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SUMMARY

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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, and other issues have led to increased interest in unconventional, or "advanced," nuclear technologies that could be less expensive and safer than existing LWRs.

An "advanced nuclear reactor" is defined in legislation enacted in 2018 as "a nuclear fission reactor with significant improvements over the most recent generation of nuclear fission reactors" or a reactor using nuclear fusion (P.L. 115-248). 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), which the Department of Energy (DOE) defines as reactors with electric generating capacity of 300 megawatts and below, in contrast to an average of about 1,000 megawatts for existing commercial reactors.

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 since the dawn of the nuclear age, but relatively few, such as sodium-cooled reactors, have advanced to commercial scale demonstration, and such demonstrations in the United States took place decades ago.

The 115th Congress enacted two bills to promote the development of advanced nuclear reactors. The first, the Nuclear Energy Innovation Capabilities Act of 2017 (NEICA), was signed into law in September 2018 (P.L. 115-248). It requires DOE to develop a versatile fast neutron test reactor that could help develop fuels and materials for advanced reactors and authorizes DOE national laboratories and other sites to host reactor testing and demonstration projects "to be proposed and funded, in whole or in part, by the private sector." The second, the Nuclear Energy Innovation and Modernization Act (NEIMA, P.L. 115-439), signed in January 2019, would require the Nuclear Regulatory Commission to develop an optional regulatory framework suitable for advanced nuclear technologies. The 115th Congress also appropriated $65 million for R&D to support development of the versatile test reactor in the Energy and Water Development Appropriations Act, FY2019, along with funding for ongoing advanced nuclear research and development programs (Division A of P.L. 115-244).

Continued debate over advanced reactor issues is anticipated in the 116th Congress. A fundamental question may be the role of the federal government in advanced nuclear power development. DOE's budget request for FY2020 focuses the federal role on "early stage research" rather than the more expensive stages of demonstration and commercialization. Controversy is also likely to continue over the need for advanced nuclear power. Supporters contend that such technology 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.

Other current issues related to advanced reactors include criteria for hosting private-sector demonstration reactors at DOE sites, the licensing framework for non-LWR reactors, longer time periods for federal agreements to purchase power from advanced reactors, and the supply of the high-assay low enriched uranium fuel that would be needed for some advanced reactor designs. There also may be congressional interest about potential federal assistance for demonstration reactors, which are expected to cost billions of dollars apiece. Major options for such assistance include federal cost sharing, loan guarantees, power purchase agreements, purchase of reactor capacity for research uses, and tax credits.

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Introduction

The nuclear power industry is facing severe economic challenges in the United States. 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 accelerated the retirement of existing reactors. As of April 2019, seven nuclear reactors had closed in the United States since 2012, and another 12 had announced that they would retire by 2025. There are currently 98 operating U.S. reactors. 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 nuclear units in the United States. The only power reactors currently under construction in the United States—two new units at the Vogtle nuclear plant in Georgia—are five years behind schedule and nearly double their original estimated cost.[1]

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. Conventional LWRs are large—with 1,000 megawatts electric generating capacity (MWe) or more—in order to spread their high construction costs among the maximum possible number of kilowatt-hours of electricity over their operating lifetime.

At the same time 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.[2] 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 overcome the economic problems, safety concerns, and other issues that have stalled the growth of conventional LWRs.

Congress enacted legislation in September 2018 that defines "advanced nuclear reactor" as "a nuclear fission reactor with significant improvements over the most recent generation of nuclear fission reactors" or a reactor using nuclear fusion (P.L. 115-248). Titled the Nuclear Energy Innovation Capabilities Act of 2017 (NEICA), the law requires the Department of Energy (DOE) to take several actions to support advanced reactor development, including studying the need for a versatile fast neutron test reactor that could help develop fuels and materials for advanced reactors. Congress included $65 million for R&D to support development of the versatile test reactor in the Energy and Water Development Appropriations Act for FY2019 (Division A of P.L. 115-244), and the Trump Administration has requested $100 million more for FY2020.[3]

A similar definition of "advanced nuclear reactor" is included in the Nuclear Energy Innovation and Modernization Act (NEIMA, P.L. 115-439), which was signed January 14, 2019. NEIMA

[1] Patel, Sonal, "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.

2 Some analyses have concluded that the average CO_2 emissions rate of electricity must decline to a range of 10-25 CO_2/kWh worldwide in order 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/.

[3] Office of Management and Budget, *A Budget for a Better America*, March 11, 2019, p. 37, https://www.whitehouse.gov/wp-content/uploads/2019/03/budget-fy2020.pdf.

would require the Nuclear Regulatory Commission (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 greenhouse gas reduction 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.[4]

NEICA lists a number of potential advantages of advanced nuclear reactors over conventional LWRs, including "inherent safety features, lower waste yields, greater fuel utilization, superior reliability, resistance to proliferation, increased thermal efficiency, and the ability to integrate into electric and non-electric applications."[5] Advanced reactors encompass a wide range of technologies, including next-generation water-cooled reactors (e.g., small modular light water reactors, 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.

Not all observers are optimistic about the potential safety, affordability, proliferation resistance and sustainability of advanced reactors.[6] 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.[7] Testing and demonstration would be required to determine the validity of advocates' claims. 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 efficiency.[8]

[4] 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.

[5] P.L. 115-248, Section 2; amending Section 951 of the Energy Policy Act of 2005 (42 U.S.C. 16271)

[6] For example, a report by the Intergovernmental Panel on Climate Change 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 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," Ch. 5, pp. 52, 57, report.ipcc.ch/sr15/pdf/sr15_chapter5.pdf.)

[7] 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 these reports. These demonstrations provided 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 from several sites to fewer 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 these 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.

[8] 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.

The U.S. advanced nuclear industry has expanded in recent years to encompass an array of developers, suppliers, and supporting institutions. By one count, there were 35 U.S. companies developing advanced nuclear reactor technologies as of November 2018.[9] Some have projected that the first U.S. advanced reactor could be providing electricity to the grid by the mid-2020s. For example, the advanced reactor company NuScale predicts that its first nuclear plant will "achieve commercial operation in 2026."[10]

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 chemical and physical 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;
- *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.

A fourth, cross-cutting category of advanced reactors is the *small modular reactor* or *SMR*. DOE defines SMRs as reactors with electric generating capacities of no more than 300 MW,[11] which "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."[12] Both advanced water-cooled reactors and non-water-cooled

[9] Third Way, "Advanced Nuclear Map 2018," database, November 9, 2018, https://docs.google.com/spreadsheets/d/1xeNK5oWjX-mgMrebec2xYWD9j6OLI_M0bz6r9eO2G58/edit?ts=5a299b10&pli=1&usp=embed_facebook. Included in the Third Way list, but not reported here, are companies working on advanced nuclear applications other than energy (e.g., medical isotopes), companies whose technologies do not utilize fission or fusion as the energy source (e.g., radioactive decay batteries), companies supporting the nuclear supply chain (e.g., fuels developers), universities conducting research, and national laboratories.

[10] NuScale, "Carbon Free Power Project," company web page, March 11, 2019, https://www.nuscalepower.com/projects/carbon-free-power-project.

[11] Compared to 1,000 MW or more for existing conventional LWRs.

[12] U.S. Department of Energy, "Advanced Small Modular Reactors (SMRs)," https://www.energy.gov/ne/nuclear-

reactors may be configured as SMRs. 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. Microreactors could be transported by truck and installed at a remote location or military base within a week, according to DOE.[13]

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.[14] 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 mid-2020s for the first small modular LWRs to midcentury 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. While some experts predict that molten salt reactors will not be available before 2050, Chinese research institutions and a Canadian/U.S. company, Terrestrial Energy, have announced plans to bring a molten salt reactor online in the next decade.[15]

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 higher 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. Thermal reactors that use low-enriched uranium (under 5% U-235) as the primary fuel use a moderator to ensure that fission occurs at a sufficient rate to produce a sustaining chain reaction. Common moderators include ordinary (light) water, heavy water (water whose hydrogen component includes a neutron), and graphite, with light water being the most prevalent.

Fast reactors, by contrast, do not use a moderator to slow neutron movement. Thus, in order to sustain a chain reaction, the fuel must have relatively high concentrations of U-235 or other fissile isotopes (generally 20%-90%) to counteract the lower rate of fission that occurs at high neutron energies. FNRs often are designed to use fissile plutonium (Pu-239) as a primary fuel because at high neutron energies plutonium produces more neutrons per fission event than uranium. Fast reactor coolants must have no neutron moderating effect. Possible coolants

reactor-technologies/small-modular-nuclear-reactors.

[13] DOE, "What Is a Nuclear Microreactor?," October 23, 2018, https://www.energy.gov/ne/articles/what-nuclear-microreactor.

[14] 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.

[15] World Nuclear Association, "Molten Salt Reactors," December 2018, http://www.world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx; and Terrestrial Energy website, April 16, 2019, https://www.terrestrialenergy.com/.

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.

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 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.[16] A drawback of the closed fuel cycle 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 on the once-through fuel cycle since the mid-1970s.

FNRs are not a new concept. The first FNR was built in 1946 in the United States,[17] and the world's first reactor to generate electricity was a U.S.-built fast reactor.[18] 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.[19] There are five fast reactors currently in operation globally.[20] Despite that experience, the commercial viability of FNRs, as with other types of advanced reactors, remains uncertain.

[16] Zyga, Lisa, "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.

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

[18] 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 Material, 2010, http://libweb.iaea.org/library/eBooks/fast-breeder-reactor.pdf.

[19] A majority of these were breeder reactors, intended to produce more nuclear fuel than they burned. 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.

[20] 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. See **Table A-1**. Several others are in various stages of development or construction. (World Nuclear Association, "Fast Neutron Reactors,"

Advanced Water-Cooled Reactors

Small Modular Light Water Reactors

Small modular reactors are defined by DOE 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. 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.[21]

A 60 MWe reactor module by U.S. company NuScale Power is currently considered the most mature light water SMR design under development. The design would allow between 6 and 12 SMR modules—depending on the energy needs of the site—to be co-located in a central pool of water, which serves as a heat sink and passive cooling system. NRC plans to complete its safety evaluation report on the design in September 2020 and subsequently issue a final design certification, although no date is currently scheduled.[22] NuScale is planning to begin operating its first 12-module plant in the mid-2020s. It is to be built at Idaho National Laboratory (an 890-square-mile DOE site) with a combination of federal government and non-federal support.[23] 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.[24]

Companies in several countries are currently developing light water SMRs. In addition to NuScale, examples of U.S.-based companies developing this technology include Holtec, Westinghouse, and GE Hitachi.

November 2018, http://www.world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx.)

[21] Lyman, Edwin, *Small Isn't Always Beautiful: Safety, Security, and Cost Concerns about Small Modular Reactors*, Union of Concerned Scientists, September 2013, https://www.ucsusa.org/sites/default/files/legacy/assets/documents/nuclear_power/small-isnt-always-beautiful.pdf.

[22] The NRC completed Phase 1 review of the NuScale SMR design in April 2018. See U.S. Nuclear Regulatory Commission, "NRC: Application Review Schedule for the NuScale Design," April 12, 2019, https://www.nrc.gov/reactors/new-reactors/design-cert/nuscale/review-schedule.html. NuScale's design certification application has 50 MWe modules, but the company currently says the modules will be 60 MWe. See NuScale, "Technology Overview," January 11, 2019, https://www.nuscalepower.com/technology/technology-overview.

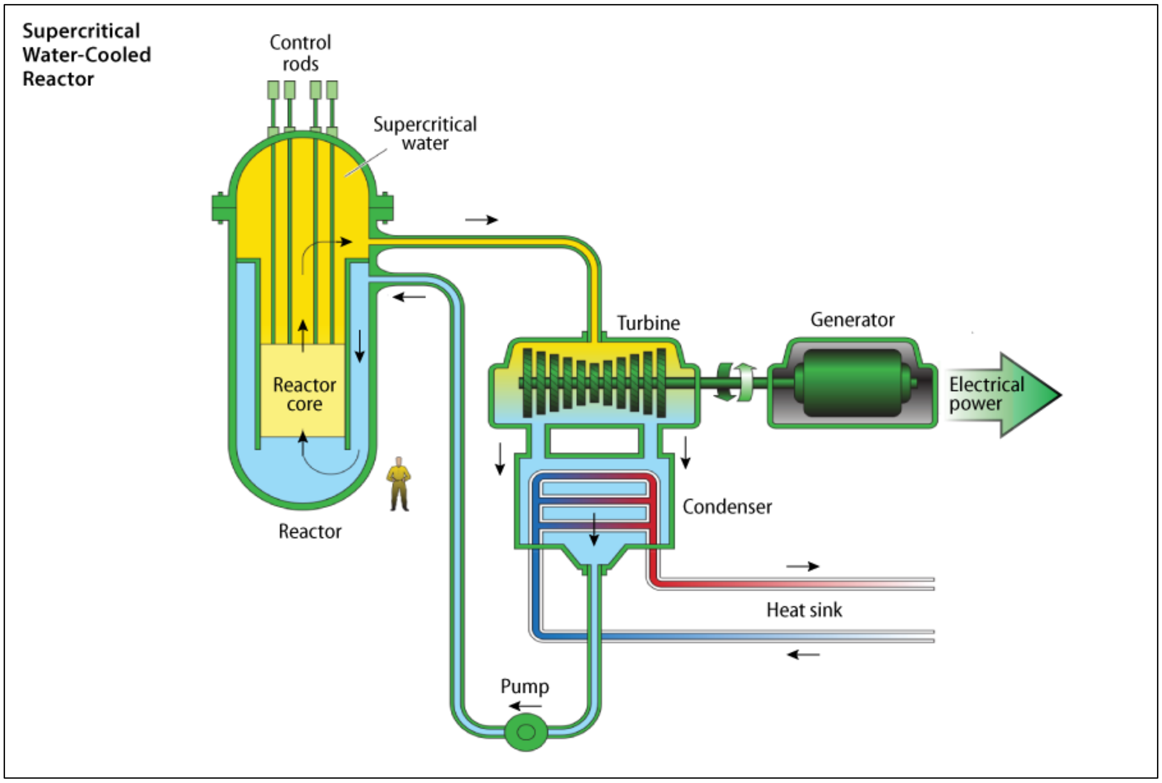
[23] NuScale Power, "Breakthrough for NuScale Power: Increase in Its SMR Output Delivers Customers 20 Percent More Power," https://newsroom.nuscalepower.com/press-release/company/breakthrough-nuscale-power-increase-its-smr-output-delivers-customers-20-perce.

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

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 34-36% for current reactors). As in a conventional boiling water reactor (BWR), liquid water would pass upward 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.[25] 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.[26]

Figure 1. Supercritical Water-Cooled Reactor



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

[25] Gen IV International Forum, "Supercritical-Water-Cooled Reactor (SCWR)," September 24, 2018, https://www.gen-4.org/gif/jcms/c_9360/scwr.

[26] Ibid.

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 to 330°C for existing LWRs.[27] This higher temperature threshold allows for 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.[28]

There are two primary design variants: In one, the core is composed of graphite blocks with removable sections that have been embedded with fuel particles; in the other, many billiard ball-sized graphite spheres, or "pebbles," with embedded fuel particles 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. Many HTGRs have been designed as SMRs.

A unique feature of these reactors is their fuel, which is composed of poppy seed-sized fuel particles that have been encased in silicon carbide and other highly heat-resistant coatings (**Figure 2**).[29] Coupled with the high heat capacity of the graphite moderator, the reactor and its fuel are designed to withstand the maximum core heat attainable during an accident. Therefore, according to HTGR proponents, even the loss of active cooling systems would not result in a core meltdown and radioactive releases to the environment.

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.[30] A small, two-unit pebble bed HTGR plant is currently under construction in China.[31]

Development of HTGRs was promoted in the United States by the Next Generation Nuclear Plant (NGNP) program, established by the Energy Policy Act of 2005 (P.L. 109-58). In 2016, DOE

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[27] Some sources differentiate between HTGRs and VHTRs based on their outlet temperatures, considering any reactor which 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 reactor can provide.

[28] Gen IV International Forum, "Very-High-Temperature Reactor (VHTR)," September 21, 2018, https://www.gen-4.org/gif/jcms/c_42153/very-high-temperature-reactor-vhtr.

[29] This is called tristructural isotropic (TRISO) 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.

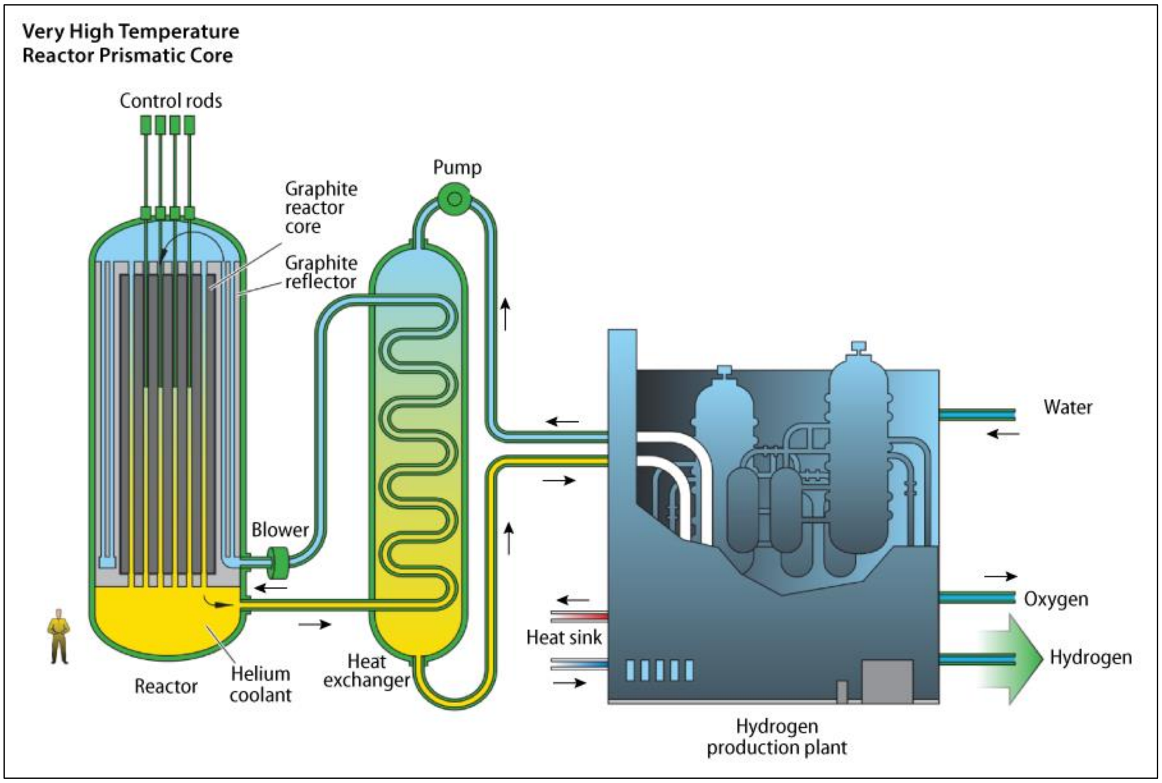
[30] Historically, two HTGRs have operated in the United States: The Peach Bottom 1 commercial reactor operated from 1967 to 1988 in Pennsylvania, and the Fort St. Vrain commercial reactor operated from 1979 to 1989 in Colorado. Some gas reactors have used carbon dioxide as a coolant.

[31] World Nuclear News, "HTR-PM Steam Generator Passes Pressure Tests," October 2, 2018, http://www.world-nuclear-news.org/Articles/HTR-PM-steam-generator-passes-pressure-tests.

awarded X-energy $53 million over five years to develop a modular pebble bed HTGR design. X-energy received a second DOE contract for $10 million in 2018. X-energy is also working with DOE and others to develop the fuel technology that would be used in an HTGR pebble bed reactor. Other U.S. companies developing HTGRs include HolosGen[32] and Hybrid Power Technologies.[33]

Figure 2. Very High Temperature Reactor

Prismatic core



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

Gas-Cooled Fast Reactor

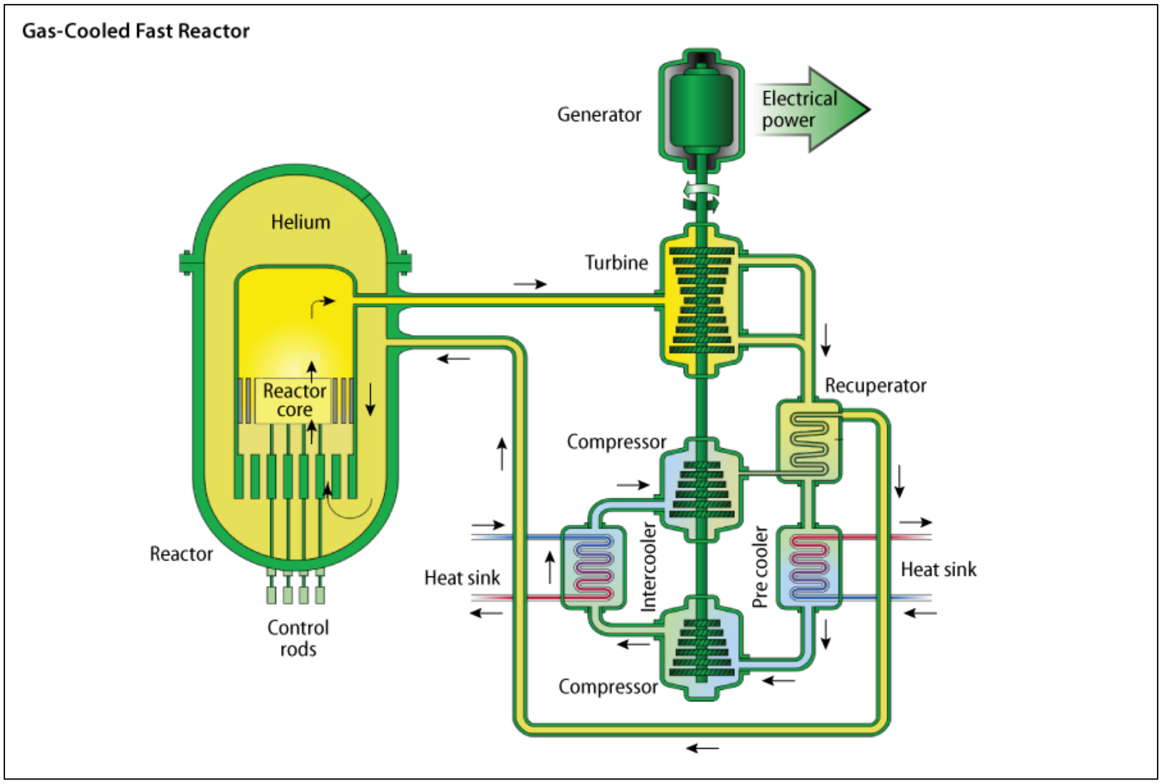
Gas-cooled fast reactors (GFRs) would be high-temperature, closed fuel cycle fast reactors using helium as a primary coolant (**Figure 3**). The primary difference between the HTGR (see above) and the GFR is the neutron spectrum: HTGRs operate in the thermal spectrum, while GFRs operate in the fast spectrum. Therefore, the GFRs would not require the massive graphite moderator of HTGRs to slow the neutrons. The GFR would use a closed U-Pu fuel cycle in which the plutonium and uranium would be recycled from the spent fuel to provide a greatly expanded fuel source if configured as a breeder. 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. One disadvantage of this design is the lower heat removal capability of the helium gas coolant compared to liquid metal coolants such as sodium and lead in the event of an accident.

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

[33] Hybrid Power Technologies, http://www.hybridpowertechnologies.com/.

In 2015, a consortium of European countries, including the Czech Republic, Hungary, Poland, and Slovakia, launched a project to jointly develop a demonstration GFR based on a French design. The group set a goal of completing the conceptual design for the ALLEGRO reactor by 2025, with construction to begin thereafter. If successful, ALLEGRO would be the first demonstration of a GFR to date.[34] General Atomics is an example of a U.S. company developing a GFR design, the Energy Multiplier Module (EM^2).[35]

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 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.[36] The SFR coolant outlet would reach a temperature of 500-550°C. This lower temperature (compared to 850°C for the GFR) would allow for the use of materials that have been developed and proven in

[34] For more information on the ALLEGRO project, see VINCO, "ALLEGRO," December 13, 2018, http://project-vinco.eu/allegro/.

[35] General Atomics, "Advanced Reactors," April 12, 2019, http://www.ga.com/advanced-reactors.

[36] 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 that has been raised about 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.[37]

Most SFR designs would use a closed fuel cycle in which plutonium and uranium would be re-used from the spent fuel to provide an indefinite fuel source when configured as a breeder; the process would be similar to that used for the GFR (above). Other designs would rely on future advances in fuel technology to extend the fuel cycle to the point where refueling would only need to occur once in a number of decades. 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.[38] 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.[39] There are five SFRs currently in operation worldwide: one in China, three in Russia, and one in India. Several others are expected to start up by 2020.[40]

Examples of U.S. companies developing SFRs include Advanced Reactor Concepts, Columbia Basin Consulting Group, General Electric-Hitachi, Oklo, and TerraPower. General Electric-Hitachi's PRISM design is the only SFR to have passed the NRC preapplication review process, and has been selected to support the Department of Energy's Versatile Test Reactor program.[41]

[37] Cochran et al., "Fast Breeder Reactor Programs: History and Status," op cit. 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.

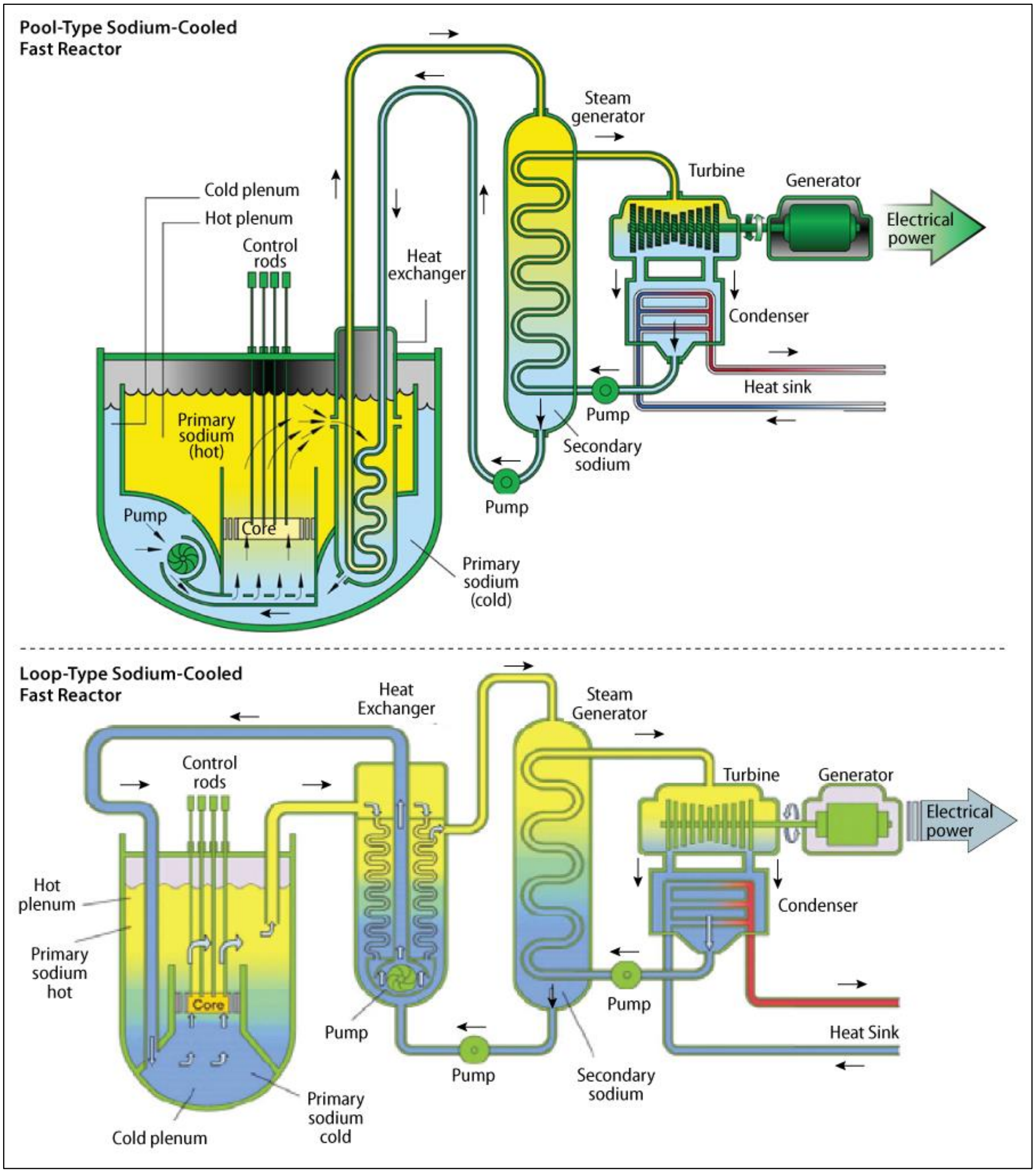
[38] Experimental Breeder Reactor I (EBR-I), a 1.2 MWt sodium-cooled experimental fast reactor, was built in 1951 in Idaho and produced both plutonium and electrical power.

[39] 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," op cit. See also, U.S. Atomic Energy Commission, Division of Reactor Development and Technology, "Liquid Metal Fast Breeder Reactor Program Plan," Vol. 1 (1968).

[40] World Nuclear Association, "Fast Neutron Reactors," November 2018, http://www.world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx.

[41] "GE Hitachi and PRISM Selected for U.S. Department of Energy's Versatile Test Reactor Program," GE Newsroom, November 13, 2018, https://www.genewsroom.com/press-releases/ge-hitachi-and-prism-selected-us-department-energy%E2%80%99s-versatile-test-reactor-program.

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**). The use of 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 offers benefits in an accident that could release radioactive materials. In such an accident, the chemical properties of the lead could prevent many of the harmful radionuclides from escaping into the atmosphere. 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.[42]

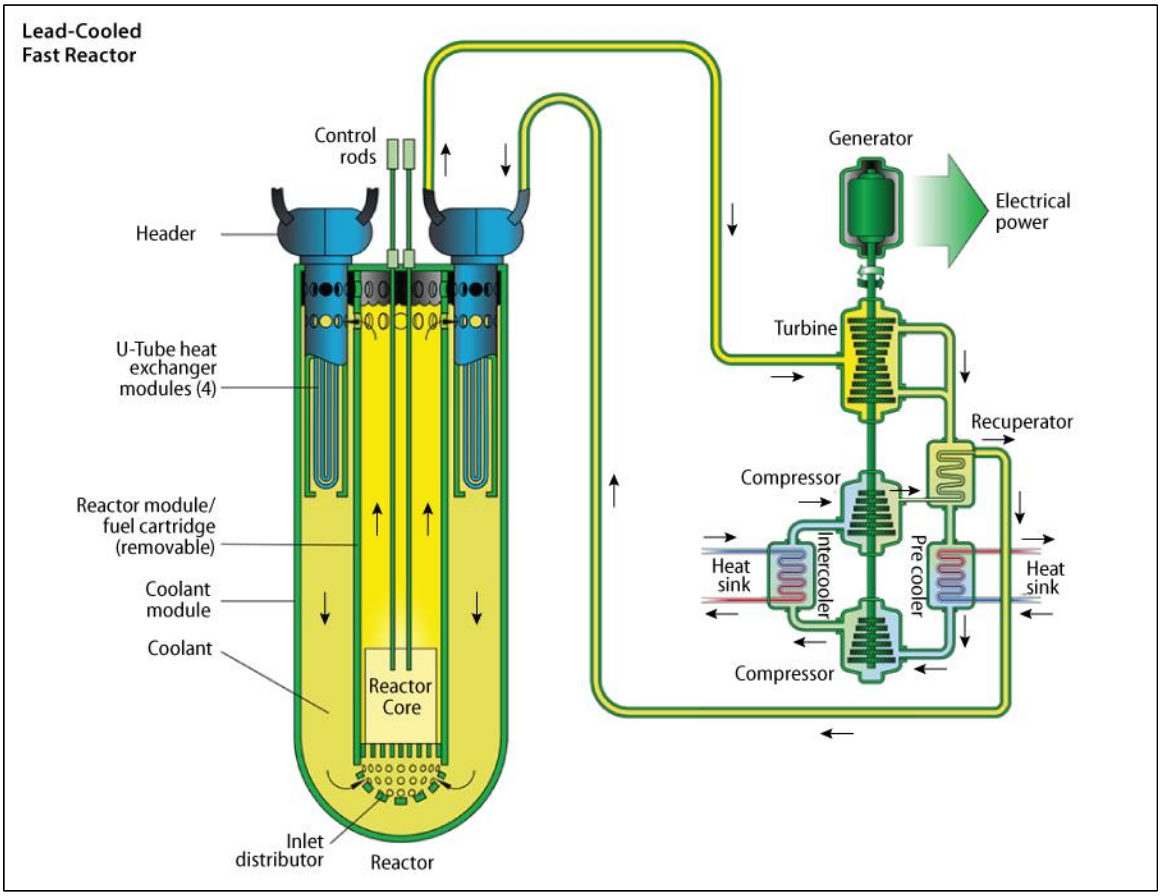
Russia is the world leader in LFR R&D, with experience building and operating seven LFRs for use in submarines. Russia has announced near-term development of two pure LFR facilities and a third facility that would be capable of using lead coolant for test purposes, in addition to other coolants.[43] Members of the European Union have also announced a collaboration to develop an LFR through the Advanced Lead Fast Reactor European Demonstrator (Alfred).[44] Other countries exploring LFR technologies include China, Japan, Korea, and Sweden. U.S. companies pursuing LFRs include Hydromine and Westinghouse.

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

[43] "Russian Reactions," *Nuclear Engineering International*, May 22, 2016, https://www.neimagazine.com/features/featurerussian-reactions-4899799/.

[44] ALFRED website, April 16, 2019, http://www.alfred-reactor.eu/.

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-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.[45]

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 700-1000°C, although there are challenges to operating at these temperatures that would need technological advances to resolve.

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**). In the event of an

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

incident that causes heat to rise in the core, the plug will melt, allowing the molten salt fuel to drain by gravity into a basin that is designed to prevent the fuel from undergoing further fission reactions and overheating. It is unknown whether spent MSR fuel could be safely stored in the long term without undergoing additional treatment after removal from the reactor.[46]

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.[47] China is currently developing two prototype MSR microreactors with expected start dates in the 2020s.[48] 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.[49] Terrestrial Energy has announced a goal of commercialization by the late 2020s. Examples of other U.S. companies developing MSRs include Alpha Tech Research Corp., Elysium Industries, Flibe Energy, Kairos Power, TerraPower, Terrestrial Energy USA, ThorCon Power, Thoreact, and Yellowstone Energy.

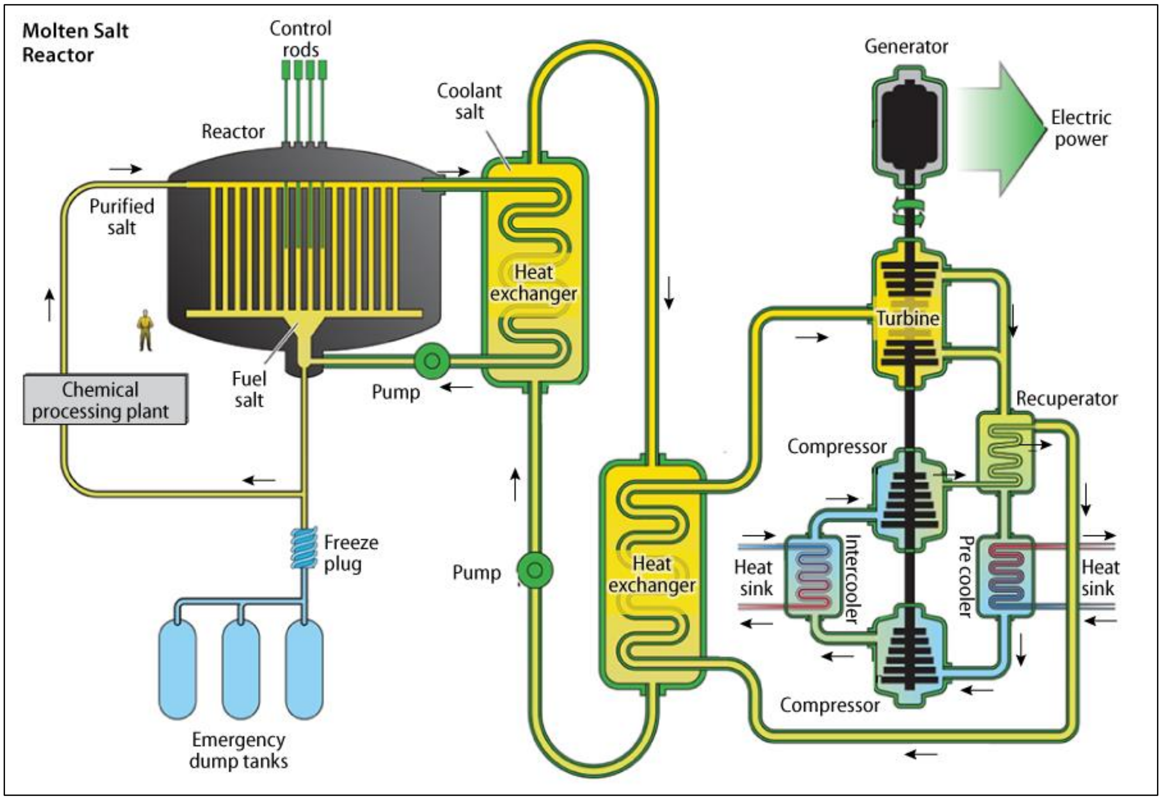
[46] Uranium tetrafluoride—the primarily fuel form for MSRs—reacts with water to form a highly corrosive acid which can cause storage containers to degrade and fail prematurely. Lindsay Krall and Allison Macfarlane, "Burning Waste or Playing with Fire? Waste Management Considerations for Non-Traditional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

[47] NRG [explain 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.

[48] World Nuclear Association, "Molten Salt Reactors," December 2018, http://www.world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx.

49 "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?feed=feed.

Figure 6. Molten Salt 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 R&D investment, including over $20 billion in international cooperative funding anticipated to build the International 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 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 fusion reaction is a major technical challenge. ITER would do this with a powerful magnetic field, while other approaches would compress a pellet of hydrogen with lasers or other intense energy sources. Fusion reactions are routinely produced at the laboratory scale, but none of these reactions have yet achieved "burning plasma," in which energy produced by fusion at least equals the energy needed to heat the plasma. A fusion power reactor would need to achieve "ignition," in which the fusion energy itself would keep the plasma heated. ITER is scheduled to produce its first plasma by the end of 2025, with full operations, including burning plasma experiments, scheduled to begin in 2035.

Several U.S. companies are pursuing various approaches toward achieving burning plasma with the aim of commercializing fusion power. 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."[50] 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.

Examples of U.S. companies developing fusion technologies include AGNI Energy, Brillouin Energy, Commonwealth Fusion Systems, General Atomics, Helion Energy, HyperV Technologies, Lawrenceville Plasma Physics, Lockheed Martin, Magneto-Inertial Fusion Technologies, NumerEx, and TAE Technologies.

Major Criteria for Evaluating Unconventional Technologies

Cost

Investment in electricity generating technologies is largely determined on the basis of cost. Nuclear energy has historically had high capital costs,[51] but relatively low production costs. In recent years, however, conventional nuclear plants have struggled to compete with falling electricity prices driven largely by natural gas and renewables, particularly in parts of the country that are 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.

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 electric power plants.[52] 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 also 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.

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%).[53] By contrast, the actual reactor and associated turbine components comprise less than 20%

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

[51] 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/.

[52] Lazard, "Lazard's Levelized Cost of Energy Analysis—Version 11.0" (Lazard, November 2017), p. 11, https://www.lazard.com/media/450337/lazard-levelized-cost-of-energy-version-110.pdf.

[53] 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."

of the capital cost of the median historical U.S. light water reactor.[54] 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.[55] NuScale, a U.S.-based SMR vendor, has estimated "overnight"[56] cost savings of approximately 10% due to modular construction of structures in its proposed SMR plant.

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. 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.

Operational Costs

Some advanced reactor concepts also show potential for reducing operational 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%, 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 safety stored, which may in turn require higher levels of security in order to limit risks of proliferation. These factors have the potential to add substantial costs to reactor operations compared with those of existing light water reactors.[57]

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

[54] Ibid.

[55] Massachusetts Institute of Technology, "The Future of Nuclear Energy in a Carbon-Constrained World," pp. 44-45.

[56] "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.

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

"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.[58]

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.

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.

One standardized analysis of cost projections from eight advanced reactor vendors[59] found the average projected LCOE for "nth-of-a-kind" (NOAK)[60] reactors to be $60/MWh for the included reactor designs.[61] A separate study projected LCOEs in the range of $110 to $120/MWh for included advanced reactor designs. [62] By comparison, the LCOEs per MWh for competing electricity sources are estimated as follows: large LWRs, $112-$183; coal, $60-$143; natural gas combined cycle, $42-$78; wind, $30-$60; utility-scale solar, $43-$53.[63] Such estimates typically exclude costs that are not currently the responsibility of plant owners, such as greenhouse gas emissions.

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.

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58 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.

59 One of these eight vendors, Transatomic Power, has since ceased operations.

60 NOAK reactors were used as the basis of estimating projected LCOEs in this study because they better represent the eventual market competitiveness of a product than costs for a first-of-a-kind reactor. NOAK cost estimates exclude costs related to licensing, demonstrating, and testing a design, and factor in an additional cost reduction due to learning curves in construction and supply chain management. There are inherent limitations to projecting NOAK costs for companies that have not yet built even a demonstration reactor.

61 Energy Options Network, "What Will Advanced Nuclear Power Plants Cost? A Standardized Cost Analysis of Advanced Nuclear Technologies in Commercial Development" (Energy Innovation Reform Project, July 1, 2017), https://www.innovationreform.org/2017/07/01/will-advanced-nuclear-power-plants-cost/.

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

63 Lazard, "Lazard's Levelized Cost of Energy Analysis—Version 11.0." See also, Energy Information Administration, "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2019," February 26, 2019, https://www.eia.gov/outlooks/aeo/electricity_generation.php.

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.[64] 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.

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).[65] SMR designs with multiple reactor modules may allow for size customization based on the needs of the customer or characteristics of the host site.

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 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.[66]

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

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

65 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.

[66] 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."

streamlined approval processes in line with the NRC's approach of risk-informed regulation.[67] The smaller size of SMRs and microreactors may also enable innovations in siting that could 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.[68]

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 to transparent coolants like water.

Advanced reactors, and even some existing conventional reactors, may also make use of advances in fuel technologies and accident-tolerant fuels (ATFs). ATFs are designed to better withstand losses in cooling capacity during an accident, reducing the risk of 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.[69]

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 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.[70]

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[67] 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," July 6, 2018, https://www.nrc.gov/reading-rm/basic-ref/glossary/risk-informed-regulation.html.)

[68] World Nuclear Association, "Small Nuclear Power Reactors," February 2019, http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx.

[69] McCaughey, Bill, DOE Office of Nuclear Energy, "Status of DOE's Accident Tolerant Fuel Program," April 12, 2018, https://www.nrc.gov/reading-rm/doc-collections/commission/slides/2018/20180412/mccaughey-04122018-atf.pdf.

[70] 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 80 (April 2015): 102–9, https://doi.org/10.1016/j.pnucene.2014.11.023.

Advanced reactors may also present unique inspection and monitoring challenges. In a 2017 workshop report, the International Atomic Energy Agency (IAEA), which functions as an inspector of nuclear states 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.[71] 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. In contrast, inspectors can visually see through cooling water to determine whether fuel rods and assemblies are present or have been removed, possibly for plutonium separation.

The 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."[72]

The utilization by some advanced reactors of more highly enriched fuels could create additional nonproliferation challenges. Many advanced designs would utilize fuel with a fissile isotope enrichment of between 5% and 20% or higher (compared to 5% or lower for most current reactors). At these higher enrichments, even very small reactors would likely contain more than enough fissile material to produce multiple nuclear weapons with further enrichment.[73] The work required to enrich uranium to weapons-grade levels declines as the initial enrichment level rises.[74] 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 entirety of the nuclear supply chain. This includes during 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 rely on reprocessing 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, and the United Kingdom have been engaged in civilian nuclear fuel reprocessing for decades. In the process, they have accumulated more than 290 metric tons of separated plutonium across various civilian facilities as of January 2017.[75] For reference, the minimum fissile inventory required to

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[71] *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.)

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

[73] Nuclear materials must generally reach a 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 in order to reach this threshold. Plutonium in reactor fuel would not need enrichment to be useable for weapons.

[74] Prasad et al., "Nonproliferation Improvements and Challenges Presented by Small Modular Reactors." See also, World Nuclear Association, "Uranium Enrichment," February 2019, http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx.

[75] International Panel on Fissile Materials, "Fissile Material Stocks," February 2018, http://fissilematerials.org/.

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.[76]

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 lacks 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 variety of advanced nuclear power plant designs have the potential to further reduce this relatively low risk, or to increase the risks, depending on the technical and policy choices and how they are implemented.

Versatility

Many advanced reactor designs are smaller than the existing fleet of LWRs and are designed for modular installation. 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). The Department of Defense (DOD) has expressed interest in using SMRs to power remote bases, such as the Eielson Air Force Base in Alaska. The John S. McCain National Defense Authorization Act for Fiscal Year 2019 instructs DOE to produce a report on how a program could be undertaken to pilot at least one microreactor at a military or DOE site by the end of 2027.[77] DOD issued a request for information about microreactor prototype designs on January 22, 2019, as a first step in its study.[78]

A recent 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.[79]

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 reactors (approximately 300-330°C). Higher operating temperatures would allow some advanced reactors to tap into the large market for heat for industrial processes.

[76] 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.

[77] P.L. 115-232 §327.

[78] Trevithick, Joseph, "The U.S. Military Wants Tiny Road Mobile Nuclear Reactors that Can Fit in a C-17," *The Warzone*, January 24, 2019, http://www.thedrive.com/the-war-zone/26152/the-u-s-military-wants-tiny-road-mobile-nuclear-reactors-that-can-fit-in-a-c-17.

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

Industrial users consume 25% of all primary energy produced in the United States, 80% of which is in the form of process heat. A report by 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.[80] Potential applications include providing process heat for district heating,[81] desalination, petroleum refining and oil shale processing, steam reforming of natural gas, 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, both physically and economically.

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. Due to the long half-lives of some of these radioactive materials (several hundred thousand years and longer), nuclear waste poses long-term health hazards.

In 2018, the U.S. inventory of spent nuclear fuel exceeded 80,000 metric tons of uranium (MTU).[82] This is projected to rise at a rate of approximately 1,800 MTU per year, resulting in an estimated 138,000 MTU by 2050. 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. [83]

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.[84] Reducing the prevalence of these long-lived waste products by transmuting them to short-lived radionuclides 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).

[80] 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.")

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

[82] Oak Ridge National Laboratory, "CURIE," December 14, 2018, https://curie.ornl.gov/map.

[83] 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. Licenses for proposed long-term spent nuclear fuel surface storage facilities in Texas and New Mexico are currently under NRC review. See NRC, "Consolidated Interim Storage Facility (CISF)," August 15, 2018, https://www.nrc.gov/waste/spent-fuel-storage/cis.html. For more information on U.S. nuclear waste policy, see CRS Report RL33461, *Civilian Nuclear Waste Disposal*, by Mark Holt.

[84] Radiactivity.eu.com, "Long-lived Fission Products," February 13, 2019, http://www.radioactivity.eu.com/site/pages/Long_Lived_Fission_Products.htm.

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 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.[85]

Some advanced reactors would use new or non-conventional fuel forms, such as metallic fuels or dissolved molten fuels. 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. Research on the safe management and disposal of advanced reactor waste will be a key element in commercializing these technologies.

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, specifically the 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.[86] Emissions of conventional air pollutants (e.g., sulfur oxides, nitrogen oxides, mercury, and particulates) from nuclear power operations and fuel cycle activities are similarly very low.

Advanced reactors are expected to have similar life-cycle air emissions, as non-combustion energy sources. 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

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

[86] 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 potential costs associated with the processing of radioactive waste from some classes of advanced reactors.[87] 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.[88]

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)[89] 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 two primary offices: the Office of Nuclear Energy and the Office of Science.[90] Collectively, advanced nuclear R&D programs (advanced fission and fusion) within these two offices received 23% of funding for energy R&D in fiscal year (FY) 2019, more than existing nuclear, renewables, or fossil energy (see **Figure 7**).[91] The Advanced Research Projects Agency—Energy (ARPA-E) also provides funding for early stage R&D for advanced nuclear projects.

[87] Krall and Macfarlane, op cit., "Burning Waste or Playing with Fire?"

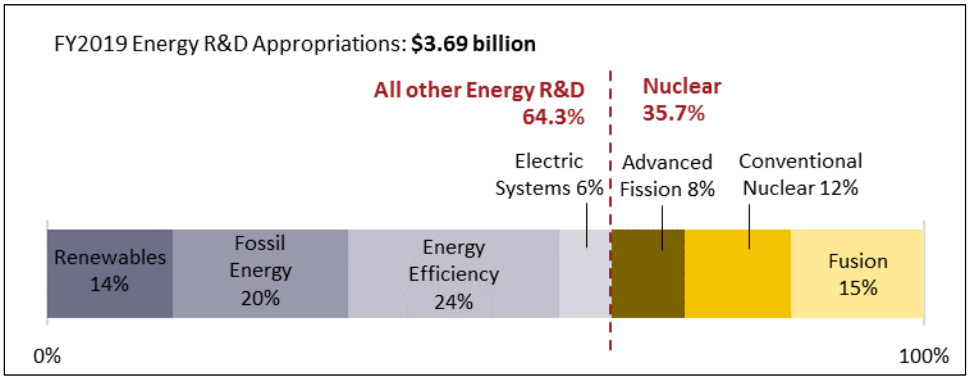
[88] In theory, by reducing the volume of this long-lived portion of the waste, smaller and fewer permanent geological repositories would be required, and the separated short-lived waste could be disposed of in landfills requiring stewardship for centuries rather than millennia. In practice, the reprocessing-related 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, 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. It is unclear whether future advanced reactor technologies would improve on this record for reprocessing wastes as much as the proponents anticipate.

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

[90] 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.

[91] These totals include only appropriations explicitly labeled as R&D in the DOE budget, and the "advanced" budget segment includes only programs that focus exclusively on advanced technologies, even though many of the other DOE nuclear energy (NE) programs include components that benefit advanced technology development.

Figure 7. FY2019 Energy R&D Appropriations



Source: Compiled by CRS from Joint Explanatory Statement of the Committee of Conference on H.R. 5895, Division A—Energy and Water Development and Related Agencies Appropriations Act, 2019.

Notes: Total energy R&D appropriations for FY2019 were $3.69 billion. R&D funding from ARPA-E is not included in this figure because appropriations for this office are not broken out by energy technology. Funding for fusion includes $432 million for nuclear fusion R&D and $132 million for the U.S. contribution to the International Thermonuclear Reactor (ITER).

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 FY2020 budget justification.[92] NE primarily supports nuclear fission technologies. NE has established a goal for advanced reactor development that "by the early 2030s, at least two non-light water advanced reactor concepts will have reached technical maturity, demonstrated safety and economic benefits, and completed licensing reviews sufficient to allow construction to go forward."[93] According to one analysis, NE reported spending approximately $2 billion on advanced reactor R&D between 1998 and 2015.[94] Analysts have contended that much higher spending levels would be needed for DOE to support the latter stages of advanced reactor R&D, such as demonstrations and commercialization.[95]

[92] DOE, *FY 2020 Congressional Budget Justification*, vol. 3, part 2, March 2019, p. 265, https://www.energy.gov/sites/prod/files/2019/04/f61/doe-fy2020-budget-volume-3-Part-2.pdf.

[93] DOE, Office of Nuclear Energy, "Vision and Strategy for the Development and Deployment of Advanced Reactors," January 2017, https://gain.inl.gov/Shared%20Documents/Vision%20and%20Strategy%20for%20the%20Development%20and%20Deployment%20of%20Advanced%20Reactors.pdf.

[94] This figure does not include funding for advanced light water reactors, such as light water SMRs. See A. Abdulla et al., "A Retrospective Analysis of Funding and Focus in US Advanced Fission Innovation," *Environmental Research Letters* 12, no. 8, August 1, 2017, 084016, https://doi.org/10.1088/1748-9326/aa7f10. The figure also does not include all facility overhead costs paid by the DOE Environmental Management program.

[95] Morgan et al., "US Nuclear Power," p. 2. See also, Abdulla et al., "A Retrospective Analysis of Funding and Focus in US Advanced Fission Innovation," p. 7.

In FY2019, Congress appropriated $753 million for NE's nuclear R&D programs.[96] Of that, Congress directed $319.5 million (42%) to be used specifically for advanced nuclear technology R&D within the following programs and activities:[97]

- *Supercritical Transformational Electric Power R&D*: $5 million appropriated to develop a supercritical carbon dioxide Brayton cycle for thermal-to-electric energy conversion in sodium-cooled fast reactors;
- *Advanced Small Modular Reactor R&D*: $100 million appropriated for this new, one-year subprogram that is to support "cost-shared public-private R&D partnerships" to address technical challenges and accelerate development of SMR reactor designs and supply chains;
- *Advanced Reactor Technologies*: $111.5 million appropriated to conduct early-stage R&D on advanced reactor technologies, including SMRs;
- *Versatile Fast Test Reactor*: $65 million appropriated for R&D to support development of a versatile fast test reactor, also called the versatile test reactor;
- *Material Recovery and Waste Form Development*: $38 million appropriated to activities related to "the improvement of the current back end of the nuclear cycle [waste management and reprocessing]," of which $27 million were specifically directed towards activities supporting advanced nuclear technologies.[98]

In addition to the programs that focus exclusively on advanced reactor R&D, several cross-cutting NE programs directly or indirectly support advanced nuclear technologies. NE's Nuclear Energy Enabling Technologies (NEET) program includes several subprograms focused on cross-cutting research to support both existing and advanced nuclear technologies. Subprograms of NEET support DOE's Gateway for Accelerated Innovation in Nuclear (GAIN) initiative, which provides technical, financial, and regulatory support for existing and advanced nuclear technologies by providing enhanced access to DOE's network of national labs and unique nuclear R&D capabilities, as well as through competitive industry funding opportunities. GAIN industry funding opportunities include

- *U.S. Industry Opportunities for Advanced Nuclear Technology Development,* a five-year funding opportunity announcement initiated in December of 2017 that offers cost-sharing opportunities for advanced reactor development, demonstration, and regulatory assistance, and for other nuclear R&D.[99] Applications are reviewed and awards are announced on a quarterly basis. DOE expects to award a total of $400 million over the five-year program.[100]

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[96] Joint Explanatory Statement of the Committee of Conference on H.R. 5895, Division A—Energy and Water Development and Related Agencies Appropriations Act, 2019, H.Rept. 115-929.

[97] Funding levels come from the Joint Explanatory Statement of the Committee of Conference on H.R. 5895; program descriptions are based on the DOE FY2019 Congressional Budget Justification. Only those programs that focus exclusively or primarily on advanced nuclear reactors and their associated technologies (e.g., advanced fuel processes) and for which Congress mandated a specific level of funding are included in this calculation. Additional support for advanced nuclear technologies may come from cross-cutting NE programs and subprograms for which Congress did not provide specific funding levels.

[98] Within the Material Recovery and Waste Form Development program, Congress directed that $7 million be used for joint fuel cycle studies and $20 million for activities to support the development of sources of high assay low enriched uranium.

[99] Cost-sharing requirements range between 20% and 50% of the total project costs depending on project type.

[100] U.S. Department of Energy, "U.S. Industry Opportunities for Advanced Nuclear Technology Development Funding

- *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. Vouchers are not direct financial awards, but rather fund the work done by the national laboratory on behalf of the awardee. Recipients are required to provide a 20% minimum cost-share. As of October 16, 2018, GAIN had distributed vouchers worth approximately $10.7 million to 22 companies.[101]

In the past, NE has also provided support for the review and licensing of advanced reactors by NRC. From FY2012 to FY2017, the NE SMR Licensing Technical Support program provided cost-sharing arrangements with industry to support first-of-a-kind costs associated with NRC design certification, design licensing, and site licensing. The program provided support for the NRC's review of NuScale's SMR design. DOE brought the program to a close at the end of FY2017.

Office of Science

Support for nuclear fusion technologies comes from DOE's Office of Science. Congress appropriated $432 million for nuclear fusion R&D in FY2019, more than for all other advanced nuclear technologies combined. Congress provided a further $132 million for the U.S. contribution to the ITER fusion project, as discussed above.

ARPA-E

DOE's ARPA-E invests in early-stage energy technologies with high potential for transformational impact. In 2017, ARPA-E announced a funding opportunity for "technologies to enable lower cost, safer advanced nuclear plant designs" as part of a new program entitled Modeling-Enhanced Innovations Trailblazing Nuclear Energy Reinvigoration program (MEITNER). In June of 2018, MEITNER awarded $24 million in funding for 10 industry and university projects focused on advanced nuclear technologies.[102] ARPA-E announced grants for five nuclear-related projects totaling $12 million in December 2018.[103]

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

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Opportunity DE-FOA-0001817," December 7, 2017, https://www.id.energy.gov/NEWS/FOA/FOAOpportunities/FOA.htm.

[101] 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.

[102] ARPA-E, "Department of Energy Announces 10 Projects to Support Advanced Nuclear Reactor Power Plants," ARPA-E, June 4, 2018, https://arpa-e.energy.gov/?q=news-item/department-energy-announces-10-projects-support-advanced-nuclear-reactor-power-plants.

[103] Green Car Congress, "ARPA-E announces $12M for five projects in nuclear materials science; first OPEN+ cohort," December 7, 2018, https://www.greencarcongress.com/2018/12/20181207-arpae.html.

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."[104]

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 Fast-Breeder Reactor Program.

Third, EM funds facility overhead operations for facilities where advanced reactor R&D is occurring or planned. "Overhead" (or "Landlord") 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 and Savannah River sites, home of the Pacific Northwest and Savannah River National Laboratories, where advanced reactor and fuels research has been conducted.

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.

The Trump Administration contends that federal support should focus on the early stages of research, where the private sector may have a tendency to underinvest.[105] "The Federal role in supporting advanced technologies is strongest in the early stages of research and development," according to DOE's FY2019 budget justification."[106]

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[104] Department of Energy, *Office of Chief Financial Officer; FY 2020 Congressional Budget Request Volume 5*; Environmental Management, DOE/CF-0155; at p. 73 (March 2019).

[105] For a discussion of the private-sector underinvestment issue, see U.S. Congress Joint Economic Committee, "The Pivotal Role of Government Investment in Basic Research," May 2010, https://www.jec.senate.gov/public/_cache/files/29aac456-fce3-4d69-956f-4add06f111c1/rd-report—final-report.pdf.

[106] DOE, FY2019 Congressional Budget Justification, vol. 3, part 2, DOE/CF-0141, March 2018, p. 441, https://www.energy.gov/sites/prod/files/2018/03/f49/FY-2019-Volume-3-Part-2.pdf.

Consistent with that policy, the Administration opposes funding for "late stage or near commercial ready technology."[107] Opponents of federal funding for energy demonstration and commercialization contend that such activities should be conducted by the private sector, where market forces would determine which technologies would succeed. As asserted by the Heritage Foundation, "By attempting to force government-developed technologies into the market, the government diminishes the role of the entrepreneur and crowds out private-sector investment. This practice of picking winners and losers denies energy technologies the opportunity to compete in the marketplace, which is the only proven way to develop market-viable products."[108]

The conferees on FY2019 DOE appropriations did not adopt the Administration's proposed focus on early-stage research, saying, "The Department is directed throughout all of its programs to maintain a diverse portfolio of early-, mid-, and late-stage research, development, and market transformation activities."[109] Supporters of a broader federal role contend that mid- and late-stage federal support is necessary for new technologies to survive the "valley of death," after federally funded early-stage research is completed but before a promising technology is able to attract private-sector funding for the more-expensive later development, demonstration, and commercialization phases. Obtaining funding for expensive and risky demonstration projects has been described as a particularly difficult obstacle. According to former DOE Under Secretary John Deutch, "energy innovation is constrained not by an absence of new ideas, but by the absence of early examples of successful implementation."[110]

Perceived Need for Advanced Nuclear Power and Competing Alternatives

World electricity generation is projected by the U.S. Energy Information Administration to grow by nearly 50% between 2015 and 2040. While renewable energy and nuclear power are projected to rise substantially during that period, fossil fuels would still constitute about 55% of total generation if current policies and trends continue.[111] 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 recent study by the Massachusetts Institute of Technology. The

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107 Statement of Administration Policy, H.R. 5895—Energy and Water, Legislative Branch, and Military Construction and Veterans Affairs Appropriations Act, 2019, June 5, 2018, https://www.whitehouse.gov/wp-content/uploads/2018/06/saphr5895hr_20180605.pdf.

108 Heritage Foundation, "Energy and Water Development," June 11, 2018, https://www.heritage.org/blueprint-balance/budget-proposals/energy-and-water-development.

109 Joint Explanatory Statement of the Committee of Conference on H.R. 5895, Division A—Energy and Water Development and Related Agencies Appropriations Act, 2019, H.Rept. 115-929.

110 Information Technology and Innovation Foundation, *Across the "Second Valley of Death": Designing Successful Energy Demonstration Projects*, July 2017, http://www2.itif.org/2017-second-valley-of-death.pdf?_ga=2.131771599.1381660923.1500900897-1058723113.1488819082.

111 Energy Information Administration, *International Energy Outlook 2017*, September 14, 2017, https://www.eia.gov/outlooks/archive/ieo17/pdf/0484(2017).pdf.

study found that the cost of worldwide greenhouse gas reductions could be minimized by the deployment of lower-cost nuclear generation.[112]

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.[113] Some environmental groups contend that the safety and other risks posed by nuclear 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."[114]

Germany adopted a policy after the Fukushima disaster in 2011 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."[115] 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.[116]

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.[117]

Versatile Test Reactor

Supporters of advanced reactor technologies are urging DOE to construct a fast spectrum Versatile Test Reactor (VTR),[118] which they consider critical for the development of nuclear fuels, materials, instrumentation, and sensors for fast neutron and other advanced reactors. "To support

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

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

[114] 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/.

[115] German Federal Ministry of Education and Research, "German Energy Transition," November 21, 2018, https://www.bmbf.de/en/german-energy-transition-2319.html.

[116] Jacobson, Mark Z 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.

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

[118] Also called the Versatile Advanced Test Reactor, the versatile neutron source, and similar names.

the innovative R&D required to revive a competitive U.S. nuclear industry, a new test reactor is required with capabilities that far exceed those of the few remaining test reactors," a senior executive from the nuclear firm General Atomics testified to Congress in 2015.[119] According to DOE's Idaho National Laboratory (INL), "Currently, only a few capabilities are available for testing fast neutron reactor technology in the world and none in the U.S."[120]

Requirements for DOE to plan and develop a "versatile reactor-based fast neutron source" by the end of 2025 are included in the Nuclear Energy Innovation Capabilities Act of 2017 (NEICA), signed into law September 28, 2018 (P.L. 115-248). In the 116th Congress, the Nuclear Energy Leadership Act (NELA, S. 903), introduced March 27, 2019, by Senator Murkowski, would authorize DOE to "provide" the facility. Funding of $65 million for R&D to support development of the VTR (referred to as a "versatile fast test reactor") is included in the Energy and Water Development and Related Agencies Appropriations Act, 2019 (Division A of P.L. 115-244). Citing the enactment of NEICA, Energy Secretary Rick Perry announced the official launch of the VTR project on February 28, 2019.[121] The Trump Administration is requesting an additional $100 million for the VTR project in FY2020.[122]

DOE announced a contract award on November 13, 2018, to GE Hitachi Nuclear Energy to help develop a conceptual design and cost estimate for the VTR, which is to be adapted from the company's PRISM sodium-cooled fast reactor design.[123] According to INL, which is managing the project, the conceptual design and cost and schedule estimates are to be completed in 2021, after which another contract would be awarded for final design and construction. The VTR is currently scheduled to be operational by October 2026.[124] An INL official estimated in February 2019 that a sodium-cooled VTR would cost $3 billion to $3.5 billion in today's dollars.[125] The Nuclear Energy Research Infrastructure Act of 2018 (H.R. 4378, 115th Congress), which passed the House February 13, 2018, but was not enacted, would have authorized $1.99 billion through FY2025 for the project.

Some who are skeptical of the VTR project have questioned whether there would be enough potential users—primarily companies developing fast reactors—to justify its construction and operating costs. Some advanced nuclear reactor developers have doubted that the VTR will begin

[119] Testimony of John A. Parmentola, Senior Vice President, Energy and Advanced Concepts, General Atomics, before the House Committee on Science, Space, and Technology, Subcommittee on Energy, May 13, 2015, https://science.house.gov/sites/republicans.science.house.gov/files/documents/hearings/HHRG-114-SY20-WState-JParmentola-20150513.pdf.

[120] Idaho National Laboratory, "GE Hitachi Awarded Subcontract for Work Supporting Proposed Versatile Test Reactor," News Release, November 13, 2018, https://www.inl.gov/article/subcontract-awarded-for-versatile-test-reactor/.

[121] DOE, "Secretary Perry Launches Versatile Test Reactor Project to Modernize Nuclear Research and Development Infrastructure," February 28, 2019, https://www.energy.gov/articles/secretary-perry-launches-versatile-test-reactor-project-modernize-nuclear-research-and.

[122] Office of Management and Budget, *A Budget for a Better America*, March 11, 2019, p. 37, https://www.whitehouse.gov/wp-content/uploads/2019/03/budget-fy2020.pdf.

[123] Idaho National Laboratory, op cit. PRISM stands for Power Reactor Innovative Small Modular. See GE Hitachi fact sheet at https://nuclear.gepower.com/content/dam/gepower-nuclear/global/en_US/documents/product-fact-sheets/PRISM-Fact-Sheet.pdf.

[124] Testimony of John Wagner, INL Associate Laboratory Director, before the House Committee on Science, Space, and Technology, Subcommittee on Energy, September 27, 2018, https://docs.house.gov/meetings/SY/SY20/20180927/108723/HHRG-115-SY20-Wstate-WagnerJ-20180927.pdf.

[125] Toth, Jacqueline, "DOE Nearing Decision Checkpoint on Versatile Test Reactor," Morning Consult, February 11, 2019, https://morningconsult.com/2019/02/11/doe-nearing-decision-checkpoint-on-versatile-test-reactor/.

operating before their designs are completed.[126] Concerns have also been raised about whether new facilities would be required to fabricate fuel for the VTR, and how much those might cost, and the cost of handling and disposing of highly radioactive spent fuel from the reactor. The potential use of plutonium-based fuel in the VTR has drawn opposition because of the usability of such fuel in nuclear weapons.[127]

DOE Hosting of Private-Sector Experimental Reactors

Proposals to authorize DOE to host privately funded experimental and demonstration reactors have been included in several bills in the 114th and 115th Congresses, including a provision enacted in NEICA. Supporters of the idea contend 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.[128] 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 to coordinate with NRC on sharing technical expertise on the advanced reactor technologies under development.

DOE announced an agreement on February 18, 2016, with Utah Associated Municipal Power Systems (UAMPS) "to support possible siting" of a first-of-a-kind NuScale SMR plant at INL. Under the agreement, "UAMPS is currently working to identify potential locations that may be suitable" at the 890-square-mile INL site for construction of the plant, according to DOE.[129] The NuScale SMR is currently undergoing NRC review for a design certification, which is to be issued sometime after 2020.[130]

In 2012, DOE announced three agreements "to develop deployment plans" for privately funded SMRs at the Department's Savannah River Site in South Carolina. The agreements with Hyperion Power Generation (now Gen4 Energy), Holtec International, and NuScale were intended to help the companies "obtain information on potential SMR reactor siting at Savannah River and

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[126] Cho, Adrian, "Congress Pushes for Multibilllion-Dollar Nuclear Reactor that Critics Call a Boondoggle," *Science*, July 3, 2018, http://www.sciencemag.org/news/2018/07/congress-pushes-multibillion-dollar-nuclear-reactor-critics-call-boondoggle.

[127] Edwin Lyman, Senior Scientist, Union of Concerned Scientists, "UCS Technical Rebuttal to the Idaho National Laboratory's Opinions on the Versatile (Fast) Test Reactor, https://s3.amazonaws.com/ucs-documents/global-security/Lyman-Response-INL-Justification.pdf. The author states, "My fundamental—and indisputable—point is that the plutonium itself is a nuclear weapon-usable material, unlike the low-enriched uranium used to fuel conventional light-water reactors. Concern about the proliferation risks of plutonium and the closed fuel cycle led the U.S. to terminate its reprocessing and fast-neutron breeder reactor programs in the 1970s."

[128] Garvey, Todd, "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.

[129] DOE, "Department of Energy Continues Commitment to the Development of Innovative Small Modular Reactors," news release, February 18, 2016, https://www.energy.gov/ne/articles/department-energy-continues-commitment-development-innovative-small-modular-reactors.

[130] NRC, "Application Review Schedule for the NuScale Design," updated April 13, 2018, https://www.nrc.gov/reactors/new-reactors/design-cert/nuscale/review-schedule.html.

provide a framework for developing land use and site services agreements to further these efforts," according to DOE.[131]

Because NEICA says reactor testing and demonstration projects would be funded "in whole or in part" by the private sector, the potential federal share of such projects could be a future issue before Congress. NEICA requires DOE to submit a report to Congress on costs and other issues that could be raised by the hosting of reactor testing and demonstration projects, including

- DOE's capabilities for safety review and oversight of privately funded advanced reactor research;
- potential DOE sites that could host privately funded experimental advanced reactors;
- contractual mechanisms that could be used for such projects; and
- responsibility for management and disposal of waste.

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. As noted above, the VTR, which would serve as a test reactor and as a demonstration of GE's PRISM reactor (although downsized from 840 MWt to 311 MWt),[132] is estimated to cost up to $3.5 billion to construct. The first 12-module NuScale plant, at 684 MWe, is estimated to cost $3 billion.[133] 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 recent estimate.[134]

The majority of U.S. advanced reactor companies surveyed in 2017 have raised only a small portion of the funding that would be necessary for commercial-scale demonstration of their designs.[135] One analysis found that commercialization of advanced reactor concepts would require significantly higher levels of public funding.[136]

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 Sec. 988 of the Energy Policy Act of 2005 (P.L. 109-58). At least 50% of demonstration costs must come from non-federal sources, although the Secretary of Energy can reduce the non-federal share

[131] DOE, "Energy Department Announces Small Modular Reactor Technology Partnerships at Savannah River Site," news release, March 2, 2012, https://www.energy.gov/articles/energy-department-announces-small-modular-reactor-technology-partnerships-savannah-river.

[132] Email from Adrian M. Collins, Idaho National Laboratory, February 26, 2019.

[133] NuScale, "A Cost-Competitive Nuclear Option for Multiple Applications," 2019, https://www.nuscalepower.com/benefits/cost-competitive.

[134] Massachusetts Institute of Technology, op cit.

[135] Energy Options Network, "What Will Advanced Nuclear Power Plants Cost? A Standardized Cost Analysis of Advanced Nuclear Technologies in Commercial Development," July 1, 2017, https://www.innovationreform.org/2017/07/01/will-advanced-nuclear-power-plants-cost/.

[136] Morgan et al., "US Nuclear Power," op cit.

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 the assistance provided to NuScale under the DOE small modular reactor licensing technical support program.

Full Funding

Construction of research facilities such as the VTR may be completely funded through congressional appropriations, with users of the facility paying to conduct research (sometimes with DOE grants or vouchers). The VTR would also demonstrate the PRISM technology, as noted above, but it would be smaller than the planned commercial version and would not produce power.[137]

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 the Utah Associated Municipal Power Systems (UAMPS), which would own the plant. [138] The MOU calls for DOE to purchase power from one of the 60 MWe modules in the plant. DOE would use another module for research under the Joint Use Modular Plant (JUMP) program. "The research is expected to focus principally on integrated energy systems that support the production of both electricity and non-electric energy products," according to DOE's announcement.[139]

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 $8.8 billion in loan guarantee authority for advanced nuclear energy projects.[140] 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.[141]

[137] Adrian M. Collins, op cit.

[138] Idaho National Laboratory, "What is the Carbon Free Power Project?," December 20, 2018, https://inl.gov/article/frequently-asked-questions/.

[139] 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.

[140] DOE Loan Programs Office, "Advanced Nuclear Energy Projects Solicitation," April 16, 2019, https://www.energy.gov/lpo/advanced-nuclear-energy-projects-solicitation.

[141] 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.

Tax Credits

Power plants using advanced nuclear technology are eligible for a federal tax credit of 1.8 cents per kilowatt-hour of electricity generated, as extended by P.L. 115-123. The 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 the tax credits could help nuclear demonstration projects procure financing and reduce the subsidy cost of DOE loan guarantees.

Choosing Projects for Federal Funding

Because the federal government may have limited funding for multibillion-dollar nuclear demonstration projects, a methodology for selecting which projects and technologies to support would likely be necessary. While this would appear to put DOE in the position of "picking winners," as discussed above, it is conceivable that some market-based selection criteria could be at least part of the selection process for demonstration reactor support. One such criterion could be evidence of a customer base, which could include letters of intent for future orders (perhaps conditioned on successful demonstration). Another market-based criterion could be the extent of private matching funds raised for the project, such as firm contracts for power sales from the demonstration plant, or other private funding. Many other criteria could also be considered, such as technology maturity level (the level of technical risk) and the financial and technical strength of the project sponsor. The potential goal of demonstrating the widest possible range of advanced technologies might also be a consideration.

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.[142] 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 in making changes during reactor construction without regulatory delays.[143]

In response to such concerns, 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.[144]

[142] 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.

[143] Ibid.

[144] Nuclear Innovation Alliance, *Enabling Nuclear Innovation: Strategies for Advanced Reactor Licensing*, April 2016,

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."[145] 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. Prior to NEIMA's enactment, NRC had begun preparing for the potential licensing of advanced reactors, issuing implementation action plans for the near, mid-, and long terms.[146]

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.[147] Transporting these new fuel forms may require additional innovation and regulation.

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 grants to advanced reactor license applicants to cover some of their NRC fees throughout the licensing process.

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.

Proposals to address this issue are included in NELA (S. 903), noted above. Section 2 of NELA would authorize the General Services Administration (GSA) to enter into PPAs for up to 40 years, an increase from the current limit of 10 years. Under 40 U.S.C. §501, GSA can delegate all or part of this authority to other agencies.[148] Under a PPA, the federal government signs a contract to purchase electricity from a public utility for a specific time period.

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p. 20, https://docs.wixstatic.com/ugd/5b05b3_71d4011545234838aa27005ab7d757f1.pdf.

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

[146] Nuclear Regulatory Commission, "Advanced Reactors (non-LWR designs)," February 22, 2019, https://www.nrc.gov/reactors/new-reactors/advanced.html.

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

[148] 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*

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 is intended to allow enough time for nuclear reactor construction costs to be recovered, according to NELA's sponsors.[149]

NELA Section 3 would require DOE to enter into at least one PPA to purchase power from a commercial nuclear reactor by the end of 2023. "Special consideration" would be given to "first-of-a-kind or early deployment nuclear technologies" that could provide reliable power to important national security facilities, especially facilities disconnected from the electricity grid. If a PPA met those criteria, then electricity rates under the agreement could be higher than the average market rate. PPAs with currently operating commercial nuclear plants would not qualify for above-market rates.

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.[150]

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 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."[151] 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, 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.

Particular concern has been raised about the availability of high-assay low enriched uranium (HALEU), which would be necessary to power many advanced nuclear reactors. Existing U.S. commercial nuclear reactors are fueled by uranium that has been enriched to between 3% and 5%

Agencies, 2015, pp. 7-8, https://www.gsa.gov/cdnstatic/Utility_Areawide_Guide_08-2015.pdf. See also 48 CFR 41.103, Statutory and Delegated Authority.

[149] "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.

[150] Kirshenberg, Seth, 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.

[151] Ibid., p. 36.

of the fissile isotope U-235. HALEU is enriched to between 5% and 20%. (At 20% and above, uranium is considered highly enriched and potentially useable for weapons.) Because HALEU is not used in existing commercial reactors, it is not readily available for advanced reactor development, according to the nuclear industry.[152]

Section 7 of NELA would require DOE to sell, transfer, or lease high-assay low enriched uranium (HALEU) for use in advanced nuclear reactors. HALEU containing at least 2 metric tons of U-235 is to be made available by the end of 2022 and a total of at least 10 metric tons by the end of 2025. The FY2019 Energy and Water Development Appropriations Act (P.L. 115-244, Division A) requires DOE to submit a plan to Congress for HALEU development and provides $20 million for preparation and testing.

DOE is currently pursuing two approaches for developing HALEU supplies. One approach is to use DOE-owned HALEU currently stored at INL to fabricate fuel for advanced reactors. DOE issued an environmental assessment on January 17, 2019, that found no significant environmental impact from fabricating the fuel at existing INL facilities.[153] In the other approach, DOE announced January 7, 2019, that it intended to sign a sole-source contract with Centrus Energy to build 16 centrifuges at DOE's Portsmouth, OH, site to enrich "a small quantity" of uranium to 19.75% U-235 by October 2020.[154]

The Nuclear Energy Institute has estimated that it would take a minimum of seven years to establish the infrastructure to supply this fuel for commercial purposes. DOE has proposed to downblend a supply of high enriched uranium to bridge this gap.[155] By some assessments, 32 GWe of deployed advanced reactor capacity would be required to ensure the economic viability of new fuel fabrication and other fuel cycle facilities.[156]

International Organizations

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."[157] IFNEC was formed in 2010 by the members of its precursor organization, the Global Nuclear Energy Partnership. Its membership includes 34 participant countries, 31 observer countries, and 4 international observer organizations. The United States is a participating country. IFNEC working groups focus on issues related to nuclear infrastructure development, reliable fuel

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[152] Nuclear Energy Institute, "NEI Urges Revamp of Fuel Industry to Support Advanced Reactors," February 22, 2018, https://www.nei.org/news/2018/revamp-of-fuel-industry-support-advanced-reactors.

[153] DOE Office of Nuclear Energy, "Environmental Assessment Completed for Use of DOE-Owned High-Assay Low-Enriched Uranium Stored at Idaho National Laboratory," January 17, 2019, https://www.energy.gov/ne/articles/environmental-assessment-completed-use-doe-owned-high-assay-low-enriched-uranium-stored.

[154] 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.

[155] 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?feed=feed.

[156] Energy Options Network, "What Will Advanced Nuclear Power Plants Cost? A Standardized Cost Analysis of Advanced Nuclear Technologies in Commercial Development."

[157] International Framework for Nuclear Energy, "History," IFNEC, October 9, 2018, https://www.ifnec.org/ifnec/jcms/g_5150/history.

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 created in 2000 with nine original members: Argentina, Brazil, Canada, France, Japan, South Korea, South Africa, the United Kingdom, and the United States. Switzerland, the European Union, China, Russia, and Australia joined subsequently.

In 2002, after reviewing 130 advanced reactor designs, the GIF identified 6 nuclear energy systems for further development. Collectively, these are known as Generation IV reactors.

The six Generation IV reactor technologies are:

- Gas-Cooled Fast Reactor,
- Lead-Cooled Fast Reactor,
- Molten Salt Reactor,
- Sodium-Cooled Fast Reactor,
- Supercritical Water-Cooled Reactor, and
- Very High Temperature Reactor.

Factors used in selecting the designs include safety, sustainability, economics, physical security, proliferation resistance, and waste minimization, and they represent a range of technologies. The GIF has suggested that commercialization of some of these technologies may occur as early as 2030, with demonstration of some technologies possibly occurring within the next decade. Each of these technologies is at a different level of technical maturity. Of these, sodium-cooled fast reactors are considered to be the most mature. Gas-cooled fast reactors, lead-cooled fast reactors, and molten salt reactors are not expected to reach commercialization until 2050 under current rates of development, although some vendors and academics have put forth more optimistic timelines.[158]

[158] Researchers from MIT estimate that this timeframe may be moved up to the mid- to late-2030s under certain conditions. (Massachusetts Institute of Technology, "The Future of Nuclear Energy in a Carbon-Constrained World.")

Appendix.

Table A-1. Existing Global Fast Reactors

Location and Status of Existing Fast Reactors

Country	Reactor Name	Operation Years	Current Status
India	FBTR	1985-present	Active
India	PFBR	Expected 2019	Under construction
Japan	Joyo	1978-2007	Inactive
Japan	Monju	1994-1996, 2010	Inactive
Russia	BOR-60	1969-present	Active
Russia	BN-600	1980-present	Active
Russia	BN-800	2014-present	Active

Source: World Nuclear Association, "Fast Neutron Reactors," November 2018, http://www.world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx.; *Times of India*, "Kalpakkam Fast Breeder Reactor May Achieve Criticality in 2019," https://timesofindia.indiatimes.com/india/kalpakkam-fast-breeder-reactor-may-achieve-criticality-in-2019/articleshow/65888098.cms.

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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