Pacific Northwest NATIONAL LABORATORY

PNNL-34156

Emerging Technologies Review: Small Modular Reactors

April 2023

Kenneth Thomas
Chuck Gunzel
Nicole Lahaye

Prepared for the Air Force Civil Engineer Center
under a Work-For-Others Agreement with the U.S. Department of Energy

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Pacific Northwest National Laboratory
Richland, Washington 99354

Executive Summary

A majority of Air Force missions depend on both water and energy. The 2021 Air Force Installation Energy Strategic Plan embraces this dependency and outlines a path to greater mission assurance through more resilient energy and water systems. The previous energy strategic plan placed equal weight on resilience, cost-effectiveness, and cleaner energy technologies. The new plan emphasizes resilience and mission-centric efforts, while also highlighting the importance of water: "Resilience has become central to DAF efforts."[1] The 2022 Air Force Climate Action Plan[2] aligns with the Energy Strategic Plan in its third priority, where it calls on the Air Force to optimize energy use and pursue alternative energy sources. The Air Force Civil Engineer Center has tasked Pacific Northwest National Laboratory with investigating emerging technologies to inform the Air Force's understanding of each technology and to guide key considerations for implementing technologies that are resilient and alternative sources to the traditional methods used in the Air Force today.

This report explores the small modular reactor (SMR) technology for potential deployment at Air Force installations. SMRs and microreactors (MRs) are advanced nuclear fission reactors with much a smaller power capacity and physical footprint than currently operating large conventional reactors.[3] SMRs and MRs are constructed using modular assemblies and have a generating capacity of generally no more than 300 megawatts-electric, roughly a third of the capacity of an operating commercial reactor in the U.S. Although nuclear reactor technology has been in operation for decades, SMR technologies continue to evolve and are expected to use novel design approaches that will leverage modular construction with onsite assembly.

The type of reactor is generally characterized by the type of neutron needed for sustaining a chain reaction and the type of coolant. Types of reactors include pressurized water reactors, boiling water reactors, sodium fast reactors, high-temperature gas-cooled reactors, and molten salt reactors. Each of these reactors uses nuclear fuel. The process to make nuclear fuel involves enriching uranium. Typical operating nuclear reactors in the U.S. use fuel enriched to approximately 5% by mass of the isotope uranium-235 (U-235). SMRs often need fuel enriched to between 5% and 20% by mass of U-235. This allows more power per unit volume, longer operating cycles between refueling, increased efficiencies, and higher fuel utilization.[4] The fuel is shaped into various forms and assembled for use appropriate for the type of reactor.

The main component of nuclear reactor plants is a system for generating and transferring heat using fluids, heat exchangers, and pumps or compressors to circulate fluids. This system is typically comprised of a reactor vessel, a steam generator, a turbine, an electric-generator, and output transformers. Other systems at the plant provide control of the reactor, monitoring, and conditioning of the fluids, electricity supply to the plant loads, testing and maintenance of the systems, security, and emergency response.

[1] Air Force Installation Energy Strategic Plan, https://www.af.mil/Portals/1/documents/2021SAF/01_Jan/AF_Installation_Energy_Strategic_Plan_15JAN2021.pdf

[2] Air Force Climate Plan, https://www.safie.hq.af.mil/Programs/Climate/

[3] Congress defined advanced nuclear reactors in the Nuclear Energy Innovation and Modernization Act (Public Law 115-439) to mean a nuclear fission or fusion reactor with significant improvements compared to commercial nuclear reactors under construction.

[4] To compare the energy in this fuel with coal, 1 kilogram of pure uranium-235 theoretically could produce as much energy as 1.5 million kilograms (1,500 tons) of coal if the uranium-235 could completely fission.

SMR designers and vendors have achieved various levels of design maturity. Light water reactor (LWR) SMRs are the most mature in terms of technology and manufacturing since the designs are derived from existing large LWR designs. Non-LWR SMRs are considered further from commercialization and deployment since they are based on reactor designs for which there are few actual deployments and fewer of them have been in operation as long as the large LWR nuclear power plants. The International Atomic Energy Agency publishes a biennial edition of "Advances in Small Modular Reactor Technology Developments." The recent edition provided information on more than 80 different designs under development globally (IAEA 2022).

There are multiple limiting factors and constraints pertinent to SMR technology deployment. A limited nuclear workforce and a limited supply of fabrication components and nuclear fuel specialized for SMRs all affect the advancement of the technology. Also, there is no current commercial deployment of any SMRs in the U.S. The Nuclear Regulatory Commission (NRC) is the sole licensing authority in the U.S. for commercial nuclear reactors, including SMRs that supply electricity and heat (42 U.S.C. § 5814). Several vendors and operators are in pre-application discussions with the NRC. The NRC is also working through various issues to address the uncertainty among vendors and communities about the overall demand for electricity, process heat, or hydrogen generation to enable large-scale factory construction to manufacture SMRs.

The social, environmental, and economic implications of deploying SMRs should also be reviewed to consider all risks and benefits associated with the technology. The NRC reviews human health risks as part of their environmental and safety reviews for nuclear power plants licensing. Community assets/equity are addressed in the environmental review process. The NRC regulations describe the scope of the analysis needed as:

> "Site selection involves consideration of the human environment, public health and safety, engineering and design, economics, institutional requirements, environmental impacts, and other factors. The potential impacts of the construction and operation of nuclear power stations on the human environment and on social, cultural, and economic features (including environmental justice) are usually similar to the potential impacts of any major industrial facility, but nuclear power stations are unique in the degree to which potential impacts of the environment on their safety must be considered. The safety requirements are primary determinants of the suitability of a site for nuclear power stations, but environmental impacts are also important and need to be evaluated."

In terms of economic and funding considerations, various DOE programs exist as part of private-public partnerships and cost-sharing initiatives to advance nuclear energy technologies such as SMRs. It is difficult to estimate the initial cost and operational budget for an SMR as none exist commercially in the U.S. Cost information about SMRs outside the U.S. is not publicly available. Similarly, construction and operational costs for commercial large-scale reactors are proprietary and not publicly available. Some experts suggest setting the initial expectation of acquisition cost for a first-of-a-kind SMR at over $1 billion (EIA 2022a), a cost that would vary based on the expected power output, reactor type, and configuration. This number will be refined as knowledge, experience, and economies of scale are realized.

There are several documents available that may assist the Air Force in determining its next steps. Pacific Northwest National Laboratory provided roadmaps for the Air Force's consideration in the Eielson Air Force Base Microreactor Pilot Project. The three draft roadmaps provide additional information on the siting, regulatory, and beyond pilot considerations and may inform potential paths forward for other Air Force applications. These documents provide valuable insight into a specific Air Force MR application. Additionally, DOE funded a study that provides options for federal agencies to purchase power supplied by SMRs. Chapter 7 of the study provides a six-step roadmap for federal agencies that wish to have reliable electric power from SMRs while efficiently using financial resources.

The Air Force will need to review the operational, technical, regulatory, environmental, and economic considerations when deciding when and where to deploy SMRs, understanding the unique benefits and challenges presented by the technology. The outcome of the EAFB project will be an indicator for future opportunities.

Acronyms and Abbreviations

AEC	Atomic Energy Commission
AFCEC	Air Force Civil Engineering Center
ANLWR	advanced non-light-water reactor
ANR	advanced nuclear reactor
ARDP	Advanced Reactor Demonstration Program
AVR	Arbeitsgemeinshaft Versuchsreactor
BWR	boiling water reactor
CFR	Code of Federal Regulations
COL	combined construction permit and operating license or combined operating license
DAF	Department of the Air Force
DOD	Department of Defense
DOE	Department of Energy
DOE-NE	Office of Nuclear Energy
EAFB	Eielson Air Force Base
EBR-I	Experimental Breeder Reactor-I
EBR-II	Experimental Breeder Reactor-II
EIS	environmental impact statement
ERDA	Energy Research and Development Administration
ESP	Early Site Permit
ESRP	Environmental Standard Review Plan
FAO	Funding Opportunity Announcement
FNPP	floating nuclear power plant
GAIN	Gateway for Accelerated Innovation in Nuclear
HALEU	high assay low enriched uranium
HEU	highly enriched uranium
HTGR	high-temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
iPWR	integral pressurized water reactor
ISG	interim staff guidance
LFTR	lithium fluoride thorium reactor
LWA	limited work authorization
LWR	light-water reactor
MR	microreactor
MSRE	Molten Salt Reactor Experiment

MSR	molten salt reactor
MWe	megawatt-electric
MWt	megawatt-thermal
NEI	Nuclear Energy Institute
NEIMA	Nuclear Energy Innovation and Modernization Act of 2019
NEPA	National Environmental Policy Act of 1969, as amended
NGNP	Next Generation Nuclear Plant
NRC	Nuclear Regulatory Commission
NUREG	Nuclear Regulatory Report
NWPA	Nuclear Waste Policy Act
O&M	operations and maintenance
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PPA	power purchase agreement
PWR	pressurized water reactor
RFP	request for proposals
RG	Regulatory Guide
SDA	standard design approval
SFR	sodium fast reactor
SMR	small modular reactor
SRP	Standard Review Plan
SSG	IAEA Specific Safety Guide
THTR	thorium cycle high-temperature
TRISO	tristructural isotropic fuel particle
TRL	technology readiness level
TVA	Tennessee Valley Authority

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1.0 Introduction

As Air Force planners work to enhance the energy and water security of mission-critical sites, it is vital to identify proven methods and processes to generate, store, and distribute electricity to meet critical mission needs. Energy resilience readiness exercises conducted by the Assistant Secretary of the Air Force for Energy, Installations, and Environment have helped to highlight the importance of resilient and reliable energy to every critical mission (Air Force 2021a). Small modular reactors (SMRs) provide a reliable source of energy that can serve as a redundant supply to alleviate the impact of utility service disruptions. This redundant supply improves installation readiness and resilience while supporting broader sustainment and environmental objectives.

1.1 Drivers

The use of alternative energy sources supports the requirements in Department of Defense (DOD) Instruction 4170.11 (DOD 2009), which states that DOD components shall “take necessary steps to ensure the security of energy and water resources.” This is also emphasized as Objective 3 of the Air Force Climate Action Plan (Air Force 2022). The Air Force’s Installation Energy Strategic Plan 2021 (Air Force 2021b) outlines a path to greater mission assurance through more resilient energy and water systems. The new plan emphasizes resilience and mission-centric efforts. The Air Force Civil Engineer Center has tasked Pacific Northwest National Laboratory (PNNL) with investigating emerging technologies to inform the Air Force’s understanding of SMRs and to guide key considerations for implementing technologies that are resilient and alternative sources to the traditional methods used in the Air Force today.

1.2 Scope

This report first describes the components, configuration, and basic operation of SMRs. The report then explores many operational considerations of SMR technology, including capacity and output, limiting factors and constraints, and operations and maintenance (O&M) requirements. Details on how the technology has matured to its current state of development are provided, showcasing successful pilots or demonstrations. A thorough regulatory overview is provided to give readers a full understanding of the applicable federal requirements. Social, environmental, and economic considerations are also reviewed to deliver a holistic view of all risks and benefits associated with employing SMRs. Finally, this review provides desirable siting characteristics, along with a recommended path forward if the Air Force decides to research SMRs further as a viable resilient energy source. See Appendix A for definitions of terms commonly used in the nuclear power industry to describe the various designs and operating characteristics.

2.0 Technology Description

Since SMRs and microreactors (MRs) are an emerging technology, there is no single, universally accepted definition of an SMR. This report aligns with the definitions of SMRs and MRs provided in the National Defense Authorization Act for Fiscal Year 2023 (Public Law 117-263). SMRs and MRs are advanced nuclear fission reactors constructed using modular assemblies with a much smaller power capacity and physical footprint than currently operating large conventional reactors.[1] SMRs are advanced nuclear reactors (ANRs) with a rated generating capacity of less than 300 megawatts-electric (MWe), roughly a third of the capacity of an operating commercial reactor in the U.S. MRs are ANRs with an electrical power production capacity no greater than 50 MWe. While both sizes are making the news and being promoted by vendors and the Department of Energy (DOE), this report focuses on SMRs with the understanding that the characteristics of an SMR will likely be true of an MR. In the infrequent occasion where the characteristics of SMRs and MRs are different, those differences are noted.

SMRs and MRs can trace their development back to the first nuclear reactors developed and used in the U.S. These early reactors were necessarily small due to the lack of uranium and other resources. The Atomic Energy Commission (AEC) designed and operated one of the first electricity-generating nuclear power plants, the Experimental Breeder Reactor-I (EBR-I), about 20 miles from Arco, Idaho. In 1951, EBR-I was initially able to generate enough electricity to power four 200-watt light bulbs. EBR-I eventually supplied 200-kWe of power to the town of Arco. The reactor was modest compared to the proposed 300-MWe SMR designs of today.

SMRs and MRs may offer distinct advantages by providing a smaller footprint than other comparably scaled carbon-free generation options like solar and wind. SMRs and MRs may require fewer resources than current large nuclear power plants, reducing the potential impacts on the environment and water resources. Based on the need for fewer resources and the reduction in construction time and costs, SMRs and MRs may require less funding to build than large nuclear reactors. Therefore, SMRs and MRs may have lower financing costs and result in a reduction in the levelized cost of electricity.

2.1 Technology Operation

All research, maritime, and commercial nuclear reactors in operation today rely on splitting (fission) the nuclei of heavy elements. Uranium is the most common reactor fuel and typically is in the reactor core. When a nucleus of the fuel absorbs a neutron, it becomes unstable and has the potential to split (fission). Once the nucleus splits, it releases fast neutrons (neutrons carrying energies above 1M electron volts or greater) that cause more fissions, radiation, and two fission products that remain within the fuel. The splitting of the nucleus releases energy that is transformed into heat within the fuel. The heat is removed from the fuel in the reactor core by a coolant, usually water. Other coolants used in reactors include gases (hydrogen, helium, and carbon dioxide), liquid metals (like lead or sodium), and molten salts. Once removed from the core, heat is usually, but not always, transferred to another fluid and the flow of the second fluid turns a turbine that is coupled to a generator. The spinning of the generator produces electricity, which is distributed to users by transmission and distribution grids.

[1] Congress defined advanced nuclear reactors in the Nuclear Energy Innovation and Modernization Act (Public Law 115-439) to mean a nuclear fission or fusion reactor with significant improvements compared to commercial nuclear reactors under construction.

2.2 Components

The main component of nuclear reactor plants is a system for generating and transferring heat using fluids, heat exchangers, and pumps or compressors to circulate fluids. Figure 1 shows a typical large commercial pressurized water reactor (PWR), a type of SMR. The system is typically comprised of the reactor vessel, a steam generator, a turbine, an electric-generator, and output transformers. These are described in greater detail below and in the glossary (Appendix A). Other systems at the plant provide control of the reactor, monitoring and conditioning of the fluids, electricity supply to the plant loads, testing and maintenance of the systems, security, and emergency response. Some systems have redundant systems to improve reliability, particularly those that the operators rely on for safety and emergency functions.

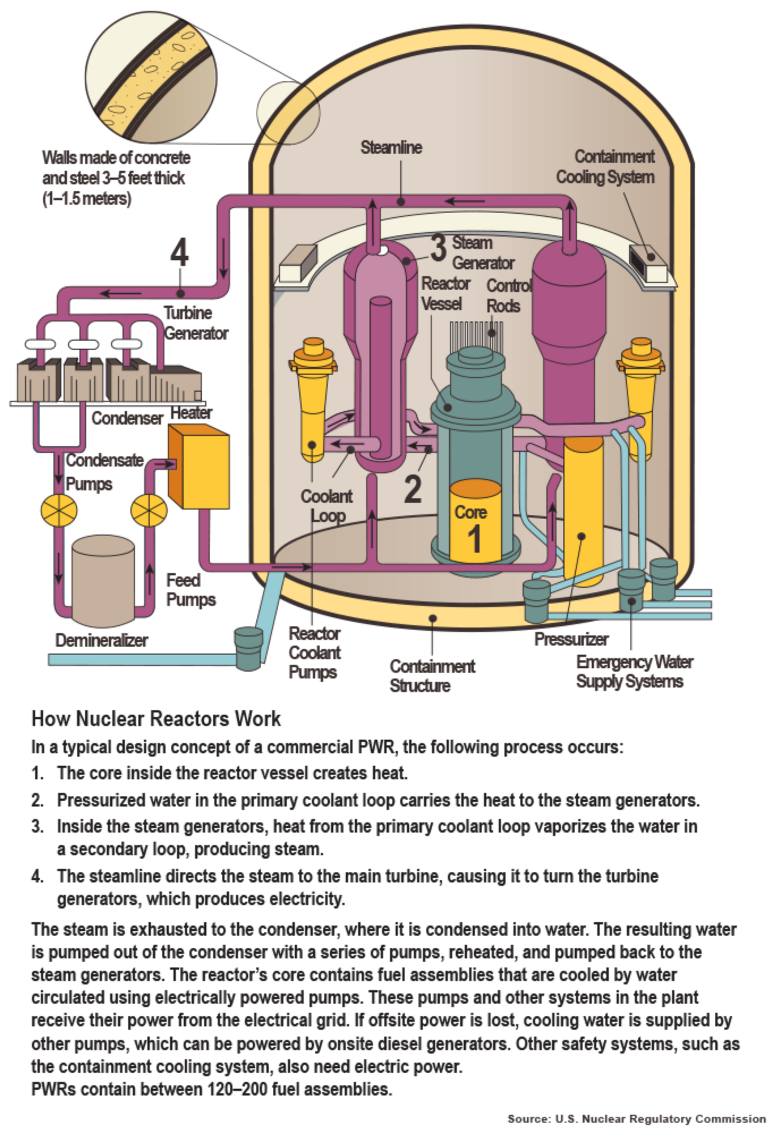

Figure 1. Typical Large Commercial Pressurized Water Reactor (NRC 2022a)

Reactor Vessel – The reactor vessel is generally a thick-walled, cylindrical shell containing the nuclear fuel and other internal components that direct the flow of the coolant, support the reactor core, and provide reactivity control and measurements. The reactor vessel may be a pressure vessel designed to withstand pressures many times the atmospheric pressure and temperatures of more than 1000°F. Many SMR designs may operate at high temperatures but near atmospheric pressure.

Coolant – The coolant removes heat generated in the nuclear fuel and transfers it to other coolants or directly uses it to generate electricity. Many SMR designs may use a secondary coolant to remove the heat from the reactor (primary) coolant to minimize the risks associated with coolant leaks. Common reactor coolants, which typically classify the type of SMR, include demineralized water (also known as light water), heavy water (water with one or two deuterium atoms instead of regular hydrogen atoms found in light water), liquid metals (sodium or lead), gases (helium), and molten salts.

Moderator – The moderator, or more precisely the neutron moderator, reduces the energy or speed of a fast neutron that is released when the nucleus is split during fission. The function of a moderator is to slow down fast neutrons until they become thermal neutrons (slow neutrons). Many SMRs are thermal nuclear reactors, which means that the fast neutrons released during fission need to lose energy or slow down to be useful for fission. “Fast reactors,” however, do not need moderation to cause fission.

Steam Generator – Within a steam generator, the reactor coolant transfers its heat to a secondary coolant, typically water, to make steam. After leaving the steam generator, the steam typically travels to a turbine. In some SMR designs, like the NuScale Power Module, the steam generator is one component within the reactor vessel. However, not all SMR designs need a steam generator, and for those using a steam generator, it does not have to be within the reactor vessel.

Turbine – A turbine is part of the turbine generator, a large machine that converts mechanical energy from a flowing fluid into rotational energy. All SMR designs generate heat, requiring a coolant to remove the heat from the nuclear fuel and transfer or convert the heat into useful work. The turbine is the first component in the system to convert the heat into useful work. The electric generator is coupled to the turbine so that when a fluid flows through the turbine, the common shaft spins and converts the rotational (mechanical) energy into electricity.

Main Transformers – The main transformers convert or step-up the output of the electric generator to the distribution grid by matching the phase sequence, voltage magnitude, frequency, and phase angle of the two systems.

Condenser – A condenser condenses the steam into liquid water using another coolant, typically water or the atmosphere.

Emergency Diesel Generators – Emergency diesel generators are the predominant means to supply onsite emergency or standby electrical power to safety-related equipment when offsite power is not available. Some SMR and MR designs indicate that onsite emergency power is not required for safe operations.

SMRs and MRs are generally small enough to allow many of the coolant system components to be placed within a single reactor vessel. The larger reactor vessels could be built and partially assembled in a factory and transported to the designated site for final assembly and installation. The small reactor vessels could be built and completely assembled in a factory before being transported to the site and installed. These approaches can reduce construction time and costs and have the potential to take advantage of economies of scale. These attributes contrast with the current large nuclear power plants that required custom designs and construction at a designated site.

The configuration of the SMR components described above depends on the reactor technology employed. The next section describes different reactor types and how their components are configured.

2.3 Nuclear Reactor Types

The type of reactor is generally characterized by the type of neutron needed for sustaining a chain reaction (fast or thermal neutrons) and the type of coolant (such as light water or sodium).

Many types of nuclear reactor technologies have been proven and have a high level of technology readiness. Within the U.S. and globally, light-water reactors, liquid metal reactors, high-temperature gas-cooled reactors (HTGRs), and molten salt reactors (MSRs) have been constructed, licensed, and operated. Table 1 provides an overview of the different types of reactors. The values for operating pressures and temperatures in the descriptions are approximate and representative of the various types, and the specific values may vary by design within each type. For example, concerning operating pressures, PWRs typically operate at around 150 atmospheres (150 times normal atmospheric pressure), while liquid metal reactors operate slightly above atmospheric pressure.

Table 1. Nuclear Reactor Types

Reactor Type	Coolant	Moderator	Neutron Spectrum
Pressurized water reactor (PWR)	Light water (H_2O)	Light water	Thermal
Boiling water reactor (BWR)	Light water (H_2O)	Light water	Thermal
Liquid metal reactor	Liquid sodium, lead, or lead-bismuth	Graphite	Thermal
		None	Fast
High-temperature gas-cooled reactor (HGTR)	Helium (hydrogen, carbon dioxide)	Graphite	Thermal
		None	Fast
Molten salt reactor	Chloride or fluoride salt mixture	Graphite	Thermal
		None	Fast

2.3.1 Pressurized Water Reactors

PWRs are nuclear fission reactors that use demineralized light water (H_2O) as the coolant. PWRs are designed to use thermal neutrons to cause fission. PWRs also use water as a moderator. The primary difference between this type of reactor and the reactors described in Sections 2.3.3 through 2.3.5 is the use of demineralized water instead of other coolants like liquid metals, gases, or salt solutions. Additionally, PWRs operate at high pressures, generally around 2,200 psi or 150 atmospheres. At these operating pressures, there is no significant boiling in the core and the coolant remains liquid at all times. To generate electricity, the water from the reactor (primary loop) heats water in a secondary loop within a steam generator. The steam leaving the steam generator drives the turbine generator to generate electricity.

PWRs were originally designed at Oak Ridge National Laboratory (ORNL) and are deployed around the world. In the U.S., about two-thirds of commercial nuclear power plants are PWRs. All U.S. Naval reactors are PWRs. The U.S. Army nuclear power program operated PWRs from 1954 until 1974.

The NuScale PWR design is the only U.S. SMR design to have a U.S. Nuclear Regulatory Commission (NRC) Design Certification and a Standard Design Approval.

Figure 2 shows the configuration of the NuScale PWR power module. Since the steam generator and reactor share the same reactor vessel, this particular design feature is commonly referred to as an integral PWR (iPWR).

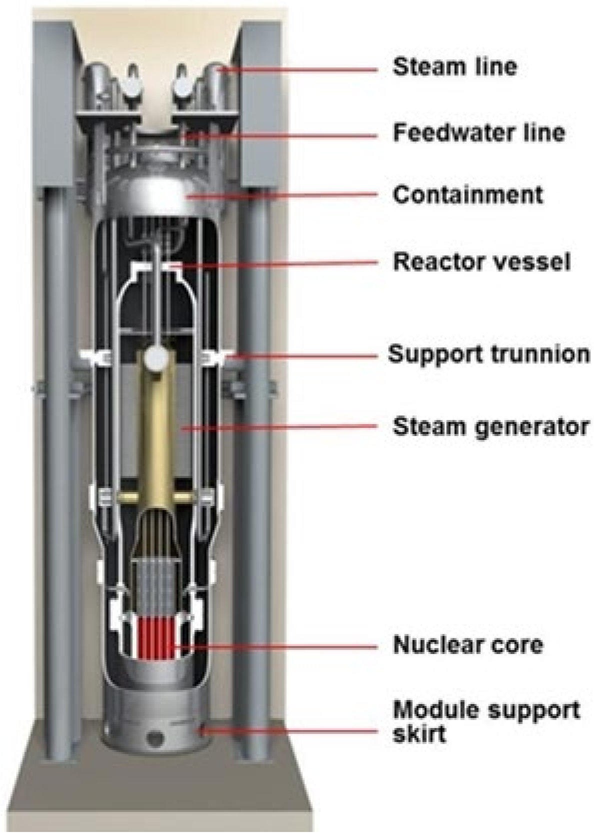

Figure 2. NuScale Power Module (NRC 2023b)

2.3.2 Boiling Water Reactors

Boiling water reactors (BWRs) are nuclear fission reactors that use demineralized water (H_2O) as the coolant. BWRs are designed to use thermal neutrons to cause fission, and use water as a moderator. The primary difference between this type of reactor and the reactors described below is the use of demineralized water instead of other coolants like liquid metals, gases, or salt solutions. Additionally, the BWRs operate at high pressures, generally around 1,000 psi or 68 atmospheres, and around 550°F (285°C). At the operating pressure and temperature, the water in the reactor core boils, and the steam from the reactor directly drives the turbine generator to generate electricity in a single loop.

Since a BWR uses a single-loop steam supply system, the steam leaves the reactor and flows to the turbine-generator. After leaving the turbine-generator, the steam is condensed into water, and then pumped back into the reactor.

BWRs were originally designed by Argonne National Laboratory and General Electric. BWRs are deployed around the world. In the U.S., about one-third of commercial nuclear power plants are BWRs. Currently, there are no BWR SMR design applications before the NRC.

2.3.3 Sodium Fast Reactors

Sodium fast reactors (SFRs) are a type of liquid metal-cooled nuclear fission reactors that use liquid sodium as the coolant. Since the SFRs are designed to use fast neutrons to cause fission, the SFRs do not use a moderator. The primary differences between this type of reactor and the reactors described above are the use of sodium instead of demineralized light water as a coolant and the use of fast neutrons instead of thermal neutrons for fission. SFRs operate at near atmospheric pressure, 1.5 psi or 0.1 atmosphere. The liquid sodium heats water in a steam generator, and the steam from the steam generator drives a turbine generator to generate electricity. Other forms of liquid metal reactors may use lead or lead-bismuth as a coolant.

SFRs were first designed in the late 1940s and built in the 1950s, and continue to operate today. In 1950, the AEC began construction of SFR EBR-I at Idaho National Laboratory (INL). EBR-I continued to operate until 1964, when it was decommissioned. During operation, it was able to supply power to its own electrical systems as well as to the City of Arco, Idaho.

Fermi 1, a 69-MWe commercial SFR located outside of Detroit, was constructed between 1956 to 1963 and operated from 1963 until 1966 and 1970 to 1972. It was permanently shut down in 1972 and decommissioned in 1975.

Currently, the Japanese test SFR Joyo (1977-1997 and 2004-2007), Russia’s two commercial SFRs BN-600 (1980-present) and BN-800 (2014-present), and the China Experimental Fast Reactor (2011-present) are all in operation. BN-600 and BN-800 are the only two operating commercial SFRs in the world.

There are no SFR SMR design applications before the NRC.

Figure 3 shows an SFR reactor design. While the design shares features with a PWR and BWR, a notable difference is the use of a heated pool of liquid sodium. The core heats the liquid sodium, and by natural convection, the liquid sodium enters a heat exchanger, heating the liquid sodium within the tubes (secondary sodium loop) while cooling the primary liquid sodium, then exits the heat exchanger and enters the region of relatively cooler liquid sodium (blue area in Figure 3). The SFR requires a “covering gas” to prevent air and humidity from entering the reactor vessel (grey region in Figure 3, above the hot and cold plenums within the reactor vessel). The secondary sodium is pumped to a steam generator, where the secondary liquid sodium heats the water within the tubes, making steam. The steam travels to the turbine generator to generate electricity. After leaving the turbine generator, the steam condenses into water, which is pumped back to the steam generator. The heat sink may be either forced air (fan) or pumped water from a river, lake, cooling pond, or ocean.

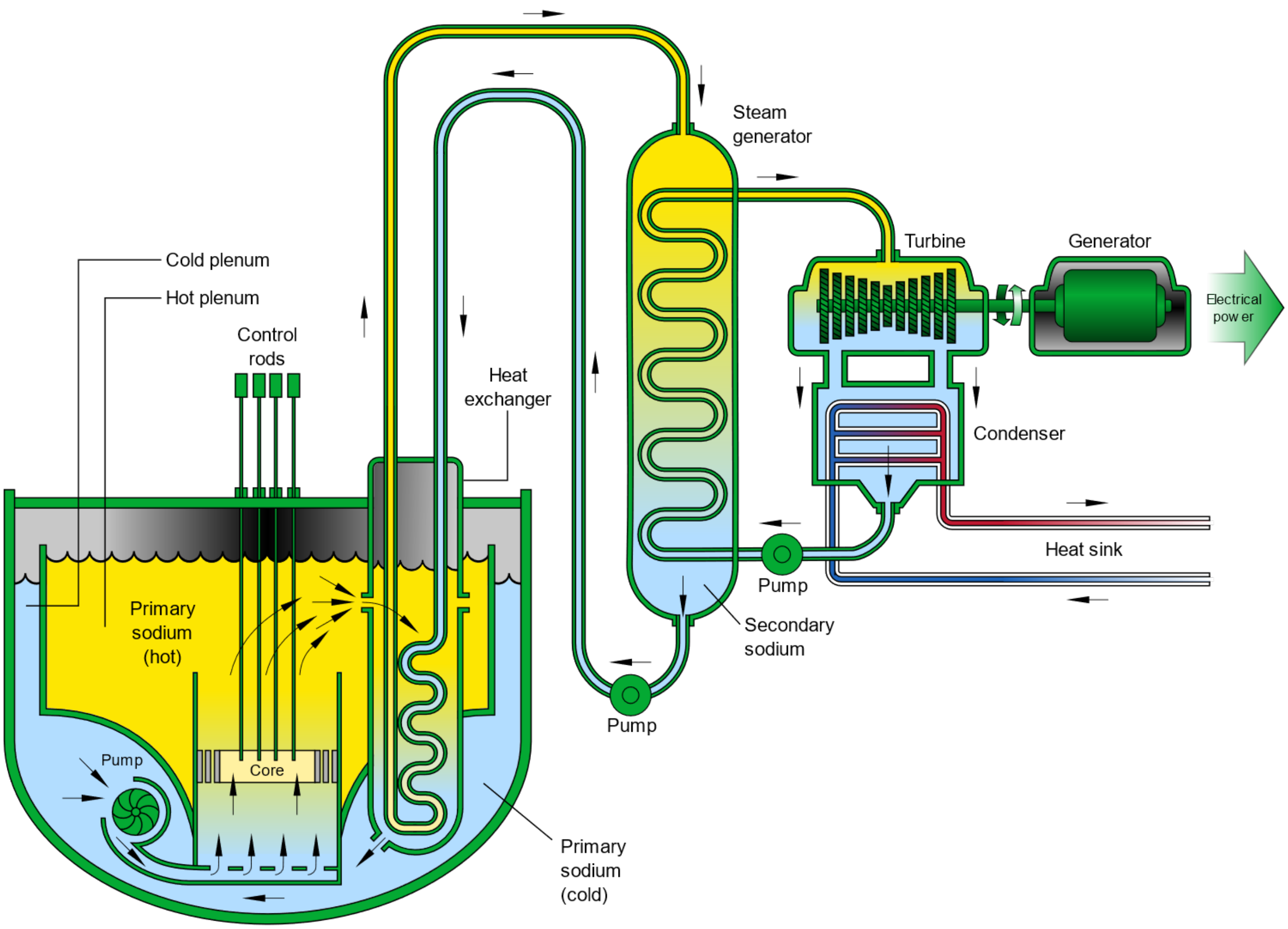

Figure 3. Sodium Fast Reactor (Public Domain)

2.3.4 High-Temperature Gas-Cooled Reactors

HTGRs are nuclear fission reactors that use gases, such as helium, as the coolant. Since most HTGRs are designed to use thermal neutrons to cause fission, most HTGRs use graphite as a moderator. However, there is no moderator for HTGR designs that use fast neutrons. The primary difference between this type of reactor and the designs described above is the use of a high-temperature gas instead of water or liquid metal as a coolant, and the use of graphite as a moderator, as needed. Additionally, HTGRs operate at lower pressures than the PWR and BWR design pressures, around 870 psi or 60 atmospheres. The gas from the reactor heats water within a steam generator. The steam drives a turbine generator to generate electricity. Some designs have the high-temperature gas drive the turbine generator directly.

There are two major HTGR designs based on the configuration of the moderator: (1) a prismatic block, where the reactor core is configured in graphite prismatic blocks, and (2) a pebble bed HTGR, where the moderator and fuel are formed in pebbles.

In 1947, the staff at Clinton Laboratories (now ORNL) proposed the first HTGR. In the 1950s, work continued on the designs for the HTGR and the gas-cooled fast reactor, particularly at General Atomics.

In 1958, the Philadelphia Electric Company ordered Peach Bottom 1, an experimental helium-cooled, graphite-moderated, 40-MWe nuclear prototype HTGR. Construction began on Peach Bottom 1 in 1962. It was commissioned in 1967, and operated until 1974, after successfully demonstrating the viability of HTGRs.

General Atomics also designed Fort St. Vrain as a proof-of-concept, helium-cooled, graphite-moderated, 330-MWe commercial HTGR. Construction began in 1968 and initial testing began in 1972. It began supplying electricity to the grid in 1979. While the project successfully proved the operating characteristics of an HTGR and other technologies, maintenance and extensive plant modifications were required to keep it operating. Based on the unacceptable economics and technical issues, the plant was decommissioned in 1989 (PSCC 1990).

The Energy Policy Act of 2005 (Public Law 109-58) required DOE and the NRC to submit to Congress a licensing strategy for the Next Generation Nuclear Plant (NGNP) (Figure 5). DOE developed the design of the NGNP from 2005 to 2013 using the same helium-cooled and graphite-moderated design concepts from the Fort St. Vrain reactor. DOE never applied for a license for the NGNP and stopped working on the design in 2011. The project was terminated in 2013.

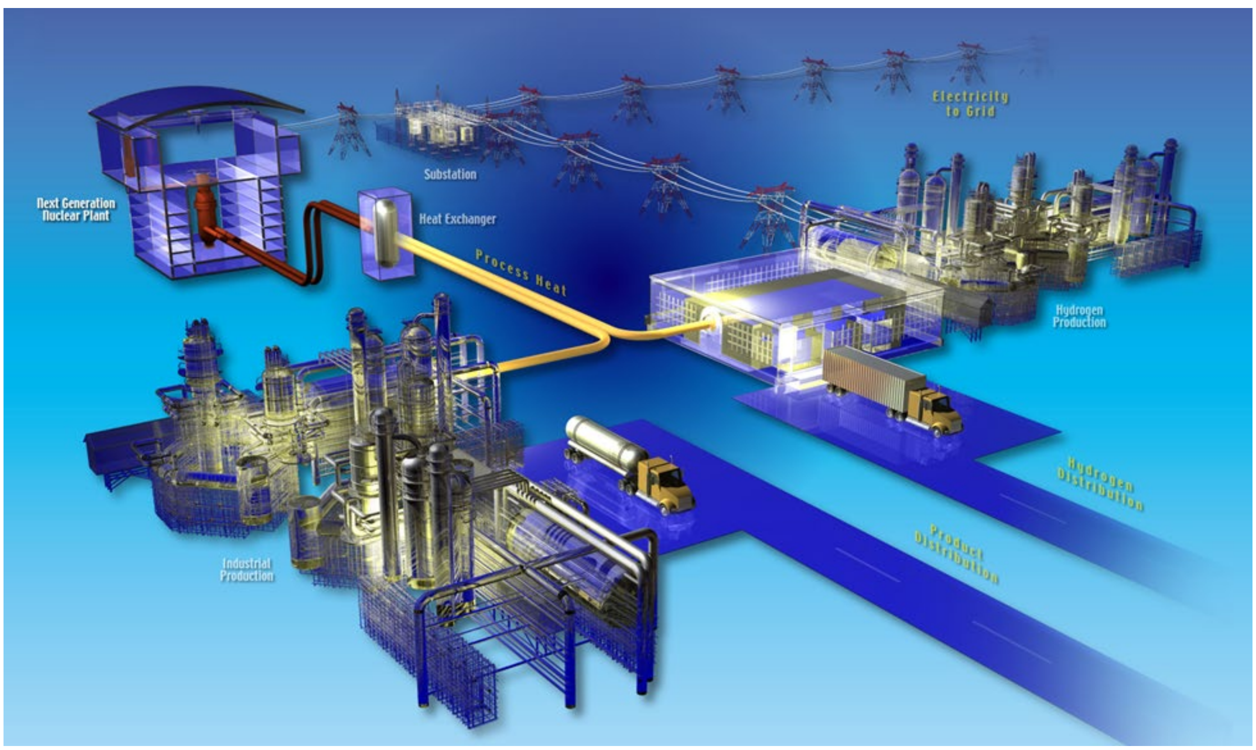

Figure 4. Next Generation Nuclear Plant (INL, Licensed Creative Commons 2)

Globally, other experimental HTGRs have been designed and operated.

- The United Kingdom Atomic Energy Authority operated the Dragon Reactor. The Dragon Reactor tested the fuel and materials for the Organization for Economic Co-operation and Development/Nuclear Energy Agency's European High Temperature Reactor Program from 1965 to 1976. The reactor design used an early form of tristructural isotropic (TRISO) fuel in various shapes. It is no longer in service and is undergoing decommissioning.

- Germany designed the Arbeitsgemeinshaft Versuchsreactor (AVR) and the thorium cycle high-temperature (THTR) 3000 reactor plants. The AVR was a 15-MWe test reactor that operated between 1967 and 1988. The THTR-300 reactor was a 300-MWe power plant that operated between 1985 and 1989. It is no longer in service.
- The Japan Atomic Energy Agency operates a high-temperature engineering test reactor. The gas-cooled, graphite-moderated reactor is designed to deliver 30 MWe. Its operation was suspended in 2011 and restarted in 2021.
- China's first high-temperature, gas-cooled, pebble-bed HTR-10 test reactor operates at Tsinghua University. It is designed to test concepts and is rated at 10 megawatt-thermal (MWt). Additionally, two high-temperature, gas-cooled, HTR-PM 100 MWe reactors began operating in China in 2021.

The NRC has not licensed an HTGR, and none currently operate in the U.S. There are no HTGR SMR design applications before the NRC.

2.3.5 Molten Salt Reactors

MSRs are nuclear fission reactors that use liquid chloride or fluoride salt mixtures as a coolant. MSRs may use liquid fuel, where the uranium-235 is mixed within a salt mixture and circulated through the reactor, or solid fuel. MSRs may also be either a thermal reactor that uses graphite as a moderator or a fast reactor where there is no need for a moderator. The primary difference between this type of reactor and the designs described above is the use of salt mixtures as a coolant. Additionally, the MSRs operate at lower pressures than the PWR and BWR design pressures, around 30 psi or 2 atmospheres. The hot salt mixture from the reactor heats a secondary loop within an intermediate heat exchanger, and then the heat from the secondary loop heats water to form steam in a steam generator. The steam drives a turbine generator to generate electricity.

In the U.S., the AEC conducted two MSR experiments: one for the U.S. Army Air Forces (which became the U.S. Air Force in 1947), and another internal one to determine if MSRs could be commercially operated safely and reliably, and maintained without excessive difficulty.

The Aircraft Nuclear Propulsion Program was initiated as a joint program between ORNL and the U.S. Army Air Forces in 1946. ORNL designed and tested a nuclear-powered aircraft reactor in 1954 as a proof-of-concept. However, it never flew, and efforts to develop a nuclear-powered long-range bomber ended. The reactor that ORNL designed for the bomber was molten salt-cooled and the uranium fuel was mixed within the fluid salt mixture and circulated through the reactor. The reactor demonstration was a success, operating for more than 100 hours over about 2 weeks.

The Molten Salt Reactor Experiment (MSRE) was a test reactor operated by ORNL to demonstrate that molten salt power reactors used primarily for electric generation could be operated safely and reliably. The 7.4-MWt molten salt-cooled, graphite-moderated, breeder reactor was constructed in 1964 and operated until 1969. It used a mixture of uranium isotopes, thorium, and plutonium fluoride salts. Figure 6 shows the different components of the MSRE.

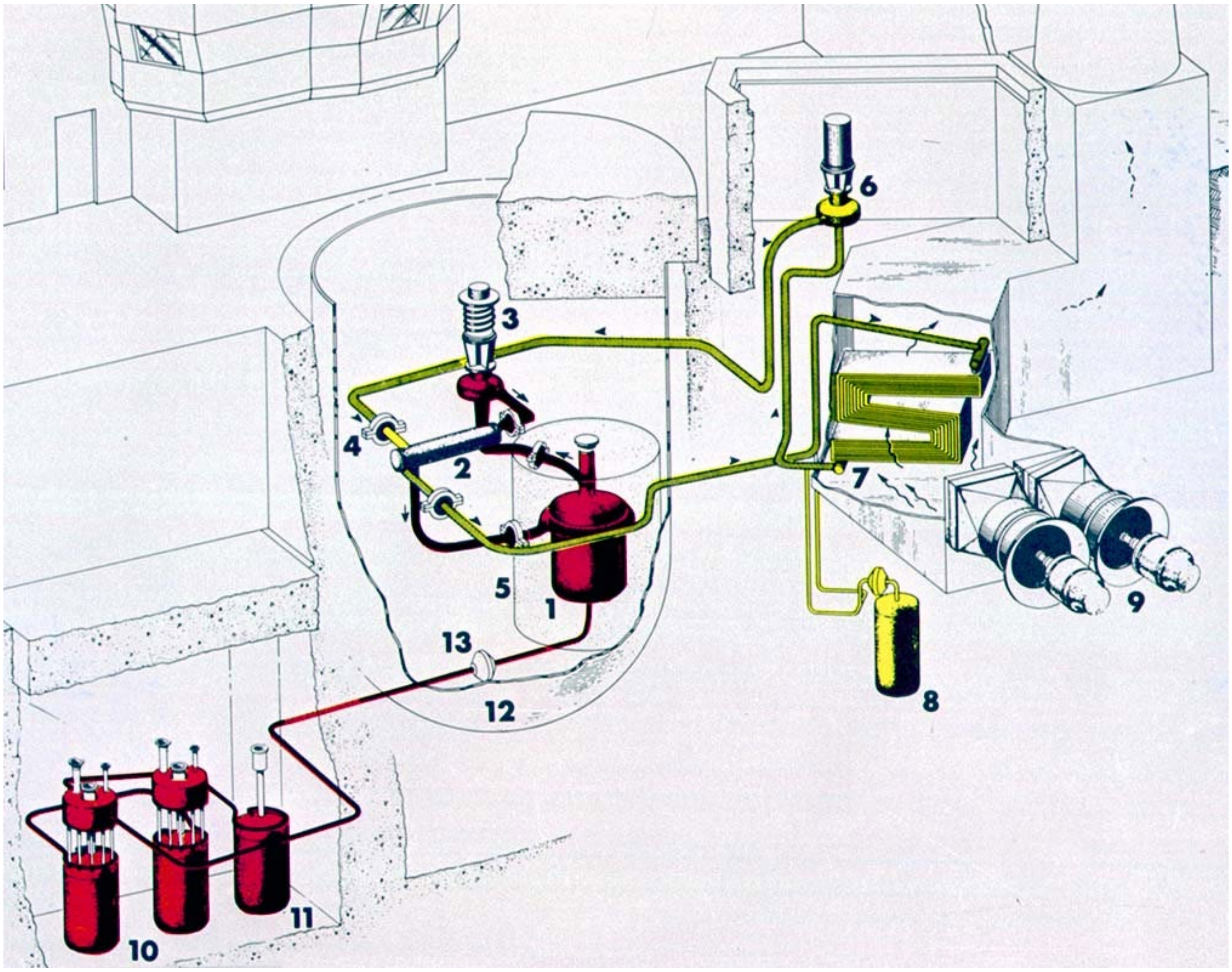

Figure 5. Molten Salt Reactor Experiment Plant Diagram (public domain): (1) reactor vessel, (2) heat exchanger, (3) fuel pump, (4) freeze flange, (5) thermal shield, (6) coolant pump, (7) radiator, (8) coolant drain tank, (9) fans, (10) fuel drain tanks, (11) flush tank, (12) containment vessel, (13) freeze valve. Also note control area in upper left and chimney upper right.

Currently, there are two MSR designs before the NRC. In September 2021, Kairos Power, LLC, submitted a construction permit application for its HERMES test reactor to the NRC. In August 2022, Abilene Christian University submitted a construction permit application to the NRC for a molten salt research reactor. The NRC is reviewing both applications and has not made a determination on either.

2.4 Fuels

The process to make nuclear fuel involves enriching uranium. SMRs may use several different types of fuel in various forms, depending on their design. These are described in the following sections. The supply of the fuels described here is discussed in Section 5.1.2.2. The disposal of nuclear fuel is discussed in Section 4.1.2.

2.4.1 Uranium-235

Nuclear fuel starts with uranium ore. The ore is processed to remove other elements and compounds, leaving very pure uranium as a uranium oxide concentrate called “yellowcake.” The yellowcake is then fluoridated and chemically converted into uranium hexafluoride (UF_6) gas.

Uranium has several different isotopes, but this report only describes relevant isotopes uranium-238 and uranium-235. The uranium ore is typically about 99.274% uranium-238 and about 0.72% uranium-235 with the other isotopes making up the difference. The process to make nuclear fuel includes enriching uranium, which increases the percentage of uranium through one of three methods: gaseous diffusion, gas centrifuge, or laser enrichment. Centrifuging is the current process used to enrich commercial uranium in the United States.

Uranium enriched to less than 5% of uranium-235 is called low enriched uranium (LEU). (The byproduct of this process is called depleted uranium and is used for other industrial and military purposes.) For PWRs and BWRs, uranium-235 is the product used to form their fuels. Typical operating nuclear reactors in the U.S. use fuel enriched to approximately 5% by mass of the isotope uranium-235 (U-235). However, for SMRs, many designs need higher enriched fuel. This product is called high assay low enriched uranium (HALEU). HALEU is fuel enriched to between 5% and 20% by mass of U-235. This allows more power per unit volume, longer operating cycles between refueling, increased efficiencies, and higher fuel utilization.[1]

2.4.2 Uranium-238 and Plutonium-239

Uranium-238 will fission only with fast neutrons, which are released directly from the splitting of a nucleus. Uranium-238 is less likely than uranium-235 to undergo fission. Uranium-238 is more likely to capture a neutron, and then become uranium-239. Uranium-239 will decay into neptunium-239, which will eventually decay into plutonium-239.

Plutonium-239 is more likely to fission than uranium-235. For the nuclei of plutonium-239 that do not fission, the nucleus will capture the neutron, which creates plutonium-240. Plutonium-240 will likely capture another neutron and create plutonium-241. Plutonium-241 has approximately the same likelihood of undergoing fission as plutonium-239.

This process is typically referred to as breeding and takes place in a “breeder reactor.”

2.4.3 Thorium-232 and Uranium-233

Although not widely used in commercial nuclear power reactors, thorium-232 was used in the MSRE discussed above. When mixed with uranium-235, thorium-232 will capture a neutron from the fission of uranium-235, and then decay (gives up energy and two beta particles) to form uranium-233. Uranium-233 can be used as reactor fuel.

[1] To compare the energy in this fuel with coal, 1 kilogram of pure uranium-235 theoretically could produce as much energy as 1.5 million kilograms (1,500 tons) of coal if the uranium-235 could completely fission.

2.4.4 Fuel Forms

2.4.4.1 Traditional Fuel Assemblies, Rods, and Pellets

Figure 6 shows a cutaway of a typical fuel assembly used by present-day operating nuclear power reactors. LWRs use solid LEU fuel formed into ceramic uranium fuel (UO_2) pellets. The pellets are about the size of a pencil eraser. The pellets are inserted into long cylinders, called cladding, to create fuel rods. The fuel rods typically are arranged in a square matrix constructed into a fuel assembly or fuel bundle. Each fuel assembly is approximately 14 feet (4.3 meters) long and contains approximately 200 fuel rods for PWRs and between 80-100 for BWRs. Each reactor core may contain hundreds of fuel assemblies.

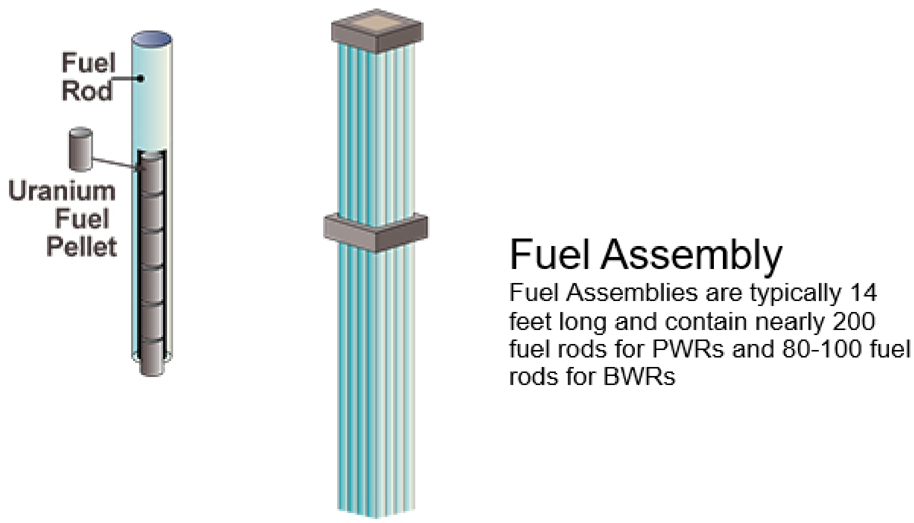

Figure 6. Fuel Assembly (NRC 2023e)

Many PWR SMR designs are similar to the design shown in Figure 6, but the dimensions and number of the fuel assemblies are smaller. For example, the NuScale power module, recently certified by the NRC, contains 37 fuel assemblies. Each fuel assembly contains 264 fuel rods arranged in a 17 x 17 matrix and is approximately 7 feet (2.2 meters) long. Assorted other instrumentation, water channels, and spacers occupy the unused locations within the 17 x 17 matrix (NuScale 2020).

2.4.4.2 Metallic Forms

Metallic fuel forms consist of metal alloys of uranium-zirconium (U-Zr), uranium-plutonium-zirconium (U-Pu-Zr), and uranium-molybdenum (U-Mo), among others. The alloys are formed into pellets or plates depending on the reactor design. Metallic fuel has been used in research reactors, particularly the Training, Research, Isotopes, General Atomic (TRIGA) reactors, where uranium zirconium hydride (UZrH) has been used.

Metal fuels have been used in LWRs and liquid metal fast breeder reactors, such as the Experimental Breeder Reactor – II (EBR-II) located in Idaho.

2.4.4.3 TRISO forms

The TRISO particle fuel was developed in the U.S. and the United Kingdom starting in the 1960s. The current form of the TRISO fuel particle consists of a center kernel of uranium oxycarbide (UCO), uranium carbide (UC_x), or uranium oxide (UO_2) that is surrounded by three layers of carbon and ceramic materials (DOE 2019). The TRISO fuel is more resistant to neutron irradiation, corrosion, oxidation, and high temperatures than the fuel used in operating commercial nuclear power plants (DOE 2019). The TRISO particle is approximately 1 mm in diameter. The reactor fuel may be fabricated from particles into either a cylinder about 0.5 inches (12 mm) or a sphere (pebble) about 2.5 inches (60 millimeters) in diameter. The cylinder TRISO fuel form is used to create prismatic graphite blocks for use in prismatic reactors, typically HTGRs or MSRs. The spherical or pebble TRISO fuel form is used in pebble-bed HTGRs or MSRs.

In these solid forms, the fuel remains stationary within the reactor core, and the reactor coolant flows through the fuel assemblies or the prismatic blocks, or around the pebbles. The coolant then exits the reactor and transfers its heat to another liquid or directly drives a turbine generator.

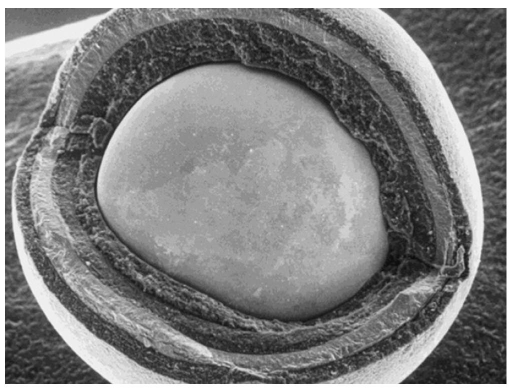

Figure 7. TRISO Fuel Particle (DOE 2019)

2.4.4.4 Homogeneous / Liquid Fuel

Homogeneous or liquid nuclear reactor fuel is different than the solid fuel forms discussed above. In a reactor that uses liquid fuel, the fuel flows through the nuclear reactor using pumps. MSRs may use a liquid fuel, where the uranium-235 or thorium-232 is mixed within a molten fluoride or chloride salt mixture. The salt mixture circulates through the reactor and then through a heat exchanger, where the heat generated in the reactor is transferred to another liquid. The liquid fuel moves to the fuel pump, where it is pumped into the reactor to complete the circuit.

The fuel for the Aircraft Reactor Experiment consisted of a mixture of uranium tetrafluoride (UF_4), sodium fluoride (NaF), and zirconium fluoride (ZrF_4). The MSRE fuel consisted of lithium fluoride (LiF), beryllium fluoride (BeF_2), ZrF_4, and UF_4. Both of the experiments used graphite as a moderator.

Thorium-232 may be used as one form of the salts within liquid fuel reactors. The lithium fluoride thorium reactor (LFTR) SMR design uses thorium in an additional salt mixture, referred to as a blanket salt. As described above, thorium-232 will decay into uranium-233 after capturing a neutron. The uranium-233 is one of the fuels that the LFTR would use after its initial startup using uranium-235. The uranium-233 would be removed from the blanket salt and injected into the fuel salt, where it would circulate through the reactor system (IAEA 2022a).

3.0 Operational Considerations

This section explores many operational considerations of SMR technology, to include O&M requirements, system scale, resilience considerations, and cybersecurity concerns.

3.1 Operations and Maintenance Requirements

Since SMR technology hasn't been deployed within the U.S. (see Section 5.2), examples from combined heat and power plants and existing small nuclear power plants can be used to estimate O&M requirements. All power plants need to have the following activities addressed at a minimum:

- Plant operations
- Engineering and maintenance of facilities
- Security
- Emergency services
- Management and administrative services

The activities would scale to meet the needs of any size and type of nuclear power plant.

All nuclear power plants undergo a system of assessments, safety reviews, and maintenance outages to address preventative and corrective maintenance to ensure the safe operation of the facility. The NRC has various rules in 10 CFR Part 50 that govern the maintenance programs and the conduct of O&M at its licensed facilities. As an example, 10 CFR 50.65 requires the owner/operator to:

> "monitor the effectiveness of maintenance at nuclear power plants specifically addressing safety-related structures, systems and components that are relied upon to remain functional during and following design basis events to ensure the integrity of the reactor coolant pressure boundary, the capability to shut down the reactor and maintain it in a safe shutdown condition, or the capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposure comparable to the guidelines in §53.34(a)(1), §50.67(b)(2), or §100.11 of this chapter, as applicable."

Additionally, the International Atomic Energy Agency (IAEA) publishes and updates guidance on maintenance, testing, surveillance, and inspections in nuclear power plants. One example is the IAEA SSG-74, Maintenance, Testing, Surveillance, and Inspection in Nuclear Power Plants (IAEA 2022c). The guidance and rules would apply to SMRs, and the owner/operators of SMRs would need to develop a maintenance plan to address vendor recommendations. Additionally, the vendors of nuclear technology typically provide subject matter experts and engineering support to the owner/operator, as well as maintain a quality control program.

3.2 Balancing Electrical and Heat Generation

SMR designers are improving the capability to vary the output power of nuclear reactors (referred to as "load-following"), unlike how large commercial nuclear reactors are typically operated today. Existing operating commercial nuclear reactors provide baseload power to the grid and the electricity transmission and distribution operators use other technologies to provide peaking generation when the seasonal or daily electricity demand is high. This operation configuration of the existing nuclear power plants and the transmission and distribution systems allow the commercial nuclear power plants to maintain steady state operations, their most efficient operation. The envisioned ability of SMRs to load-follow will allow the owner/operator to adjust the power delivered to meet the demands of the grid.

Since some SMRs may provide process heat in addition to electricity, their output can vary between generating electricity and heat. They may supply more heat to meet the increased seasonal and daily demand during the colder months and then supply less heat in the warmer months when demand is lower.

3.3 Scale of System

Due to their modular design, SMRs may provide a means to incrementally add generation capacity at a given facility to meet the long-term trends in electricity or heating demands. As energy and heating demands increase locally, additional SMRs can be added.

3.4 Resilience

SMRs can provide a resilient energy source inside the fence line for military installations. SMRs could deliver primary, redundant, or emergency power to respond to and minimize the disruption of the energy supply. SMRs could supply long-term energy without off-base resources.

Two use cases that may be of interest to the Air Force are the ability of the SMRs to black start and operate in island mode. SMRs can supply reliable electricity for months or even years without external fuel supplies. This capability would enable the Air Force base to execute critical missions or extended operations at remote locations without using other resources. SMRs eliminate the logistical tail associated with operating fossil-fuel generation sources inside the fence line. This capability could conserve resources, such as drivers to haul fuel, in hazardous operating conditions or after catastrophic events.

3.4.1 Black Start

Black start describes the capability to restart the external power distribution grid should it go offline (black). Some SMRs may have the capability to restart the grid. 10 CFR 50 Appendix A contains nuclear power plant safety requirements for redundant independent, power systems. These regulations require nuclear reactor plants to have emergency diesel generators to provide electricity to cool the nuclear fuel after the reactor stops operating, unless a vendor demonstrates that their design does not require alternating current electricity for safety-related systems and requests a specific exemption to the NRC regulations. The diesel generator can provide electricity to the systems to restart the SMR, if it is offline, independently of the external grid. Once the SMR is restarted, it can supply electricity to the local power buses and restart the distribution grid.

3.4.2 Island Mode

Island mode operation is the grid operating condition where an electricity generator supplies power to its loads and a limited number of dedicated loads while being isolated from transmission grids or other loads. This configuration powers the SMR's own electrical systems as well as the mission loads of an Air Force base using its own dedicated grid or the existing grid when it is isolated from the normal power distribution grid. This insulates the Air Force base's grid and loads from further power disruptions affecting the larger transmission or distribution grids.

3.5 Cybersecurity Considerations

SMRs need to follow standard cybersecurity guidelines to protect Air Force assets as well as nuclear-specific cybersecurity guidelines. The Air Force uses COINE (Community of Interest Network Enclave) as its cybersecurity standard.

The NRC provides guidance to its licensees in Regulatory Guide (RG) 5.71, Cyber Security Programs for Nuclear Facilities (NRC 2023c), and the Nuclear Energy Institute (NEI) published guidance to the industry in NEI 08-09, Cyber Security Plan for Nuclear Power Plants (NEI 2010). The combined guidance provides the nuclear facilities information to aid the development of individual cybersecurity plans to meet the NRC requirements in 10 CFR 73.54, Protection of Digital Computer and Communications Systems and Networks.

NRC license holders are required to protect digital computer networks and communication systems. The licensee must provide protection from cyber-attacks that could potentially modify, destroy, or compromise information and control of systems. They also must provide protection from unauthorized access to systems, services, or data. Lastly, licensees must provide protection from attacks that could impact the operations of systems or networks and their associated equipment. The license holder's cybersecurity plan must address the protection of the systems or networks that:

- Perform safety-related and important-to-safety functions
- Perform security functions
- Perform emergency preparedness functions, including offsite communications
- Support systems and equipment that, if compromised, could adversely impact safety, security, or emergency preparedness

A cybersecurity plan is required for the NRC to review and approve an SMR facility application (NEI 2010).

4.0 Regulatory Overview

The Atomic Energy Act of 1946 established the AEC, a predecessor agency of DOE and NRC. The AEC had responsibility for the development and production of nuclear weapons and for the development and safety regulation of civilian uses of nuclear materials.

The AEC was abolished under the Energy Reorganization Act of 1974 (42 U.S.C. §§ 5801 et. seq.), which split two functions. The Act assigned The Energy Research and Development Administration (ERDA) the responsibility of development and production of nuclear weapons, the promotion of nuclear power, and other energy-related work. The Act assigned the NRC the authority to regulate and license nuclear materials for the peaceful use of atomic energy. The NRC is the sole licensing authority in the U.S. for commercial nuclear reactors, including SMRs that supply electricity and heat (42 U.S.C. § 5814). The Department of Energy Organization Act (42 U.S.C. §§ 7101 et. seq.) abolished ERDA in 1977 and established DOE in the Executive Branch as the successor to ERDA.

The Department of Energy Organization Act consolidated the federal government's energy policy, research, and development into a cabinet-level department. DOE promotes, researches, and develops nuclear energy technology by providing funding, facilities, national laboratories, and oversight.

4.1 The U.S. Nuclear Regulatory Commission Rules and Authorities

Since SMRs are designed to use fuel and do not produce plutonium or uranium-233 for weapons, they meet the definition of a "utilization facility" and fall under the current regulations and statutes for utilization facilities. Title 10 of the Code of Federal Regulations, Energy, Part 50 (Domestic Licensing of Production and Utilization Facilities) or Part 52 (Licenses, Certifications, and Approvals for Nuclear Power Plants) would be the primary licensing regulations, that implement the licensing requirements of the Atomic Energy Act of 1954 (42 U.S.C. § 2011, et seq.) as amended. The NRC regulations relating to the licensing, operations, maintenance, siting, construction, nuclear fuels, operator licenses, and physical protection are in Title 10 of the Code for Federal Regulations, Chapter 1. A complete list of the NRC regulations is available online through the U.S. Government Office of the Federal Register. The following sections describe most of the pertinent ones for licensing SMRs.

4.1.1 Title 10 of the Code of Federal Regulations, Chapter 1

The NRC published the Nuclear Power Plant Licensing Process (NRC 2009) to provide an overview of its licensing process. The NRC uses two separate, but interconnected, review processes for all nuclear power plants. Under either review process, the applicant must obtain NRC approval before they can build and operate a nuclear power plant. The NRC conducts a safety review under the provisions in 10 CFR Part 50 or Part 52 as requested by an applicant. The NRC also conducts an environmental review using the provisions in 10 CFR Part 51 concurrently with the safety review. Figure 8 depicts the overall process and the details are described below.

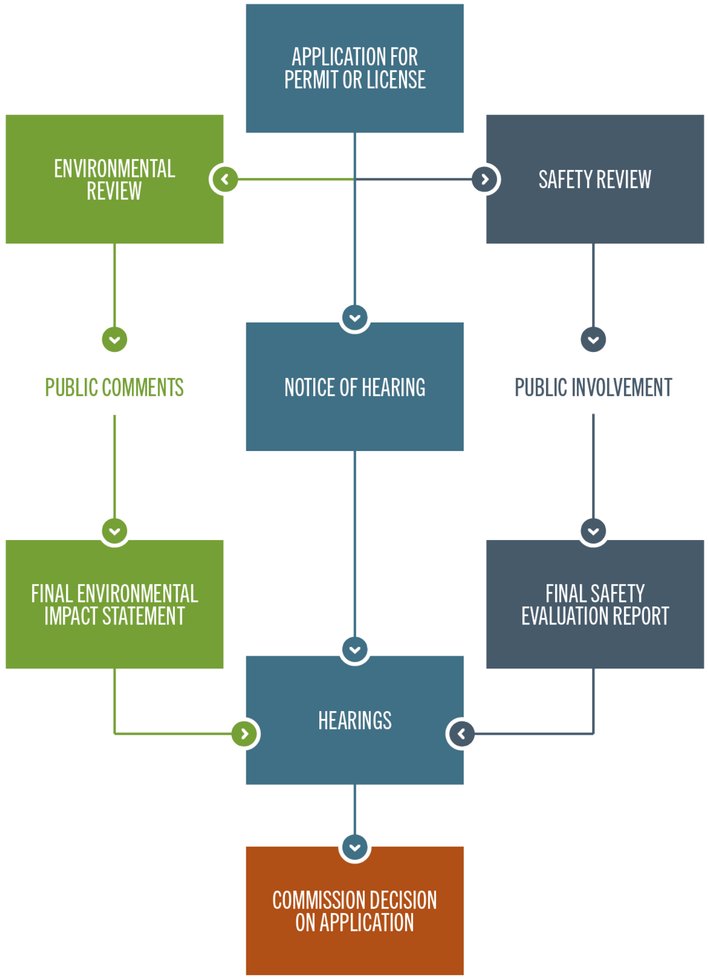

Figure 8. NRC Licensing Process

4.1.1.1 10 CFR Part 50

The licensing process outlined in 10 CFR Part 50 describes how to apply for a license, the requirements for the contents of an application, how to maintain a license, and how to decommission a nuclear power plant at the end of its lifecycle. The regulations also describe the requirements for notification, financial assurance, environmental reporting, security, emergency preparedness, various design criteria, quality assurance, and other operational programs.

The regulations in Part 50 provide for a two-step process to obtain an operating license. In the first step, an owner/operator develops a construction permit application, provides the contents required, and submits it to the NRC for review. As a part of the application, the applicant may request a limited work authorization (LWA). LWAs authorize certain limited safety-related construction activities to commence before a construction permit or combined license (discussed below) is issued. The NRC is required to conduct safety and environmental reviews before issuing an LWA. After the NRC reviews the construction permit application, it will determine the suitability of the design and site for the nuclear reactor. If the NRC grants the permit, the owner and operator may begin construction on reactor-specific structures, systems, and components.

Once the plant is nearing final construction, the owner/operator would apply for an operating license. Following the requirements in 10 CFR Part 50 for the contents and application process, the NRC will review the "as-built" construction of the plant and the operational plans and make a final determination of the plant's suitability to operate. If the NRC approves the operating license, the NRC will issue the operating license to the owner/operator of the facility for an initial term of 40 years.

The NRC sets generic milestones for completing application reviews for various regulatory activities. A complete list of the licensing and regulatory activities and the corresponding generic milestones are published on the NRC public website (NRC 2021d). The review time period would begin after the NRC completed its acceptance review and docketed the application for review, and end when the staff completes the safety evaluation report. Construction permit reviews take 36 months; operating license reviews take 36 to 42 months.

4.1.1.2 10 CFR Part 52

In 1989, the NRC established an alternative licensing process that combines a construction permit and an operating license, with certain conditions, into a single license. This license is called a combined construction permit and operating license (combined license), or COL.

10 CFR Part 52 also allows for an owner/operator to apply for an Early Site Permit (ESP), where the NRC will determine if the site is suitable for a nuclear power plant. If the owner/operator wishes to pursue an ESP, the application would address site safety issues, environmental protection, and plans for responding to emergencies without needing to review the specific design of a nuclear power plant. As a part of the application, the owner/operator may also request an LWA. An ESP is not required before an owner/operator applies for a COL, but it could be advantageous since it would settle any particular site safety issues before applying for a COL.

If the owner/operator received an ESP from the NRC, those issues are final and would not be reviewed as a part of the COL application except under very limited circumstances. If the owner/operator did not apply for, or the NRC did not issue, an ESP, then the owner/operator would provide site safety and environmental issues in the contents of the COL application with the required contents for the specific nuclear power plant design. The NRC would review the site safety issues (if required) and the nuclear power plant design to determine whether the plant meets the NRC requirements and whether the plant and site are compatible. If so, the NRC would issue the COL for an initial term of 40 years and the owner/operator could begin construction. Before completion of construction, the NRC would review the as-built design and inspection, testing, and analysis results to ensure that the plant continues to meet NRC requirements. Once the NRC determines that the requirements are met, the NRC would issue a finding in accordance with the regulation in 10 CFR 52.103(g) that all acceptance criteria were met. After the NRC issues the 103(g) finding, the NRC would authorize the owner/operator to operate the plant, and the COL's 40-year license term starts. COL can be renewed for an additional 20 years.

Before completion of construction, the NRC would review the as-built design and inspection, testing, and analysis results to ensure that the plant continues to meet NRC requirements. If requirements are met, the NRC would then authorize the owner/operator to operate the plant.

Other separate processes within 10 CFR Part 52 are the plant design certification and standard design certification. If the COL applicant has decided on a particular plant design and that design has received an NRC certification, the application may incorporate that information by referencing it. Further, once the NRC certifies the design through rulemaking, any applicant may reference it. An application for a COL may reference a standard design certification, an ESP, both, or neither.

The NRC set generic milestones for completing application reviews for various regulatory activities. A complete list of the licensing and regulatory activities and the corresponding generic milestones are published on the NRC public website (NRC 2021d). The review time period would begin after the NRC completed its acceptance review and docketed the application for review, and end when the staff completes the safety evaluation report. Early Site Permit reviews take 24 months; combined license reviews take 30 to 42 months

4.1.1.3 10 CFR Part 51

10 CFR Part 51 contains the environmental protection regulations that the NRC uses to implement the requirements in the National Environmental Policy Act of 1969 (NEPA) as amended, Section 102(2). The regulations in Part 51 include requirements for applicants to submit an environmental report that provides the results of its environmental assessment as a part of the licensing application.

Once the owner/operator submits their application, the NRC reviews it. If the NRC accepts the application for docketing (because the application has enough information within it to complete the evaluation), the NRC begins the safety and environmental reviews. The NRC publishes a notice of intent to prepare an environmental impact statement (EIS). For the environmental review, the NRC conducts “scoping” by requesting public comments and holding public meetings, publishing a Federal Register notice, and allowing the public to comment electronically or through U.S. mail.

As part of its review, the NRC reviews the environmental report submitted with the application and gathers additional information to support the development of the EIS. Based on all the information it has collected, the NRC publishes a draft EIS for comment. The NRC reviews all the public comments it receives on the draft, responds to the comments by making appropriate changes to the EIS, and then creates and publishes a final EIS. In many situations, this will be reviewed as part of a mandatory hearing before a decision is made on whether to issue the requested license or permit.

Currently, the NRC staff estimates that the environmental review process will take approximately 24-36 months. The NRC staff conducts its environmental reviews of nuclear power reactor licensing applications using Nuclear Regulatory Report (NUREG)-1555, Environmental Standard Review Plan (ESRP) (NRC 1999).

4.1.1.4 Operator License Regulation

The NRC provides requirements for the licensing of the individual operators at a nuclear power reactor in 10 CFR Parts 50, 52, and 55, Operators’ Licenses. The NRC also provides several regulatory guides (listed below) to address various aspects of training and qualifications, medical evaluations of licensed operators, use of a simulated control room for operator license examinations, and guidance to the licensed operators. The NRC published a comprehensive website, Licensing Process for Operators, that describes the process in detail, including links to the forms and examination preparations (NRC 2022d). Among other guidance, the NRC published the following regulatory guides:

- RG 1.8, Qualification and Training of Personnel for Nuclear Power Plants
- RG 1.114, Guidance to Operators at the Controls and to Senior Operators in the Control Room of a Nuclear Power Unit
- RG 1.134, Medical Evaluation of Licensed Personnel for Nuclear Power Plants
- RG 1.149, Nuclear Power Plant Simulation Facilities for Use in Operator License Examinations
- RG 1.206, Applications for Nuclear Power Plants

The U.S. nuclear industry published standards that the NRC endorsed for their use with some exceptions, clarifications, and additions.

- ANSI/ANS-3.1-2014 (R2020), Selection, Qualification, and Training of Personnel for Nuclear Power Plants
- ANSI/ANS-3.4-2013 (R2018), Medical Certification and Monitoring of Personnel Requiring Operator Licenses For Nuclear Power Plants
- ANSI/ANS-3.5-2018, Nuclear Power Plant Simulators for Use in Operator Training and Examination
- NEI 09-09, Nuclear Power Plant-Referenced Simulator Scenario Based Testing Methodology

4.1.1.5 Various Other NRC Regulations

Applicants for a construction permit, operating license, or COL generally also request byproduct materials licenses under 10 CFR Part 30, source material licenses under 10 CFR Part 40, and special nuclear material licenses under 10 CFR Part 70. The NRC regulations allow the applicant to combine all of the applications for those licenses into one application.

Additional regulations that the SMR applicant needs to comply with are provided within NUREG-0800, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition (referred to as the Standard Review Plan, or SRP), and RG 1.206, Applications for Nuclear Power Plants. Sections 6.2 and 6.3 of this report provide more details on the specific environmental and safety considerations, respectively, and the associated guidance.

The NRC regulations regarding regulatory fees are published in 10 CFR Parts 170 and 171. Since the NRC recovers most of its operating budget through fees, the NRC regularly updates these regulations and provides resource estimators and timelines on the NRC public webpage https://www.nrc.gov/about-nrc/regulatory/licensing/fees.html. On the website, the NRC publishes its annual Proposed Revision of the Fee Schedules and Fee Recovery for the Fiscal Year. In the proposed rule, the NRC publishes its professional hourly rate and the justification of any proposed budget increases. The NRC is required by NEIMA (Nuclear Energy Innovation and Modernization Act) to recover, to the maximum extent practicable, approximately 100% of its annual budget less excluded amounts. The latest proposed fee rule was published on March 3, 2023, in the Federal Register, 88 FR 13357 (OFR 2023).

4.1.2 Nuclear Waste Policy Act of 1982

In 1982, Congress passed the Nuclear Waste Policy Act (NWPA) (Public Law 97-425) "to provide for the development of repositories for the disposal of high-level radioactive waste and spent nuclear fuel, to establish a program of research, development, and demonstration regarding the disposal of high-level radioactive waste and spent nuclear fuel." The U.S. has over 86,000 metric tons of spent nuclear fuel from commercial nuclear power plants. Estimates project an additional 2,000 metric tons of spent nuclear fuel each year from commercial nuclear power plants (GAO 2021).

Per the NWPA, DOE is responsible for developing a permanent geologic repository for high-level waste; however, DOE has yet to build a facility. Thus, all commercial nuclear power plants and many of those that were decommissioned still store their high-level radiological wastes locally. The federal government has paid billions of dollars to commercial utilities for the contractual and financial damages caused by storing high-level radiological wastes on sites.

Section 302 of the NWPA also establishes the Nuclear Waste Fund, which authorizes the Secretary of Energy to make contracts with owner/operators who generate or hold title to high-level radioactive waste or spent nuclear fuel in the U.S. Under the provisions of Section 302(b) of NWPA, the NRC cannot issue an operating license or COL unless:

(a) the owners/operators have entered into a contract with DOE, or

(b) the Secretary of Energy affirms in writing that the owners/operators are actively and in good faith negotiating a contract for the disposal of high-level radioactive waste and spent nuclear fuel that may result from the use of such licenses.

The owner/operator would need to pay the fee as set in the NWPA at $1 per kilowatt-hour generated. However, in 2013 the U.S. Court of Appeals for Washington D.C. ruled that DOE had to stop collecting the fee from the utilities until the DOE concludes how it will permanently dispose of the nuclear wastes. The fee may resume if Congress enacts another plan or when the DOE finalizes a permanent repository (DOE 2022d). As of December 2022, the Nuclear Waste Fund has more than $46 billion in assets (DOE 2022e).

4.1.3 Environmental Acts

NEPA (Public Law 91-190), as amended, requires federal agencies to consider and evaluate the environmental impact caused by their actions, and publish the evaluations in an environmental assessment or as an EIS. In considering and evaluating the environmental impacts, federal agencies must ensure that environmental factors in decision-making receive the same weight as other factors.

Other acts may play a role in assessing environmental impacts and may require separate consultation or coordination with other federal, state, or Tribal agencies. These include, but are not limited to, the Clean Air Act, Resource Conservation and Recovery Act, Safe Drinking Water Act, Endangered Species Act, National Historic Preservation Act, Migratory Bird Treaty Act, and the Federal Insecticide, Fungicide and Rodenticide Act. All of these acts apply to all federal construction projects.

4.1.4 Nuclear Energy Innovation and Modernization Act (NEIMA)

In 2019, Congress passed NEIMA to require the NRC to develop new processes for licensing nuclear reactors, including staged licensing of ANRs. NEIMA requires, in part, the NRC to (1) establish stages within the licensing process; (2) increase the use of risk-informed, performance-based licensing evaluation techniques and guidance; and (3) establish by the end of 2027 a technology-inclusive regulatory framework that encourages greater technology innovation. In meeting NEIMA requirements, the NRC initiated a rulemaking on 10 CFR Part 53, Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors. The rule may provide for an optional technology-inclusive regulatory framework for use by applicants for new commercial advanced reactors. The option that would be provided in Part 53 is in addition to the licensing frameworks for Parts 50 and 52, described above. Since the NRC began the rulemaking in 2019 and the rule's language is not final, the impacts on SMRs cannot be determined.

4.2 State Regulatory Activity

State regulatory structures vary a great deal. Some states are more open to using nuclear power to reduce greenhouse gas emissions; however, many states have restrictions on developing new nuclear reactor plants.

The NEI published a status report, State Legislation and Regulations Supporting Nuclear Energy, in January 2023. It provides a state-by-state overview of legislation, executive orders, and regulations that support nuclear energy. The report indicates that 19 states are considering legislation and 12 states are enacting policies to support existing and new nuclear generation (NEI 2023). Among the trends described in the report are:

- Valuing carbon-free electricity generation
- Financing and tax incentives
- Task forces, commissions, studies, and state energy plans
- Removing prohibitions
- Increasing state regulatory responsibility

All states have environmental, natural resource, conservation, and utility regulations, but they vary widely in their degree of licensing, regulation, and oversight. Each state has a unique set of environmental concerns, natural resources, conservation needs, and utilities. How each state approaches these concerns is driven by the state's internal priorities.

Emergency response requirements are common among states. All states have either statutory or constitutional requirements to protect the health and safety of the citizens of that state and their property. However, states protect health, safety, and property differently and to varying extents. For example, some states provide local government officials with more expansive authority, while in other states, the governor or their delegate has more authority over the local government to mandate and direct protection and preservation efforts.

Therefore, further analysis of the specific state would need to be conducted when suitable sites for SMRs are identified and evaluated.

5.0 Technical Considerations

SMR technologies are emerging based on nearly 70 years of development and operation of larger reactors. Innovations in the design and application of new technologies can provide for simpler systems when compared to the nuclear reactors designed and operated decades ago.

5.1 Limiting Factors and Constraints (other than siting characteristics)

5.1.1 Nuclear Workforce

Operating a nuclear power plant requires a highly skilled and knowledgeable workforce with several years of training on the specific technology. Therefore, identifying the technology and beginning the training programs early is vital to successful SMR deployment. This is a key consideration regardless of whether the Air Force decides to contract out plant operation or keep operations in-house. The IAEA published several documents outlining specific activities that a human resources department could employ to recruit, train, and qualify personnel for nuclear power plant operations. IAEA Specific Safety Guide (SSG)-75 addresses the objectives, roles, and responsibilities of the owner/operator of nuclear power plants for the recruitment, qualification, and training of personnel. The goal is to develop and maintain highly competent operators, engineers, maintenance staff, managers and supervisors, and instructors (IAEA 2022b).

5.1.2 Component Availability/Supply Chain Issues

In 2022, the DOE published a Nuclear Energy Supply Chain Deep Dive Assessment that responds to Executive Order 14017, which describes the current and potential future roles for the various segments of the nuclear energy supply chain (DOE 2022c).

5.1.2.1 Supply of Materials

There is an ongoing concern within the nuclear energy industry about developing and expanding supply chains for the existing nuclear plants and for the deployment of SMRs. Suppliers have undergone consolidation. And since the technology has remained stable in existing nuclear power plants, many suppliers have found new markets and drifted away from nuclear supply production. In what amounts to a chicken-and-egg situation, many suppliers are waiting on increased demand before investing resources in the SMR market, and many potential SMR customers are hesitant to commit without a reliable supply of the required high-quality components, such as stainless steel, alloy metals, and rare earth metals and minerals.

Fabrication of components and other materials requires minerals and metals. Lithium, graphite, copper, nickel, cobalt, platinum, and other rare earth metals are produced outside of the U.S. and the industry will likely rely on imports to support the deployment of SMRs (DOE 2022c).

5.1.2.2 Supply of Fuels

Nuclear fuel supply in the U.S. is one of the more limiting factors in deploying SMRs. However, there is recent progress in improving the domestic nuclear feedstock for advanced reactors.

HALEU

Many advanced reactor designs designed in the U.S. require HALEU fuel. However, it is not available in significant quantities, and the U.S. has very limited production capability. Currently, there is no commercial HALEU enrichment capacity in the U.S. In 2019, INL published a notice of opportunity to access HALEU for the development of fuel and demonstrations of MR technologies (INL 2019). In 2021, the DOE-Nuclear Energy (NE) Gateway for Accelerated Innovation in Nuclear (GAIN) issued a request for information regarding a program to support the availability of HALEU for civilian domestic research, development, demonstration, and commercial use. The objective was to gather information for a congressional report that would describe actions that DOE could carry out under their 3-year demonstration program to build HALEU production capability (DOE 2021a, 2022c).

In 2021, the NRC approved a license amendment request from Centrus Energy's Piketon, Ohio, enrichment facility to produce HALEU (NRC 2021c) for the DOE 3-year demonstration program. The NRC subsequently approved an extension to continue producing HALEU until November 20, 2022 (NRC 2022e). Currently, the NRC is reviewing Centrus Energy's request to extend NRC approval for HALEU production (NRC 2023d). The goal of the demonstration project is to increase production from tens of kilograms of HALEU to hundreds of kilograms per year. The product will help DOE provide nuclear fuel for the initial loading into two reactor demonstration projects that DOE awarded in their Advanced Reactor Demonstration Program (ARDP).

To support another ARDP project, TerraPower is beginning to build its commercial fuel production capability to support one of its designs for an SFR (DOE 2022c). The facility will produce HALEU and fabricate it into metal fuel assemblies.

DOE identified the production of HALEU and other fuel forms as a near term-opportunity to further ANR design. To meet the challenge of producing nuclear reactor forms, the DOE will be working to align investment and production levels with possible future needs that depend on timing, size, and the number of new plants (DOE 2022c).

TRISO

Many advanced reactors designed in the U.S. require TRISO fuel, but significant quantities are not available, and the U.S. has very limited production capability.

The NRC, the Canadian Nuclear Safety Commission, the DOE, and the commercial nuclear industry started developing the capability to fabricate high-quality TRISO fuel and demonstrate its performance characteristics (NRC 2022a). The company X-energy created a subsidiary company, TRISO-X, to build and fabricate TRISO fuel.

The DOE provided TRISO-X with $18 million to support the development of the TRISO-X Fuel Fabrication Facility (TF3) design and NRC license application through the ARDP. Overall, DOE has provided more than $200 million to support the continued development of TRISO fuel, focusing on safety enhancements and manufacturing methods to further the development of advanced HTGRs (DOE 2022a).

TF3 groundbreaking occurred on October 13, 2022, in Oak Ridge, Tennessee. TRISO-X submitted the application for a fuel cycle facility for NRC approval on April 4, 2022. The NRC accepted the application and docketed it on November 18, 2022 (NRC 2022c). NRC review of the application is ongoing. The facility is set to be commissioned by 2025 (X-energy 2022; RCN 2022).

5.1.3 Key Regulatory Challenges and Barriers to Adoption

The following are the primary regulatory challenges to deploying SMRs in the United States:

- There is no current commercial deployment of any SMRs in the U.S. Although the technologies have been tested in different settings, the designs have not been tested. Several vendors and operators are in pre-application discussions with the NRC (NRC 2022f). Below is a partial list of vendors that is subject to change as pre-application discussions begin and end.
  - Utah Associated Municipal Power Systems/Carbon Free Power Project for the NuScale US460
  - SMR, LLC for the SMR-160 design from SMR, LLC, a subsidiary of Holtec International.
  - GE-Hitachi Nuclear Energy for the BWXT-300 design
  - BWXT mPower, Inc. for the BWXT mPower design
- There is regulatory uncertainty when there are no licensed SMRs or ANRs. In Commission Papers (SECY) 93-092 (NRC 1993), 10-0034 (NRC 2010), and 15-0077 (NRC 2015), the NRC staff describe their efforts in meeting with the DOE and SMR designers to identify potential policy and licensing issues:
  - Licensing basis event selection and evaluation
  - Implementation of the defense-in-depth philosophy for advanced reactors
  - Appropriate source term (a measure of radiological contamination), dose calculations (estimates of the amount of the impacts from radiological contamination), and siting for SMRs
  - Appropriate requirements for operator staffing for small or multi-module facilities
  - Security and safeguards requirements for SMRs
  - Containment performance in preventing or mitigating releases of radiological materials
  - Emergency preparedness
- In SECY 23-0022, Advanced Reactor Program Status (NRC 2023f), the NRC describes its progress in resolving potential policy and licensing issues presented in previous Commission Papers and other issues identified during licensing and pre-application discussions. The NRC continues to engage with developers in the regulatory review and pre-application processes. NRC efforts to resolve policy and licensing issues may reduce regulatory uncertainty and allow for flexibility in meeting the NRC regulations.
- The NRC is working through these and other issues and has been directed by Congress to implement certain solutions as required by Section 103 of NEIMA (Public Law 115-439). NEIMA requires the NRC to:
  - Develop and implement strategies for the increased use of risk-informed, performance-based licensing evaluation techniques.
  - Develop guidance for commercial ANRs and research and test reactors within the existing regulatory framework.

- Complete rulemaking to establish a technology-inclusive regulatory framework for optional use by commercial ANR applicants for new reactor license applications.
- Address uncertainty among vendors and communities about the overall demand for electricity, process heat, or hydrogen generation to enable large-scale factory construction to manufacture SMRs.
- Address the cost competitiveness of nuclear power as compared to other sources of energy for first-of-a-kind demonstrations.

5.2 Current State of Technology Development

Based on the DOD technology readiness level (TRL) definitions published by the Government Accountability Office (GAO 2020), the TRL of SMRs could be 5 or 6. A TRL of 5 means that the basic technology components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. A TRL of 6 means that the systems or subsystems have been demonstrated in a relevant environment. Since each of the reactor types listed in Table 1 has been or is being used to generate heat or electricity in a large power plant or as an SMR at least once, the technologies seem to be viable for SMR applications within the U.S. and potentially for the Air Force.

Currently, the only SMRs in operation are located in Russia and China.

- The Akademik Lomonosov floating nuclear power plant (FNPP) provides heat and electricity to the village of Pevek in Chukota, Russia. The FNPP consists of two 35-Mwe light-water PWRs, where the water serves as the coolant and the moderator.
- China operates a pebble-bed, modular, high-temperature, gas-cooled SMR in Shidaowan, Shandong province. Like the FNPP, the Shidaowan plant consists of two reactors, but combines their joint 210-Mwe output through a single turbine generator. The pebble-bed design uses helium instead of light water as its coolant, and graphite as its moderator.
- China is also constructing an SMR at the Changjiang nuclear power plant. The ACP100 is an iPWR rated at 100 MWt or about 30 Mwe, and is nearing a high level of technology readiness. In 2016, the ACP100 became the first SMR to pass an IAEA Generic Reactor Safety Review.

SMR designers and vendors have achieved various levels of design maturity. LWR SMRs are the most mature in terms of technology and manufacturing since the designs are derived from existing large LWR designs. Non-light-water SMRs are considered farther from commercialization and deployment since they are based on reactor designs for which there are few actual deployments and fewer of them have been in operation as long as the large LWR nuclear power plants.

The IAEA publishes a biennial edition of Advances in Small Modular Reactor Technology Developments. The recent edition provided information on more than 80 different designs under development globally. Table 2 provides information from the 2022 edition about the characteristics of U.S. vendors' basic designs. The IAEA also provides information on topics ranging from lessons learned in regulating SMRs to design safety considerations for water-cooled SMRs.

Table 2. Characteristics for U.S. SMR Designs (IAEA 2022a)

Plant Design	Vendor	Power Generation Capacity (Mwe)	Coolant Technology	Fuel Type	Landscape Footprint (m^2)
VOYGR	NuScale Power, LLC	77	PWR light water	UO_2 pellet	140,000
BWXT-300	GE-Hitachi Nuclear Energy	270-290	BWR light water	UO_2 pellet	9800
SMR-160	Holtec International	160	PWR light water	UO_2 pellet	28,000
Westinghouse SMR	Westinghouse Electric Co, LLC	>225	PWR light water	UO_2 pellet	65,000
mPower	BWX Technologies, Inc	195	PWR light water	UO_2 pellet	157,000
Open20	Last Energy, Inc	22	PWR light water	UO_2 pellet	2023
Energy M2	General Atomics	265	HTGR helium	U-carbide pellet	90,000
Fast Modular Reactor	General Atomics	50	HTGR helium	UO_2 pellet	38,000
Xe-100	X-energy, LLC	82.5	HTGR helium	TRISO	115,600
SC-HTGR	Framatome, Inc	272	HTGR helium	TRISO	8000
KP-FHR	Kairos Power	140	MSR FliBe	TRISO pebble bed	
Westinghouse Lead FR	Westinghouse Electric Company	300-600	Liquid metal lead	UO_2	40,000
Mk1 PB-FHR	UC-Berkely	100	MSR fluoride high temp	TRISO pebble bed	45,000
MCSFR	Elysium Industries	50/200/400/ 1200	MSR chloride	Liquid fuel U-Pu	
Lithium Fluoride Thorium Reactor	Flibe Energy	250	MSR FliBe	U-233 & Th-232	
ThorCon	ThorCon International	250	MSR	Liquid fuel UF_4	10,854
Aurora	Oklo, Inc	1.5 – 50	Liquid metal	Metal	<10,000
HOLOS-QUAD	HolosGen, LLC	10	HTGR helium	TRISO	30
MARVEL	INL	0.015-0.027	Liquid metal sodium potassium	U-Zr hydride	8.9
MMR	Ultra Safe Nuclear Corp	>10	HTGR helium	TRISO	12,480
eVinci	Westinghouse Electric Co, LLC	2-3.5	Heat pipe	TRISO	4000
Natrium*	TerraPower, LLC	345 MWe	Liquid metal Sodium Fast Reactor	HALEU Metal Fuel	178,062

*Natrium Reactor by TerraPower is not included in the IAEA SMR Book (IAEA 2022a) since its generation capacity exceeds the definition of an SMR (TerraPower 2023, NRC 2023g).

5.2.1 NRC Licensing Status of SMRs

Within the U.S., the NRC issued a standard design approval (SDA) to NuScale Power for its light-water-cooled NuScale Power Module, named VOYGR, in 2020 (NRC 2020a), and issued the final rule for the certified design in 2023 (NRC 2023a, 88 FR 2387). The SDA allows the NuScale SMR standard design to be referenced by another applicant for a construction permit or operating license. The SDA may also be referenced within a COL or a manufacturing license process (in 10 CFR Part 52). NuScale is the only SMR design to receive an SDA to date.

The NRC issued an ESP to the Tennessee Valley Authority (TVA) for two or more SMR modules at the Clinch River Nuclear Site in Oak Ridge, Tennessee (NRC 2019). While having an ESP means that the Clinch River Nuclear Site is suitable for SMRs, the ESP does not allow for the construction or operation of an SMR. Before TVA could build and operate SMRs at the site, they would need to apply for a COL for a specific design and the NRC would need to approve and issue the COL.

5.2.2 U.S. SMR Development

The DOE Office of Nuclear Energy (NE) supports a variety of SMRs that are ANR designs for the U.S. with the goal of commercializing the technologies within 15 years by working with the industry (DOE 2020). DOE ranks the technology deployment in terms of years using approximately 5- to 7-year windows. Below are some advanced nuclear SMRs on DOE's radar.

- Demonstration phase to test, license, and build operational SMRs within 5-7 years:
  - Natrium Reactor: A sodium-cooled fast reactor using molten salt energy storage power developed by TerraPower
  - Xe-100: An HTGR developed by X-energy
- Risk reduction phase to solve technical, operational, and regulatory challenges to support SMR demonstration within 10-14 years:
  - KP-FHR: A fluoride salt-cooled, high-temperature reactor developed by Kairos Power
  - eVinci: A heat pipe-cooled MR developed by Westinghouse Nuclear
  - BWXT Advanced Nuclear Reactor (BANR): An HTGR developed by BWX Technologies
  - SMR-160: An advanced light-water SMR developed by Holtec International
  - Molten Chloride Fast Reactor developed by Southern Company
- Concept development phase to solidify the concept to mature technology for potential SMR or MR demonstration by the mid-2030s:
  - Advanced Sodium-Cooled Reactor facility developed by Advance Reactor Concepts
  - Fast Modular Reactor developed by General Atomics
  - Horizontal Compact HTGR developed by the Massachusetts Institute of Technology

5.2.3 Successful Pilots or Demonstrations

Commercial SMRs have not been piloted or demonstrated in the U.S. However, Russia and China have both deployed SMRs.

5.2.3.1 Russia

The FNPP is a pilot and a working prototype of a potential floating network of SMRs along the northern and eastern coastal regions of Russia. Russia's interior landscape makes it very costly to construct, maintain, and operate thousands of miles of transmission and transportation routes. The Russian landscape is covered by widespread permafrost, amounting to as much as 70% of its terrain, and is sparsely populated by small settlements centered around mining, raw material processing facilities, and military bases. These small settlements do not require an expansive generation, transmission, or distribution system. The northern and eastern regions are extremely cold, requiring heating as well as electricity. The infrastructure connections from the northern and eastern shores to more populated areas in the south and west are unreliable or nonexistent during the winter and for prolonged periods due to melting soil conditions. Therefore, Russian communities need reliable sources of electricity and heat that operate over long periods without the need for fuel delivery. Hence, SMRs are a good fit for the Russian landscape and conditions. However, since the FNPP has only been operating for a few years, its overall success has not been determined.

5.2.3.2 China

China's HTR-PM reactors began operating in late 2021, when the first reactor was connected to the state power grid. Both reactors achieved full power operations in late 2022. Since the HTR-PM power plants at Shidao Bay Nuclear Power Plant are only a couple of years old, their overall success has not been determined. China plans to update the HTR-PM design to deliver 600 Mwe based on the success to date (HTR 2014).

5.3 Technical Resources Available

Adequate technical resources to inform designers, regulators, potential buyers, and the public are available through private industry, public institutions, the IAEA, and the U.S. government.

DOE-NE supports research, development, and deployment activities to make U.S.-based SMR technologies available. The Office has partnered with NuScale Power and the Utah Associated Municipal Power Systems to build and demonstrate a first-of-a-kind SMR at INL. This effort should resolve many generic SMR technical and licensing issues. Further, DOE operates nonpower nuclear research reactors at its laboratories. INL operates five research and test reactors, and ORNL and Sandia National Laboratories each operate one reactor (NRC 2021a).

Other U.S. government organizations operate research and test reactors: The Armed Forces Radiobiology Research Reactor in Bethesda, Maryland; National Institute of Standards and Technology in Gaithersburg, Maryland; and the U.S. Geological Survey in Denver, Colorado, have operating reactors of similar size to MRs. Although the research reactors are not designed to deliver electricity or heat for extended periods, they have licensing, training, and similar experiences developed from decades of operation (NRC 2021a).

Supporting the deployment of SMRs, PNNL provides technical support to the NRC for environmental and safety reviews, conducts policy and regulatory analysis, and develops technical reports that support various research efforts for the NRC. PNNL also supports the Army Reactor Program.

The U.S. operating reactors provide a substantial body of knowledge and technical information spanning all aspects of operating nuclear power plants. U.S. nuclear power plants are owned and operated by 21 different companies. These owners and operators have experience in plant operations, maintenance, and licensing. The nuclear power plants are designed to deliver electricity to the transmission and distribution grids across 28 different states (Figure 9, NRC 2021a).

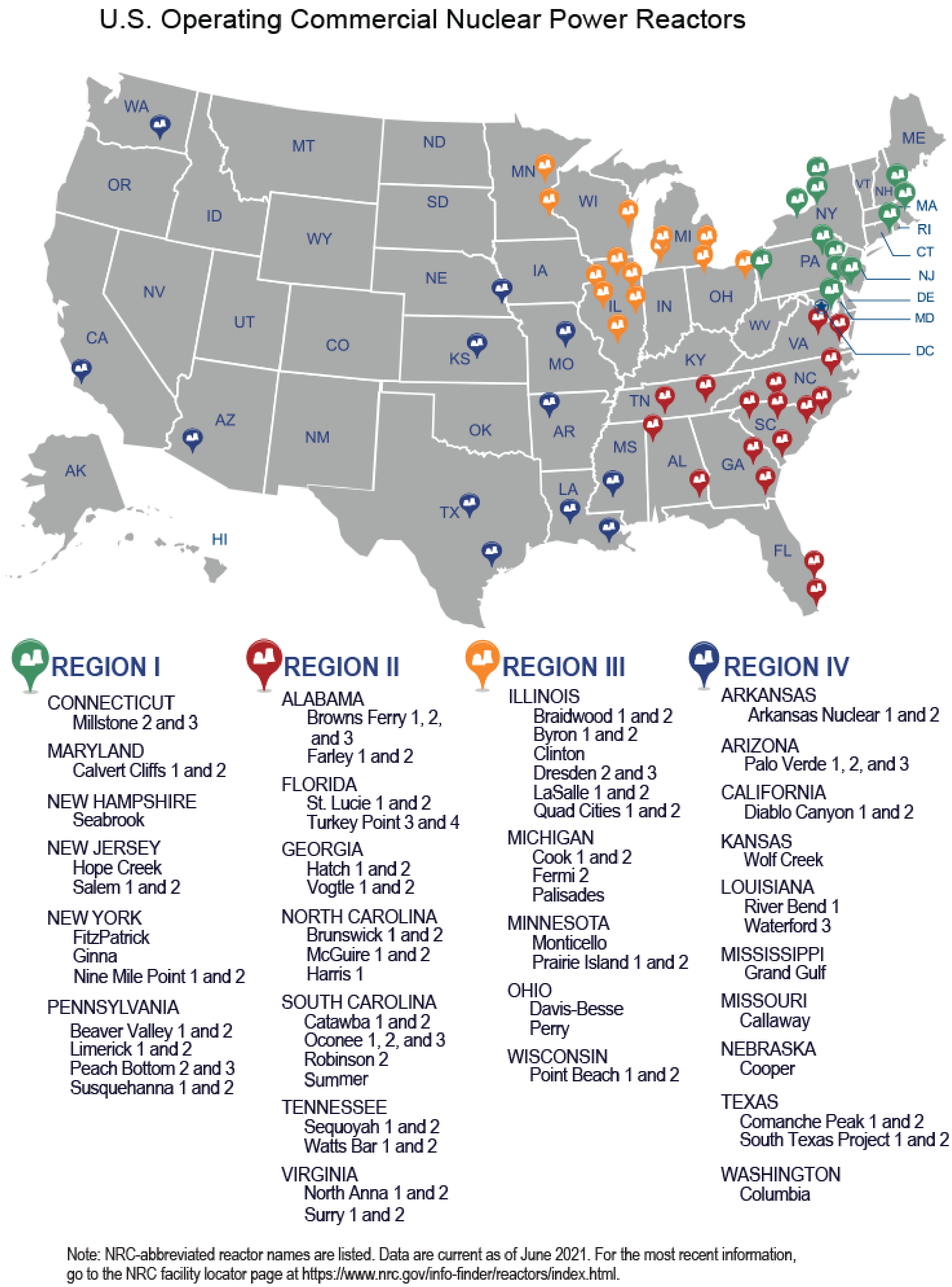

Figure 9. U.S. Operating Commercial Nuclear Power Reactors (NRC 2021a)

Additionally, national organizations, such as the Electric Power Research Institute, the Institute of Nuclear Power Operations, and the NEI, provide guidance, performance objectives, criteria, research, and knowledge transfer tools.

Colleges and universities across the U.S. operate research reactors and are developing the next generation of engineers and operators and innovating systems and materials to support nuclear operations (NRC 2021a).

6.0 Risks

Risks are a significant barrier to SMR deployment, and continue to be studied and evaluated as the technology is considered for further deployment.

6.1 Social Considerations

6.1.1 Human Health Risk and Social Equity

The NRC requires that applicants include a study of human health impacts in their applications for construction permits and operating licenses. Human health impacts are analyzed from different aspects: transportation, occupational doses to workers, impacts to the public, fuel-cycle and waste management, and environmental justice. This study includes analysis of radiological and non-radiological health impacts for chemical, biological, and physical hazards to the plant workforce and the public (NRC 1999). The NRC reviews human health risks as part of their environmental and safety reviews for nuclear power plants licensing. Community assets/equity are addressed in the environmental review process, and the specific impacts would be addressed when the NRC or Air Force develops an EIS. The content and format of the applicant's environmental report are explored more in Section 6.2, Environmental Considerations.

6.1.2 Public Perception Barriers

An article in the American Nuclear Society's Nuclear Newswire (ANS 2019) provides potential insight into the formation of public perception barriers. The article states that "[p]ublic opinion on nuclear energy topics is based largely on impressions, as few feel very well informed about the topic." However, about 75% of the public agree that nuclear energy needs to be a part of a mix of carbon-free energy sources.

The World Nuclear News identifies perception and lack of knowledge on nuclear power and its benefits as barriers to nuclear energy (WNN 2020). One strategy to change perception is an effective communication plan starting at an early stage of the nuclear power plant project. The plan should engage the public and other key stakeholders to address their concerns to develop a high level of acceptance.

Nuclear incidents also present public perception barriers. The Three Mile Island, Chernobyl, and Fukushima accidents have had a negative impact on public opinion about the safety of nuclear reactors. The NRC amended the regulations after each of the accidents to address the causes. NRC also required the industry to provide additional safety and safeguards to prevent and mitigate future accidents. The reactor systems are designed to be safe and engineered to provide safe operation and design margins, and even address failures caused by humans and natural phenomena. The plants have redundant systems and backups to ensure that the safety systems perform their intended functions. When compared to existing large commercial reactors, SMR designs are simpler and rely "more extensively on inherent, as well as passive, safety features" (IAEA 2021).

6.2 Environmental Considerations

As described in Section 4.0, the NRC would evaluate the potential for impacts on the environment by the SMR during its environmental assessment and would document the assessment in an EIS per their regulations in 10 CFR Part 51.

The NRC has well-established requirements for implementing NEPA in 10 CFR Part 51, and guidance in the ESRP (NRC 1999). To supplement the guidance, the NRC published three interim staff guidance (ISG) documents to inform the emerging SMR vendors and applicants on how the NRC will use the ESRP to review applications for new reactors, including SMRs:

- Interim Staff Guidance on Environmental Issues Associated with New Reactors, COL/ESP-ISG-026 (NRC 2014a).
- Interim Staff Guidance on Specific Environmental Guidance for Light Water Small Modular Reactors, COL/ESP-ISG-027 (NRC 2014b)
- Environmental Considerations Associated with Micro-reactors, COL-ISG-029 (NRC 2020b)

The first two ISGs inform applicants and NRC staff on how the NRC will adapt the ESRP, NUREG-1555 (NRC 1999), to review the environmental report of an SMR license and permit application. The third ISG provides guidance to potential MR applicants on what the NRC considers appropriate scope and level of detail about the specific aspects of the applicant's environmental review.

MR and SMR applicants need to describe in their environmental reports how the site and design address the following:

- Occupies only a small area of land, disturbs only previously disturbed lands, or both
- Uses zero or only small quantities of resources, such as water or fuel
- Releases zero or only small quantities of emissions to the environment
- Avoids environmentally sensitive areas such as wetlands and floodplains
- Avoids areas with cultural, historic, or environmental justice significance
- Avoids habitat for threatened or endangered species
- Uses mitigation to reduce impacts
- Involves only low levels of employment for both construction and operation
- Uses simpler designs than those for large LWRs, with limited interfaces with the exterior environment

6.2.1 Environmental Impact Statement

The unique environmental impact from SMR operations is an uncontrolled or unplanned release of radiological materials. Those materials could form gas or vapor plumes, liquid plumes into waterways, and particulates entrained in other plumes. Those releases could vary in potential magnitude and form based on the specific designs. SMR designs that operate near atmospheric pressure have little energy to propel a gas or vapor plume, and those plants that are small have a much smaller inventory of radiological materials available for release. Further, other chemical or coolant releases could result from ANRs. The magnitude and type of release are design dependent.

The NRC is developing a report to analyze potential environmental impacts common to many or most ANRs that could be addressed generically. This would eliminate the need to conduct and report the same analysis each time a license application is submitted to the NRC. Removing this burden would also allow the owner/operator to focus their environmental reviews on site-specific issues.

The draft Generic Environmental Impact Statement for Advanced Nuclear Reactors (NRC 2021b) was released to the public for information. It is currently under review by the NRC Commission and has not been issued as a draft for public comment as of the date of this report.

Human health and societal impacts are addressed in the environmental report that the owner/operator provides to the NRC as part of the operating license or COL application. The NRC would develop an EIS per the regulations in 10 CFR Part 51 and the guidance in the ESRP and COL/ESP-ISG-026. The specific content that the owner/operator of the SMR would need to supply within the environmental report depends on the type of application the NRC receives. The general content requirements are found in 10 CFR 51.45(b):

The environmental report shall describe the proposed action, its purposes, and the environment affected, and discuss the following:

1. The impact of the proposed action on the environment. Impacts shall be discussed in proportion to their significance.

2. Any adverse environmental effects that cannot be avoided should the proposal be implemented.

3. Alternatives to the proposed action. The discussion of alternatives shall be sufficiently complete to aid the Commission in developing and exploring, pursuant to section 102(2)€ of NEP“, "appropriate alternatives to recommended courses of action in any proposal which involves unresolved conflicts concerning alternative uses of available resources." To the extent practicable, the environmental impacts of the proposal and the alternatives should be presented in comparative form.

4. The relationship between local short-term uses of the human environment and the maintenance and enhancement of long-term productivity.

5. Any irreversible and irretrievable commitments of resources that would be involved in the proposed action should it be implemented.

6. Further, the owner/operator would need to supply an analysis of the considerations and environmental effects of their proposal. The requirement for the analysis is in 10 CFR 50.45(c) and states:

   “Analysis. The environmental report must include an analysis that considers and balances the environmental effects of the proposed action, the environmental impacts of alternatives to the proposed action, and alternatives available for reducing or avoiding adverse environmental effects.”

The specific requirements for the content of the environmental report for the type of application are provided in 10 CFR 51.50, Environmental report-construction permit, ESP, or combined license stage. RG 4.2 (NRC 2018) provides the format for preparing an environmental report for the NRC.

6.3 Safety Considerations

The NRC would evaluate the SMR design and the impact of natural phenomena on the SMR and site during the licensing process. The safety review process is described in Section 4.0, Regulatory Overview.

The NRC uses various guidance to evaluate whether the applicant's safety analysis report that is submitted as part of the application complies with the NRC regulations. The primary guidance documents that the NRC uses are NUREG-0800, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition (referred to as the Standard Review Plan, or SRP), and RG 1.206, Applications for Nuclear Power Plants. Part 2 of the SRP contains guidance for the NRC to review light-water SMRs. The SRP is a comprehensive and integrated document that describes the acceptable methods and approaches for meeting the NRC regulations. Although the applicant does not need to conform to guidance, conforming to the guidance eliminates the need to provide additional and sufficient information for the NRC to independently confirm that the applicant's results and conclusions comply with regulations. By complying with the regulations, the NRC can conclude that there is adequate protection of public health and safety.

The NRC safety regulations for SMRs are found in 10 CFR Parts 50 and 52. The NRC uses the regulations in 10 CFR Part 52 when the applicant requests an ESP or a COL. Many of the regulations in 10 CFR Part 52 incorporate by reference safety regulations in 10 CFR Part 50. If an SMR applicant requests a construction permit or an operating license, the NRC would use the regulations in 10 CFR Part 50 and not 10 CFR Part 52.

In addition to the regulations in 10 CFR Part 50 and Part 52, the application would need to comply with other regulations and the NRC staff reviews these additional regulations as part of its safety review. The following is a partial list of additional regulations that an SMR application would have to demonstrate compliance with. A complete list of regulations and the associated guidance specific to the review topic is found in the SRP and RG 1.206.

- 10 CFR Part 2, Agency Rules of Practice and Procedure
- 10 CFR Part 20, Standards for Protection against Radiation
- 10 CFR Part 21, Reporting Defects and Noncompliance
- 10 CFR Part 25, Access Authorization
- 10 CFR Part 26, Fitness for Duty Programs
- 10 CFR Part 30, Rules of General Applicability to Domestic Licensing of Byproduct Material
- 10 CFR Part 40, Domestic Licensing of Source Material
- 10 CFR Part 50, Appendix A, General Design Criteria for Nuclear Power Plants, while the applicant may use RG 1.232, Guidance for Developing Principle Design Criteria

for Non-Light-Water Reactors, to demonstrate how a non-light-water SMR may meet the General Design Criteria.

- 10 CFR Part 50, Appendix B, Quality Assurance Criteria for Nuclear Power Plants and Fuel Processing Plants
- 10 CFR Part 70, Domestic Licensing of Special Nuclear Material
- 10 CFR Part 73, Physical Protection of Plants and Materials
- 10 CFR Part 74, Material Control and Accounting of Special Nuclear Material
- 10 CFR Part 100, Reactor Site Criteria
- 10 CFR Part 140, Financial Protection Requirements and Indemnity Agreements

7.0 Economic and Funding Considerations

As part of the DOE investments in SMR development, the Nuclear Energy Innovation Capabilities Act of 2017 (Public Law 115-248) authorizes DOE to provide an advanced nuclear energy licensing cost-share program to provide grants to nonfederal developers of advanced reactor technologies to help offset the fees charged by the NRC for certain licensing-related costs. For commercial SMRs, various DOE programs exist as part of private-public partnerships and cost-sharing initiatives. In ARDP (mentioned in Section 5.0) the DOE partners with private industry by sharing costs to design and demonstrate advanced reactors domestically.

As another example of federal partnership, Project Pele is an engineering design contest launched by the DOD's Strategic Capabilities Office inviting private industry to develop a transportable MR. Pele is led by the Strategic Capabilities Office in collaboration with the DOE, NRC, and U.S. Army Corps of Engineers. The Pele reactor is to be a single prototype, which will be demonstrated only within the United States, under the safety oversight of the DOE. As an HTGR using TRISO fuel, Project Pele is a fourth-generation nuclear reactor, which can serve as a pathfinder for commercial adoption of such technologies, thereby reducing the nation's carbon emissions and providing new tools for disaster relief and critical infrastructure support. The project initially awarded contracts to three separate MR designers: BWX Technologies, Westinghouse Government Services, and X-energy. BWXT's design was eventually selected for assembly and initial operations at INL. This will be the first electricity-generating Generation IV nuclear reactor built in the U.S. DOD will decide in the future whether to transition the technology and use it operationally (DOD 2022).

These are both examples of the federal government economically encouraging the transition of the next generation of nuclear reactors from concept to demonstration.

7.1 Installed System Costs

Other than some historical U.S. Army reactors and the U.S. Navy's current maritime fleet of PWRs, what is being studied here has not been done nor even approximately done within the U.S. Some experts suggest setting the initial expectation of acquisition cost for a first-of-a-kind SMR at over $1 billion (EIA 2022a), a cost that would vary based on the expected power output. This would be refined as knowledge, experience, and economies of scale are realized. Cost information about SMRs outside the U.S. is not publicly available. Similarly, construction and operational costs for commercial large-scale reactors are proprietary and not publicly available.

Since SMR technology is still developing and is not deployed in the U.S., information is scarce concerning the various costs for O&M, decommissioning and end-of-life dissolution, property restoration and site cleanup, and waste management. Prototypes such as DOD's PELE project will need to be leveraged to build the knowledge to accurately predict lifecycle funding requirements.

The variable O&M costs per megawatt-hour are estimated at $3.14 and fixed O&M costs per kilowatt-year are estimated at $99.46 (EIA 2022b). Since the costs are estimated based on the power delivered and are projected for SMRs that have not been constructed or operated, the estimates will be refined as further information becomes available.

In 2020, the Nuclear Energy Agency and the International Energy Agency published a joint report, Projected Costs of Generating Electricity, projecting the costs of generating electricity from natural gas, coal, nuclear, and a range of renewable technologies. The report provides detailed plant-level cost data for 243 power plants across 24 different countries. The trend that the report provides is that the levelized costs of electricity “of low-carbon generation technologies are falling and are increasingly below the costs of conventional fossil fuel generation.” The report further states that “electricity from the long-term operation of nuclear power plants constitutes the least cost option for low-carbon generation” (NEA 2020).

The NEA (2020) report provides information concerning the U.S. long-term operating nuclear power plants, assuming an 85% capacity factor over 10 years and a 7% investment, at $7.74/megawatt-hour, and over 20 years at $5.13/megawatt-hour.

7.2 Potential Funding Mechanisms

Given the enormous gap between the current technology maturity, the necessary development costs, and the need to prototype and build a useful scale for acquisitions and steady-state operations, public funding is most likely necessary. It is envisioned that a public-private partnership could be created where the federal government (DOD, DOE, etc.) would incentivize the maturation of technology, the maturity of operational methods, and the staff necessary to reach a fully adopted and useful capability within the DOD and the private sector.

To do this, the DOD could consider using real-time operational/mission needs and significant funding resources (appropriated funding) to devise a method to stimulate the industrial base. Specifically, the DOD could consider “department-wide” energy needs to maximize the economies of scale to attract private investment. To do this, an analysis is needed to determine if a block purchase could be feasible for SMRs. A block purchase or block buy is where the DOD purchases multiple units of a specific design, similar to the procurement of multiple aircraft carriers or airframes. It’s a form of contracting that Congress allows the DOD to use for specific defense procurement programs. Block purchasing is designed to reduce the costs to DOD and bring stability to the market by creating a predictable product demand for the manufacturer. The demand ensures the manufacturer can maintain a skilled workforce and brings certainty to suppliers.

DOE-NE works to advance nuclear power. It has three objectives in advancing nuclear power by providing funding opportunities:

- Enhance the long-term viability and competitiveness of the existing U.S. reactor fleet.
- Develop and advance reactor pipeline
- Implement and maintain national strategic fuel cycle and supply chain infrastructure

The Air Force could use the following DOE-NE programs to help share costs associated with ANR deployment:

- The U.S. Industry Opportunities for Advanced Nuclear Technology Development Funding Opportunity Announcement (FAO) provides opportunities to support innovation and competitiveness using cost-sharing projects for basic and applied research and development, and demonstration and commercial applications for research and development activities.
- The GAIN program provides vouchers to the nuclear industry to provide funds to assist applicants seeking access to DOE laboratory expertise and capabilities.

- The Consolidated Innovative Nuclear Research FAO promotes three support activities:
  - The Nuclear Energy University Program supports research performed at universities that aligns with DOE-NE's mission and goals. The program supports the transfer of knowledge from the aging workforce to the next generation of workers.
  - Nuclear Energy Enabling Technologies Crosscutting Technology Development conducts research and development in crosscutting technologies that support and enable the development of new and advanced reactor designs and fuel cycle technologies.
  - Nuclear Science User Facilities provide access to facilities to advance nuclear science and technologies at no cost to the user. The user receives access to state-of-the-art experimental irradiation testing and post-irradiation examination facilities and assistance to design and analyze reactor experiments.
- The Scientific Infrastructure Support for Consolidated Innovative Nuclear Research FAO provides assistance to equip or fund activities to support research, teaching, and education. The program assists with the purchase, setup, and vendor installation costs for equipment and instrumentation, and building modifications that support the installation and operation of the equipment.

Another funding avenue exists in the form of a power purchase agreement (PPA). The Air Force, in partnership with the Defense Logistics Agency Energy, recently announced its request for proposals (RFP) to pilot its first MR at Eielson Air Force Base (EAFB). In a PPA, a third-party developer installs, owns, and operates an energy system on a customer's property, or in this case EAFB. The customer (Air Force) signs a contract to purchase power from the electricity-generating technology (MR) installed on the customer's property for a predetermined contract term. In some instances, the developer may sell excess power to the utility at a negotiated rate. This RFP will demonstrate whether a PPA is a viable funding mechanism for the Air Force.

8.0 Siting Considerations

SMRs should be sited considering their purpose and end users, their impact on the environment, distances to population centers, availability of existing infrastructure, and other considerations.

The Nuclear Energy Innovation Capabilities Act of 2017 (Public Law 115-248) establishes the National Reactor Innovation Center to facilitate the siting of privately funded advanced reactor prototypes at DOE sites through partnerships between DOE and private industry. The DOE established the National Reactor Innovation Center at INL to allow collaboration to support the construction and demonstration of advanced reactor systems.

8.1 Desirable Siting Characteristics

The NRC has regulations that provide reactor siting criteria in 10 CFR Part 100 and guidance in RG 4.7 (NRC 2014c). A site selection process is described in RGs 4.2 and 4.7 and the scope of the analysis needed is stated in RG 4.7:

> “Site selection involves consideration of the human environment, public health and safety, engineering and design, economics, institutional requirements, environmental impacts, and other factors. The potential impacts of the construction and operation of nuclear power stations on the human environment and on social, cultural, and economic features (including environmental justice) are usually similar to the potential impacts of any major industrial facility, but nuclear power stations are unique in the degree to which potential impacts of the environment on their safety must be considered. The safety requirements are primary determinants of the suitability of a site for nuclear power stations, but environmental impacts are also important and need to be evaluated.”

8.1.1 Land/Space Requirements and Site Preparation

Land requirements for SMRs vary widely. According to the IAEA’s 2022 SMR Booklet (IAEA 2022a), the average planned footprint for an SMR design is 38,416 m^2 (9.5 acres), with the middle 50% of the footprint ranging from 4,755 to 41,250 m^2 (1.2 to 10.2 acres). Additionally, many of the SMR designs are sized for multiple units as a basis for their land requirements.

Of the U.S. SMR designs, the land requirements averaged 35,767 m^2 (8.8 acres), with 50% of the plant footprints requiring 4,320 to 40,000 m^2 (1.1 to 9.8 acres), where the smallest footprint was 9 m^2 and the largest was 256,100 m^2 (0.002 and 63 acres, respectively). Many of the SMR designs are sized for multiple units.

The time and resources needed for the excavation and site preparation to host an SMR would be on the same order of magnitude as other construction projects with a similar footprint. The specific design of the SMR would dictate the specific requirements and resources needed for site preparation.

8.1.2 Infrastructure Requirements and Resource Availability

Infrastructure and resource requirements to support an SMR are highly dependent on the design and are not addressed in this report. Each plant design is unique and may require different amounts of fuel, water, sewer infrastructure, and other resources.

Like other industrial sites, there are requirements for potable water, electrical grid connections, sewer systems, trash and refuse collection, and communications. NRC regulations require at least two independent electrical circuits from the offsite grid as well as redundant communication systems, where the primary communication is typically telephones.

Many SMR vendors are marketing their designs to allow for the replacement of fossil fuel electric generation by placing SMRs at existing power plants and using the existing supporting infrastructure. Using the existing electrical transmission and distribution connections and ample water supplies reduces the overall construction costs and minimizes the environmental impacts of constructing a new plant at a new site. Further, since one of the designed uses of SMRs is providing process heat to industries, the SMRs would necessarily be located near the end users to provide the heat. As SMRs are deployed, the optimal configuration for locating multiple SMRs will emerge.

8.2 Potential Air Force Siting Locations

As discussed earlier, the Air Force has announced an RFP pursuing a MR (rather than an SMR) PPA for EAFB (DLA 2023). Although the RFP proposes an MR for EAFB, a similar case could be made to site an SMR there. The conditions at EAFB are similar to those at the FNPP in northeastern Russia. Both locations need reliable electricity and heat generation capacity for a relatively small area in a colder climate. Additionally, communities in Alaska may not require expansive generation, transmission, and distribution grids.

Alaska’s landscape and sparse population, and the expense of maintaining infrastructure to deliver energy from offsite, may make deploying SMRs a viable option. EAFB currently operates a combined heat and power coal plant and switching to an SMR would reduce greenhouse gas emissions associated with power production. The infrastructure at EAFB could support both black start capability and island mode operations if the site’s connection to the offsite grid was not available.

EAFB provides a glimpse into what an SMR site location might entail. Many factors may play into a decision for the Air Force to site an SMR. The NRC regulations in 10 CFR Part 100, Reactor Site Criteria, provide the requirements for the content of an application for a construction permit or an ESP. Other business factors the Air Force could consider are:

- Remote locations that are difficult to access for fuel deliveries
- Requirement for resilient and reliable energy to support power needs with sufficient energy demand to necessitate an SMR
- Favorable state regulatory environment
- Higher cost of energy and higher greenhouse gas emissions at the site and region
- Suitable and sufficient footprint for SMR to mitigate environmental and cultural resource impacts
- Limited impacts to site from future climate change (sea-level rise, etc.).

9.0 Recommendations and Path Forward

The research and reports highlighted below are example roadmaps that may assist the Air Force in determining its next steps.

PNNL provided roadmaps for the Air Force's consideration in the EAFB Microreactor Pilot Project. The three draft roadmaps cited below provide additional information on the siting, regulatory, and beyond pilot considerations and may inform potential paths forward. These documents provide valuable insight into a specific Air Force MR application.

- Fuentes TL, TA Ikenberry, KM Thomas, and AL Miracle. 2022. Microreactor Site Selection Roadmap. PNNL-33711. Richland, WA: Pacific Northwest National Laboratory.
- McDowell BK, NP DiNunzio, AB Rigato, SJ Maheras, CA Gunzel, D Goodman, and KM Thomas, et al. 2022. Microreactor Regulatory Roadmap Draft. PNNL-33713. Richland, WA: Pacific Northwest National Laboratory.
- Thomas KM, TA Ikenberry, and AL Miracle. 2022. Eielson Air Force Base Beyond the Microreactor Pilot Roadmap. PNNL-33710. Richland, WA: Pacific Northwest National Laboratory.

DOE funded a study (KRSC 2017) that provides options for federal agencies to purchase power supplied by SMRs. Chapter 7 of the study provides a six-step roadmap (below) for federal agencies that wish to have reliable electric power from SMRs while efficiently using financial resources. Since federal agencies have substantial purchasing power, the purchasing of power from SMRs could provide meaningful support for the development of commercial SMRs. The DOE study provides insights specific to SMR technology.

1. Determine long-term load requirements.
2. Identify alternatives for meeting the projected load.
3. Evaluate economics of each option.
4. Determine contract structure.
5. Develop procurement plan.
6. Negotiate terms and execute contract.

Additionally, the NEI published a roadmap for the deployment of MRs (NEI 2018) that could apply to deployment of SMRs on Air Force installations. The NEI roadmap recommends the following:

1. DOD should identify a base and site, assess the designs, and develop a contract to purchase power.
2. DOE should supply HALEU and support the development of HALEU transportation packages.
3. Designers should continue the development of designs using milestones while minimizing scheduling risks.
4. DOD, the NRC, and the industry should identify and resolve regulatory issues for DOD-sited reactors.

5. The industry and the NRC should explore options for accelerating the regulatory reviews and processes for training and licensing operators.

The Air Force will need to review the operational, technical, regulatory, environmental, and economic considerations documented in this report when deciding when and where to deploy SMRs, understanding the unique benefits and challenges presented by the technology. The outcome of the EAFB project will be an indicator for future opportunities.

10.0 References

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10 CFR 73.54, Protection of Digital Computer and Communications Systems and Networks. Code of Federal Regulations, as amended.

10 CFR Part 100, Reactor Site Criteria. Code of Federal Regulations, as amended.

10 CFR Part 170, General Provisions. Code of Federal Regulations, as amended.

10 CFR Part 171, Annual Fees for Reactor Licenses and Fuel Cycle Licenses and Materials Licenses, Including Holders of Certificates of Compliance, Registrations, and Quality Assurance Program Approvals and Government Agencies Licensed by the NRC. Code of Federal Regulations, as amended.

10 CFR Part 30, Rules of General Applicability to Domestic Licensing of Byproduct Material. Code of Federal Regulation, as amended.

10 CFR Part 40, Domestic Licensing of Source Material. Code of Federal Regulation, as amended.

10 CFR Part 50, Domestic Licensing of Production and Utilization Facilities. Code of Federal Regulations, as amended.

10 CFR Part 51, Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions, Code of Federal Regulations, as amended.

10 CFR Part 52, Licenses, Certifications, and Approvals for Nuclear Power Plants. Code of Federal Regulations, as amended.

10 CFR Part 53, Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors. Code of Federal Regulations, as amended. Proposed rule. Accessed on 25 March 2023 at https://www.regulations.gov/docket/NRC-2019-0062.

10 CFR Part 55, Operators' Licenses. Code of Federal Regulations, as amended.

10 CFR Part 70, Domestic Licensing of Special Nuclear Material. Code of Federal Regulation, as amended.

42 U.S.C. § 2011, Congressional declaration of policy. United States Code, as amended.

42 U.S.C. § 5801, Congressional declaration of policy and purpose. United States Code, as amended.

42 U.S.C. § 5814, Abolition and transfers. United States Code, as amended.

42 U.S.C. § 7101, Definitions. United States Code, as amended.

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Appendix A – Glossary

This glossary contains terms commonly used in the nuclear power industry to describe the various designs and operating characteristics. Many of the references supply definitions, and readers may often see subtle differences between the uses across the references. The IAEA, NRC, and DOE glossaries were consulted to provide the terms that best reflect their use within this document.

advanced non-light water reactor (ANLWR): An advanced nuclear reactor that does not use light water as the reactor coolant. For the NRC, an advanced non-light water reactor does not use water as the reactor coolant.

advanced nuclear reactor (ANR): A nuclear fission or fusion reactor, including a prototype plant with significant improvements compared to commercial nuclear reactors under construction, including improvements such as:

- additional inherent safety features,
- significantly lower levelized cost of electricity,
- lower waste yields,
- greater fuel utilization,
- enhanced reliability,
- increased proliferation resistance,
- increased thermal efficiency, or
- ability to integrate into electric and non-electric applications. (NEIMA 2019, Public Law 115-439)

baseload power: Consistent electrical output from a generating source; does not vary over time unless operated to do so.

black start: The capability to provide electrical power generation from shutdown conditions without relying on the external power grid.

commercial reactor: A highly reliable reactor power plant that has been built to full-scale and is intended solely for commercial use in the generation of electricity or process heat, or both, for industrial applications. (IAEA)

condenser: A heat exchanger, typically of a shell and tube construction, that is used to condense the exhaust steam from the turbine into condensate (liquid).

containment: A structure or enclosure around a nuclear reactor to contain fission products or prevent the release of fission products into the environment. In advanced reactor designs, the containment may be a functional confinement instead of a physical structure.

demonstration or prototype reactor: A plant that is intended to demonstrate overall plant performance, reliability, safety systems, and economics. A demonstration plant will typically generate electrical power or process heat or both for industrial applications at some limited scale. (IAEA) Also referred to as pilot projects.

dose calculations: Estimates of the amount contributed to radiological contamination or operations from a source term. The source term provides information concerning the magnitude, rate, duration, orientation, release type, or other parameters to determine the impacts on health, the environment, or on other materials.

experimental reactor: Typically the first design of a new innovative reactor technology that has been constructed to validate the performance of the reactor core materials and fuels, explore safety limits and uncertainties, and gain critical lessons learned so that the technology may be licensed and commercialized. Experimental reactors are often low-power reactors and typically are not used to produce reliable electrical power to the power grid. (IAEA)

fission: A type of nuclear reaction where a heavy nucleus splits either spontaneously or on impact with another particle with the release of energy.

fuel cycle: The series of steps in the mining, production, and final storage of nuclear fuel. (IAEA)

gas-cooled reactor: A nuclear reactor that uses graphite as a neutron moderator and hydrogen (helium can also be used) as a coolant. (IAEA)

high assay low enriched uranium (HALEU): HALEU (hay-loo) is enriched uranium between 5% and 20% by weight of the uranium-235 isotope.

highly enriched uranium (HEU): Uranium enriched to at least 20% by weight of the uranium-235 isotope.

island mode: Island mode operation is the grid operating condition where an electricity generator supplies power to its loads and a limited number of dedicated loads while being isolated from transmission grids or other loads.

levelized cost of electricity (LCOE): A measure of the average net present cost of electricity generation for a specific generator over its project lifecycle.

light-water reactor (LWR): A type of thermal-neutron reactor that uses ordinary water (H_20) as both a coolant and a moderator. Contrast light water with a heavy-water reactor that uses a different isotope of hydrogen, deuterium (^2H), in a water molecule either with one deuterium atom, $HO(^2H)$, or with two, $(^2H)_2O$.

microreactor (MR): A nuclear reactor that has output power below roughly 30 MWe. Note that this definition is not universally agreed upon. See Small Modular Reactor for a different perspective.

moderator: A moderator, or a neutron moderator, is a material or medium that reduces the energy of a neutron that results from the splitting of a nucleus. The released neutron is referred to as “fast” before it is moderated and has an energy greater than 1 million electron-volts (MeV). After the moderator removes the energy, ideally without absorbing the neutron, the neutron is referred to as “thermal“, and has an energy of about 0.025 electron-volts (eV). (“Thermal” is used here to mean that the neutron is at thermal equilibrium with its surroundings.)

molten salt reactor (MSR): A class of nuclear fission reactors where a molten salt mixture is used as the coolant, which at the same time can be the fuel. MSRs run at higher temperatures, thus increasing the thermodynamic efficiency, while staying at low vapor pressure. They can be operated at near atmospheric pressures, thus reducing the mechanical stress on the system, simplifying aspects of reactor design, and improving safety. (IAEA)

nuclear power plant: A thermal power station in which the heat source is one or more nuclear reactors. As in a conventional thermal power station, the heat is used to generate steam, which drives a steam turbine connected to a generator, which produces electricity. (IAEA)

safety-related: Any system, structure, component, procedure, or control relied upon to remain functional during and following a design-basis event. The safety-related item is critical to preserving the health and safety of the public and meeting key regulatory criteria.

small modular reactor (SMR): As used in this document and commonly in the industry, an SMR is a small nuclear reactor, modularly constructed, that provides output power up to 300 MWe. The NRC specifies in its definition of an SMR in 10 CFR 170.3 that it is a light-water nuclear reactor. “SMR” typically refers to the size, modular construction, and capacity, and does not depend on the type of nuclear reactor coolant or the neutron energy spectrum (thermal-fast).

sodium fast reactor (SFR): A fast-neutron nuclear reactor that is cooled by liquid sodium.

source term: Concerning radiological materials, a source term provides information concerning the magnitude, rate, duration, orientation, release type if any, or other parameters to determine the impacts on health, the environment, or on other materials.

spent nuclear fuel (SNF): Nuclear fuel that has been irradiated in a nuclear reactor and is generally no longer useful in sustaining nuclear reaction in a thermal nuclear reactor.

tristructural isotropic fuel (TRISO): A particle consisting of a uranium, carbon, and oxygen fuel kernel surrounded by three layers of carbon- and ceramic-based materials that prevent the release of radioactive fission products.

turbine generator: A device that converts the mechanical energy of a rotor shaft into electrical energy. Mechanical energy is created when a moving fluid pushes blades on a shaft to rotate and spin.

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