreactor at INL. The prototype is to be transportable in standard shipping containers and be moveable to different locations. It is to generate 1-5 MWe to power forward operating bases and other military facilities. In addition to hosting the prototype reactor, DOE is to provide safety oversight, fuel, technical assistance, and other support, fully funded by DOD.[52]

In a separate project, DOE awarded an 80% cost-shared contract to BWXT in December 2020 under ARDP to reduce the technological risk of potential future demonstrations. Under the award, BWXT is to develop the technology for a transportable 17 MWe HTGR microreactor for civilian applications, which would be licensed by NRC. DOE is providing funding of up to $89 million over seven years, but the award does not include demonstration funding.[53]

Ultra Safe Nuclear Corporation is working with the University of Illinois Urbana-Champaign in conducting NRC pre-application activities for an HTGR test microreactor, which would have 15 MW of thermal power.[54] Ultra Safe opened a pilot facility in Oak Ridge, TN, to produce TRISO fuel for the reactor in August 2022.[55]

Another example of a U.S. company developing HTGRs is HolosGen, which is developing a transportable reactor with generating capacity ranging from 3 MWe to 81 MWe. It is based on aircraft nuclear propulsion systems studied by the U.S. Atomic Energy Commission (a predecessor of DOE) in the 1950s.[56]

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[49] DOE Office of Nuclear Energy, "X-energy Completes $40 Million Project to Further Develop High-Temperature Gas Reactor," August 23, 2022, https://www.energy.gov/ne/articles/x-energy-completes-40-million-project-further-develop-high-temperature-gas-reactor.

[50] Government Accountability Office, *Nuclear Energy Projects: DOE Should Institutionalize Oversight Plans for Demonstrations of New Reactor Types*, GAO-22-105394, September 2022, p. 9, https://www.gao.gov/assets/gao-22-105394.pdf. The report notes that DOE provided an additional $19 million for design and licensing of a TRISO fuel fabrication facility through FY2022.

[51] X-energy, "TRISO-X Breaks Ground on North America's First Commercial Advanced Nuclear Fuel Facility," October 13, 2022, https://x-energy.com/media/news-releases/triso-x-breaks-ground-on-north-americas-first-commercial-advanced-nuclear-fuel-facility.

[52] World Nuclear News, "BWX Technologies Selected to Build Project Pele Microreactor," June 9, 2022, https://www.world-nuclear-news.org/Articles/BWX-Technologies-selected-to-build-Project-Pele-mi; and email from DOE Office of Congressional Affairs, November 1, 2022.

[53] DOE Office of Nuclear Energy, "Energy Department's Advanced Reactor Demonstration Program Awards $30 Million in Initial Funding for Risk Reduction Projects," December 16, 2020, https://www.energy.gov/ne/articles/energy-departments-advanced-reactor-demonstration-program-awards-30-million-initial; and email from DOE Office of Congressional Affairs, November 1, 2022.

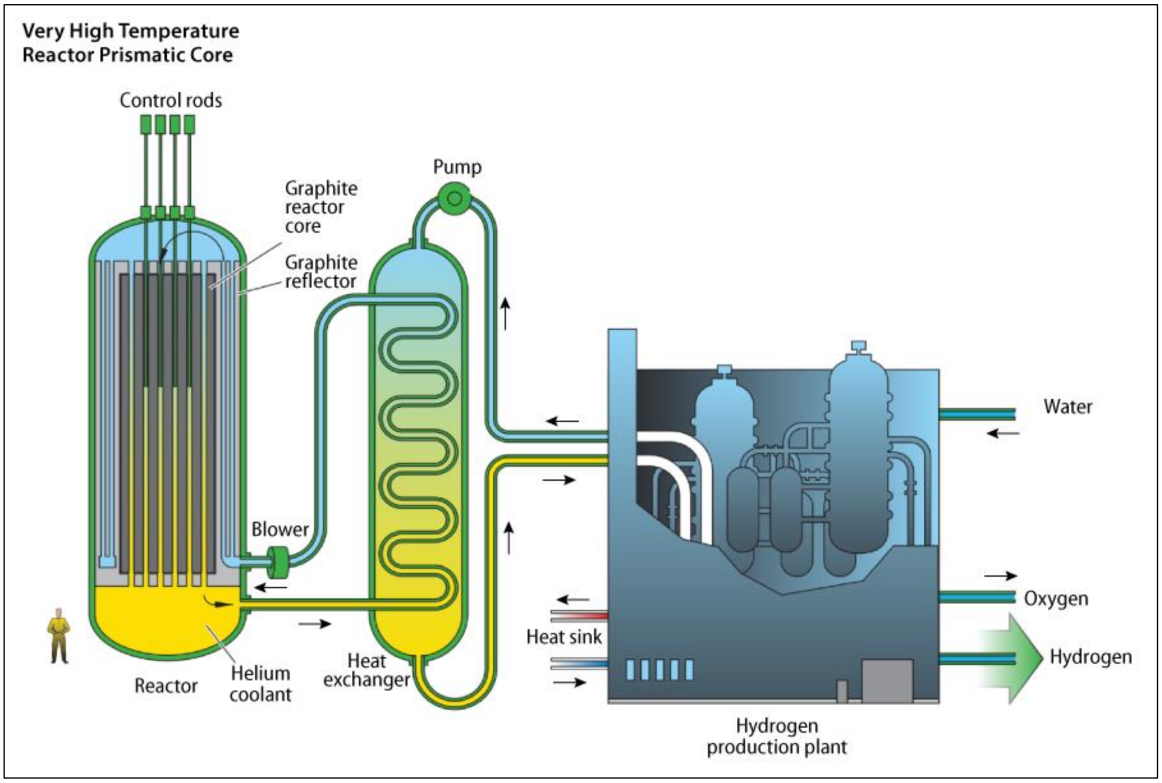
[54] NRC, "University of Illinois at Urbana-Champaign," October 3, 2022, https://www.nrc.gov/reactors/new-reactors/advanced/licensing-activities/pre-application-activities/university-of-illinois-at-urbana-champaign.html.

[55] Ultra Safe Nuclear Corporation, "Ultra Safe Nuclear Corporation Announces the Opening of Pilot Fuel Manufacturing Facility in Oak Ridge, Tenn.," August 19, 2022, https://www.usnc.com/ultra-safe-nuclear-corporation-announces-the-opening-of-pilot-fuel-manufacturing-facility-in-oak-ridge-tenn.

[56] HolosGen, http://www.holosgen.com/.

Figure 2. Very High Temperature Reactor

Prismatic core



Source: U.S. Department of Energy, modified by CRS.

Gas-Cooled Fast Reactor

Gas-cooled fast reactors (GFRs) would be high-temperature fast reactors using helium as a primary coolant (**Figure 3**). The primary difference between the HTGR (see above) and the GFR is the neutron spectrum: HTGRs operate in the thermal spectrum, while GFRs operate in the fast spectrum. Therefore, the GFRs would not require the graphite moderator of HTGRs to slow the neutrons. The GFR could use a closed U-Pu fuel cycle in which the plutonium and uranium could be recycled from the spent fuel to provide a greatly expanded fuel source if configured as a breeder (with the potential nonproliferation and waste drawbacks noted in the Fast Reactors box above). GFRs would have operating temperatures similar to those of HTGRs—850°C compared to 330°C for existing LWRs—making them suitable for providing process heat for industrial purposes, in addition to producing electric power. GFRs are considered experimental technology, because none have been built to date.[57]

General Atomics received a $24.8 milliion cost-shared DOE award in January 2021 under its Advanced Reactor Concepts program to develop a conceptual design for a 50 MW gas-cooled fast reactor in collaboration with the French company Framatome, and is currently engaged in

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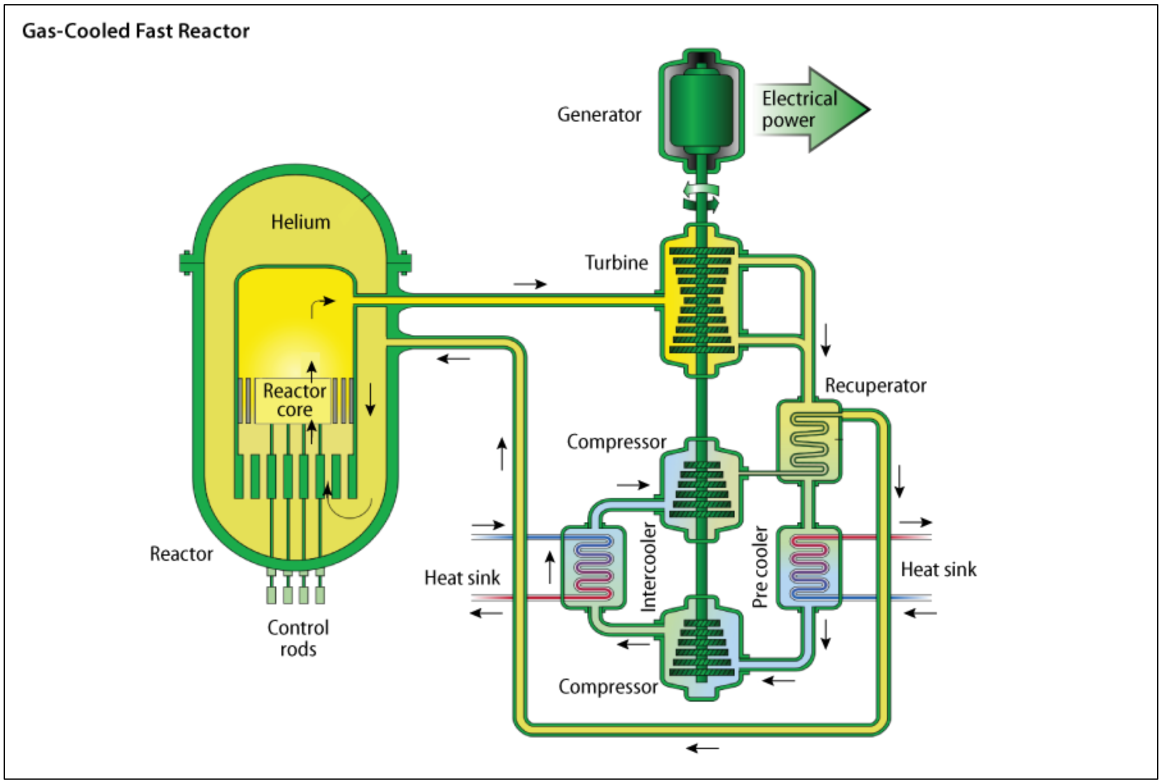
[57] NASEM, *Merits and Viability of Different Nuclear Fuel Cycles of Advanced Nuclear Reactors*, p. 64.

NRC pre-application activities.[58] A consortium of European countries, including the Czech Republic, Hungary, Poland, and Slovakia, is jointly developing a conceptual GFR design.[59]

Figure 3. Gas-Cooled Fast Reactor



Source: U.S. Department of Energy, modified by CRS.

Sodium-Cooled Fast Reactor

Along with HTGRs, sodium-cooled fast reactors (SFRs) are among the most technologically mature of the unconventional nuclear concepts. SFRs use fast reactor technology with liquid sodium metal as the primary coolant. The use of a liquid metal as the coolant allows the primary coolant circuit to operate under lower, near-atmospheric pressure conditions. In addition, even in an emergency without backup electricity, the high heat-transfer properties of liquid sodium (100 times greater than water) would allow for passive cooling through natural circulation.[60] The SFR coolant outlet would reach a temperature of 500°-550°C. This lower temperature (compared with 850°C for the GFR) would allow for the use of materials that have been developed and proven in

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[58] General Atomics, "General Atomics Selected for the Department of Energy's Advanced Reactor Concepts-20 Program," January 13, 2021, https://www.ga.com/general-atomics-selected-for-the-department-of-energys-advanced-reactor-concepts-20-program; and NRC, "Fast Modular Reactor," November 8, 2022, https://www.nrc.gov/reactors/new-reactors/advanced/licensing-activities/pre-application-activities/general-atomics.

[59] V4G4 Centre of Excellence, "Allegro Project Overview," February 2021, https://snetp.eu/wp-content/uploads/2021/02/Presentation_Branislav-Hatala-Petr-Vacha.pdf.

[60] U.S. Department of Energy, Office of Nuclear Energy, "Sodium-cooled Fast Reactor (SFR) Technology and Safety Overview," February 18, 2015, https://gain.inl.gov/SiteAssets/Fast%20Reactors/SFR-NRCTechnologyandSafetyOverview18Feb15.pdf.

prior fast reactors. SFRs come in two main design variants: loop-type and pool-type designs (see **Figure 4**). In the pool-type SFR, the reactor core and primary heat exchanger are immersed in a single pool of liquid metal, while the loop-type houses the primary heat exchanger in a separate vessel. SFR technologies are conducive to modularization.

A disadvantage of using sodium as a coolant is that it reacts violently with both air and water. As a result, the primary sodium coolant system (which contains highly radioactive sodium) is often isolated from the steam generation system by an intermediary coolant to prevent a release of radioactivity in the case of an accident. This adds costs and complexity to the system, complicates maintenance and refueling, and introduces an additional safety concern. Fires resulting from sodium leaks have caused shutdowns in several SFRs that have been built to date.[61]

As with other fast reactors, SFRs could use a closed fuel cycle in which plutonium and uranium would be re-used from the spent fuel to provide a long-term fuel source when configured as a breeder. SFRs can achieve high burnup of actinides in spent fuel, potentially reducing the long-term radioactivity of high-level nuclear waste.

The first SFR was built in the United States in 1951.[62] Since then, approximately 20 SFRs have been built around the world, most of which have been experimental. The United States maintained SFRs as a high priority focus of its nuclear R&D program (primarily due to the technology's plutonium breeding capabilities) up until the cancellation of the Clinch River Breeder Reactor demonstration plant in 1983 amid public opposition, rising construction costs, and increased concern over weapons proliferation.[63] There are five SFRs currently in operation worldwide: one in China, three in Russia, and one in India. Two others are currently under construction and several others are planned.[64]

DOE announced a 50% cost-shared ARDP award to TerraPower in October 2020, with federal funding of up to $2 billion, for an SFR demonstration plant in Wyoming to begin operation by 2030. TerraPower's Natrium plant uses an SFR designed by GE Hitachi (called PRISM) in conjunction with a molten-salt heat storage system that would allow variable electrical output as high as 500 MW. According to TerraPower, the Natrium reactor will use HALEU fuel rather than plutonium. Spent fuel from the reactor will not be reprocessed to separate plutonium and uranium for new fuel, according to the company, but long fuel burnup and high energy efficiency will "reduce the volume of waste per megawatt hour of energy produced at the back end of the fuel cycle, by five times."[65] GE Hitachi's PRISM design was selected as the basis for the design

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[61] Cochran et al., "Fast Breeder Reactor Programs: History and Status." For more information on the fire risk presented by liquid sodium coolants, see Tara Jean Olivier et al., "Metal Fire Implications for Advanced Reactors, Part 1: Literature Review," Sandia National Laboratories, October 1, 2007, https://doi.org/10.2172/946583. For a description of past SFR accidents, see Union of Concerned Scientists, "A Brief History of Nuclear Accidents Worldwide," https://www.ucsusa.org/nuclear-power/nuclear-power-accidents/history-nuclear-accidents#.XA7fV2N7mUk.

[62] Experimental Breeder Reactor I (EBR-I), a 1.2 MWt sodium-cooled experimental fast reactor, was built in 1951 in Idaho and produced both plutonium and electrical power. For a brief history of the reactor, see Rick Michal, "Fifty Years Ago in December: Atomic Reactor EBR-1 Produced First Electricity," *Nuclear News*, November 2001, https://www.ne.anl.gov/About/reactors/ebr1/2001-11-2.pdf.

[63] R&D activities related to SFRs and spent fuel reprocessing continued after 1983. For more on the history of the U.S. program on liquid metal fast breeder reactors, see Cochran et al., "Fast Breeder Reactor Programs: History and Status," See also U.S. Atomic Energy Commission, Division of Reactor Development and Technology, "Liquid Metal Fast Breeder Reactor Program Plan," Vol. 1 (1968).

[64] World Nuclear Association, "Fast Neutron Reactors," August 2021, http://www.world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx.

[65] TerraPower, "The Natrium Program," May 18, 2021, https://www.terrapower.com/natrium-program-summary; Government Accountability Office, *Nuclear Energy Projects: DOE Should Institutionalize Oversight Plans for*

ofDOE's planned Versatile Test Reactor at INL, although the project has not received new appropriations since FY2021.[66]

ARC Clean Technology is developing a 100 MWe SFR based on the now-closed Experimental Breeder Reactor II at INL.[67] DOE awarded the company $27.5 million over three years in December 2020 to develop a conceptual design.[68]

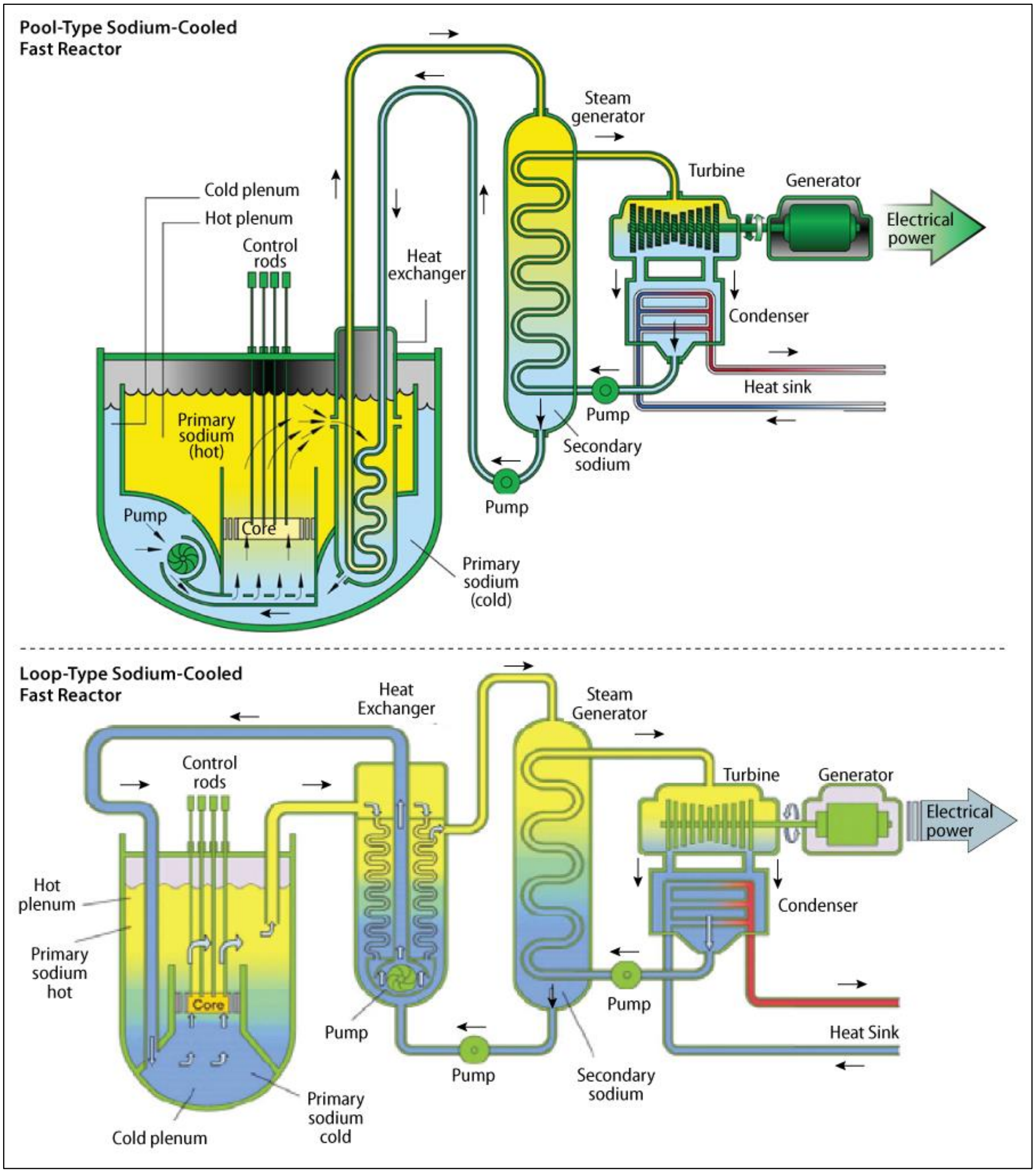
Demonstrations of New Reactor Types, GAO-22-105394, September 2022, p. 9, https://www.gao.gov/assets/gao-22-105394.pdf.

[66] DOE Office of Nuclear Energy, *Draft Versatile Test Reactor Environmental Impact Statement Summary*, DOE/EIS-0542, December 2020.

[67] ARC Clean Technology, https://www.arc-cleantech.com.

[68] DOE, "Energy Department's Advanced Reactor Demonstration Program Awards $20 million for Advanced Reactor Concepts," December 22, 2020, https://www.energy.gov/ne/articles/energy-departments-advanced-reactor-demonstration-program-awards-20-million-advanced.

Figure 4. Pool-Type and Loop-Type Sodium-Cooled Fast Reactors



Source: U.S. Department of Energy, modified by CRS.

Lead-Cooled Fast Reactor

Lead-cooled fast reactors (LFRs) are designed to use a closed fuel cycle with either molten lead or lead-bismuth eutectic (LBE) alloy as a primary reactor coolant (see **Figure 5**).[69] The use of

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[69] "The eutectic mixture is the specific composition of at least two solid components that produces a change of phase to liquid at a certain temperature." ScienceDirect, "Eutectic Mixture," https://www.sciencedirect.com/topics/chemistry/eutectic-mixture.

lead as a coolant is seen to confer several advantages. As with the SFR, the use of a liquid metal coolant allows for low-pressure operation and passive cooling in an accident. In contrast to liquid sodium, however, molten lead is relatively inert, adding additional safety and economic advantages. Lead also has a high rate of retention of radioactive fission products, which could reduce accidental releases of radioactive materials to the environment. LFRs can also be designed for high burnup of waste actinides, allowing for reduced long-term radioactive wastes.

Lead does present some challenges that may require further research and innovation to overcome. At high temperatures, lead tends to corrode structural steel. Achieving commercialization for designs in the higher temperature ranges would thus need further technological advances in corrosion-resistance for structural steel components coming into contact with the liquid lead coolant. Lead is also highly opaque, presenting visibility and monitoring challenges within the core, and very heavy, due to its high density. The high melting point of lead also presents challenges in terms of keeping the lead in liquid form so that it can continue to circulate under lower-temperature scenarios.[70]

Russia is the world leader in LFR R&D, with experience building and operating seven LFRs for use in submarines. Russia is building a lead-cooled demonstration fast reactor, the BREST-300 (300 MWe), in Seversk, with larger units to follow if the first is successful.[71] Members of the European Union have also announced a collaboration to develop an LFR through the Advanced Lead Fast Reactor European Demonstrator (Alfred).[72] Other countries exploring LFR technologies include China, Japan, Korea, Sweden, and the United Kingdom. U.S. companies pursuing LFRs include Westinghouse.[73]

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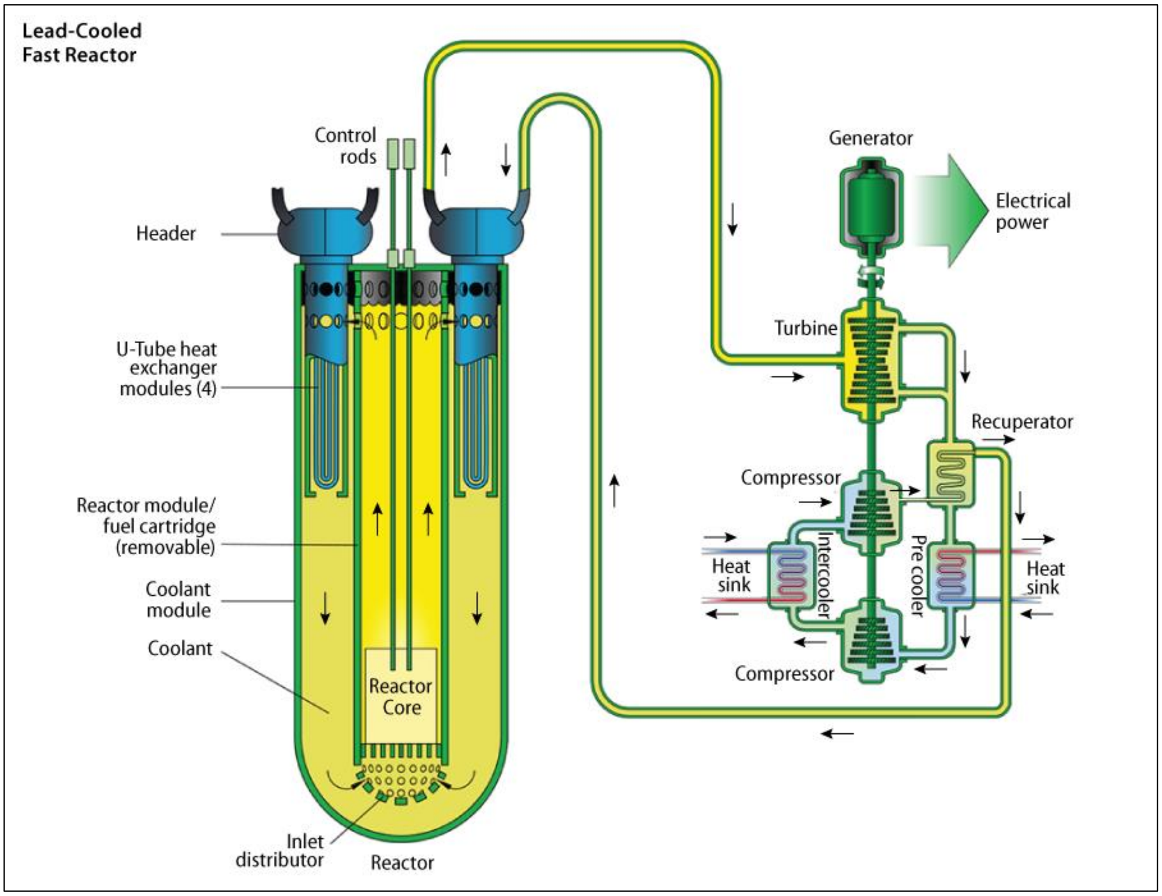
[70] Generation IV International Forum, "Lead-Cooled Fast Reactor (LFR)," 2019, https://www.gen-4.org/gif/jcms/c_42149/lead-cooled-fast-reactor-lfr.

[71] World Nuclear Association, "Nuclear Power in Russia," December 2021, http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-power.aspx; "Russian Reactions," *Nuclear Engineering International*, May 22, 2016, https://www.neimagazine.com/features/featurerussian-reactions-4899799/.

[72] "Ansaldo Nucleare Signs Contract for Lead-Cooled Reactor," *Nuclear Engineering International*, November 25, 2021, https://www.neimagazine.com/news/newsansaldo-nucleare-signs-contract-for-lead-cooled-reactor-9277875.

[73] Westinghouse, "Lead-cooled Fast Reactor (LFR): The Next Generation of Nuclear Technology," viewed November 14, 2022, https://www.westinghousenuclear.com/energy-systems/lead-cooled-fast-reactor.

Figure 5. Lead-Cooled Fast Reactor



Source: U.S. Department of Energy, modified by CRS.

Molten Salt Reactors and Fluoride Salt-Cooled High Temperature Reactors

Any reactor that uses molten salts as a coolant or fuel may be considered a molten salt reactor (MSR). Salt-cooled MSRs (also known as fluoride salt-cooled high temperature reactors or FHRs) employ molten salts to cool the core, which is composed of solid fuel blocks configured much like an HTGR. Salt-fueled MSRs, by contrast, are unique in that the fuel is not solid, but rather is dissolved in the molten salt coolant.[74]

MSRs vary in their design; there are fast and thermal variants, and different moderator materials have been proposed for the thermal variants. Molten salt fast reactors (MSFRs) exhibit high potential for waste actinide burnup and fuel resource conservation. Different molten salts may also be used, depending on the other design features. Outlet temperature specifications range from 700°-1,000°C, although there are challenges to operating at these temperatures that would need technological advances to resolve. Despite the high temperatures, MSRs would operate at low pressure and would not explosively react with air or water. It is unknown whether spent MSR

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[74] Oak Ridge National Laboratory, "Fluoride-Salt-Cooled High-Temperature Reactors," January 30, 2018, https://www.ornl.gov/content/fluoride-salt-cooled-high-temperature-reactors.

fuel could be safely stored in the long term without undergoing additional treatment after removal from the reactor.[75]

Unique to MSR salt-fueled designs is a safety feature called a "freeze plug" below the reactor core, consisting of a salt plug that is cooled to a solid state (see **Figure 6**). If an incident caused heat to rise in the core, the plug would melt, allowing the molten salt fuel to drain by gravity into a basin designed to prevent the fuel from undergoing further fission reactions and overheating.

In theory, molten salt-fueled reactors could have on-line refueling, as well as on-line removal of fission products and other impurities through a variety of potential processes. Such on-line fuel processing could pose challenges for nuclear material inventory tracking for nonproliferation purposes.[76]

MSR technology has been under development for decades. Two thermal-spectrum experimental reactors were built in the United States at Oak Ridge National Laboratory in the 1950s and 1960s. The first molten salt fuel irradiation tests since the completion of those early experiments were conducted in 2017 in the Netherlands, where research on waste treatment is also being pursued.[77] China is currently developing two prototype MSR microreactors with expected start dates in the 2020s.[78]

Terrestrial Energy, a Canadian company with a U.S. subsidiary, is in the second stage of design review with the Canadian Nuclear Safety Commission for its integral molten salt reactor (IMSR). The IMSR is the first advanced reactor design to complete phase one of the Canadian pre-licensing process.[79] The company's U.S. subsidiary is conducting pre-application activities for the IMSR with NRC.[80] Terrestrial Energy has announced a goal of commercialization by the late 2020s.

Kairos Power received a 50% cost-shared ARDP risk reduction grant for its molten salt cooled reactor technology in December 2020, with total federal funding of up to $303 million over seven years.[81] Kairos submitted a construction permit application to NRC in September 2021 to build a

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[75] Uranium tetrafluoride—the primarily fuel form for MSRs—reacts with water to form a highly corrosive acid which can cause storage containers to degrade and fail prematurely. Lindsay Krall and Allison Macfarlane, "Burning Waste or Playing with Fire? Waste Management Considerations for Non-Traditional Reactors," *Bulletin of the Atomic Scientists* 74, no. 5 (September 3, 2018): 326-34, https://doi.org/10.1080/00963402.2018.1507791.

[76] NASEM, *Potential Merits and Viability of Advanced Nuclear Reactors and Associated Fuel Cycles*, p. 67. Most reactors, both existing and proposed, require periodic shutdowns for refueling. Canadian-designed CANDU reactors provide an existing example of on-line refueling.

[77] NRG, "MSR Irradiation Program at NRG Petten," presentation by P.R. Hania to MSR Workshop 2018, Oak Ridge National Laboratory, October 4, 2018, https://msrworkshop.ornl.gov/wp-content/uploads/2018/10/MSR2018-presentation-Hania-NRGEU.pdf.

[78] World Nuclear Association, "Molten Salt Reactors," May 2021, http://www.world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx.

[79] "IMSR Starts Second Stage of Canadian Design Review," World Nuclear News, October 17, 2018, http://www.world-nuclear-news.org/Articles/IMSR-starts-second-stage-of-Canadian-design-review; and "Terrestrial Energy Completes Safeguards Work at Canadian Nuclear Laboratories," press release, August 31, 2022, https://www.terrestrialenergy.com/2022/08/31/terrestrial-energy-completes-safeguards-work-at-canadian-nuclear-laboratories.

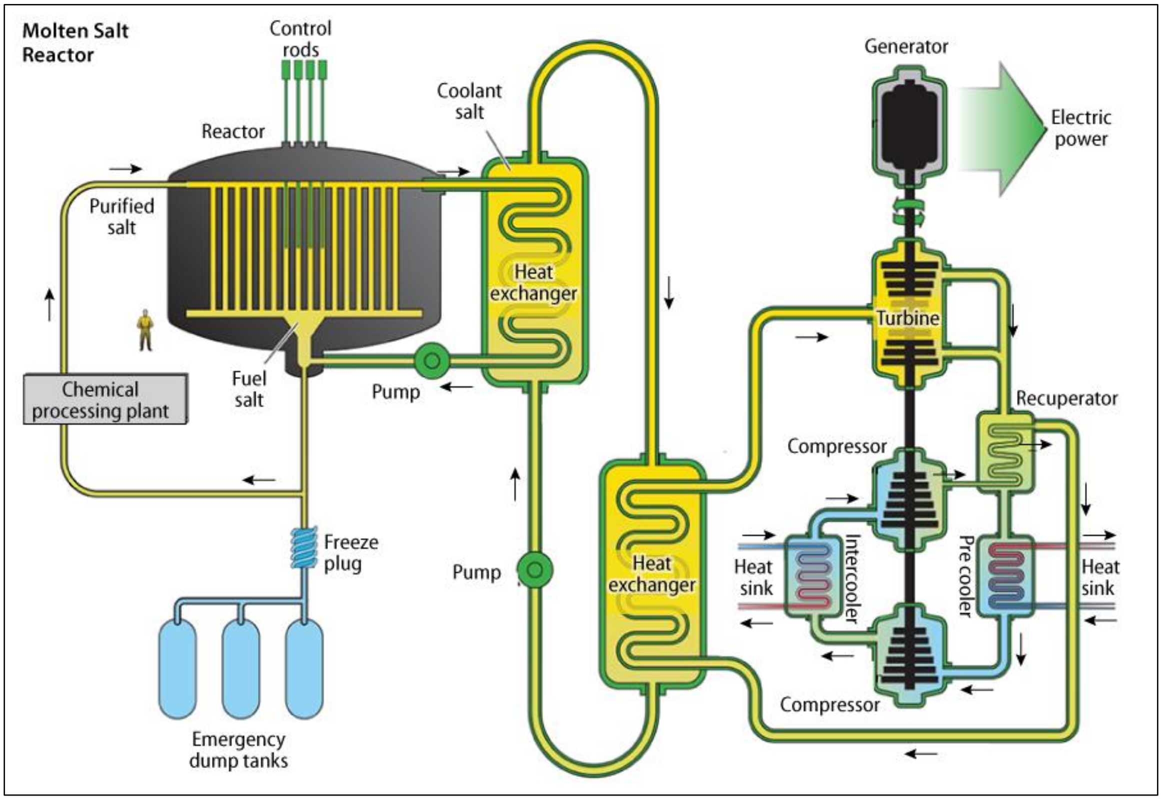
[80] NRC, "Integral Molten Salt Reactor (IMSR)," May 31, 2022, https://www.nrc.gov/reactors/new-reactors/advanced/licensing-activities/pre-application-activities/imsr.html.

[81] DOE, "Energy Department's Advanced Reactor Demonstration Program Awards $30 Million in Initial Funding for Risk Reduction Projects," December 16, 2020, https://www.energy.gov/ne/articles/energy-departments-advanced-reactor-demonstration-program-awards-30-million-initial.

35 MW (thermal) test reactor called Hermes at Oak Ridge, TN, supported by the ARDP grant.[82] The Kairos technology consists of pebble bed TRISO fuel cooled by cooled by liquid fluoride salt. The commercial version of the reactor, which is undergoing NRC pre-application activities, would have a capacity of 145 MW(e).[83]

Examples of other U.S. companies developing MSRs include Alpha Tech Research Corp., Elysium Industries, Flibe Energy, Micronuclear, and TerraPower.[84]

Figure 6. Molten Salt Fueled Reactor



Source: U.S. Department of Energy, modified by CRS.

Fusion Reactors

Fusion reactors would fuse light atomic nuclei—as opposed to the fissioning of heavy nuclei—to produce power. Fusion R&D has received significant federal investment over time, including billions of dollars in international cooperative funding anticipated to build the International

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[82] NRC, "Hermes—Kairos Application," November 14, 2022, https://www.nrc.gov/reactors/non-power/hermes-kairos.html.

[83] Kairos Power, "How It Works," https://kairospower.com/technology; NRC, "Kairos," August 21, 2022, https://www.nrc.gov/reactors/new-reactors/advanced/licensing-activities/pre-application-activities/kairos.html.

[84] World Nuclear Association, "Molten Salt Reactor," May 2021, https://world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx; and DOE, Gateway for Accelerated Innovation in Nuclear, *Advanced Nuclear Directory*, June 2021, https://gain.inl.gov/SiteAssets/Advanced%20Nuclear%20Directory/Archive/GAINAdvancedNuclearDirectory-SeventhEdition_07.01.2021.pdf.

Thermonuclear Experimental Reactor (ITER), a fusion research and demonstration reactor under construction in France. The United States is a major participant in the project.

Fusion power would require light atoms, generally isotopes of hydrogen, to be heated to 100 million degrees Celsius to form a plasma, a state of matter in which electrons are stripped away from the atomic nucleus. Holding the plasma together while it is heated sufficiently to create a sustained fusion reaction is a major technical challenge. ITER would do this with a powerful magnetic field (magnetic confinement fusion), while other approaches would compress a pellet of hydrogen with lasers or other intense energy sources (inertial confinement fusion). Fusion reactions are routinely produced at the laboratory scale. A key goal of ITER is to achieve "burning plasma," in which the plasma is heated mostly by its own fusion reactions rather than by external energy sources. A fusion power reactor would need to go beyond this to achieve "ignition," in which the fusion energy exceeds the external energy input, allowing the fusion reaction to be self-sustaining. ITER had been scheduled to produce its first plasma by the end of 2025, with full operations, including burning plasma experiments, scheduled to begin in 2035.[85] However, the need for "extensive repairs" in key installed components will delay that schedule, the project's director announced in November 2022.[86]

DOE announced two milestones in the development of inertial confinement fusion in 2022. In January, the National Ignition Facility at Lawrence Livermore National Laboratory achieved a burning plasma, and in December the same facility achieved ignition. During the December announcement, Livermore Lab Director Kimberly S. Budil said commercialization of the technology would still take "a few decades," but was "moving to the foreground."[87] The primary purpose of the National Ignition Facility is to provide data for stewardship of the nation's nuclear weapons stockpile. Most researchers continue to see magnetic confinement fusion as the more promising option for energy applications.[88]

Fusion power technology potentially has several safety and waste advantages over fission power plants. Fusion reactions do not produce the intensely hot and radioactive spent fuel that results from the fission process. If a fusion reactor shuts down, there is no radioactive core that must continue to be cooled as in a fission reactor. According to the Fusion Industry Association, "fusion produces no harmful emissions or waste fuel. A fusion power plant is physically incapable of having a meltdown. There is no fissile radioactive waste left over."[89] However, some reactor materials would be made radioactive by neutron exposure during a fusion reaction, and tritium, a primary anticipated fuel source, is radioactive, although far less so than fission products.[90]

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[85] ITER, "Building ITER," September 30, 2022, https://www.iter.org/construction/construction. This timeline is according to the project's 2016 baseline schedule, but an update is currently underway. ITER construction was 77.5% complete toward production of first plasma as of September 30, 2022, according to the project website.

[86] "ITER Project Addressing Challenges," ITER press release, November 17, 2022, https://www.iter.org/doc/www/content/com/Lists/list_items/Attachments/1061/2022_11_IC-31.pdf.

[87] Ben Lefebvre, "America Has Achieved a Tremendous Scientific Breakthrough," Politico, December 13, 2022, https://www.politico.com/news/2022/12/13/fusion-breakthrough-doe-energy-sustainability-00073666; DOE, "DOE National Laboratory Makes History by Achieving Fusion Ignition," December 13, 2022, https://www.energy.gov/articles/doe-national-laboratory-makes-history-achieving-fusion-ignition.

[88] For example, the advocacy group U.S. Fusion Energy describes magnetic confinement fusion as "the leading global approach." See U.S. Fusion Energy, "Approaches to Fusion," https://www.fusionindustryassociation.org/fusionenergy.

[89] Fusion Industry Association, "About Fusion," April 12, 2019, https://www.fusionindustryassociation.org/fusionenergy.

[90] Paul Humrickhouse, Idaho National Laboratory, "Safety Considerations of Building a Fusion Pilot Plant," June 23,

Examples of U.S. companies developing fusion technologies include Commonwealth Fusion Systems,[91] Helion Energy,[92] HyperV Technologies,[93] Lawrenceville Plasma Physics,[94] Lockheed Martin, Magneto,-Inertial Fusion Technologies,[95] and TAE Technologies.[96]

Major Criteria for Evaluating Unconventional Technologies

With dozens of advanced nuclear technology developers vying for commercialization of their concepts—as well as for federal support toward achieving that goal—several major criteria are likely to help determine which reactor designs, if any, ultimately succeed. These include cost and economic competitiveness, safety, weapons proliferation risk and security, versatility in size and use, waste management, and other environmental effects. Cost and market viability are heavily weighted criteria for ARDP demonstrations, along with technical feasibility and ability to meet NRC safety and licensing requirements. Advanced reactor developers contend that their designs offer major improvements in many or all of these criteria over existing conventional reactors, although some critics have expressed skepticism.[97]

Cost

Investment in electricity generating technologies is largely determined on the basis of cost. Nuclear energy has historically had high capital costs,[98] but relatively low fuel and other production costs. Conventional nuclear power plants have struggled to compete with natural gas and renewable energy plants, particularly in regions of the country served by competitive electricity markets. The success of advanced reactors in entering these markets may depend on their ability to reduce capital costs relative to conventional reactors and to offer electricity prices that are competitive with non-nuclear sources of baseload power. Government mandates and subsidies for low-carbon generating technologies could help overcome cost differentials with fossil fuel plants.

Commercial scale demonstration plants could help with the development of realistic cost estimates. As noted by NASEM in its December 2022 report, “Because of the absence of current commercial operational experience with advanced reactor technologies in the United States, reliable cost data and estimates for these technologies and their associated fuel cycle components

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2020, https://suli.pppl.gov/2020/course/SULI_Safety_2020-06-23.pdf.

[91] Commonwealth Fusion Systems, https://cfs.energy.

[92] Helion Energy, https://www.helionenergy.com.

[93] HyperV Technologies, http://hyperv.com.

[94] LPP Fusion, https://www.lppfusion.com.

[95] Magneto-Inertial Fusion Technologies, https://miftec.com.

[96] TAE Technologies, https://tae.com.

[97] For example, see Edwin Lyman, ‘*Advanced’ Isn’t Always Better: Assessing the Safety, Security, and Environmental Impacts of Non-Light-Water Reactors*, Union of Concerned Scientists, March 18, 2021, https://www.ucsusa.org/resources/advanced-isnt-always-better.

[98] EIA defines capital cost as “the cost of field development and plant construction and the equipment required for industry operations.” See EIA, “Glossary,” EIA, November 9, 2018, https://www.eia.gov/tools/glossary/.

are lacking." NASEM recommended that DOE obtain independent expert cost estimates for commercial deployment of advanced reactor technologies.[99]

Capital Costs

High capital costs present a significant barrier to deployment of new nuclear plants in the United States. Conventional nuclear reactors are more expensive to build than most other power plants.[100] Nuclear plants must submit to much more rigorous safety regulation and quality standards than other producers of electricity because of the risk posed by a release of radioactive materials. As a result, they require highly specialized construction materials (e.g., nuclear-grade steel), engineering knowledge, and construction expertise, all of which add to a plant's costs. Large conventional reactors require a great deal of on-site fabrication of structures and components that are too large to be built in a factory, further adding to costs. High capital costs and consequent financing needs make nuclear power plant construction especially vulnerable to rising interest rates.

Capital cost estimates for advanced reactors vary by technology and design. Some designs, such as SMRs, may allow for greater factory fabrication than conventional designs. Costs will remain highly uncertain until demonstration plants are constructed. According to an MIT study, conventional nuclear capital costs are dominated by labor and engineering costs (approximately 60%).[101] By contrast, the actual reactor and associated turbine components comprise less than 20% of the capital cost of the median historical U.S. light water reactor.[102] Accordingly, achieving cost reductions relative to these conventional plants would require that advanced reactor developers find ways to improve upon existing construction methods for nuclear reactors.

One advanced reactor design innovation that holds potential for reducing construction costs is modularization of structures and components. Modularity is intended to increase factory production of nuclear components. Manufactured components could then be delivered to the construction site for installation, cutting down on onsite labor, reducing the specialized knowledge needed to custom-build each component on-site, and potentially improving quality. Modularized construction has been shown to improve the pace of construction and reduce costs in other industries, as well as in some recent nuclear construction projects in Asia.[103] NuScale, a U.S.-based SMR vendor, has estimated "overnight" (excluding interest incurred during construction)[104] cost savings of approximately 10% due to modular construction of structures in its proposed SMR plant. The Westinghouse AP1000 design, based on existing large conventional reactors, is also intended to maximize modular construction, but the two AP1000 units under

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[99] National Academies of Sciences, Engineering, and Medicine, *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*, December 2022, p. 9, https://nap.nationalacademies.org/catalog/26500/merits-and-viability-of-different-nuclear-fuel-cycles-and-technology-options-and-the-waste-aspects-of-advanced-nuclear-reactors.

[100] Lazard, "Lazard's Levelized Cost of Energy Analysis—Version 15.0," October 2021, p. 11, https://www.lazard.com/media/451881/lazards-levelized-cost-of-energy-version-150-vf.pdf.

[101] A particularly large component of these costs comes from civil works required to prepare a site to host a nuclear reactor. These include "excavations and foundations, the ultimate heat sink (cooling towers or river cooling), other equipment, and the installation of plant components." Massachusetts Institute of Technology, "The Future of Nuclear Energy in a Carbon-Constrained World."

[102] Ibid.

[103] Ibid., pp. 44-45.

[104] "Overnight cost" is a method of comparing construction costs that assumes a plant could be built instantly, or "overnight," thus eliminating financing costs incurred during construction.

construction at the Vogtle plant in Georgia have experienced long schedule delays and cost overruns.

Advanced reactor developers and advocates have also highlighted the cost reduction potential of such characteristics as simplified reactor designs, standardized reactor components, and smaller overall reactor sizes. Designs using TRISO fuel contend that conventional containment structures will not be needed because the multiple fuel coatings serve as a "functional containment."[105] Advanced reactors may also offer the potential to reduce financing costs as a result of shorter construction times and, in the case of SMRs, the ability to begin generating revenue after the installation of the first module, even as work continues on additional modules.

Operating Costs

Some advanced reactor concepts also show potential for reducing operating costs. Some designs would utilize simpler systems or increased automation to reduce human labor costs during operation. Many advanced reactor developers contend their designs would improve upon the thermal efficiencies of older generations of nuclear plants by operating at higher temperatures or through use of more efficient power conversion technologies. More-efficient plants may be able to reduce their payback periods relative to their less efficient peers.

Not all aspects of advanced reactor concepts would lead to cost reductions. Some reactor designs would have lower power ratings and/or lower power densities (less power for a given core volume) than conventional reactors, which could reduce the cost advantages that existing large reactors achieve through economies of scale. The majority of advanced designs would require fuels with a fissile isotope enrichment of between 5% and 20% (HALEU), compared with 3%-5% for most existing commercial reactors. Enriching fuel to these higher percentages would add costs. Some designs would use as-yet-unlicensed fuel forms, which may be associated with higher fuel fabrication costs. Some advanced reactors would also require spent fuel reprocessing and treatment on the back end before wastes could be safely stored, which may in turn require higher levels of security in order to limit risks of proliferation. According to NASEM, "Reprocessing will likely be a costly addition to the fuel cycle, and notably, a single reprocessing technology will not support the wide array of advanced reactor designs."[106]

Some research on SMRs has suggested that their small size will prevent them from achieving economies of scale. Modularization may allow this disadvantage to be balanced by so-called "economies of multiples." One analysis found that, while SMRs may be cheaper than traditional reactors to construct, the cost per unit of power generated is likely to be higher.[107]

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[105] "The term 'functional containment' is applicable to advanced non-LWRs without a pressure retaining containment structure. A functional containment can be defined as 'a barrier, or set of barriers taken together, that effectively limit the physical transport and release of radionuclides to the environment across a full range of normal operating conditions, AOOs [anticipated operational occurrences], and accident conditions.'" X-energy, *TRISO-X Pebble Fuel Qualification Methodology*, p. 36, https://www.nrc.gov/docs/ML2124/ML21246A289.pdf.

[106] National Academies of Sciences, Engineering, and Medicine, *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*, December 2022, p. 138, https://nap.nationalacademies.org/catalog/26500/merits-and-viability-of-different-nuclear-fuel-cycles-and-technology-options-and-the-waste-aspects-of-advanced-nuclear-reactors.

[107] M. Granger Morgan et al., "US Nuclear Power: The Vanishing Low-Carbon Wedge," Proceedings of the National Academy of Sciences 115, no. 28 (July 10, 2018): 7184–89, https://doi.org/10.1073/pnas.1804655115.

Cost Estimates for Advanced Reactors

It is difficult to accurately estimate the costs of advanced reactors. Many advanced reactor concepts remain in the early stages of design and development, and vendor companies generally do not include detailed costs in their publicly available content. Academic analyses of the costs of non-traditional reactors have produced a range of results. The potential cost of fuel cycle facilities raises additional uncertainty. For example, reactors that would use new types of fuel may need new fuel fabrication plants, and technologies based on a closed fuel cycle would require spent fuel reprocessing plants.

A common metric for measuring and comparing the cost of electricity production among sources is the levelized cost of electricity (LCOE). LCOE is a measure of the unit cost of producing electricity from a given generating source (e.g., coal, natural gas, solar, wind, etc.) and is calculated by dividing the total costs of constructing and operating a plant over its lifetime by its total electricity output over the same period. LCOE can be a useful tool for comparing production costs across sources; however, because there are additional factors that influence the economic competitiveness of a proposed plant, relying upon a single metric for comparison may be misleading. Other possible cost measures include the cost of construction per kilowatt or megawatt of electric generating capacity and the costs of air emissions. Such estimates typically exclude costs that are not currently the responsibility of plant owners, such as greenhouse gas emissions.

The Energy Information Administration (EIA) estimates that the LCOE for new nuclear reactors is $88.24/MWh, excluding tax credits.[108] An LCOE analysis by Lazard estimates that new nuclear plants, unsubsidized and excluding decommissioning costs, would range from $151/MWh to $196/MWh.[109] Both are based on new plants using the most advanced currently available technology. A comparison of levelized cost estimates for new nuclear plants and other new generating capacity is shown in **Table 3**. Recent inflation could increase the uncertainty of such estimates, however. For example, NuScale announced in November 2022 that the LCOE of its planned first plant at INL had risen from $58/MWh to nearly $90/MWh, including federal subsidies. The increases were attributed to rising supply and financing costs.[110] A recent analysis estimates that those costs would be above $100/MWh without DOE subsidies and the tax credits in the Inflation Reduction Act.[111] The overnight cost of the NuScale plant at INL is currently estimated at $6.8 billion before federal subsidies.[112]

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[108] EIA, Levelized Costs of New Generation Resources in the Annual Energy Outlook 2022, March 2022, https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

[109] Lazard, *Lazard's Levelized Cost of Energy Analysis—Version 15.0*, October 2021, https://www.lazard.com/media/451905/lazards-levelized-cost-of-energy-version-150-vf.pdf.

[110] Jeff Beattie, "NuScale Says Costs of SMR Plant in Idaho Have Climbed Due to Inflation, *Nucleonics Week*, November 23, 2022. A description of federal funding for the nuclear energy industry is provided by Taxpayers for Common Sense, *Doubling Down: Taxpayers' Losing Bet on NuScale and Small Modular Reactors*, December 2021, https://www.taxpayer.net/wp-content/uploads/2021/12/TCS_Doubling-Down-SMR-Report_Dec.-2021.pdf.

[111] David Schlissel, Institute for Energy Economics and Financial Analysis, *Small Modular Reactor Update: The Fading Promise of Low-Cost Power from UAMPS' SMR*, November 17, 2022, https://ieefa.org/resources/small-modular-reactor-update-fading-promise-low-cost-power-uamps-smr.

[112] Michael McAuliffe, "NuScale Extends Cost Guarantees to Owners of First US SMR Plant," *Nucleonics Week*, January 18, 2023, p. 1.

Table 3. Levelized Cost of Energy (LCOE) Estimates for New Power Plants Using Selected Technologies

($ per megawatt-hour, excluding federal subsidies)

Energy Source	EIA	Lazard	Notes
Nuclear	88	131-204	Advanced large LWRs, currently available technology
Coal	83	65-152	Ultra-supercritical; Lazard high estimate includes carbon capture
Natural gas	40	45-74	Combined cycle
Geothermal	40	56-93	Hydrothermal
Biomass	90		
Wind, onshore	40	26-50	
Wind, offshore	137	83	
Solar	36	30-41	Utility-scale photovoltaic

Sources: EIA, Levelized Costs of New Generation Resources in the Annual Energy Outlook 2022, March 2022, https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf; Lazard, Lazard's Levelized Cost of Energy Analysis—Version 15.0, October 2021, https://www.lazard.com/media/451905/lazards-levelized-cost-of-energy-version-150-vf.pdf.

Size

Advanced reactor designs come in a wide range of sizes, from less than 15 MWe to 1,500 MWe or more. In some cases, the optimal reactor size may be influenced by the particular characteristics of a given design. In others, the size may be determined by the needs of the customer or site.

A commonality among many unconventional reactor concepts is an increased focus on small reactor designs. As noted earlier, advanced SMRs, 300 MWe and below, "employ modular construction techniques, ship major components from factory fabrication locations to the plant site by rail or truck, and include designs that simplify plant site activities required for plant assembly," according to DOE.[113] The smallest of these—under 20 MW of thermal energy—may also be referred to as microreactors. As noted above, most existing conventional reactors in the United States have an electrical generating capacity of 1,000 MWe or more. Many proposed advanced reactor technologies, according to proponents, would have fundamental characteristics, such as inherent safety, that would make them commercially viable at small sizes and not need the economies of scale required by existing LWR technology.

The small size and modular nature of SMRs gives them the potential to expand the types of sites and applications for which nuclear energy may be considered suitable (see section on Versatility).[114] SMR designs with multiple reactor modules may allow for size customization based on the needs of the customer or characteristics of the host site. For example, SMRs may be sized to directly replace retiring coal-fired power plants, as planned by the TerraPower Natrium project in Wyoming. Small size may also make safety systems simpler and more reliable, as discussed below.

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[113] DOE, "Advanced Small Modular Reactors (SMRs)," February 5, 2019, https://www.energy.gov/ne/nuclear-reactor-technologies/small-modular-nuclear-reactors.

[114] Small nuclear reactors are not a new concept. The U.S. military has built and used small nuclear reactor for dozens of years, most notably to power submarines and large surface ships.

According to NASEM,

> Commercial viability will depend on understanding whether there is an optimal size for a small modular reactor from an economic point of view and when the breakeven point will be reached for the construction of an nth-of-a-kind reactor [in the middle of series production] for a particular type of small modular reactor to become economically competitive. In other words, the learning curve for both small modular reactor construction costs and deployment needs to be understood.[115]

Safety

Safety with respect to nuclear energy refers primarily to the minimization of the risk of release of radioactivity into the environment. Advanced reactor systems may have both safety advantages and disadvantages in comparison with existing reactors as a result of their size and design, and the chemical properties of their main components (e.g. the coolant, fuel, and moderator). Because many of these technologies are in the design phase, the operational safety of many of these systems has not yet been established in practice. Testing and demonstration would be needed to fully validate the safety claims of advanced reactor vendors.

Conventional nuclear plants use multiple independent and redundant safety systems to minimize risk. In the majority of cases, these systems are "active," meaning that they rely on electricity or mechanical systems to operate. Advanced nuclear reactors tend to incorporate passive and inherent safety systems as opposed to active systems. Passive systems refer primarily to two types of safety features: (1) the ability of these reactors to self-regulate the rate at which fission occurs through negative feedback mechanisms that naturally reduce power output when certain system parameters (such as temperature) are exceeded, and (2) the ability to provide sufficient cooling of the core in the event of a loss of electricity or other active safety systems.[116]

The chemical properties of various advanced coolants, fuels, and moderators may also contribute inherent safety advantages. Examples include higher boiling points for coolants, higher heat capacities for fuels and moderators, and higher retention of radioactive fission products for some coolants. Some advanced reactor coolants (such as liquid metals) remain at atmospheric pressure under high reactor temperatures, putting less stress on primary reactor components than high-pressure coolants such as water. Advanced reactors that can operate at or near atmospheric pressure enable simplification of the coolant system design and safety systems, as well as the potential for improved economic performance.

Proponents of small reactors have suggested that SMRs, and microreactors in particular, may pose less of a safety risk due to the smaller total volume of radioactive material on site and lower risk of release to the environment. Consequently, some have argued that they should face streamlined approval processes in line with the NRC's approach of risk-informed regulation.[117] The smaller size of SMRs and microreactors may also enable innovations in siting that could

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[115] NASEM, *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*, p. 137.

[116] Reactors that are designed such that the maximum temperature at equilibrium (when heat generation equals passive heat removal) is below the point where fuel and reactor damage would occur are sometimes described by vendors as being "walkaway safe."

[117] The NRC defines "risk-informed regulation" as "an approach to regulation taken by the NRC, which incorporates an assessment of safety significance or relative risk," and states that this approach "ensures that the regulatory burden imposed by an individual regulation or process is appropriate to its importance in protecting the health and safety of the public and the environment." (NRC, "Risk-Informed Regulation," March 9, 2021, https://www.nrc.gov/reading-rm/basic-ref/glossary/risk-informed-regulation.html.)

contribute to plant safety. Some have suggested that siting these reactors underground or on floating platforms at sea could reduce risks related accidental release of radioactive materials and seismic activity, respectively.[118]

While some advanced reactor coolants and moderators may have the advantages described above, some also have chemical properties that pose safety concerns. Examples include reactivity, toxicity, or corrosiveness of the primary coolant in the case of sodium, lead, and molten salts, respectively. Molten salt-cooled reactors would incorporate the dissolved fuel into the coolant, posing a safety concern for plant workers who must be shielded from the higher levels of radioactivity flowing through the coolant system as a result. Opaque coolants present additional challenges to visual core monitoring and inspection compared with transparent coolants like water.

Advanced reactors, as well as some existing conventional reactors, may make use of advances in fuel technologies and accident-tolerant fuels (ATFs). ATFs are designed to better withstand overheating during an accident, reducing the risk of cladding oxidization and fuel meltdown and allowing reactor operators more time to respond to accidents. Near-term ATF concepts (e.g. coated zirconium cladding, iron-chrome-aluminum-based cladding) may be commercially available as soon as the mid-2020s, while longer-term ATF concepts (e.g. metallic fuels, silicide fuel, and silicon carbide cladding) would need more testing before they could be licensed.[119]

Advanced reactor technologies that would rely on spent fuel reprocessing and recycling, as well as on HALEU fuel, could introduce safety concerns beyond those related to reactor operation. Enrichment levels in HALEU, which are higher than in conventional fuel, would require added measures to prevent accidental criticality (nuclear chain reactions) in fuel conversion, enrichment, and fabrication facilities. Commercial reprocessing facilities, currently not operated in the United States, would also require criticality controls, along with prevention of such industrial hazards as fires, leaks, and chemical reactions that could spread radioactivity.[120]

Security and Weapons Proliferation Risk

In addition to producing energy for peaceful purposes, nuclear fuels such as uranium and plutonium can be used by states to manufacture nuclear weapons material for military use or diverted by non-state actors to produce weapons of mass destruction. The risk of weapons proliferation from civilian nuclear materials and facilities presents a challenge for all nuclear energy reactors to varying degrees, and for international controls on nuclear materials. Advanced reactor designs may offer both advantages and disadvantages with respect to their potential effects on nuclear weapons proliferation.

Advocates contend that many advanced reactor designs would be more resistant to weapons proliferation than existing LWRs because of factors such as "sealed" or difficult-to-access core designs, infrequent refueling, smaller inventories of fissile materials in the core, and remote monitoring capabilities, among others. Some designs may produce waste that is less attractive for weapons proliferation for a variety of reasons.[121]

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[118] World Nuclear Association, "Small Nuclear Power Reactors," May 2022, http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx.

[119] NRC, "Accident Tolerant Fuel Regulatory Activities," October 25, 2022, https://www.nrc.gov/reactors/atf.html.

[120] NASEM, *Merits and Viability of Different Nuclear Fuel Cycles of Advanced Nuclear Reactors*, p. 140.

[121] For a discussion of these advantages, as well as disadvantages, see Shikha Prasad et al., "Nonproliferation Improvements and Challenges Presented by Small Modular Reactors," *Progress in Nuclear Energy*, vol. 80 (April

Advanced reactors may also present unique inspection and monitoring challenges. In a 2017 workshop report, IAEA, which inspects nuclear sites to ensure compliance with international nonproliferation agreements, noted that some of the characteristics of advanced reactors may make them more difficult to monitor and safeguard.[122] For instance, the opacity of certain advanced coolants, such as sodium, lead, and molten salts, may make it more difficult to monitor reactor cores to ensure nuclear materials are not being diverted for weapons purposes. In contrast, inspectors can visually see through cooling water to determine whether fuel rods and assemblies are present or have been removed, possibly to separate plutonium for weapons.

The 2017 IAEA report identified several advanced reactor technologies that pose unique and particularly difficult safeguarding challenges, including transportable reactors, pebble-bed design HTGRs, molten salt reactors, and certain waste reprocessing facilities. The report also noted that "proliferation resistance and ease to verify (safeguardability) are not interchangeable; and most of the features lending proliferation resistance to Generation-IV reactors actually make safeguards nuclear material accountancy more difficult."[123]

The utilization by some advanced reactors of more highly enriched fuels could create additional nonproliferation challenges. Many advanced designs would utilize HALEU, with a fissile isotope enrichment of between 5% and 20%. At these higher enrichments, even very small reactors would likely contain more than enough fissile material to produce multiple nuclear weapons with further enrichment.[124] The total work required to enrich uranium to weapons-grade levels declines as the initial enrichment level rises.[125] Some designs would also produce spent fuel with higher concentrations of isotopes that are desirable from the point of view of weapons production, making them a more attractive target of diversion than current LWR fuel. Additional security measures may be necessary to safeguard against such eventualities.

The need to safeguard nuclear materials is present not just at reactor sites, but through the entire nuclear fuel supply chain. This includes during uranium enrichment, the fuel fabrication process, in transit, and, if applicable, during fuel reprocessing. Many advanced reactors would require or would offer the option to reprocess the spent fuel to extract remaining fissile materials. Some advanced reactor technologies would rely on reprocessing and recycling to make them cost-effective. Separating these materials from the radioactive wastes makes them more attractive both to thieves for making radiological dispersal devices and to countries that might use them to produce weapons. France, Japan, India, Russia, and the United Kingdom have longstanding civilian nuclear fuel programs. According to one independent estimate, about 545 metric tons of separated plutonium was held around the world as of May 2022 in weapons or in stockpiles of

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2015): 102–9, https://doi.org/10.1016/j.pnucene.2014.11.023.

[122] IAEA, *Emerging Technologies Workshop: Trends and Implications for Safeguards*, February 2017, https://www.iaea.org/sites/default/files/18/09/emerging-technologies-130217.pdf. *Safeguards* are defined by the IAEA as "activities by which the IAEA can verify that a State is living up to its international commitments not to use nuclear programmes for nuclear-weapons purposes." (See https://www.iaea.org/publications/factsheets/iaea-safeguards-overview.)

[123] IAEA, Emerging Technologies Workshop. For more information about IAEA, see CRS Report RL33865, *Arms Control and Nonproliferation: A Catalog of Treaties and Agreements*, by Paul K. Kerr and Mary Beth D. Nikitin.

[124] Nuclear materials must generally reach fissile isotope enrichments of 90% or greater to be considered "weapons-grade." Accordingly, nuclear materials diverted from nuclear energy reactors at 5%-20% enrichment would require further enrichment to reach this threshold. Plutonium in reactor fuel would not need enrichment to be useable for weapons.

[125] Prasad et al., "Nonproliferation Improvements and Challenges Presented by Small Modular Reactors." See also World Nuclear Association, "Uranium Enrichment," October 2022, http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx.

varying isotopic composition.[126] For reference, the minimum fissile inventory required to produce a nuclear weapon from plutonium is generally cited as 10 kg of Pu-239. This figure may vary considerably based on the percentage of other plutonium isotopes mixed with Pu-239 and the sophistication of weapons designs.[127]

For existing nuclear power plants in the United States, security and proliferation risks are generally considered to be low, given the current fuel cycle and safeguards regimes in place. In particular, the low-enriched uranium fuel (3%-5% U-235) in U.S. reactors cannot be used for a nuclear explosive device without separation and further enrichment, and the United States does not have commercial facilities for chemical separation of plutonium. Many observers view the lack of reprocessing in the United States as a policy signal to other countries that the country with the largest number of nuclear power plants in the world has been able to support this fleet without reprocessing.

The 2022 NASEM study points out that IAEA has relatively little experience in safeguarding fast reactors and pebble-bed reactors, and that "molten salt-fueled reactors are completely unexplored territory for IAEA safeguards." The report urges that the United States place all its advanced reactors and fuel facilities under IAEA safeguards as soon as possible to help develop effective safeguards methods for these technologies. "To the extent possible, these efforts would be comprehensive and serve as models for full IAEA verification protocols in non-nuclear weapon states where advanced reactors and fuel cycle facilities may be exported," according to the report.[128]

Versatility

Many advanced reactor designs are smaller than the existing fleet of LWRs and are designed for modular installation of each generating unit. Because the number of modules may be altered to meet the power and heating needs of the site, SMRs are intended to accommodate a range of sizes and types of uses, including those that may have been considered too small in the past. SMRs and microreactors have potential applications in providing power to remote and isolated areas, on-site heating for industrial or municipal clients, and heat or power to mobile or temporary clients (e.g. remote construction sites and temporary military stations). DOD has expressed interest in using SMRs to power remote bases. As noted above, DOD announced in June 2022 that BWXT had been selected to build the first advanced nuclear microreactor under "Project Pele." The reactor is to produce 1-5 MW and be operational by 2024.[129] SMRs have also been described as potential replacements for coal-fired generating units, which are generally far smaller than existing large

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[126] About 140 metric tons was estimated to be in nuclear weapons or available for weapons. International Panel on Fissile Materials, "Fissile Material Stocks," May 2, 2022, http://fissilematerials.org. For a description of national civilian reprocessing programs, see Appendix H of National Academies of Sciences, Engineering, and Medicine, *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*, December 2022, https://nap.nationalacademies.org/catalog/26500/merits-and-viability-of-different-nuclear-fuel-cycles-and-technology-options-and-the-waste-aspects-of-advanced-nuclear-reactors.

[127] Weapons-grade plutonium has at least 94% Pu-239, although other grades are potentially useable for weapons. Federation of American Scientists, "The Basics of Nuclear Weapons: Physics, Fuel Cycles, Effects and Arsenals," February 8, 2016, https://fas.org/wp-content/uploads/2014/05/Brief2016_CNP-MIIS_.pdf.

[128] NASEM, *Merits and Viability of Different Nuclear Fuel Cycles of Advanced Nuclear Reactors*, p. 195.

[129] BWX Technologies, "BWXT to Build First Advanced Microreactor in United States," June 9, 2022, https://www.businesswire.com/news/home/20220609005154/en/BWXT-to-Build-First-Advanced-Microreactor-in-United-States.

reactors.[130] For example, the TerraPower Natrium demonstration plant in Wyoming is replacing a closing coal-fired power plant that has units of similar size.

The 2018 MIT study cautioned that small size alone would not necessarily give advanced reactors a market edge:

> The industry's problem is not that it has overlooked valuable market segments that need smaller reactors. The problem is that even its optimally scaled reactors are too expensive on a per-unit-power basis. A focus on serving the market segments that need smaller reactor sizes will be of no use unless the smaller design first accomplishes the task of radically reducing per-unit capital cost.[131]

Advanced reactors may also be designed for new applications or to capture new markets. Many advanced nuclear reactors would operate at higher temperatures (500°-1,000°C) than existing commercial LWRs (approximately 300°-330°C). Higher operating temperatures would allow some advanced reactors to tap into the large market for heat for industrial processes. Some advanced reactor designs, such as the Natrium plant, are being designed to rapidly change their electrical output from stored heat to match utility demand (load following), such as in areas with high percentages of highly variable wind and solar power.

Industrial users consume 25% of all primary energy produced in the United States, 80% of which is in the form of process heat. MIT estimates that 17%-19% (or 134-151 GWt) of the U.S. market for industrial heat could be supplied by small (150-300 MWt) advanced reactors.[132] Potential applications include providing heat for district heating,[133] desalination, petroleum refining and oil shale processing, cogeneration, biomass or coal gasification, and hydrogen production, among others. Advanced reactors may nevertheless face steep barriers to entry into these markets in the form of competition from other sources, such as natural gas plants (with or without carbon capture and storage), that are perceived as being less risky, in both safety and economics.

Waste Management

The radioactivity of nuclear waste presents waste management and facility contamination challenges that are unique to nuclear energy. Radioactivity builds up in a nuclear reactor in three primary ways: 1) through the accumulation of radioactive "fission products" that result from the splitting of fissile nuclei, 2) through the accumulation of radioactive "actinides" that form when heavy atoms in the reactor core absorb a neutron but do not undergo fission, and 3) through the generation of "activation products" in the coolant, moderator, or reactor components that occurs when these materials are made radioactive by absorbing neutrons. The vast majority of the initial radioactivity in nuclear waste comes from the fission products. Because of the long half-lives of some of these radioactive materials, nuclear waste poses long-term health hazards.[134]

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[130] DOE, *Investigating Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants*, INL/RPT-22-67964, September 2022, https://fuelcycleoptions.inl.gov/SiteAssets/SitePages/Home/C2N2022Report.pdf.

[131] Massachusetts Institute of Technology, "The Future of Nuclear Energy in a Carbon-Constrained World."

[132] The potential market for nuclear-supplied process heat could expand significantly if there were an increase in the demand for hydrogen for fuel cell vehicles or biomass-based synthetic fuels. (Massachusetts Institute of Technology, "The Future of Nuclear Energy in a Carbon-Constrained World.")

[133] Central heat for multiple buildings in a specified area.

[134] NRC defines "half life" as the "time in which one half of the atoms of a particular radioactive substance disintegrate into another nuclear form. Measured half-lives vary from millionths of a second to billions of years." See NRC glossary at https://www.nrc.gov/reading-rm/basic-ref/glossary/half-life.html.

In 2022, the U.S. inventory of spent nuclear fuel from commercial reactors exceeded 90,000 metric tons of uranium (MTU) at 74 sites. This is projected to rise at an average rate of approximately 1,800 MTU per year, based on the planned phaseout of the current reactor fleet, resulting in an estimated 137,000 MTU by 2050.[135] Because no long-term repository or consolidated storage facility for high-level nuclear waste has been licensed by NRC, newly discharged spent nuclear waste is currently stored onsite at nuclear plant locations.[136]

Unconventional reactors may offer some waste management advantages over existing commercial reactors. Fast reactors, and some other unconventional reactors, would be more effective at destroying actinides compared with commercial reactors. Actinides are responsible for the vast majority of the radioactive hazard that remains in nuclear waste after the first few centuries.[137] Reducing the prevalence of these long-lived waste products by transmuting them to short-lived radionuclides through reprocessing and recycling may reduce the health risk associated with a release of spent fuel that occurs far in the future (when storage containers may be more likely to fail).

In theory, by reducing the volume of this long-lived portion of the waste, smaller and fewer permanent geological repositories would be required, and the separated short-lived waste could be disposed of in landfills requiring stewardship for centuries rather than millennia. In practice, the reprocessing-related liquid radioactive waste (generally nitric acid raffinate with mixed fission products) have been technically difficult and expensive to manage. In the United States, where recycling/reprocessing has occurred at four major sites, primarily for defense purposes, the estimated environmental liability to stabilize, remediate, and provide stewardship is estimated at hundreds of billions of dollars, requiring more than 75 years of active remedial efforts.

Proponents of advanced nuclear technologies contend that future reprocessing plants would successfully treat waste for disposal as it is produced. However, it is unclear whether future advanced reactor technologies would improve on past handling of reprocessing wastes as much as proponents anticipate. As noted by the 2022 NASEM report, "The amounts and types of waste that will be generated by advanced reactors are difficult to estimate at this early stage of the development of advanced reactors; yet, this type of information is required in order to determine the impact of advanced reactors and advanced fuel cycles on the back end of the fuel cycle."[138]

Actinides are not the only long-lived nuclear wastes, however; some fission products remain radioactive hazards for hundreds of thousands of years and longer. The presence of these fission products in nuclear wastes might not be appreciably reduced by unconventional reactors. As a result, some have argued that, even if advanced reactors are able to deliver the improvements in

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[135] Oak Ridge National Laboratory, "CURIE," viewed November 28, 2022, https://curie.ornl.gov/map.

[136] The Nuclear Waste Policy Act (P.L. 97-425) designates the Yucca Mountain site in Nevada as the sole candidate site for a national repository, but no funds for licensing the Yucca Mountain repository have been appropriated since FY2010. A 20-year license for a storage facility in Utah was issued by NRC in 2006, but the facility was never built. NRC issued a license for a consolidated interim storage facility (CISF) in Texas on September 13, 2021, and is considering a license application for a CISF in New Mexico. See the NRC news release on the Texas CISF license at https://www.nrc.gov/reading-rm/doc-collections/news/2021/21-036.pdf. For more background, see CRS Report RL33461, *Civilian Nuclear Waste Disposal*, by Mark Holt.

[137] Radiactivity.eu.com, "Long-Lived Fission Products," 2023, https://radioactivity.eu.com/nuclearenergy/long_lived_fission_products.

[138] NASEM, *Management and Disposal of Nuclear Waste from Advanced Reactors*, p. 164.

actinide management that some advocates have claimed are possible, adoption of these reactors at scale would not materially alter the need for a long-term waste repository.[139]

Some advanced reactors would use new or non-conventional fuel forms, such as metallic fuels, dissolved molten fuels, or TRISO fuel. Some of these fuels pose additional waste management challenges as a result of their tendency to corrode storage containers or otherwise react with the environment in ways that complicate their safe storage and disposal. Gas-cooled reactors may produce large volumes of radioactive graphite waste, while sodium-cooled fast reactor fuel may require special treatment before safe disposal is possible. Fuel and coolant from molten salt reactors may remain volatile even after solidification. Research on the safe management and disposal of advanced reactor waste will be a key element in commercializing these technologies.[140]

Environmental Effects

Environmental impacts for any electric power source must be evaluated based on air emissions, water discharges, and waste management challenges, considering the full life cycle of the technology. The recent focus for nuclear power environmental impacts has been on air emissions, particularly its limited greenhouse gas footprint. Historically, however, much attention has been given to the waste management challenges associated with nuclear power. The environmental impacts of current LWR nuclear technologies are well studied. The stated goal of many advanced reactor technologies is to reduce environmental impacts. The impacts for newer advanced technologies would need to be evaluated on a case-by-case basis, and assessed empirically to determine whether the impacts are greater or less than current technologies, and whether advanced technologies eliminated any existing challenges in practice or raised new challenges requiring new technologies, regulatory systems, and support industries.

Nuclear energy is a low-carbon source of electricity, with no direct emissions from the fission process. As such, it is one of a number of energy technologies available for reducing the carbon emissions associated with electricity production (and potentially other uses of energy, such as industrial heat). The nuclear energy industry is not zero-carbon, however. Historically, fossil fuel-powered plants and equipment have provided energy to support the nuclear supply chain. Uranium enrichment facilities, in particular, have high energy requirements, and U.S. enrichment plants in the past used electricity primarily from coal-fired power plants. Current uranium enrichment plants use only a fraction of the electricity of older enrichment technology and are generally less reliant on coal-fired generation. A study by the DOE National Renewable Energy Laboratory of the life-cycle greenhouse gas emissions of major electric generating technologies found that conventional nuclear reactor emissions were similar to those of renewable energy technologies and only a fraction of coal and natural gas plant emissions.[141] Emissions of conventional air pollutants (e.g., sulfur oxides, nitrogen oxides, mercury, and particulates) from nuclear power operations and fuel cycle activities are similarly low.

Advanced reactors are expected to have similar life-cycle air emissions to those of existing reactors. Supporters of advanced reactor technologies contend that they could reduce the obstacles to nuclear power expansion related to cost, safety, waste management, and fuel supply

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[139] Krall and Macfarlane, "Burning Waste or Playing with Fire?"

[140] NASEM, *Management and Disposal of Nuclear Waste from Advanced Reactors*, p. 164.

[141] National Renewable Energy Laboratory, "Life Cycle Assessment Harmonization," February 13, 2019, https://www.nrel.gov/analysis/life-cycle-assessment.html.

and therefore allow nuclear power to play a greatly expanded role in worldwide greenhouse gas reduction strategies.

Some have argued that decarbonization goals could be achieved more effectively through improvements in existing light water reactor technologies. In particular, such a strategy could avoid additional waste management technical challenges and costs associated with the processing of radioactive waste from some types of advanced reactors. This could include the near-term management of potentially large volumes of low activity reprocessing waste.[142] On the other hand, as noted above, proponents of advanced reactor technologies contend that nuclear fuel recycling/reprocessing could reduce the long-term radioactivity of nuclear waste and produce waste forms more resistant to deterioration than LWR spent fuel.[143]

Plants with higher thermal efficiencies reject less heat into the environment per kilowatt-hour (KWh) of electricity generated. This can help reduce ecosystem impacts related to heat rejection. For example, increased efficiency may contribute to significant reductions in the amount of water used for waste heat rejection (up to 50% less)[144] per unit of electricity generated, and reduce the amount of heat absorbed by adjacent water bodies. This could have particularly significant implications for the use of nuclear energy in arid environments.

DOE Nuclear Energy Programs

The Department of Energy supports the development of advanced nuclear technologies through research and development (R&D) programs housed in several DOE offices: particularly the Office of Nuclear Energy, the Office of Science, and the Office of Clean Energy Demonstrations.[145] The Advanced Research Projects Agency—Energy (ARPA-E) also provides funding for early stage R&D for advanced nuclear projects, and the National Nuclear Security Administration (NNSA) funds inertial confinement fusion research primarily for defense purposes. Collectively, nuclear R&D programs (including advanced fission and fusion) received about 29% of funding for energy R&D in fiscal year (FY) 2023 (see **Table 4**).

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[142] Krall and Macfarlane, "Burning Waste or Playing with Fire?"

[143] This issue is discussed in more detail at NASEM, *Management and Disposal of Nuclear Waste from Advanced Reactors*, p. 164.

[144] Massachusetts Institute of Technology, "The Future of Nuclear Energy in a Carbon-Constrained World."

[145] Activities related to the development of advanced nuclear technologies may also receive direct or indirect support and funding from other DOE programs and accounts, including through budgets for facilities management, environmental management, and others. This report focuses on funding provided for R&D through the congressional appropriations process.

Table 4. FY2023 Energy R&D Appropriations

$ in Millions

	All Other Energy R&D					Nuclear			ARPA-E
	Renewables	Fossil	Energy Efficiency and Vehicles	Electric Systems	Demonstration	Fission	Reactor Demonstration	Fusion	Any Energy Type
Regular appropriations	792	890	1,687	164	89	1,323	285	1,393	470
Supplementals	300	1,444	110		3,826	100	800		
Total	1,092	2,234	1,797	164	3,915	1,423	1,085	1,393	470
Percent	8%	17%	13%	1%	29%	10%	8%	10%	3%
Class %	68%					29%			3%

Source: Explanatory statement for Consolidated Appropriations Act, 2023; P.L. 117-58.

Notes: Includes appropriations for programs and activities related primarily to R&D. Fusion includes defense programs. Includes R&D-related FY2023 emergency supplemental appropriations for DOE programs in the Infrastructure Investment and Jobs Act (P.L. 117-58) and additional FY2023 appropriations in P.L. 117-328 Division M. Excludes FY2022 appropriations in P.L. 117-169 for DOE national laboratory infrastructure available through FY2027.

Office of Nuclear Energy

The Office of Nuclear Energy (NE) "focuses on three major mission areas: the nation's existing nuclear fleet, the development of advanced nuclear reactor concepts, and fuel cycle technologies," according to DOE's FY2023 budget justification.[146] NE primarily supports nuclear fission technologies at all stages of development, ranging from lab-scale experiments and computer modeling to technology demonstration and support. Five advanced reactor demonstration projects—two of which are to begin operating by around 2030—were initially funded by NE and are transitioning to DOE's Office of Clean Energy Demonstrations (OCED).

In FY2023, Congress appropriated $2.508 billion for DOE nuclear energy programs in NE and OCED.[147] These include the following:

- *Nuclear Energy Enabling Technologies*: $96 million, includes crosscutting technology development, modeling and simulation, and nuclear science user facilities;
- *Fuel Cycle Research and Development*: $422 million, includes HALEU fuel availability, TRISO fuel qualification, and waste management R&D;
- *Reactor Concepts Research, Development, and Deployment:* $259 million, includes advanced SMR RD&D and advanced reactor technologies; and
- *Advanced Reactor Demonstration Program:* $1.085 billion (including supplemental appropriations), provides 50% cost sharing for two near-term demonstration projects and 80% cost-sharing for three longer-term projects for potential demonstration, as well as support for an advanced reactor licensing framework and the National Reactor Innovation Center at INL.

To support private-sector nuclear energy innovation, DOE's Gateway for Accelerated Innovation in Nuclear (GAIN) initiative, begun in 2016, provides enhanced access to DOE's network of national labs and nuclear R&D capabilities, as well as through competitive industry funding opportunities. A major industry funding mechanism under GAIN is the Nuclear Energy Voucher Program, which provides industry awardees with access to DOE nuclear expertise and capabilities in the form of vouchers redeemable for research and technical support activities at one of DOE's national laboratories. Recipients are required to provide a 20% minimum cost-share.[148]

Office of Science

Support for fusion research is provided by the Fusion Energy Sciences (FES) program in DOE's Office of Science. FES focuses its research on magnetic confinement of plasmas (matter in which electrons have been stripped away from atomic nuclei) to potentially create a "sustainable fusion

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[146] DOE, *FY2023 Congressional Budget Justification*, vol. 4, "Nuclear Energy," March 2022, https://www.energy.gov/sites/default/files/2022-04/doe-fy2023-budget-volume-4-ne.pdf.

[147] Joint Explanatory Statement on the Consolidated Appropriations Act, 2023, Division D—Energy and Water Development and Related Agencies Appropriations Act, 2023. Includes $300 million for the DOE Nuclear Energy account in Division M—Additional Ukraine Supplemental Appropriations Act, 2023, and $600 million for ARDP in IIJA. Excludes $150 million for Idaho sitewide security.

[148] Not all Nuclear Energy Vouchers are awarded for advanced nuclear projects. Some projects are focused on innovations to existing light water reactor technologies and related purposes. For more information, visit GAIN's NE Vouchers website at https://gain.inl.gov/SitePages/Nuclear%20Energy%20Vouchers.aspx.

energy source."[149] Congress appropriated $763 million for FES in FY2023, including $242 million for the U.S. contribution to the ITER fusion project, as discussed above.

National Nuclear Security Administration

NNSA's Inertial Confinement Fusion program conducts experiments at Lawarence Livermore National Laboratory's National Ignition Facility (NIF) and other facilities to create miniature fusion reactions similar to those in nuclear weapons and stars.[150] The program received appropriations of $630 million in FY2023.

ARPA-E

ARPA-E invests in early-stage energy technologies with high potential for transformational impact, currently including several research programs involving advanced nuclear technologies. The Modeling-Enhanced Innovations Trailblazing Nuclear Energy Reinvigoration program (MEITNER), begun in 2018, has since its creation funded nine projects to develop "technologies to enable lower cost, safer advanced nuclear plant designs." The Galvanizing Advances in Market-Aligned Fusion for an Overabundance of Watts (GAMOW), begun in 2020, has funded 14 projects since its creation. The Generating Electricity Managed by Intelligent Nuclear Assets (GEMINA) program, begun in 2019, has nine projects to "develop digital twin technology for advanced nuclear reactors and transform operations and maintenance (O&M) systems in the next generation of nuclear power plants."[151]

Offices of Environmental Management and Legacy Management

The DOE's Office of Environmental Management (EM) and Office of Legacy Management (LM) provide a variety of functions supporting advanced reactor R&D.

First, EM provides waste management services for ongoing advanced reactor R&D activities. For example, EM manages the spent nuclear fuel from the Advanced Test Reactor at the Idaho National Laboratory. DOE describes the Advanced Test Reactor as "the only U.S. research reactor capable of providing large-volume, high-flux neutron irradiation in a prototype environment … to study the results of years of intense neutron and gamma radiation on reactor materials and fuels for … research and power reactors."[152]

Second, EM funds and manages environmental remediation and decontamination and decommissioning for several advanced reactor facilities, including the Energy Technology Engineering Center at the Santa Susana Field Laboratory in California, various facilities at the Idaho National Laboratory, and the Hanford site in the state of Washington. At Hanford, EM has conducted decontamination and decommissioning activities at the Fast Flux Test Facility (FFTF) since 1992, which operated for 10 years (1982-1992) as a 400 MWt liquid-metal (sodium)-cooled nuclear research and test reactor to develop and test advanced fuels and materials for the Liquid Metal Fast-Breeder Reactor Program.

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[149] DOE Office of Science, "Fusion Energy Sciences (FES)," https://science.osti.gov/fes.

[150] Lawrence Livermore National Laboratory, "NIF and Stockpile Stewardship," https://lasers.llnl.gov/science/nif-and-stockpile-stewardship.

[151] ARPA-E, "Search Our Programs," https://arpa-e.energy.gov/technologies/programs. The keyword "nuclear" and technical category "generation" were used to find programs related to advanced nuclear technology.

[152] Department of Energy, *Office of Chief Financial Officer; FY2020 Congressional Budget Request Volume 5*; Environmental Management, DOE/CF-0155; at p. 73 (March 2019).

Third, EM funds facility overhead operations for facilities where advanced reactor R&D is occurring or planned. “Overhead” costs can include infrastructure maintenance (e.g., power, water, roads, bridges), site safeguards and security, worker health and safety, and program direction and administration. For example, EM funds site overhead costs at the Hanford Site, home of Pacific Northwest Laboratory.

Congressional Issues

Role of the Federal Government in Technology Development

What is the appropriate level of federal support for each stage of technology development? That is a fundamental question in the longstanding national debate over R&D policy writ large. For nuclear energy technology development, major stages include research on fuels and materials, development of reactor concepts and designs, component testing and evaluation, licensing by NRC, demonstration, and commercialization. Typically, the earliest stages of development involve laboratory-scale work and computer modeling and simulation, some of which may be relatively inexpensive and applicable to a broad range of nuclear technology. The later stages focus on specific reactor designs and require construction of full- or nearly full-scale nuclear power plants potentially costing billions of dollars. Even early-stage nuclear research often requires the construction and operation of test reactors, shielded hot cells for remote handling of intensely radioactive materials, and other expensive facilities and infrastructure.

A 2023 report by the Nuclear Innovation Alliance called for DOE to support a “diverse selection of early-stage advanced nuclear energy technologies” to lay the groundwork for demonstration and commercialization of those that prove most promising. By giving these technologies “several rounds of funding in small increments,” DOE would develop “a technology portfolio that sorts a large number of ideas according to their level of feasibility.” This approach, according to the report, “increases the likelihood that a greater number of viable technologies will emerge for DOE to select from for demonstrations.”[153]

The 116th and 117th Congresses—along with the Trump and Biden administrations—accelerated funding for all stages of advanced nuclear reactor development, and particularly for the expensive demonstration phase. In 2021, Congress appropriated through the IIJA $2.477 billion for the Advanced Reactor Demonstration Program (divided in annual amounts through FY2025, to remain available until expended), in addition to regular DOE appropriations for the program. Funding for DOE’s Nuclear Energy account in annual appropriations bills steadily rose from $1.493 billion in FY2020 to $1.773 billion in FY2023 (up 18%).[154] “Nuclear energy is a key element of the President’s plan to put the United States on a path to net-zero emissions by 2050,” according to DOE’s FY2023 budget justification. Interest in advanced nuclear reactors, including oversight of previously appropriated funding, is likely to continue in the 118th Congress.

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[153] Nuclear Innovation Alliance, *Transforming the U.S. Department of Energy: Paving the Way to Commercialize Advanced Nuclear Energy*, January 2023, p. 19, https://nuclearinnovationalliance.org/transforming-us-department-energy-paving-way-commercialize-advanced-nuclear-energy.

[154] Annual appropriations acts for FY2020 through FY2023, CRS, Appropriations Status Table,” https://www.crs.gov/AppropriationsStatusTable/Index.

Perceived Need for Advanced Nuclear Power and Competing Alternatives

EIA projects that world electricity generation will grow by more than 40% between 2020 and 2040. While renewable energy and nuclear power are projected to rise substantially during that period, fossil fuels would still constitute about 40% of total generation if current policies and trends continue.[155] Proponents of unconventional nuclear power contend that advanced reactors could mitigate the concerns about safety, cost, radioactive waste, weapons proliferation, and fuel supply that are seen as inhibiting greater utilization of nuclear energy. Under that view, advanced nuclear technology would be indispensable for meeting the world's rapidly increasing demand for electricity without emitting greenhouse gases.

"In the 21st century the world faces the new challenge of drastically reducing emissions of greenhouse gases while simultaneously expanding energy access and economic opportunity to billions of people," according to a 2018 study by the Massachusetts Institute of Technology. The study found that the cost of worldwide greenhouse gas reductions could be minimized by the deployment of lower-cost nuclear generation.[156] A 2021 IAEA report asserted, "Nuclear energy is key to achieving global net zero objectives, working in partnership with renewable energy sources and other low carbon options, as part of a sustainable energy system to decarbonize electricity and non-electric energy production."[157]

That finding is disputed by various environmental and other groups that contend that a combination of renewable energy and efficiency is the lowest-cost option for eliminating greenhouse gas emissions and could be implemented more quickly. "With technology already available, renewable energy sources like wind, solar, and geothermal can provide 96 percent of our electricity and 98 percent of heating demand—the vast majority of U.S. energy use," according to the environmental advocacy group Greenpeace USA.[158] Some environmental groups contend that the safety and other risks posed by nuclear energy make it unacceptable in any case, even with advanced technology. The Nuclear Information and Resource Service advocacy group says, "There is nothing environmentally friendly about nuclear power. It only creates different environmental problems than fossil fuel energy sources. But neither fossil fuels nor nuclear power are safe, sustainable, or healthy for humans and the environment."[159]

Germany adopted a policy after the 2011 Fukushima disaster to greatly reduce carbon emissions through renewable energy and efficiency while eliminating nuclear power. The policy, called "Energiewende," or energy transition, calls for Germany's consumption of primary energy (the initial energy content of fuels and other energy sources) to be reduced by 50% in 2050 from its 2008 level, while greatly increasing the use of renewable energy throughout the economy. According to the German government, "By 2050 renewable energies should make up 60 percent of the gross final consumption of energy, and 80 percent of the gross electricity consumption."[160]

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[155] Energy Information Administration, *International Energy Outlook 2021*, October 2021, Table E1.gen, electricity generation: World, Reference case, https://www.eia.gov/outlooks/ieo/tables_side_xls.php.

[156] Massachusetts Institute of Technology, "The Future of Nuclear Energy in a Carbon-Constrained World."

[157] IAEA, *Nuclear Energy for a Net Zero World,* September 2021, https://www.iaea.org/sites/default/files/21/10/nuclear-energy-for-a-net-zero-world.pdf.

[158] Greenpeace USA, "Fighting Global Warming," November 21, 2018, https://www.greenpeace.org/usa/global-warming/.

[159] Nuclear Information and Resource Service, "Nuclear Energy Frequently Asked Questions," November 21, 2018, https://www.nirs.org/basics-of-nuclear-power/nuclear-power-frequently-asked-questions/.

[160] German Federal Ministry of Education and Research, "German Energy Transition," viewed December 22, 2022,

A 2017 study by an academic team developed "roadmaps" for 139 countries to convert to 100% renewable energy by 2050. The study concluded that renewable energy production could be expanded with more certainty than nuclear and other non-emitting sources.[161] In response to the loss of natural gas supplies caused by Russia's invasion of Ukraine in February 2022, Germany has delayed the permanent shutdown of its final three operating reactors until April 2023 and has reopened some coal-fired power plants.[162]

The National Renewable Energy Laboratory issued a study in 2012 of the impact of increasing U.S. renewable electricity generation to up to 90% by 2050. The study found that renewables could "adequately supply 80% of total U.S. electricity generation in 2050," with nuclear, coal, and gas supplying the remaining 20%. Nuclear power plants were projected to be located almost entirely east of the Mississippi River for economic and other reasons.[163]

DOE Hosting of Private-Sector Experimental Reactors

NEICA authorizes DOE to host privately funded experimental and demonstration reactors, with the expectation that reactor developers could benefit from the expertise and facilities at DOE national laboratories. Safety oversight of private-sector experimental reactors at national laboratories could possibly be conducted by DOE and not require NRC licensing,[164] but NEICA specifies that reactors intended to demonstrate commercial suitability would require NRC licenses, even at DOE sites.

NEICA added Section 958 to the Energy Policy Act of 2005 (P.L. 109-58), which authorizes a DOE National Reactor Innovation Center (NRIC). This program would "enable the testing and demonstration of reactor concepts to be proposed and funded, in whole or in part, by the private sector." Such testing and demonstration would take place at DOE national laboratories or other Department-owned sites. In implementing the NRIC program, DOE is required to coordinate with NRC on sharing technical expertise on the advanced reactor technologies under development.

DOE signed an agreement on February 17, 2016, with UAMPS to provide a potential site for a first-of-a-kind NuScale SMR plant at INL, called the Carbon Free Power Project. Under the agreement, UAMPS is to identify a suitable location at the 890-square-mile INL site, with DOE's concurrence, for construction of the plant.[165] NRC published its final design certification rule for a NuScale plant with up to a dozen 50 MWe modules on January 19, 2023.[166] On January 4, 2023,

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https://www.bmbf.de/bmbf/en/research/energy-and-economy/german-energy-transition/german-energy-transition_node.html.

[161] Mark Z. Jacobson et al., "100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World," *Joule*, September 6, 2017, http://web.stanford.edu/group/efmh/jacobson/Articles/I/CountriesWWS.pdf.

[162] World Nuclear Association, "Nuclear Power in Germaney," October 2022, https://world-nuclear.org/information-library/country-profiles/countries-g-n/germany.aspx; Robert Bryce, "The Iron Law of Electricity Strikes Again: Germany Re-Opens Five Lignite-Fired Power Plants," *Forbes*, October 28, 2022, https://www.forbes.com/sites/robertbryce/2022/10/28/the-iron-law-of-electricity-strikes-again-germany-re-opens-five-lignite-fired-power-plants.

[163] National Renewable Energy Laboratory, *Renewable Energy Futures Study*, 2012, https://www.nrel.gov/analysis/re-futures.html.

[164] Todd Garvey, "NRC Licensing of Proposed DOE Nuclear Facilities," memorandum for the House Committee on Science, Space, and Technology, July 20, 2015, https://docs.house.gov/meetings/SY/SY20/20150729/103833/HHRG-114-SY20-20150729-SD009.pdf.

[165] U.S. Department Of Energy Use Permit No. DE-NE700065, February 17, 2016, https://www.id.energy.gov/insideneid/PDF/DOE_UAMPS%20Use%20Permit%20DE-N700065.pdf.

[166] NRC, "NuScale Small Modular Reactor Design Certification," 88 *Federal Register* 3287, January 19, 2023,

NuScale announced its submission of an application to NRC for standard design approval of a plant with six 77 MWe modules.[167]

Funding of Demonstration Reactors

A crucial stage in the commercialization of nuclear technology is the construction of demonstration reactors, which are expected to cost several billion dollars apiece, depending on their size and level of technical maturity. For example, in 2022, the Natrium demonstration plant and its separate fuel fabrication facility were estimated to cost $4 billion to construct.[168] Including the demonstration stage, bringing a new reactor technology to the market could require up to 30 years and cost up to $15 billion, according to one estimate.[169]

DOE has a range of options for supporting the construction of demonstration reactors and helping bring them to the commercial market.

Cost Sharing

DOE can carry out technology demonstration projects on a cost-shared basis under Section 988 of the Energy Policy Act of 2005 (P.L. 109-58). At least 50% of demonstration costs must come from nonfederal sources, although the Secretary of Energy can reduce the nonfederal share based on technological risk and other factors. Repayment of the federal contribution is not required. In addition to construction costs, federal cost sharing can apply to licensing, design work, and "first of a kind" engineering, such as assistance previously provided to NuScale under the DOE small modular reactor licensing technical support program. As discussed above, under ARDP, DOE is providing up to 50% of the costs for two demonstration plants and up to 80% of the cost for five technologies for possible future demonstration.

Full Funding

Construction of research and test reactor facilities to be owned by DOE may be completely funded through congressional appropriations, with users of the facility paying to conduct research (sometimes with DOE grants or vouchers). DOE's proposed Versatile Test Reactor at INL would produce fast neutrons to test reactor fuels and materials and would also demonstrate the PRISM technology being used for the Natrium reactor demonstration project in Wyoming.[170] However, the Versatile Test Reactor project received no appropriations in FY2022 or FY2023.[171]

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https://www.govinfo.gov/content/pkg/FR-2023-01-19/pdf/2023-00729.pdf.

[167] NuScale, "NuScale Builds Upon Unparalleled Licensing Progress With Second Standard Design Approval Application Submittal," news release, January 4, 2023, https://www.nuscalepower.com/en/news/press-releases/2023/nuscale-builds-upon-unparalleled-licensing-progress-with-second-standard-design-approval. See also NRC, "Standard Design Approval (SDA) Application—NuScale US460," September 15, 2022, https://www.nrc.gov/reactors/new-reactors/smr/licensing-activities/pre-application-activities/nuscale-720-sda.html.

[168] TerraPower, "Frequently Asked Questions," viewed January 5, 2022, https://natriumpower.com/frequently-asked-questions.

[169] Massachusetts Institute of Technology, "The Future of Nuclear Energy in a Carbon-Constrained World."

[170] DOE, "Versatile Test Reactor Fact Sheet," October 7, 2019, https://www.energy.gov/ne/articles/versatile-test-reactor-fact-sheet.

[171] *Congressional Record*, December 20, 2022, p. S8377, https://www.congress.gov/117/crec/2022/12/20/168/198/CREC-2022-12-20.pdf.

Federal Payments for Power and Research Use

The federal government can purchase power generated by demonstration reactors and also pay for research use of the reactors. For the proposed NuScale demonstration, DOE announced a memorandum of understanding (MOU) in December 2018 with UAMPS, which would own the plant, to purchase power from one of the plant's modules and use another module for research. However, the MOU was superseded by DOE's agreement in 2020 to provide up to $1.4 billion toward the plant's construction costs.[172] Federal payments for power are discussed in more detail below in the section on "Power Purchase Agreements."

Loan Guarantees

DOE can issue loan guarantees to build advanced nuclear reactors under Title XVII of the Energy Policy Act of 2005. DOE currently has $10.9 billion in loan guarantee authority available for advanced nuclear energy projects.[173] To receive a DOE loan guarantee, projects must be found financially viable and they must pay an up-front fee called a "subsidy cost." The subsidy cost is the present value of the government's potential cost of the loan guarantee that could result from future loan defaults. A project considered to be relatively risky would be assessed a relatively high subsidy cost. Title XVII loan guarantees cannot be given to projects that would use federal funds other than the federally guaranteed funding (P.L. 111-8, Division C). DOE has awarded $12 billion in Title XVII loan guarantees for the construction of two new reactors at the Vogtle nuclear power plant in Georgia.[174]

Tax Credits

Inflation Reduction Act (IRA) Section 13701 established tax credits for nuclear power plants and other zero-emission generating facilities (as defined in the law) placed into service after 2024 (26 U.S.C. §45Y). Eligible plants can receive a 10-year electricity production tax credit of up to 2.6 cents/kilowatt-hour (adjusted for inflation) or a 30% investment tax credit. Developers of the planned NuScale plant at INL expect the investment tax credit to reduce the project's estimated $9.3 billion construction cost (including interest) by about $3 billion.[175] IRA also created a production tax credit for existing nuclear plants. These IRA credits are not available to nuclear plant owners taking the Section 45J credit described below.[176]

Under 26 U.S.C. §45J, power plants using advanced nuclear technology are eligible for a federal tax credit of 1.8 cents per kilowatt-hour of electricity generated. This credit was established by

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[172] Department of Energy, "DOE Office of Nuclear Energy Announces Agreement Supporting Power Generated from Small Modular Reactors," December 21, 2018, https://www.energy.gov/ne/articles/doe-office-nuclear-energy-announces-agreement-supporting-power-generated-small-modular; Taxpayers for Common Sense, *Doubling Down: Taxpayers' Losing Bet on NuScale and Small Modular Reactors*, December 2021, p 12, https://www.taxpayer.net/wp-content/uploads/2021/12/TCS_Doubling-Down-SMR-Report_Dec.-2021.pdf.

[173] DOE Loan Programs Office, *Federal Loan Guarantees for Innovative Clean Energy: Nuclear*, loan guarantee solicitation announcement, April 18, 2022, https://www.energy.gov/sites/default/files/2022-04/DOE-LPO_Innovative_Clean_Energy_Nuclear_Loan_Guarantee_Solicitation_18Apr22.pdf.

[174] DOE, "Secretary Perry Announces Financial Close on Additional Loan Guarantees During Trip to Vogtle Advanced Nuclear Energy Project," news release, March 22, 2019, https://www.energy.gov/articles/secretary-perry-announces-financial-close-additional-loan-guarantees-during-trip-vogtle.

[175] Michael McAuliffe, "NuScale Extends Cost Guarantees to Owners of First US SMR Plant," *Nucleonics Week*, January 18, 2023, p. 1.

[176] For more details, see CRS Report R47202, *Tax Provisions in the Inflation Reduction Act of 2022 (H.R. 5376)*, coordinated by Molly F. Sherlock.

the Energy Policy Act of 2005 (P.L. 109-58) and extended by the Bipartisan Budget Act of 2018 (P.L. 115-123). The 45J nuclear production tax credits do not have an expiration date, but total credits are limited to 6,000 MW of capacity, limited to $125 million per year per 1,000 MW of capacity for eight years of operation. The availability of 45Y and 45J tax credits could help nuclear demonstration projects procure financing and reduce the subsidy cost of any DOE loan guarantees.

Choosing Projects for Federal Funding

The multibillion-dollar cost of nuclear demonstration projects makes it unlikely that the federal government would support demonstrations of all the advanced nuclear technologies currently under development. As noted, Congress to date has authorized two ARDP demonstration projects and five potential future demonstrations. DOE has also agreed to support the Carbon Free Power Project at INL subject to congressional appropriations. In selecting applicants to receive the two ARDP demonstration awards, DOE used the following weighted criteria:[177]

- technical feasibility that a demonstration reactor can be operational within seven years (30%);
- likelihood that the proposed design can be licensed by NRC (20%);
- strength of project management processes (15%);
- cost-competitiveness in the commercial market (20%); and
- technical abilities and qualifications of the project team (15%).

A longstanding concern with federal support for energy demonstration projects is that it could put DOE in the position of "picking winners" and undermine market efficiency. The ARDP selection process has some market-based elements, such as the 50% matching requirement, and the cost-competitiveness selection criterion. Another market-based criterion could be evidence of a customer base, which could include letters of intent for future orders (perhaps conditioned on successful demonstration). The potential goal of demonstrating the widest possible range of advanced technologies might also be a consideration. Other potential factors are described in the above section on "Major Criteria for Evaluating Unconventional Technologies."

Licensing Framework for New Technologies

The U.S. nuclear industry has argued that current NRC procedures for reviewing and licensing new nuclear reactors are overly burdensome and inflexible, contributing to high regulatory costs and long reviews.[178] Existing licensing pathways and safety regulations, which tend to be based on conventional LWR designs, are not necessarily well-suited to accommodate newer, advanced reactors. Consequently, industry groups and some outside experts have argued for a transition to a technology-neutral regulatory framework, a process which these groups have estimated may take up to five years to complete. The industry has also called for greater flexibility to make design changes during reactor construction without triggering regulatory delays.[179]

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[177] DOE, "Advanced Reactor Demonstration," Funding Opportunity Number DE-FOA-0002271, May 14, 2020, p. 44, under "related documents" at https://www.grants.gov/web/grants/view-opportunity.html?oppId=326997.

[178] Nuclear Innovation Alliance, Nuclear Energy Institute, and Nuclear Infrastructure Council, "Ensuring The Future of US Nuclear Energy: Creating A Streamlined And Predictable Licensing Pathway To Deployment," January 23, 2018. https://www.nei.org/resources/reports-briefs/ensuring-the-future-of-us-nuclear-energy.

[179] Ibid.

To provide the “regulatory processes necessary to allow innovation and the commercialization of advanced nuclear reactors,” NEIMA includes several provisions on advanced nuclear reactor licensing. In the near term, NRC is required to establish “stages in the licensing process for commercial advanced nuclear reactors,” which would allow license applicants to gain formal approval for completing each step in the licensing process, such as a conceptual design assessment. A 2016 industry report recommending staged licensing noted that such a process is currently used in Canada and the United Kingdom. “The step-wise pre-licensing design review processes in Canada and the UK provide earlier opportunities for reactor vendors to demonstrate to their investors and potential investors that the reactor design technology will be licensable,” according to the report.[180]

NEIMA also requires NRC to develop procedures for using “licensing project plans,” which are described by the committee report as “agreements between the agency and applicants early in the application process that reflect mutual commitments on schedules and deliverables to support resource planning for both the agency and the applicant.”[181] NRC must also increase the use of risk-informed and performance-based licensing evaluation techniques “within the existing regulatory framework.” Using such techniques, the evaluation of specific safety and other issues would be informed by the calculated level of risk, and performance standards would be used to evaluate safety, “when appropriate,” rather than specific reactor design requirements.

NEIMA requires NRC to issue a “technology-inclusive” regulatory framework for optional use by advanced reactor applicants. As noted above, NRC regulations currently focus on light water reactors, which are the only commercial reactors currently used in the United States. NRC also must issue a report that would include an evaluation of the need for additional legislation to implement such a regulatory framework.

NRC is preparing a “Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors” to be consistent with the NEIMA requirements. NRC staff issued preliminary proposed rule language to implement the regulatory framework in May and June of 2022. The new regulatory framework, to be codified at 10 C.F.R. Part 53, is currently scheduled to be issued as a final rule by July 2025.[182]

New nuclear fuels are also subject to NRC regulation. Depending on the design, it can take up to six years to develop, test, and license new fuels.[183] Transporting these new fuel forms may require additional innovation and regulation. NRC published regulatory guidance on “Fuel Qualification for Advanced Reactors” in March 2022. The guidance notes that a qualification methodology for molten salt reactor fuel is under development.[184]

The nuclear industry has contended that fees charged by NRC for reviewing reactor designs, new fuels, and license applications constitute a significant obstacle to advanced reactor deployment, particularly by relatively small, independent companies. NEICA authorizes DOE to provide

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[180] Nuclear Innovation Alliance, *Enabling Nuclear Innovation: Strategies for Advanced Reactor Licensing*, April 2016, p. 20, https://docs.wixstatic.com/ugd/5b05b3_71d4011545234838aa27005ab7d757f1.pdf.

[181] Senate Committee on Environment and Public Works, S.Rept. 115-86, May 25, 2017, p. 9.

[182] Nuclear Regulatory Commission, “Part 53—Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors,” October 4, 2022, https://www.nrc.gov/reactors/new-reactors/advanced/rulemaking-and-guidance/part-53.html.

[183] Nuclear Energy Institute, “Roadmap for the Deployment of Micro-Reactors for U.S. Department of Defense Domestic Installations,” October 4, 2018.

[184] NRC, “Fuel Qualification for Advanced Reactors,” March 2022, https://www.nrc.gov/docs/ML2206/ML22063A131.pdf.

grants to advanced reactor license applicants to cover some of their NRC fees throughout the licensing process. DOE grants for advanced reactor demonstrations include NRC licensing costs necessary for initial operation.[185]

Power Purchase Agreements

Federal agency agreements to purchase power from advanced reactors could substantially improve the financial feasibility of such projects, both at the demonstration and commercialization stages. Such power purchase agreements (PPAs) would provide a projected revenue stream that could help advanced reactor projects obtain financing and potentially reduce their financing costs. Federal agencies could also offer above-market prices for the power to encourage commercialization of nuclear technologies, if authorized by Congress.

A bill introduced in the 117th Congress (H.R. 4834) would have required DOE to enter into at least one contract to purchase power from a new nuclear power plant for up to 40 years, an increase from the current limit of 10 years. Bills introduced in the 116th Congress (S. 903, H.R. 3306) would have authorized the General Services Administration (GSA) to enter into PPAs for up to 40 years. Under 40 U.S.C. §501, GSA can delegate all or part of this authority to other agencies.[186]

Electricity payments during a PPA contract period, along with any other customer revenues, are intended to be sufficient to allow the power plant developer to recover its construction and other costs, plus a profit, if applicable. The proposed lengthening of the 10-year limit on PPAs was intended to allow enough time for nuclear reactor construction costs to be recovered, according to the legislation's sponsors.[187] The bills would have allowed federal PPAs with advanced reactors that met certain criteria to pay electricity rates above the average market rate. Federal PPAs of any duration are subject to cancellation each year if sufficient funds are not appropriated by Congress, and to cancellation at any time for the convenience of the government.[188]

DOE's Western Area Power Administration (WAPA), which markets electricity from federal dams and other projects in much of the Western United States, has the authority to sign power sale contracts for up to 40 years (43 U.S.C. §485h(c)). This authority could potentially facilitate PPAs for demonstration reactors at INL or elsewhere in the WAPA service area. According to a 2017 report produced for DOE, "A federal agency located within WAPA's jurisdiction may leverage WAPA's long-term contract authority by entering into an Interagency Agreement with

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[185] DOE, "Advanced Reactor Demonstration," p. 7. TerraPower makes this statement on its website: "The goal of the demonstration pathway is to test, license and build operational advanced reactors within seven years. Under this public-private partnership, the Department of Energy authorizes up to $2 billion for the Natrium project and TerraPower and partners will match this investment dollar for dollar." Natrium, "Frequently Asked Questions, U.S. Government Support," https://natriumpower.com/frequently-asked-questions/#us-government-support.

[186] According to GSA, authority has been delegated to the Department of Defense and the Department of Energy for all utility services, and to the Department of Veterans Affairs for connection charges only. For more information, see GSA, *Procurement Guide for Public Utility Services: A Practical Guide to Procuring Utility Services for Federal Agencies, 2015*, pp. 7-8, https://www.gsa.gov/cdnstatic/Utility_Areawide_Guide_08-2015.pdf. See also 48 C.F.R. §41.103, Statutory and Delegated Authority.

[187] "Nuclear Energy Leadership Act Section-by-Section," posted on the Senate Energy and Natural Resources Committee website, https://www.energy.senate.gov/public/index.cfm?a=files.serve&File_id=5DBB1AFE-D9AF-4AF4-817B-C2DFFF7683AF.

[188] Seth Kirshenberg and Hilary Jackler, *Purchasing Power Produced by Small Modular Reactors: Federal Agency Options*, report for DOE Office of Nuclear Energy, January 2017, p. 24, https://www.energy.gov/sites/prod/files/2017/02/f34/Purchasing%20Power%20Produced%20by%20Small%20Modular%20Reactors%20-%20Federal%20Agency%20Options%20-%20Final%201-27-17.pdf.

WAPA and allowing WAPA, in turn, to enter into a PPA with a power provider on such federal agency's behalf for a term of up to 40 years."[189] Under that scenario, WAPA could reach an interagency agreement with a military base in California under which WAPA would award a 40-year PPA on behalf of the base to a demonstration reactor at INL and then deliver the power to the base.

Advanced Reactor Fuel Availability

Many advanced reactors would use fuels that are not currently commercially available in the United States, either due to lack of demand or technological immaturity. These include higher-enriched versions of existing uranium fuel as well as new types of fuels that are currently under development. Without near-term investment in fuel processing and fabrication capabilities, there may be insufficient supply of next generation fuels to support the deployment of some advanced reactors.

As noted previously, particular concern has been raised about the availability of HALEU, which would be necessary for many advanced reactor concepts. Because HALEU is not used in existing commercial reactors, it is not readily available for advanced reactor development and demonstration, and potentially useable federal government stockpiles are mostly committed to defense and other national priorities, according to DOE.[190]

The only current commercial source of HALEU is Russia, which had been expected to supply the initial fuel for some advanced reactor demonstrations. But according to TerraPower, "As a result of the invasion in Ukraine, this is no longer a viable approach and the urgency to develop domestic advanced fuel infrastructure has been thrust to the forefront."[191]

DOE estimates that "more than 40 metric tons of HALEU will be needed by 2030" to provide the initial fuel for currently planned advanced reactors.[192] Section 2001 of the Energy Act of 2020 requires DOE to implement a program to "support the availability" of HALEU for civilian use, including establishment of an industry consortium to provide information about HALEU needs, purchase HALEU for consortium members, and carry out HALEU demonstration projects. DOE established the consortium on December 7, 2022, and invited eligible entities to apply for membership.[193]

DOE is currently pursuing two approaches for developing HALEU supplies. One approach is to produce about 10 metric tons of HALEU from DOE-owned material currently stored at INL.[194] In

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[189] Ibid., p. 36.

[190] DOE, "Request for Information (RFI) Regarding Planning for Establishment of a Program to Support the Availability of High-Assay Low-Enriched Uranium (HALEU) for Civilian Domestic Research, Development, Demonstration, and Commercial Use," 86 *Federal Register* 71055, December 14, 2021, https://www.federalregister.gov/documents/2021/12/14/2021-26984/request-for-information-rfi-regarding-planning-for-establishment-of-a-program-to-support-the.

[191] TerraPower, "Nuclear Energy Needs a Domestic HALEU Supply Chain," August 12, 2022, https://www.terrapower.com/nuclear-energy-needs-a-domestic-haleu-supply-chain.

[192] DOE, "U.S. Department of Energy Seeks Input on Creation of HALEU Availability Program," December 14, 2021, https://www.energy.gov/ne/articles/us-department-energy-seeks-input-creation-haleu-availability-program.

[193] DOE, "Notice of Establishment: High-Assay Low-Enriched Uranium (HALEU) Consortium," 87 *Federal Register* 75048, December 7, 2022, https://www.federalregister.gov/documents/2022/12/07/2022-26577/notice-of-establishment-high-assay-low-enriched-uranium-haleu-consortium.

[194] World Nuclear News, "Idaho Proposed for HALEU Fuel Fabrication," November 2, 2018, http://www.world-nuclear-news.org/Articles/Idaho-proposed-for-HALEU-fuel-fabrication.

the other approach, DOE contracted with Centrus Energy to build 16 uranium enrichment centrifuges at DOE's Portsmouth, OH, site to produce HALEU. DOE announced a cost-shared award on November 10, 2022, to produce 900 kilograms (nearly one metric ton) of HALEU per year starting in 2024 and continuing thereafter and possibly increasing based on available funding.[195]

The Inflation Reduction Act appropriated $700 million for HALEU fuel availability through FY2026. The Biden Administration requested an additional $1.5 billion in FY2023 for low-enriched uranium for existing reactors and HALEU "to address potential future shortfalls in access to Russian uranium and fuel services."[196] That funding was not provided, but the Consolidated Appropriations Act, 2023, included additional appropriations of $100 million for advanced nuclear fuel availability (HALEU) in Divison M.

International Organizations

DOE helped establish and currently participates in two international organizations, described below, focused on the development of advanced reactor technologies and fuel cycles. These organizations are intended to foster international scientific collaboration and develop technologies that could encourage the safe and secure use of the nuclear materials needed by advanced reactors.

International Framework on Nuclear Energy Cooperation

The International Framework on Nuclear Energy Cooperation (IFNEC) is an international body dedicated to ensuring that the "use of nuclear energy for peaceful purposes proceeds in a manner that is efficient and meets the highest standards of safety, security and non-proliferation."[197] IFNEC was formed in 2010 by the members of its precursor organization, the Global Nuclear Energy Partnership. Its membership includes 33 participant countries, 31 observer countries, and 5 international observer organizations. The United States is a participating country. IFNEC working groups focus on issues related to nuclear infrastructure development, reliable fuel services and spent fuel management, and nuclear supply chains and supplier-customer relationships.

Generation IV International Forum

The Generation IV International Forum (GIF) is a collaborative international initiative to promote the development of the next generation of nuclear energy systems through shared R&D. GIF was chartered in 2001 with nine original members: Argentina, Brazil, Canada, France, Japan, South Korea, South Africa, the United Kingdom, and the United States. Switzerland, the European

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[195] DOE, "DOE Announces Cost-Shared Award for First-Ever Domestic Production of HALEU for Advanced Nuclear Reactors," November 10, 2022, https://www.energy.gov/articles/doe-announces-cost-shared-award-first-ever-domestic-production-haleu-advanced-nuclear; DOE, "Notice of Intent to Sole Source," January 7, 2019, https://www.fbo.gov/index?s=opportunity&mode=form&id=f2ea2ab3c8258c1c1a77503c889ab6a3&tab=core&_cview=0.

[196] White House, "FY 2023 Continuing Resolution (CR) Appropriations Issues," p. 35, https://www.whitehouse.gov/wp-content/uploads/2022/09/CR_Package_9-2-22.pdf.

[197] International Framework for Nuclear Energy Cooperation, "History," IFNEC, viewed January 12, 2023, https://www.ifnec.org/ifnec/jcms/g_5150/history.

Union, China, Russia, and Australia joined subsequently. All but Argentina and Brazil have signed the GIF framework agreement for international R&D collaboration.[198]

In 2002, after reviewing 130 advanced reactor designs, GIF identified 6 nuclear energy systems for further development (described in the section on "Advanced Reactor Technologies":

- Gas-Cooled Fast Reactor (GFR),
- Lead-Cooled Fast Reactor (LFR),
- Molten Salt Reactor (MSR),
- Sodium-Cooled Fast Reactor (SFR),
- Supercritical Water-Cooled Reactor (SCWR), and
- Very High Temperature Reactor (VHTR).

Factors used in selecting the designs include safety, sustainability, economics, physical security, proliferation resistance, and waste minimization, and they represent a range of technologies. GIF has suggested that full-scale demonstration of some technologies could occur within the next decade and commercialization during the 2030s. Each of these technologies is at a different level of technical maturity.

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[198] Generation IV International Forum, viewed January 12, 2023, https://www.gen-4.org/gif.

Appendix.

Table A-1. Existing Global Fast Reactors

Location and Status of Existing Fast Reactors

Country	Reactor Name	Operation Years	Current Status
China	CEFR	2010-present	Active
India	FBTR	1985-present	Active
Russia	BOR-60	1969-present	Active
India	PFBR	Scheduled for 2024	Under construction
Russia	BN-600	1980-present	Active
Russia	BN-800	2014-present	Active

Source: World Nuclear Association, "Fast Neutron Reactors," August 2021, http://www.world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx.; "India's prototype fast breeder reactor delayed further, likely to be commissioned in 2024," *Nuclear Asia*, December 21, 2022, https://www.nuclearasia.com/news/indias-prototype-fast-breeder-reactor-delayed-further-likely-to-be-commissioned-in-2024/4912.

Table A-2. Characteristics of Advanced Fission Reactors

Reactor	Neutron Spectrum	Coolant	Outlet Temperature (°C)	Fuel Cycle
Light Water SMR	Thermal	Water	300-330	Open
SCWR	Thermal/Fast	Water	510-625	Open/Closed
HTGR/VHTR	Thermal	Helium	700-1,000	Open
GFR	Fast	Helium	850	Closed
SFR	Fast	Sodium	500-550	Closed
LFR	Fast	Lead	480-570	Closed
MSR	Thermal/Fast	Molten Salts	700-800	Open/Closed

Source: GIF, https://www.gen-4.org/gif/jcms/c_40486/technology-systems.

Note: SMR=small modular reactor, SCWR=supercritical water-cooled reactor, HTGR=high temperature gas-cooled reactor, VHTR=very high temperature reactor, GFR=gas-cooled fast reactor, SFR=sodium-cooled fast reactor, LFR=lead-cooled fast reactor, MSR=molten salt reactor.

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