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Chapter 14

Small Modular Reactors

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ABSTRACT

Small Modular Reactors (SMRs) have been a very promising development in nuclear power over the last two decades. SMRs are defined as nuclear reactors with a power output of less than 300 MWe. This is in comparison to gigawatt-size reactors, which can have electrical output of 1000–1500 MWe or more. This chapter will consist of two major sections. The first will be a detailed summary of the small modular reactor designs being proposed around the world. This section will focus on those that are the furthest along in their development, but will also include some information about the wide variety of proposed designs that require significant research and development. The second part will be a discussion of the remaining challenges to the adoption of SMRs as a major energy source. SMRs are not a new concept, but they do represent a new vision for an older concept. These reactors have the potential to become a major source of energy in the near future. The development of small, modular designs can help promote the adoption of nuclear energy by reducing upfront costs, reducing the financial risk associated with nuclear power, and the barriers to entry. However, the adoption of SMRs is not without challenges. Regulatory and licensing changes to address the unique benefits and concerns associated with SMRs will continue to be a challenge as regulators adapt to the unique features emerging from the design process. The development of new instrumentation and control systems is an ongoing issue. And economics is possibly the most significant challenge, with high construction costs, cheap natural gas, and government subsidies, combining to result in significant financial risk associated with adopting nuclear generation.

Keywords: Nuclear engineering; small modular reactor; energy systems; energy engineering; design challenges; power engineering; safety engineering and energy sustainability.

1. Introduction

Small Modular Reactors (SMRs) have been a very promising development in nuclear power over the last two decades. SMRs are defined as nuclear reactors with a power output of less than 300 MWe. This is in comparison to gigawatt-size reactors, which can have electrical outputs of 1000 to 1500 MWe or more.

Despite the recent interest in SMRs, the concept is not novel. The first commercial reactors were, in many ways, SMRs. Shippingport Atomic Power Station, the first commercial nuclear power plant, began operation in 1958 with an output power of 60 Mwe [1]. Most of the initial plant designs proposed in the 1950s had operating power between 12 and 100 MWe. Several other nuclear reactors constructed soon after had power output of 100 to 300 MWe.

In the 1970s, concern over the economics of nuclear energy led the nuclear industry to develop larger reactors. Today the largest online reactor, the Taishan reactor in China, has an electrical output of 1,750

MWe. The basic idea was that a larger reactor could take advantage of the economics of scale. Essentially, a large nuclear reactor could produce the same amount of energy using fewer components, and therefore do so more cheaply.

Unfortunately, such gigawatt-size reactors have run into a number of challenges resulting in skyrocketing expenses. Like all megaprojects, massive nuclear power projects suffer from construction delays and resulting cost overruns such as those encountered at Vogtle during the construction of two Westinghouse AP1000 units. This is compounded by the fact that each large reactor was, in many ways, a custom design. That means each design was essentially the first of its kind. Because of this, it has been difficult to build up the design and construction expertise necessary to shorten construction times that can be achieved when multiple identical units are constructed. This type of improvement can be seen in the experience of South Korea, which achieved cost reductions of as much as 20% in "n^{th}-of-a-kind designs" [2]. Such large plants also have quite stringent site requirements, limiting the locations where they can be constructed. Perhaps one of the most important features of gigawatt-sized reactors is the decay heat produced by the reactor after shutdown. This is extremely important during accident scenarios, where the decay heat must be removed. In gigawatt-sized reactors, this requires large, complex, and expensive cooling and backup systems to be installed. This has led to expensive redesigns and refits for large nuclear reactors [3]. Finally, supply chain issues have become a major problem. Only a few facilities around the world are capable of forging pressure vessels or manufacturing components for gigawatt-sized reactors. Long waits for replacement components contributed to the closing of the San Onofre Nuclear Power Station in 2013 [4].

It is because of these challenges that SMRs are experiencing a resurgence. Smaller construction projects are less likely to face the same kind of delays and cost overruns. The construction of many smaller reactors can benefit from n^{th}-of-a-kind engineering, which leads to reduced costs as more units are built [5]. They can also benefit from significantly reduced cooling requirements, meaning fewer cooling systems and reduced costs [2], and more flexibility in siting can also help reduce costs. The supply chain for smaller components such as pressure vessels, turbines, and pumps is also more robust [6]. All of these steps can reduce the financial risk of nuclear power projects, and potentially promote the deployment of nuclear power worldwide.

The rest of this chapter will consist of two major sections. The first will be a detailed summary of the small modular reactor designs being proposed around the world. This section will focus on those that are the farthest along in their development, but will also include some information about the wide variety of proposed designs that require significant research and development. The second part will be a discussion of the remaining challenges to the adoption of SMRs as a major energy source. These sections will be followed by brief conclusions.

2. Small Modular Reactor Designs

The International Atomic Energy Agency (IAEA) prepared a web database that provides comprehensive information on advanced SMR designs, applications, and development progress with all of its member countries. SMR technical development information was published in a series of books distributed to the public, member states, and stakeholders, and most of them are available online. In the latest edition, the 2020 edition, 72 SMR designs were presented. These designs vary in their target applications, design features, safety systems, expected operational performances, instrumentation and

control systems, electrical systems, and plant layout. An overview of the development of SMR technology worldwide is presented in Figure 1 [7]. Fuel cycle and waste management issues are crucial for SMRs and especially for newcomer countries, so these issues have been incorporated into the latest SMR edition by the IAEA.

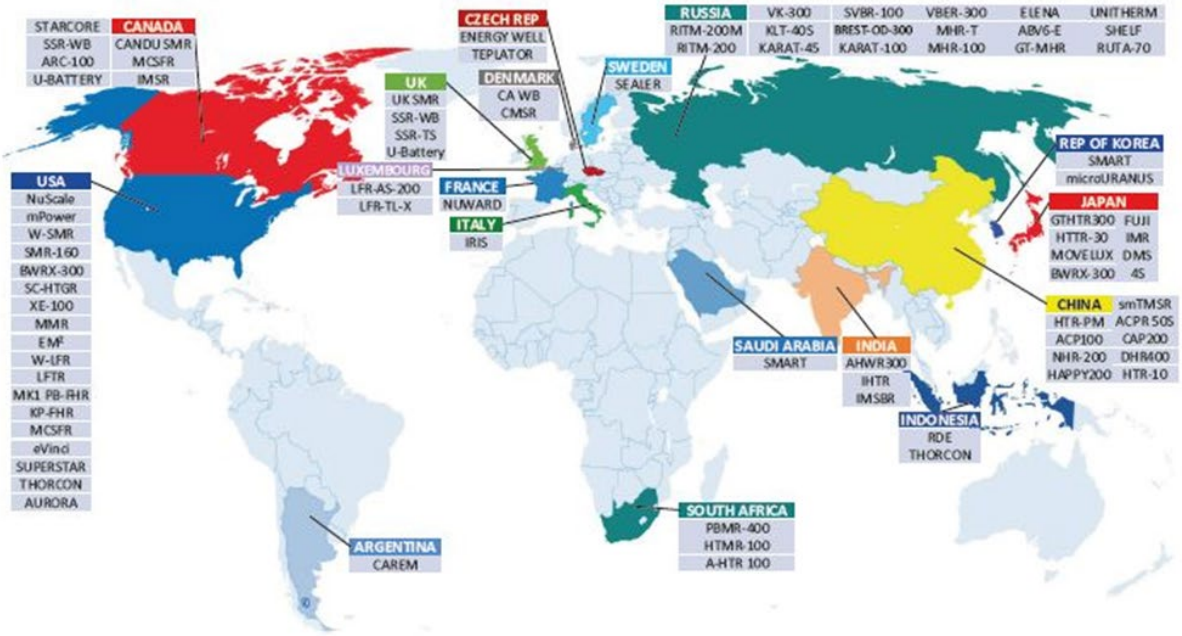

Figure 1: Global map of SMR technology development [7]

The expected timeline and deployment progress of various SMRs are presented in Figure 2 [7]. Most SMRs are in the conceptual design stage, and some were approved or are in the process of approval from the respective regulatory authorities. Only a few SMRs were in the final construction and initial operational stages. The Russian Federation-developed floating power SMR, Akademik Lomonosov KLT4S, started commercial operation in May 2020 with two units. In addition, a high-temperature gas-cooled (HTR) SMR developed by China started commercial operation recently. One integral pressurized water reactor (PWR)-type SMR, CAREM, was developed by Argentina and is scheduled to start operation by 2023.

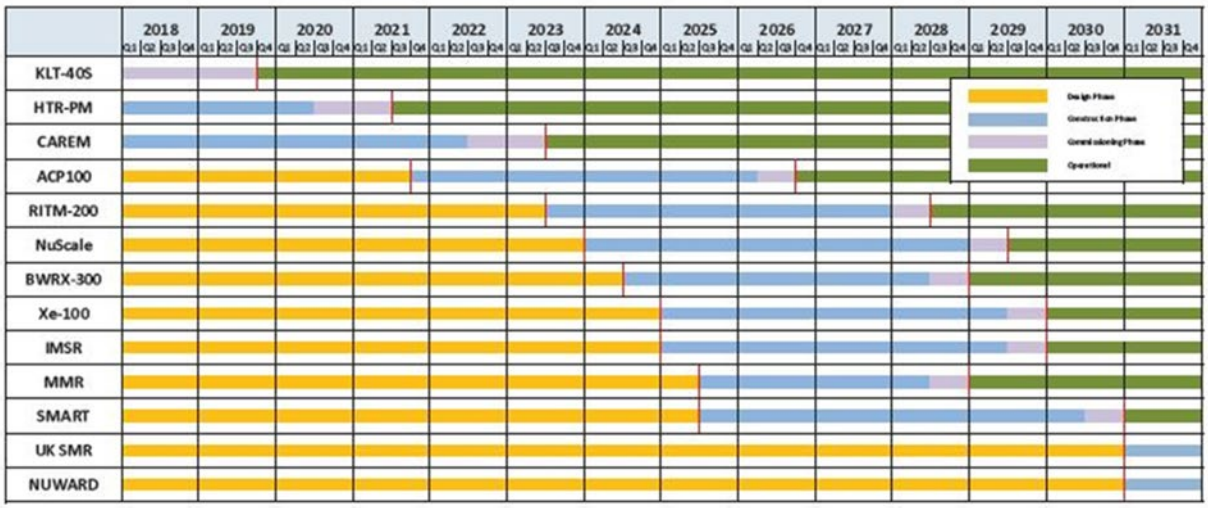

Figure 2: Timeline of deployment of SMR designs to 2030 [7]

Reactor technology development takes several years of design, demonstration, and deployment. Therefore, it is essential to understand the SMR technology roadmap. A general flowchart of the SMR technology roadmap is presented in Figure 3 [7], which follows several stages. The first stage is selecting the SMR technology that consists of near- or long-term technology development goals. Near-term technology development can be accomplished by adopting or buying existing technology. However, long-term technology development is required for innovative design ideas, which require detailed design, testing, analysis, and licensing. The IAEA's SMR technology booklet provides information on the roadmaps for buying, developing, and inventing cases in sections 5.1, 5.2, and 6. The current SMR deploying monopolies are expected to last until the end of 2030. By 2025 we will most likely see only three SMRs in their initial years of operation in Argentina, China, and the Russian Federation. However, several other designs may start construction by 2025 with completion prior to 2030. By 2030, certification of other designs will likely follow.

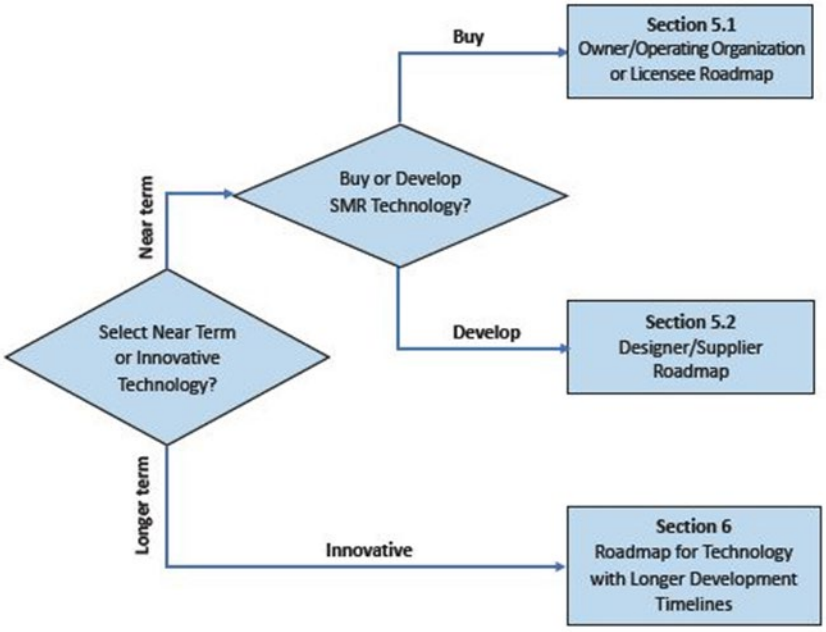

Figure 3: SMR technology roadmaps flowchart, IAEA [7]

There are several phases in the reactor technology assessment (RTA) with specific milestones, as presented in Figure 4 [8]. Phase Zero includes making nuclear energy the national energy strategy, and planning for the first nuclear power plant. This phase is important for countries that do not currently have nuclear infrastructure, but are interested in deploying nuclear power plants (NPP). Phase One consists of the decision to launch a nuclear power program followed by Milestone One, the project feasibility study. If the NPP project is feasible, Phase Two is to complete the preparatory project work for NPP construction. Phase Two is followed by Milestone Two, inviting bids for the NPP. Phase Three is construction of the NPP and completing the milestone of plant commission. The final stage and final milestone are to operate the plant successfully.

SMRs must maintain economic competitiveness. The economic competitiveness is often estimated by the levelized cost of energy (LCOE) or the levelized cost of electricity. LCOE measures the average net present cost of electricity generation for a generating plant over its lifetime, including the capital, operation, decommissioning, and expected profit margin. LCOE considers the plant capacity and capacity factor. Nuclear power plants consider decommissioning cost in the LCOE, approximately 6% of the total plant cost. Other conventional non-nuclear energy sources do not consider the decommissioning cost [7]. In addition to LCOE, the Overnight Construction Cost (OCC) is often used to measure the financial risk associated with a project. OCC considers the expenses required to begin operation before any power is produced by the facility.

The IAEA report identified six broad categories or types of SMR designs. These are land-based water-cooled SMRs, marine-based water-cooled SMRs, high-temperature gas-cooled SMRs, fast neutron spectrum SMRs, molten-salt SMRs, and micro-sized SMRs. Depending on the reactor design, certification will require scaled experimental data to validate the models and correlations used for reactor licensing [9]. Each reactor type has opportunities as well as challenges that mean high risk and potentially high

profits for the investors in novel designs [10]. In most cases, water-cooled SMRs are integral PWRs which are expected to demonstrate similar technology to the existing fleet of reactors. A BWR-type SMR will be easier to construct, with a higher thermal efficiency, but it would be challenging to obtain system validation and licensing [11]. Typically, marine-based water-cooled SMRs will be the PWR type to avoid operation challenges during submersion due to fluctuations in void fraction and reactivity. Gas-cooled SMRs are excellent candidates for industrial process heating applications rather than only electricity generation. Fast neutron spectrum SMRs are dominated by liquid-metal-cooled reactors based on compactness and higher coolant heat transfer [7]. They will be challenging to deploy because of technology readiness issues and industry availability. Molten-salt SMRs may be a good candidate for an innovative design, but the reactor materials and the fuel and coolant behavior are likely to present challenges.

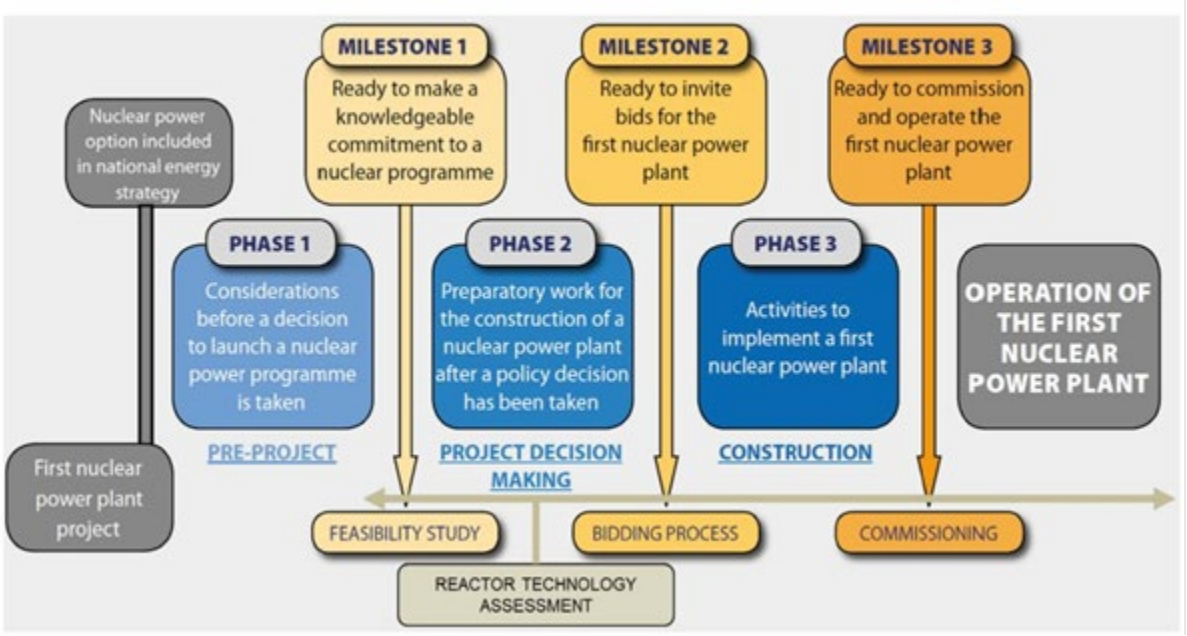

Figure 4: Reactor Technology Assessment and deployments phases and milestones [8]

2.1. Land-based water-cooled SMRs

The most common type reactors under design are light-water reactors (LWR) and heavy water reactors (HWR). Water-cooled SMRs are further grouped based on design features and configurations. Reactors proposed so far include integral-PWRs, compact-PWRs, loop-PWRs, BWRs, CANDU-SMR, and pool-SMR designs. As the reactor technology for water-cooled reactors is well-developed in the present reactor fleet, this technology is proven and reliable. However, numerous design changes mean SMRs require design verification and validation for licensing [9]. There are 25 such reactors in development and demonstration phases, as presented in Table 1 [12]. Only three reactors have completed design certification at this time. This section focuses on reactors under construction, licensed, or in advanced design/pre-licensing stages.

Table 1: Design and Status of water-cooled land-based SMR [12]

Design	Output (MWe)	Type	Designers	Country	Status
CAREM	30	PWR	CNEA	Argentina	Construction
ACP100	100	PWR	CNNC	China	Detailed Design
CANDU SMR	300	PHWR	Candu Energy Inc (SNCLavalin Group)	Canada	Con. Design
CAP200	200	PWR	SNERDI/SPIC	China	Con. Design
DHR400	400 MW(t)	LWR (pool)	CNNC	China	Basic Design
HAPPY200	200 MW(t)	PWR	SPIC	China	Detailed Design
TEPLATOR™	50 MW(t)	HWR	UWB Pilsen & CIIRC CTU	Czech Republic	Con. Design
NUWARD	2 × 170	PWR	EDF, CEA, TA, Naval Group	France	Con. Design
IRIS	335	PWR	IRIS Consortium	Multiple	Basic Design
DMS	300	BWR	Hitachi-GE Nuclear Energy	Japan	Basic Design
IMR	350	PWR	MHI	Japan	Con. Design
SMART	107	PWR	KAERI and K.A.CARE	ROK, KSA	Certified Design
RITM-200	2 × 53	PWR	JSC “Afrikantov OKBM”	RF	Under Development
UNITHERM	6.6	PWR	NIKIET	RF	Con. Design
VK-300	250	BWR	NIKIET	RF	Detailed Design
KARAT-45	45 - 50	BWR	NIKIET	RF	Con. Design
KARAT-100	100	BWR	NIKIET	RF	Con. Design
RUTA-70	70 MW(t)	PWR	NIKIET	RF	Con. Design
ELENA	68 kW(e)	PWR	National Research Centre “Kurchatov Institute”	RF	Con. Design
UK SMR	443	PWR	Rolls-Royce and Partners	UK	Con. Design
NuScale	12 × 60	PWR	NuScale Power Inc.	USA	License approved
BWRX-300	270 - 290	BWR	GE-Hitachi	USA	Pre-licensing
SMR-160	160	PWR	Holtec International	USA	Preliminary Design
W-SMR	225	PWR	Westinghouse Electric Company, LLC	USA	Con. Design
mPower	2 × 195	PWR	BWX Technologies, Inc	USA	Con. Design

Note: RF—Russian Federation, ROK—Republic of Korea, KSA—Kingdom of Saudi Arabia, Con. design—conceptual design

CAREM (Central Argentina de Elementos Modulares) was developed by Argentina as a simplified 100 MWt iPWR SMR [13, 14]. It is now under construction, and the first concrete pouring was in 2014. The project target is to manufacture 70% of components locally and complete construction by 2021; however, construction is delayed [12]. The reactor pressure vessel is made from forged steel with stainless steel liner and is 11-meters high and 3.5-meters in diameter. The pressure vessel contains the primary coolant system with an integrated pressurizer, core cooling, and reactor safety system based on passive mechanisms (natural circulation with no core recirculation pumps), and in-vessel control rod drive mechanism (CDRM) [15]. It uses enriched PWR fuel (1.9%, 2.6%, and 3.1% U-235) with 61 fuel assemblies in a hexagonal arrangement, and it is refueled annually with 50% core replacement. Heat removal from the fuel relies entirely on convection. The core reactivity control is designed with burnable poison (Gd_2O_3) in specific fuel rods and movable absorbing elements (Ag-In-Cd alloy) as control rods without any burnable poison in the coolant. Twelve mini-helical vertical steam generators with counterflow arrangement are used to produce superheated steam at 4.7 MPa. Two separate and independent reactor protection systems (RPS) are used: passive residual heat removal systems (PRHRS) and containment safety systems. The first control rod shutdown system is backed up by a passive injection (borated water) system. The plant system is supported by 36 hours of a passive cooling grace period for loss of heat sink or Station Blackout (SBO). The containment system with a pressure suppression pool serves as the ultimate heat sink. The containment system, which consists of a stainless-steel inner surface and 1.2-meter-thick reinforced concrete, can withstand the pressure of 0.5 MPa.

NuScale is an iPWR-type reactor developed by NuScale LLC, USA. It is a scalable reactor with a unit capacity of 60 MWe and can be integrated in groups of up to 12 units [12, 16, 17]. This multi-module reactor operates independently from a single control room and adopts proven light-water reactor technology. The reactor system relies on natural circulation in the primary loop with pressure at primary and secondary sides of 13.8 MPa and 4.3 MPa, respectively [12]. The reactor passive safety system consists of a decay heat removal system (DHRS), an emergency core-cooling system (ECCS), and a containment system. The reactor design is thought to provide unlimited grace period passive cooling after a design basis accident without operator action [16]. This reactor adopted standard fuel of UO_2 with enrichment < 4.95%, 17×17 square fuel arrays per assembly, and 37 assemblies in the core. The core inlet and outlet temperatures are 265°C and 321°C, respectively and core discharge burnup is less than 30 GWd/ton with a 2-year refueling cycle. Sixteen control rods made of B_4C and soluble boron poison are used for reactivity control, and the reactor is equipped with passive retardant safety systems. The reactor pressure vessel is 17.7-meters in height and 2.7-meters in diameter, whereas the steel-cylinder containment is 23.1-meters in height and 4.5-meters in diameter. The reactor containment houses the RPV, CRDM, and the associate piping and components. The plant life is estimated at 60 years.

SMART is iPWR-type SMR with an electric power output of 107 MWe for multi-purpose applications developed by KAERI, Republic of Korea [12, 18, 19]. The reactor system relies on forced circulation in the primary loop with pressure at primary and secondary sides of 15 MPa and 5.8 MPa, respectively [18]. The reactor passive safety system that consists of an automatic depressurization system (ADS), decay heat removal system (DHRS), emergency core cooling system (ECCS), and containment system and is considered top provide unlimited grace period passive cooling after a design basis accident without operator action [12]. This reactor adopted standard fuel of UO_2 with enrichment < 5%, 17×17 square fuel arrays per assembly, and 57 assemblies in the core. The core inlet and outlet temperate are 296°C and

322°C, core discharge burnup is less than 54 GWd/ton, refueling cycle is 30 months, and spent fuel capacity is 30 years. Control rods, burnable poison rods, and soluble boron poison are used for reactivity control, and the reactor is equipped with passive retardant safety systems [19]. The reactor pressure vessel is 18.5 meters in height and 6.5 meters in diameter. The reactor pressure vessel houses eight once-through steam generators, four reactor coolant pumps, 25 CRDM, and other core internals. The reactor containment houses the RPV and the associate piping, systems, and components of the steam supply and plant system.

VK-300 is a simplified passive BWR-type SMR with unit capacity of 250 MWe developed by NIKIET, Russian Federation [12, 20]. It adopted the major component and systems—like the reactor pressure vessel, fuel element, and containment—from the WWER-1000 and the operation experience of VK-50, which was operated successfully for 50 years [21, 22]. The reactor system relies on natural circulation in the steam supply system consisting of reactor coolant loop with pressure of 6.9 MPa [20]. The reactor passive safety system consists of a decay heat removal system (RHRS), emergency core cooling system (ECCS), and containment system and is considered to provide unlimited grace period passive cooling after a design basis accident without operator action [23]. This reactor adopted standard fuel of UO_2 with enrichment of 4%, 107 fuel rods in hexahedron arrays in the fuel assembly, and 313 assemblies in the core. The core inlet and outlet temperate are 190°C and 285°C, and the core discharge burnup is less than 41.4 GWd/ton with a 6-year refueling cycle. Control rod insertion is used for reactivity control with backup boric acid solution injection in case of control rod insertion failure [12]. The reactor is equipped with passive retardant safety systems. It uses in-vessel cyclone separators for the vertical steam generators of the WWER-1000. The reactor pressure vessel is 13.1 meters in height and 4.535 meters in diameter. This reactor has innovative metal-lined primary containment (PC) of reinforced concrete that consider containment leak rate (i.e., 50% of the volume per day) design pressure of 0.15 MPa and houses the RPV, CRDM, passive heat removal by steam condensation system, and the associate piping and components [12]. The plant life is estimated at 60 years. It requires spent fuel cooling at the reactor site for 3 years, and its design adopted a once-through fuel cycle.

BWRX-300 is a simplified passive BWR-type SMR with unit capacity of 270 to 290 MWe developed in collaboration between GE-Hitachi Nuclear Energy of USA and Japan [12, 24, 25]. It adopted the major design philosophy of the economical simplified boiling water reactor (ESBWR) and the system and components such as the reactor pressure vessel, fuel element, and containment are all based on that design. It is designed for load following from 50% to 100% of full power, with a ramp rate of 0.5% per minute [12]. The reactor system relies on natural circulation in the coolant loop. The passive safety system consists of a reactor coolant pressure boundary (RCPB). One distinctive feature is that RPV isolation valves and an isolation condenser system (ICS) enable dry containment and the elimination of safety relief valves [25]. The ICS is used as a decay heat removal system after a reactor isolation event. The other engineered safety system is the passive containment-cooling system (PCCS), which removes the decay heat and maintains reactor containment pressure for a reactor design basis accident. This reactor adopted standard BWR fuel of UO_2 with enrichment of 4% and 240 fuel assemblies in the core. There are 78 full-length fuel rods, 14 part-length fuel rods, and two large central water rods in 10×10 rod arrays in each fuel assembly [12]. The core inlet and outlet temperates are 270°C and 287°C, and the core discharge burnup is less than 49.5 GWd/ton with a 1 to 2-year refueling cycle. In each refueling, 15% to 25% of the bundles in the core are replaced with fresh fuel. Reactivity is controlled by control rods and solid burnable absorbers (B4C,

Hf, and Gd2O3) with fine motion control rod drives (FMCRDs) and control blades. The FMCRDs consist of motor-driven fine control for reactivity control during normal operation and rapid hydraulic insertion during a scram. The reactor pressure vessel is 26 meters in height and 4 meters in diameter. It houses the RPV, FMCRDs, piping, and isolation valves. The plant life is estimated at 60 years with an adopted open fuel cycle.

2.2. Marine-based water-cooled SMRs

Marine-based SMRs can be deployed either as barge-mounted floating power units or immersible underwater power units [12]. This unique application provides many flexible deployment options. Six marine-based water-cooled SMRs are under development. Some of them have been deployed as nuclear icebreaker ships, as presented in Table 2 [12]. The first SMR connected to the grid is from this category, the KLT-40S for the Akademik Lomonosov floating nuclear power plant in Pevek, Russian Federation, that started commercial operation in May 2020.

Table 2: Design and Status of water-cooled marine-based SMR [12]

Design	Output (MWe)	Type	Designers	Country	Status
KLT-40S	2 × 35	PWR in Floating NPP	JSC Afrikantov OKBM	Russian Federation	In Operation
RITM-200M	2 × 50	PWR in FNPP	JSC Afrikantov OKBM	Russian Federation	Under Development
ACPR50S	50	PWR in FNPP	CGNPC	China	Conceptual Design
ABV-6E	9-Jun	PWR in FNPP	JSC Afrikantov OKBM	Russian Federation	Final design
VBER-300	325	PWR in FNPP	JSC Afrikantov OKBM	Russian Federation	Licensing Stage
SHELF	6.6	PWR in Immersed NPP	NIKIET	Russian Federation	Detailed Design

Note: FNPP—Floating NPP, JSC- Joint Stock Company, OKBM—OKB Mechanical Engineering

KLT-40S is a floating marine PWR SMR in commercial operation from May 2020 in Pevek, Russian Federation. It has a unit capacity of 35 MWe from 150 MW thermal output using forced circulation in the primary loop [12, 26]. The reactor design pressure is 12.7 MP with core inlet and outlet temperatures 280°C and 316°C. It uses UO_2 fuel pellets with enrichment of 18.6% in silumin matrix, maintaining 121 assemblies in the core [12]. The core discharge burnup is 45.4 GWd/ton with a refueling cycle of 30 to 36 months with no onsite refueling and spent fuel take-back option. Six control rod systems—similar to a conventional PWR—are used for reactivity control and emergency SCRAM [26]. The reactor pressure vessel is 4.8 meters in height and 2.0 meters in diameter. The pressurizer is not an integral part, and the once-through coiled steam generator uses a coaxial hydraulic path for efficient heat transfer. The containment is a steel shell to sustain mild pressurization. The KLT-40S is equipped with active and partially passive retardant safety systems and has a design life of 40 years [12]. The safety system consists of decay heat removal and emergency systems with two cooling trains ensuring cooling to 24 hours.

SHELF is an iPWR SMR designed for a unit capacity of 6.6 MWe by NIKIET, Russian Federation, that is applicable for floating and submerged nuclear power applications for remote and hard-to-reach locations [12, 27]. It uses forced and natural circulation for the primary coolant loop with core inlet and outlet temperatures 270°C and 316°C. It uses UO_2 fuel with enrichment of 19.7% in hexagonal rod array, with 163 fuel assemblies in the core. The core discharge burnup is up to 160 GWd/ton with a refueling cycle of 6 years and a plant capacity factor of 80%. Ammonia additive is used in the coolant to generate hydrogen and prevent corrosive oxidative radiolysis product generation. The operating pressures in the primary and secondary loops are 14.7 MPa and 4.7 MPa [12]. Control rods made of boron carbide and titanium diboride are used for control rod and emergency control with a backup boron carbide solution for emergency purposes. The reactor pressure vessel is 3 meters in height and 1.3 meters in diameter including integral pressurizer, steam generator, reactor core, CRDM, and associated piping. The reactor system is housed in a containment named a power capsule that is 8 meters in diameter and 14 meters long, with a controlled ambient temperature of 50°C. The reactor is equipped with active and partially passive retardant safety systems and has a design life of 60 years. The reactor safety system consists of a decay heat removal system, an ECCS, and containment safety systems.

2.3. High Temperature Gas Cooled SMRs

Several modular-type high-temperature gas reactors (HTGRs) are under development or under construction. HTGRs provide high-temperature heat that can be utilized for more efficient electricity generation, a variety of industrial applications, as well as for cogeneration. High temperature gas-cooled reactor-pebble-bed module (HTR-PM) is expected to start operation in 2021 in China. Two HTGR test reactors have been in operation for technology testing purposes in Japan and China for over 20 years, as presented in Table 3 [12]. Another commercial design, GTHTR 300, is in the pre-licensing phase in Japan.

GTHTR-300 is an HTGR-type SMR designed for 100–300 MWe unit capacity and a design life of 60 years by Japan Atomic Energy Agency (JAEA), Japan [12, 28]. It uses helium coolant and a graphite moderator with forced circulation in the primary loop for the operating pressure of 7 MPa and maintained core inlet and outlet temperatures 587–633°C and 850–950°C. It uses UO_2 TRISO ceramic-coated fuel with enrichment of 14%, and 90 fuel assemblies in the core [12]. The core discharge burnup is up to 120 GWd/ton, the refueling cycle is 4 years, and a once-through fuel cycle is used. Thirty pairs of control rods control reactivity with the rod insertion technique. Reactor safety systems consist of active and passive systems, such as a reactor cavity cooling systems and air-cooled, passive DHRS [28]. The reactor pressure vessel is 23 meters in height and 8 meters in diameter and it encloses the reactor core, CRDM, and associated piping.

HTTR-30 is an operational HTGR type SMR designed for 30 MWe unit capacity and a design life of 20 years by JAEA, Japan [12, 29]. It has similarities with the GTHTR-300 in terms of coolant, moderator, primary circulation, fuel type, and reactivity control technique. However, it is designed for 4 MPa primary pressure, core inlet and outlet temperatures of 395°C and 850°C (max 950°C), fuel enrichment of 6% (average), 150 fuel blocks in the core, and active reactor safety features [12]. The core discharge burnup is 22 GWd/ton, with a refueling cycle of 660 EFPD [29]. The system is currently operational, having passed the safety demonstration test.

Table 3: Design and Status of high temperature gas-cooled SMR [12]

Design	Output (MWe)	Type	Designers	Country	Status
HTR-PM	210	HTGR	INET, Tsinghua University	China	Under Construction
StarCore	14/20/60	HTGR	StarCore Nuclear	Canada/UK/US	Pre-Conceptual Design
GTHTR300	100 - 300	HTGR	JAEA	Japan	Pre-licensing
GT-MHR	288	HTGR	JSC Afrikantov OKBM	RF	Preliminary Design
MHR-T	4 × 205.5	HTGR	JSC Afrikantov OKBM	RF	Conceptual Design
MHR-100	25 – 87	HTGR	JSC Afrikantov OKBM	RF	Conceptual Design
PBMR-400	165	HTGR	PBMR SOC Ltd	South Africa	Preliminary Design
A-HTR-100	50	HTGR	Eskom Holdings SOC Ltd.	South Africa	Conceptual Design
HTMR-100	35	HTGR	Steenkampskraal Thorium Limited	South Africa	Conceptual Design
Xe-100	82.5	HTGR	X-Energy LLC	USA	Basic Design
SC-HTGR	272	HTGR	Framatome, Inc.	USA	Conceptual Design
HTR-10	2.5	HTGR	INET, Tsinghua University	China	Operational
HTTR-30	30 (t)	HTGR	JAEA	Japan	Operational
RDE	3	HTGR	BATAN	Indonesia	Conceptual Design

Note: INET—Institute of Nuclear and New Energy Technology, JAEA—Japan Atomic Energy Agency

2.4. Fast Neutron Spectrum SMRs

Eleven SMR designs that adopt fast neutron spectrum with varying coolant options, including sodium, heavy liquid metal (e.g., lead or lead bismuth), and helium-gas, have been identified, as presented in Table 4 [12]. Tangible advances in technology development and deployment on SMRs in this category have been made. The BREST-OD-300, a lead-cooled fast reactor, is in the process of construction at a site in Seversk, Russian Federation, with a scheduled operation by end of 2026. This is a demo-prototype project for future design with enough power to enable a closed nuclear fuel cycle.

4S is a pool-type fast SMR with a unit capacity of 10 or 50 MWe and a design life of 60 years developed by Toshiba Energy Systems & Solutions Corporation, Japan [12, 30]. It uses liquid sodium with forced circulation in the primary loop with no pressurization (approximately 0.3 MPa). Core inlet and outlet temperatures are 355°C and 510°C. It uses U-Zr alloy metal fuel with enrichment <20%, with 18 fuel assemblies in the core for core discharge burnup of 34 GWd/ton without onsite refueling [12, 31]. Axially movable reflectors and fixed absorbers control reactivity. The reactor pressure vessel is 24 meters in height and 3.5 meters in diameter. The steam generator uses wire-meshed double-wall tubes to prevent

sodium-water interaction in the case of a tube failure. There are active and passive safety systems, like reactor cavity cooling systems and air-cooled, passive DHRS.

SVBR is a lead-bismuth (LBE) cooled fast SMR designed by the Russian Federation for 100 MWe unit capacity and a life of 60 years [12, 32]. It uses forced circulation in the primary coolant loop but low pressure, UO_2 fuel in a hexagonal array, and 61 fuel assemblies in the core. The fuel enrichment is 19.3%, and the core discharge burnup is 60 GWd/ton with a refueling cycle of 6–7 years [12]. The reactor pressure vessel is 8.2 meters in height and 4.53 meters in diameter.

Table 4: Design and Status of fast neutron SMR [12]

Design	Output (MWe)	Type	Designers	Country	Status
BREST-OD-300	300	LMFR	NIKIET	Russian Federation	Detailed Design
ARC-100	100	Liquid Sodium	ARC Nuclear Canada, Inc.	Canada	Conceptual Design
4S	10	LMFR	Toshiba Corporation	Japan	Detailed Design
microURANUS	20	LBR	UNIST	ROK	Pre-Conceptual Design
LFR-AS-200	200	LMFR	Hydromine Nuclear Energy	Luxembourg	Preliminary Design
LFR-TL-X	5~20	LMFR	Hydromine Nuclear Energy	Luxembourg	Conceptual Design
SVBR	100	LMFR	JSC AKME Engineering	RF	Detailed Design
SEALER	3	LMFR	LeadCold	Sweden	Conceptual Design
EM^2	265	GMFR	General Atomics	USA	Conceptual Design
Westinghouse LFR	450	LMFR	Westinghouse Electric Company, LLC.	USA	Conceptual Design
SUPERSTAR	120	LMFR	Argonne National Laboratory	USA	Conceptual Design

2.5. Molten Salt SMRs

Ten SMR designs have been proposed in the molten salt-fueled or cooled advanced reactor technology (MSRs), which is also one of the six Generation IV reactor designs, as presented in Table 5. [12] MSRs promise many advantages including enhanced safety due to salt's inherent properties, a low-pressure single-phase coolant system that eliminates the need of large containment, a high temperature system that results in high efficiency, and a flexible fuel cycle. Several MSR designs are conducting preliminary licensing activities in Canada, the United Kingdom, and the United States.

Table 5: Design and Status of molten-salt SMRs [12]

Design	Output (MWe)	Type	Designers	Country	Status
Integral MSR	195	MSR	Terrestrial Energy Inc.	Canada	Conceptual Design
smTMSR-400	168	MSR	SINAP, CAS	China	Pre-Conceptual Design
CA Waste Burner 0.2.5	20 MW(t)	MSR	Copenhagen Atomics	Denmark	Conceptual Design
ThorCon	250	MSR	ThorCon International	International Consortium	Basic Design
FUJI	200	MSR	International Thorium Molten-Salt Forum: TMSF	Japan	Experimental Phase
Stable Salt Reactor - Wasteburner	300	MSR	Moltex Energy	UK / Canada	Conceptual Design
LFTR	250	MSR	Flibe Energy, Inc.	USA	Conceptual Design
KP-FHR	140	Pebble-bed salt cooled Reactor	KAIROS Power, LLC.	USA	Conceptual Design
Mk1 PB-FHR	100	FHR	University of California at Berkeley	USA	Pre-Conceptual Design
MCSFR	50 - 1200	MSR	Elysium Industries	USA and Canada	Conceptual Design

FUJI is a molten-salt-type SMR designed for a 200 MWe unit capacity and a life of 30 years by ITMSF, Japan [12, 33]. It uses molten fluoride coolant, graphite moderator, forced circulation in the primary loop for an operating pressure of 0.5 MPa, and core inlet and outlet temperatures of 565°C and 704°C, respectively. It uses molten salt with Th and U fuel with enrichment of 2%, no mechanical limit for burnup, and continuous operation without refueling aside from removal of fission gases and refresh of the fuel salt after 7 years [12, 34]. Reactivity control is by control rod, pump speed, or fuel concentration. Passive safety systems include a sub-critical drain tank through a freeze valve, DHRS, ECCS, ADS, and core cooling system (CCS). The reactor pressure vessel is 5.4 meters in height and 5.34 meters in diameter and encloses the reactor core, CRDM, and associated piping.

Integral MSR is a molten-salt SMR designed for 195 MWe unit capacity and a life of 56 years by Terrestrial Energy Inc., Canada [12, 35]. It has similarities with FUJI in terms of coolant, moderator, primary circulation, fuel type, and reactor passive safety. However, it is designed for 0.4 MPa pressure, core inlet and outlet temperatures of 620°C and 700°C, fuel enrichment less than 5%, and replacement of core unit after 7 years [12]. Reactivity control approaches include the negative temperature coefficient for the short term and the addition of liquid fuel for the long term. The reactor pressure vessel is 10 meters in height and 3.7 meters in diameter.

KP-FHR is molten salt-cooled, pebble bed, high-temperature SMR designed for 140 MWe unit capacity and a life of 20 years for the vessel and 80 years for the plant by Kairos Power, LLC, USA [12, 36]. It has similarities with the FUJI and Integral MSR in coolant type, moderator, primary circulation, and reactor passive safety. However, it is designed for 0.2 MPa pressure, core inlet and outlet temperatures of 550°C and 650°C, fuel enrichment less than 19.75%, and online refueling. Control elements and boron are used in reactivity control. In a loss-of-coolant accident, the reactor safety system ensures more than 72 hours of core cooling [37].

3. Major Challenges to SMR Adoption

Despite the potential advantages of SMR technology, there are still several challenges facing the deployment of SMRs. These challenges have been categorized in a few ways [38,39]. The major challenges they addressed include proving new technology, addressing complex engineering tasks, reliability issues, economic viability, and licensing and regulatory challenges, as shown in Figure 5. These challenges are driven by the inclusion of innovative features that were not necessarily part of the previous generation of reactors and are therefore not addressed by current techniques.

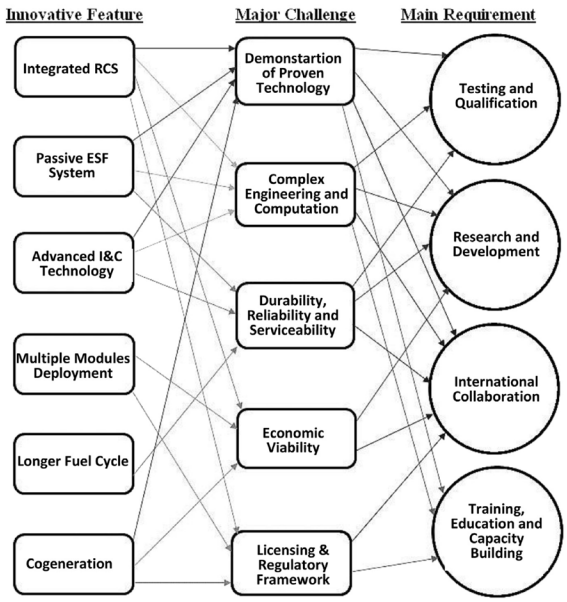

Figure 5: SMR Deployment Challenges [39]

Alternately, Subki [40] used expert surveys to categorize and rank the major challenges for SMR deployment as shown in Figure 6. The clear top priorities indicated are necessary regulatory and licensing changes and proving the effectiveness of passive safety systems. The next tier of challenges involve economics (lower cost to build and operate, cogeneration, deployment scheme). Then the final tier is related to design features such as automation or proliferation resistance.

A wide variety of SMR designs are being developed worldwide, and many are in competition with each other regarding technological readiness, economic viability, and safety features, in addition to the need for SMRs to compete with other energy technologies. This may lead to significant expenditure of resources on designs that may never be built, as well as pressure to deploy technology early to gain advantage over competing designs. This pressure must be addressed, as failures in initiatives that are deployed prematurely may result in delayed or reduced funding, canceled projects, and delays in deploying more technologically mature options.

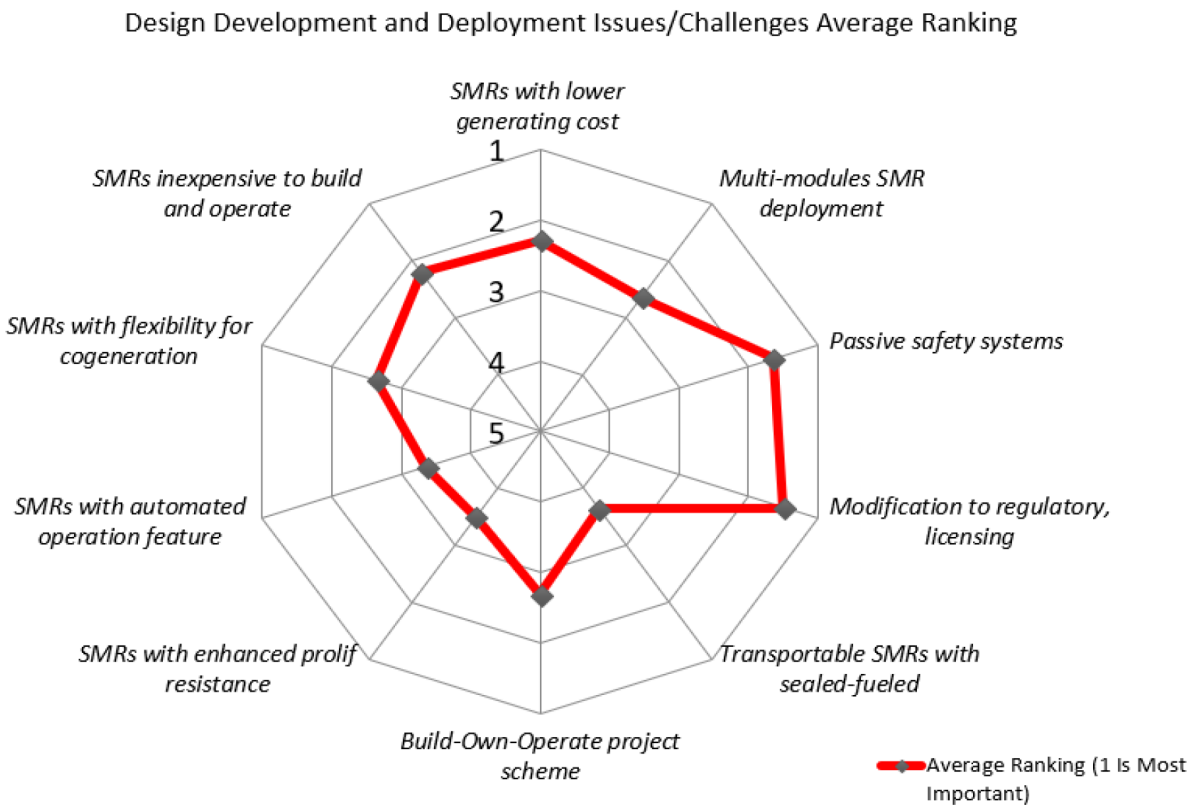

Figure 6: Ranking Major Deployment Challenges [40]

3.1. Updated Codes, Standards, and Regulations

The root of many challenges facing SMRs is the prevalence of novel systems and components. These systems and components often face more stringent challenges than their equivalents in previous generations of reactors. This can lead to questions about reliability in extreme environments and concerns about updating regulations and standards. For example the in-vessel Control Rod Drive Mechanism (CRDM), integrated steam generator, and integrated pressurizer in integral PWRs are subjected to higher temperatures and pressures than standard PWRs [41, 42]. Because of this, new designs must be developed and built, then qualified for nuclear systems and evaluated for long-term reliability data important to Probabilistic Risk Analysis (PRA) and risk-informed regulations.

These innovative systems also may require updates to existing nuclear codes and standards [38]. For instance, the ASME codes for in-vessel components only address core support structure requirements. In many SMRs, additional components (as mentioned above) have been placed inside the vessel to reduce the probability of Loss of Coolant Accidents (LOCAs). Similarly, factory fabrication and transport may require updates to the regulations governing transport of radioactive material. There are also unique operational challenges in instrumentation and controls as well as operator training that may require updates to licensing and operator training requirements.

The recent efforts by the Tennessee Valley Authority (TVA) and the U.S. Nuclear Regulatory Commission (US NRC) on emergency planning zones represents a successful collaboration between regulators and industry for this type of regulatory update [43]. Analysis by TVA showed that the reduced

fuel load, lower reactor power, and reliance on passive safety mechanisms would allow the Emergency Planning Zone (EPZ) to be restricted to the plant site for some SMRs rather than the 10-mile plume exposure EPZ and 50-mile ingestion EPZ. To address this, the NRC recently proposed a new rule that would allow plant-specific EPZ determination for SMRs, reducing the costs associated with emergency planning.

3.2. Passive Safety

The use of passive safety systems in most SMRs has the potential to greatly reduce the already very low risk associated with nuclear energy. However, there are some issues that may need to be addressed through engineering design or through the development of new procedures. One such concern is the use of natural circulation for coolant flow. This eliminates the need for pumps and therefore eliminates loss-of-flow accidents for the reactor. However, it also means that the driving potential for the flow relies on the energy being produced in the reactor. This can give rise to a number of flow instabilities during reactor startup in both pressurized water and boiling water designs [11, 44]. Current designs, such as NuScale, use procedures to ensure that inlet subcooling is always high enough to prevent instability [45].

There are also concerns related to correctly modeling new safety features. As one example, several SMR designs feature steam condensation on the inside of the containment as part of their emergency core-cooling strategy. However, this was not a concern in previous reactor designs, so the models for predicting this behavior have not been rigorously evaluated and qualified and the experimental database for doing so is severely limited [9, 46, 47]. Other unique or novel safety features will necessitate additional Separate-Effects Tests (SETs) to evaluate system modeling software performance for these cases.

3.3. Instrumentation and Controls

A number of technological and regulatory challenges related to instrumentation and controls were identified by the International Atomic Energy Agency and others [48, 49]. NuScale Power alone has been granted 14 patents for new instrumentation and control systems for core monitoring, remote monitoring, etc. [50]. Some key challenges include ex-vessel neutron detectors used to monitor the reactor power. Current detectors may not work in SMRs due to the lower influence of these designs compared to traditional reactors [48]. Placing the detectors closer to the core can address this, but must be done very carefully to prevent disruption of the coolant flow. This also leads to harsher environments, namely higher temperatures and pressures, than existing detectors are designed for. That means that the reliability of the detectors may be a concern. This is especially true for SMRs designed for longer fuel cycles, when calibration of the detectors may be difficult.

Another potential concern is the lack of traditional flow paths. In particular, most current methods for metering coolant flow require a pipe or other flow path that will not exist in some SMR designs like integral PWRs. This means that either better methods for indirectly measuring flow rates or a new reliable solution for flow measurement is needed.

New control techniques may also be required for integrated steam generator designs. Most current control techniques are based on measuring the water level and adjusting the feedwater input to maintain optimum conditions in the steam generator using Proportional-Integral-Derivative (PID) controllers, Programmable Logic Controllers (PLCs), and operator action. Integral steam generators typically have secondary flow inside the steam generator tubes rather than outside, so water level can no longer be used

as an indicator. Therefore, new indicators and control mechanisms or procedures must be developed and implemented.

One other major concern will be control room design and Human Machine Interface (HMI). SMRs have simplified designs and reduced size, but they are also being explored for process heat applications and multiple-module sites. These will lead to significant differences in procedures and HMI challenges. There is further economic pressure to reduce costs, especially operating costs such as personnel. Resolving these issues will require collaboration between stakeholders—everyone from the vendors who design the systems, to regulators who develop operator licensing requirements, to licensees who develop and implement training programs. As with existing reactors, control room simulators and human factors engineering will play a role.

As new devices are qualified, cybersecurity will become a major area of concern for nuclear installations. This will be especially true for SMRs, which will incorporate more distributed systems as well as smart components. Protecting vulnerable smart sensors and control systems will be paramount for SMRs, and cyber-physical risks associated with the transportation of reactor modules will need to be addressed.

3.4. Economics

Competition from cheap natural gas and subsidized renewables has been a challenge for nuclear energy in the past, and will continue to challenge the development and deployment of SMRs. Worldwide, 53 nations have implemented a carbon pricing scheme, which can include either a carbon tax or an emissions trading system. In the U.S., cost-accounting methods for clean energy such as zero-emission credits established in states such as New York, Illinois, and New Jersey may help offset the advantages of the production tax credits for renewable energy sources.

There is significant pressure to reduce both operating and initial costs for SMRs [51, 52]. Researchers at MIT [51] investigated the costs of decarbonizing electricity generation for various scenarios accounting for overnight construction costs of nuclear power installations. The nominal cost was $5,500/kW. The low-cost scenario was $4,100/kW. For comparison, Vogtle 3 and 4 are now estimated to cost $12,000/kW or more [53], but reactors have been built in South Korea at prices approaching $2,500/kW. NuScale estimates their first plant will have an overnight construction cost of $5,100/kW with eventual reductions to $3,600/kW [54], while General Electric estimates that their BWRX-300 will cost as little as $2,250/kW [55]. Construction costs can be mitigated by taking advantage of the unique properties of SMRs: design standardization and modular construction should reduce the need for design modifications, and faster construction times will reduce indirect costs and the cost of financing which can be very significant components in the cost of major construction projects. Data from the construction of standardized South Korean reactor designs indicate that cost savings.

The cost of constructing new natural gas generation is about $1000/kW. These can rise up to $2,300/kW if carbon capture and storage technologies are implemented [56]. Carbon pricing schemes have been proposed that may further narrow this cost gap. Carbon pricing up to $25 per ton will more accurately account for the external costs of fossil-fuel generation and help promote the deployment of SMRs by highlighting the low-emission character of nuclear energy [51]. Construction costs for wind and solar are approximately $1800/kW and $2,600/kW, respectively. Battery storage to complement renewable systems is expected to cost an additional $2,800/kW [56]. However, SMR vendors can make a

strong economic case for providing stable and reliable baseload power to be used in conjunction with renewables to decarbonize electricity generation.

There are two typical targets for reducing operational costs: reducing staffing and reducing down time. It has been argued that SMRs, being smaller and easier to operate, could be subject to less stringent control room staffing requirements than the current regulatory requirement of at least one reactor operator and one senior reactor operator per reactor. NuScale has tested a simulated control room for 12 units, with one reactor operator overseeing three NuScale modules and one senior reactor operator overseeing the entire control room [57]. The modular nature of SMRs may also allow for reduced staffing in other areas of operations or in security personnel as well. Altering those regulations will likely require extensive human factors engineering efforts and human failure data for risk analysis. Extensive changes to the existing training programs will also be necessary to address the unique challenges of such multi-module control rooms.

Reducing down time means reducing or eliminating unplanned shutdowns and streamlining the refueling process. Many SMRs have proposed using factory construction and simply shipping a new module to the site to replace the expended module to reduce refueling time, but this has yet to be demonstrated as a feasible and cost-effective option in comparison with more traditional refueling.

Building up the supply chain for SMR construction will also be a major concern [58, 59]. A lack of new nuclear construction in the 1980s and 1990s resulted in loss of the supply chain that was built up during the 1950s through the 1970s. Some of that supply chain has been rebuilt in recent years, but more must be done before a reliable supply chain can be established. First-of-a-kind SMR construction will find it difficult to establish on-time, reliable procurement of key equipment. This may result in delays and increase costs, unless vendors can establish key partnerships in advance

Because SMRs are being considered for smaller electrical grids or in countries without the infrastructure to support larger designs, spent fuel disposition may be a challenge in some locations. Economic costs associated with managing spent fuel will need to be considered. Some SMR designs can help mitigate this through longer fuel lifetimes [60].

3.5. Multiple-Module Plants

A number of unique challenges in all of these areas occur when proposing multi-module plants, such as NuScale's proposed 12-unit facility [48]. It is not clear whether regulations will consider each module a separate facility, or whether all modules will be considered a single facility. If several modules together will be considered a single facility, there is no clear guidance on the maximum number of modules that can be considered a single facility or the criteria that will be used to make that determination. Many SMR designs propose shared control rooms between modules, but in the past each reactor was required to have its own, independent control room. Common control rooms may lead to significant instrumentation and staffing challenges which may need to be addressed. There will also be a need for PRA on the entire site. Regulations and training governing procedures for operating during construction of additional units may also need to be developed.

In addition to these challenges, SMRs often propose new missions such as process heat and cogeneration [7]. Hydrogen production, desalination, district heating, and many other suggestions have been proposed. Will regulators allow multiple processes at a single site? Can a single unit to be used for both electricity generation and process heat, or must each module be dedicated to a single application?

If modules can be used for multiple applications, will they be allowed to perform both functions at the same time? These novel uses create novel control problems, as the load must now be balanced between multiple applications. Additional processes on-site may also mean that new hazards and safety concerns must be accounted for in risk analyses. These might include fire, explosion, chemical release, etc. The additional controls complexity may also result in additional required training for reactor operators and senior reactor operators.

4. Conclusions

SMRs are not a new concept, but they do represent a new vision for an older concept. These reactors have the potential to become a major source of energy in the near future. The development of small, modular designs can help promote the adoption of nuclear energy by reducing up-front costs, the financial risk associated with nuclear power, and the barriers to entry. Several SMR designs based on proven technology are ready for construction, or will be soon. Worldwide, six designs have completed design certification. Two designs are already under construction in China and Argentina, and one is already in operation in Russia. SMRs may also encourage the development of Generation IV designs by reducing the financial risk to early adopters and providing operational experience that will help guide further research and development.

The adoption of SMRs is not without challenges, however. Regulatory and licensing changes to address the unique benefits and concerns associated with SMRs will continue to be a challenge as regulators adapt to the unique features emerging from the design process. The development of new instrumentation and control systems is an ongoing issue. Economics is possibly the most significant challenge with high construction costs, cheap natural gas, and government subsidies combining to result is significant financial risk associated with adopting nuclear energy generation. Rebuilding the nuclear technology supply chain will be necessary to reduce construction times and associated costs. Leaner staffing and streamlined refueling and maintenance are important goals, but may not be enough to mitigate these financial risks.

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