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## Energy and Telecommunications Interim Committee

# ADVANCED NUCLEAR TECHNOLOGY 101: FOURTH GENERATION REACTOR CONSIDERATIONS

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### INTRODUCTION

Historically the nuclear power generation sector in the United States relies on large light water reactors (LWRs) first constructed in the 1950s and early 1960s. The large, on average, 1,000 megawatt plants are cooled by water, moderating the nuclear fission reaction that creates the heat needed for electric generation. In recent years the sector, facing the high construction costs of large LWRs, and safety concerns have turned to "advanced" nuclear technologies that could prove less expensive and safer than conventional reactors while maintaining a viable, noncarbon emitting baseload generation source for the future.

The federal Nuclear Energy Innovation Capabilities Act of 2017 defined "advanced nuclear reactors" as "a nuclear fission reactor with significant improvements over the most recent generation of nuclear fission reactors" or a reactor using nuclear fusion.<sup>1</sup>

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Advanced reactors are often referred to as "Generation IV" nuclear technologies, with existing commercial reactors

referred to as "Generation III." Advanced reactors include advanced water-cooled reactors, gas-cooled reactors, liquid metal-cooled reactors, and fusion reactors, which would release energy through the combination of light atomic nuclei rather than the splitting (fission) of heavy nuclei such as uranium. Most of these concepts have been studied, but few, have advanced to commercial scale demonstration.

As the Energy and Telecommunications Interim Committee begins its study of advanced nuclear power's feasibility in Montana, this report aims to provide an overview of existing advanced technologies and a brief overview of the issues surrounding advanced nuclear power.

## ADVANCED REACTOR DESIGN

Advanced reactor designs use new and existing technologies and materials to attempt to improve nuclear reactors in one or more of the following areas: cost, safety, security, waste management, and versatility. To achieve these improvements, advanced designs may incorporate inherent or passive safety features, simplified or modular designs, enhanced load-following capabilities, high chemical and physical stability, fast neutron spectrums, and "closed" fuel cycles.

Typically, advanced reactors are grouped into three major technology types:

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

<sup>&</sup>lt;sup>1</sup> P.L. 115-248

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

Small modular reactor technology can be found in each of the three categories. The U.S. Department of Energy defines SMRs as a reactor with a generating capacity no more than 300 megawatts, which employ modular construction techniques, "employ modular construction techniques, ship major components from factory fabrication locations to the plant site by rail or truck, and include designs that simplify plant site activities required for plant assembly."<sup>2</sup> Both advanced water-cooled reactors and non-water-cooled reactors may be configured as SMRs.

Most proposed advanced reactors would be considered "small modular reactors" (SMRs), which DOE defines as having generating capacity of 300 MW or below. Supporters of SMRs contend that they would be small enough to be assembled in factories and shipped to reactor sites to reduce construction costs. In addition, SMRs could reduce the financial risks of building a new nuclear power plant, because each module would cost less than today's large reactors and revenues could begin when the first module was complete. However, some analysts contend that SMRs would be too small to achieve the economies of scale needed for economic viability.

Light water-cooled SMRs, high-temperature gas-cooled reactors, and sodium-cooled fast reactors are considered to be among the most mature of the unconventional reactor technologies. Molten salt reactors, gas-cooled fast reactors, and fusion reactors are generally considered to be further from commercialization.

Estimates of operational timeframes of these technologies range widely, from the mid-2020s for the first small modular LWRs to midcentury or later for some advanced reactor concepts, such as molten salt reactors and gas-cooled fast reactors. <sup>3</sup>

#### ADVANCED WATER-COOLED REACTORS

#### LIGHT-WATER SMALL MODULAR DESIGNS

Light water reactor SMR designs are based on existing commercial LWR technology but are small enough to allow all major reactor components to be placed in a single pressure vessel. The reactor vessel and its components are designed to be assembled in a factory and transported to the plant site for installation, potentially reducing construction time and costs from those of large LWRs. If large numbers of SMRs were ordered, mass production could further reduce manufacturing costs and construction schedules, according to proponents of the technology.

SMRs require a fraction of the capital investment of a large conventional nuclear unit, reducing the financial risk to plant owners. However, some observers have suggested that the smaller size of SMRs would reduce the economies of scale available to larger reactors, potentially negating any SMR cost advantages.<sup>4</sup>

<sup>&</sup>lt;sup>2</sup> U.S. Department of Energy, "Advanced Small Modular Reactors (SMRs)"

<sup>&</sup>lt;sup>3</sup> Massachusetts Institute of Technology, "The Future of Nuclear Energy in a Carbon-Constrained World."

<sup>&</sup>lt;sup>4</sup> Lyman, Edwin, "Small Isn't Always Beautiful: Safety, Security, and Cost Concerns about Small Modular Reactors,"

Union of Concerned Scientists, September 2013

## NUSCALE POWER MODULE™

NATURAL CIRCULATION OF REACTOR COOLANT FLOW

#### CONDUCTION

Heat is transferred from the primary coolant through the walls of the tubes in the steam generator, heating the water (secondary coolant) inside them to turn it to steam.

#### CONVECTION

Energy from nuclear reaction heats the primary reactor coolant causing it to rise by convection and natural buoyancy through the riser, much like a chimney effect.

## 🌗 gravity

Colder (denser) primary coolant "falls" to bottom of reactor pressure vessel, cycle continues.



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A 60 MW reactor module by U.S. company NuScale Power is considered the most mature light water SMR design under development. The design would allow between 6 and 12 SMR modules—depending on the energy needs of the site—to be co-located in a central pool of water, which serves as a heat sink and passive cooling system. NuScale is planning to begin operating its first 12-module plant in the mid-2020s. It is to be built at Idaho National Laboratory with a combination of federal government and non-federal support. The major components of the NuScale plant are designed to be factory fabricated and shipped to the plant site for installation.<sup>5</sup>

In addition to NuScale, examples of U.S.-based companies developing this technology include Holtec, Westinghouse, and GE Hitachi.

#### SUPERCRITICAL WATER-COOLED REACTORS

The supercritical water-cooled reactor (SCWR) is a high-temperature version of LWR technology. SCWRs use water heated to a temperature and pressure leaving liquid and vapor states indistinguishable efficiency. As in a conventional boiling water reactor (BWR), liquid water passes through the reactor core and turns directly to steam, driving a turbine-generator. The superheated conditions would eliminate the need in current BWRs for reactor coolant pumps and steam separators and dryers.<sup>6</sup>



<sup>&</sup>lt;sup>5</sup> NuScale Power

<sup>&</sup>lt;sup>6</sup> Gen IV International Forum, "Supercritical-Water-Cooled Reactor (SCWR)," September 24, 2018

Supercritical water is already used to boost plant efficiency in some advanced coal- and gas-fired power plants. Organizations in Canada, China, the European Union, Japan, and Russia are developing SCWRs.

#### NON-WATER COOLED REACTORS

#### HIGH TEMPERATURE GAS REACTORS

High temperature gas reactors (HTGRs), including very high temperature gas reactors (VHTRs), are helium-cooled, graphite-moderated thermal reactors. They operate at higher coolant outlet temperatures than most existing reactors. This higher temperature allows for the provision of heat for industrial processes, such as the cogeneration of electricity and hydrogen, and hightemperature processes in the iron, oil, and chemical industries.<sup>7</sup>

There are two primary design variants: In one, the core is composed of graphite blocks with removable sections that have been embedded with fuel particles; in the other, many billiard ball sized graphite spheres, or "pebbles," with embedded fuel particles are loaded into the core to form a "pebble bed." The spheres are steadily removed from the bottom of the reactor, tested for their level of burnup, and returned to the top of the reactor if they are still viable as fuel and replaced if not. Many HTGRs have been designed as SMRs.



A unique feature of these reactors is their fuel, which is composed of poppy seed-sized fuel particles that have been encased in silicon carbide and other highly heat-resistant coatings. Coupled with the high heat capacity of the graphite moderator, the reactor and its fuel are designed to withstand the maximum core heat attainable during an

<sup>&</sup>lt;sup>7</sup> Gen IV International Forum, "Very-High-Temperature Reactor (VHTR)," September 21, 2018

accident. Therefore, according to HTGR proponents, even the loss of active cooling systems would not result in a core meltdown and radioactive releases to the environment.

HTGRs are among the most technologically mature of the advanced reactor concepts. Since the 1960s a number of experimental and commercial HTGRs have been built in multiple countries, including the United States, United Kingdom, Japan, Germany, and China. A small, two-unit pebble bed HTGR plant is currently under construction in China.

Development of HTGRs was promoted in the United States by the Next Generation Nuclear Plant (NGNP) program, established by the Energy Policy Act of 2005.<sup>8</sup> In 2016, DOE awarded X-energy \$53 million over five years to develop a modular pebble bed HTGR design. Xenergy received a second DOE contract for \$10 million in 2018. X-energy is also working with DOE and others to develop the fuel technology that would be used in an HTGR pebble bed reactor. Other U.S. companies developing HTGRs include HolosGen32 and Hybrid Power Technologies.

#### GAS-COOLED FAST REACTOR

Gas-cooled fast reactors (GFRs) are high-temperature, closed fuel cycle fast reactors using helium as a primary coolant (Figure 3). The primary difference between the HTGR and the GFR is the neutron spectrum: HTGRs operate in the thermal spectrum, while GFRs operate in the fast spectrum. Therefore, the GFRs would not require the massive



graphite moderator of HTGRs to slow the neutrons. The GFR would use a closed U-Pu fuel cycle in which the plutonium and uranium would be recycled from the spent fuel to provide a greatly expanded fuel source. GFRs have operating temperatures similar to those of HTGRs making them suitable for providing process heat for industrial purposes, in addition to producing electric power. One disadvantage of this design is the lower heat

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<sup>&</sup>lt;sup>8</sup> P.L. 109-58

removal capability of the helium gas coolant compared to liquid metal coolants such as sodium and lead in the event of an accident.

In 2015, a consortium of European countries, including the Czech Republic, Hungary, Poland, and Slovakia, launched a project to jointly develop a demonstration GFR based on a French design. The group set a goal of completing the conceptual design for the ALLEGRO reactor by 2025, with construction to begin thereafter. If successful, ALLEGRO would be the first demonstration of a GFR to date. General Atomics is an example of a U.S. company developing a GFR design, the Energy Multiplier Module (EM2).

#### SODIUM-COOLED FAST REACTORS

Sodium-cooled fast reactors (SFRs) are among the most mature of the unconventional nuclear concepts. SFRs use fast reactor technology with liquid sodium as the primary coolant. The use of a liquid metal as the coolant allows the primary coolant circuit to operate under lower, near-atmospheric pressure conditions. In addition, even in an emergency without backup electricity, the high heat-transfer properties of liquid sodium (100 times greater than water) would allow for passive cooling through natural circulation.<sup>9</sup>

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



<sup>&</sup>lt;sup>9</sup> U.S. Department of Energy, Office of Nuclear Energy, "Sodium-cooled Fast Reactor (SFR) Technology and Safety Overview," February 18, 2015

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

Most SFR designs would use a closed fuel cycle in which plutonium and uranium would be reused from the spent fuel to provide an indefinite fuel source when configured as a breeder; the process would be similar to that used for the GFR (above). Other designs would rely on future advances in fuel technology to extend the fuel cycle to the point where refueling would only need to occur once in a number of decades. SFRs can achieve high burnup of actinides in spent fuel, potentially reducing the long-term radioactivity of high-level nuclear waste.

The first SFR was built in the United States in 1951. The United States maintained SFRs as a high priority focus of its nuclear R&D program (primarily due to the technology's plutonium breeding capabilities) up until the cancellation of the Clinch River Breeder Reactor demonstration plant in 1983 amid public opposition, rising construction costs, and increased concern over weapons proliferation.

Examples of U.S. companies developing SFRs include Advanced Reactor Concepts, Columbia Basin Consulting Group, General Electric-Hitachi, Oklo, and TerraPower.



#### LEAD-COOLED FAST REACTORS

Lead-cooled fast reactors (LFRs) are designed to use a closed fuel cycle with either molten lead or leadbismuth eutectic (LBE) alloy as a primary reactor coolant (see Figure 5). The use of lead as a coolant is seen to confer several advantages. As with the SFR, the use of a liquid metal coolant allows for low-pressure operation and passive cooling in an accident. In contrast to liquid sodium, however, molten lead is relatively inert, adding additional safety and economic advantages. Lead

also has a high rate of retention of radioactive fission products, which offers benefits in an accident that could release radioactive materials. In such an accident, the chemical properties of the lead could prevent many of the harmful radionuclides from escaping into the atmosphere.

At high temperatures, lead tends to corrode structural steel. Lead is also highly opaque, presenting visibility and monitoring challenges within the core, and very heavy, due to its high density. The high melting point of lead also presents challenges in terms of keeping the lead in liquid form so that it can continue to circulate under lowertemperature scenarios.

Russia is the world leader in LFR R&D, with experience building and operating seven LFRs for use in submarines. Russia has announced near-term development of two pure LFR facilities and a third facility that would be capable of using lead coolant for test purposes, in addition to other coolants.43 Members of the European Union have also announced a collaboration to develop an LFR through the Advanced Lead Fast Reactor European Demonstrator (Alfred). Other countries exploring LFR technologies include China, Japan, Korea, and Sweden. U.S. companies pursuing LFRs include Hydromine and Westinghouse.<sup>10</sup>

#### MOLTEN SALT REACTORS

Any reactor that uses molten salts as a coolant or fuel may be considered a molten salt reactor (MSR). Salt-cooled MSRs (also known as fluoride-cooled high temperature reactors or FHRs) employ molten salts to cool the core, which is composed of solid fuel blocks configured much like an HTGR. Salt-fueled MSRs, by contrast, are unique in that the fuel is not solid, but rather is dissolved in the molten salt coolant.<sup>11</sup>

Unique to MSR salt-fueled designs is a safety feature called a "freeze plug" below the reactor core, consisting of a salt plug that is cooled to a solid state. In the event of an incident that causes heat to rise in the core, the plug will melt, allowing the molten salt fuel to drain by gravity into a basin that is designed to prevent the fuel from undergoing further fission reactions and overheating. It is unknown whether spent MSR fuel could be safely stored in the long term without



<sup>&</sup>lt;sup>10</sup> Generation IV International Forum, "Lead-Cooled Fast Reactor (LFR)," 2019

<sup>&</sup>lt;sup>11</sup> Oak Ridge National Laboratory, "Fluoride-Salt-Cooled High-Temperature Reactors," January 30, 2018

undergoing additional treatment after removal from the reactor.

MSR technology has been under development for decades. Two thermal-spectrum experimental reactors were built in the United States at Oak Ridge National Laboratory in the 1950s and 1960s. The first molten salt fuel irradiation tests since the completion of those early experiments were conducted in 2017 in the Netherlands, where research on waste treatment is also being pursued.

China is currently developing two prototype MSR microreactors with expected start dates in the 2020s. Terrestrial Energy, a Canadian company with a U.S. subsidiary, is in the second stage of design review with the Canadian Nuclear Safety Commission for its integral molten salt reactor (IMSR). The IMSR is the first advanced reactor design to complete phase one of the Canadian pre-licensing process. Terrestrial Energy has announced a goal of commercialization by the late 2020s. Examples of other U.S. companies developing MSRs include Alpha Tech Research Corp., Elysium Industries, Flibe Energy, Kairos Power, TerraPower, Terrestrial Energy USA, ThorCon Power, Thoreact, and Yellowstone Energy.

#### FUSION REACTORS

Fusion reactors would fuse light atomic nuclei—as opposed to the fissioning or splitting of nuclei—to produce power.

Fusion power would require light atoms, generally isotopes of hydrogen, to be heated to 100 million degrees to form a plasma, a state of matter in which electrons are stripped away from the atomic nucleus. Holding the plasma together while it is heated sufficiently to create a fusion reaction is a major technical challenge. Fusion reactions are routinely produced at the laboratory scale, but none of these reactions have yet achieved "burning plasma," in which energy produced by fusion at least equals the energy needed to heat the plasma. A fusion power reactor would need to achieve "ignition," in which the fusion energy itself would keep the plasma heated.

Several U.S. companies are pursuing various approaches toward achieving burning plasma with the aim of commercializing fusion power. According to the Fusion Industry Association, "fusion produces no harmful emissions or waste fuel. A fusion power plant is physically incapable of having a meltdown. There is no fissile radioactive waste left over."<sup>12</sup> However, some reactor materials would be made radioactive by neutron exposure during a fusion reaction, and tritium, a primary anticipated fuel source, is radioactive, although far less so than fission products.

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

<sup>&</sup>lt;sup>12</sup> Fusion Industry Association, "About Fusion," April 12, 2019

## ADVANCED REACTOR DECISION POINTS

Advanced reactors present an opportunity for viable base load power with zero carbon emissions. The technology does present several decision points for policy makers conducting a study of the sector. The following are key issues to consider regarding advanced nuclear technology.

#### COSTS

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

#### CAPITAL COSTS

Conventional nuclear reactors are more expensive to build than most other electric power plants. Nuclear plants must submit to rigorous regulation and quality standards because of the risk posed by a release of radioactive materials. As a result, they require highly specialized construction materials (e.g., nuclear-grade steel), engineering knowledge, and construction expertise, all of which add to a plant's costs.

Modularity in advanced reactors is intended to increase factory production of nuclear components. Modularized construction has been shown to improve the pace of construction and reduce costs in other industries, as well as in some recent nuclear construction projects in Asia. NuScale, a U.S.-based SMR vendor, has estimated cost savings of approximately 10 percent due to modular construction of structures in its proposed SMR plant.

#### **OPERATIONAL COST**

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

#### COST ESTIMATES FOR ADVANCED REACTORS

It is difficult to accurately estimate the costs of advanced reactors. Many advanced reactor concepts remain in the early stages of design and development, and vendor companies generally do not include detailed costs in their publicly available content. Academic analyses of the costs of non-traditional reactors have produced a range of results.

#### SIZE

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

The small size and modular nature of SMRs gives them the potential to expand the types of sites and applications for which nuclear energy may be considered suitable (see section on Versatility). SMR designs with multiple reactor modules may allow for size customization based on the needs of the customer or characteristics of the host site.

#### WASTE MANAGEMENT

The radioactivity of nuclear waste presents waste management and facility contamination challenges that are unique to nuclear energy. Radioactivity builds up in a nuclear reactor in the accumulation of radioactive "fission products" that result from the splitting of fissile nuclei, through the accumulation of radioactive "actinides" that form when heavy atoms in the reactor core absorb a neutron but do not undergo fission, and through the generation of "activation products" in the coolant, moderator, or reactor components that occur when these materials are made radioactive by absorbing neutrons. The vast majority of the initial radioactivity in nuclear waste comes from the fission products. Due to the long half-lives of some of these radioactive materials (several hundred thousand years and longer), nuclear waste poses long-term health hazards.

In 2018, the U.S. inventory of spent nuclear fuel exceeded 80,000 metric tons of uranium (MTU).<sup>13</sup> This is projected to rise at a rate of approximately 1,800 MTU per year, resulting in an estimated 138,000 MTU by 2050. Because no long-term repository or consolidated storage facility for high-level nuclear waste has been licensed by NRC, newly discharged spent nuclear waste is currently stored onsite at nuclear plant locations.

Unconventional reactors may offer some waste management advantages over existing commercial reactors. Fast reactors, and some other unconventional reactors, would be more effective at destroying actinides compared with commercial reactors.

Actinides are not the only long-lived nuclear wastes, however; some fission products remain radioactive hazards for hundreds of thousands of years and longer. Some advanced reactors would use new or non-conventional fuel forms, such as metallic fuels or dissolved molten fuels. Some of these fuels pose additional waste management challenges as a result of their tendency to corrode storage containers or otherwise react with the environment in ways that complicate their safe storage and disposal.

#### ENVIRONMENTAL EFFECTS

Environmental impacts for any electric power source must be evaluated based on air emissions, water discharges, and waste management challenges, considering the full life cycle of the technology.

<sup>&</sup>lt;sup>13</sup> Oak Ridge National Laboratory, "CURIE," December 14, 2018