SAFETY AND SECURITY FOR SMALL MODULAR NUCLEAR REACTORS IN CANADA

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Abstract

In the past decade, there have been significant developments in Small Modular Reactor (SMR) technology. SMRs range from approximately one-third the size of current nuclear power plants or about 300 MWe, to as low as 3 MWe. SMRs are promoted as economically competitive alternatives to large Nuclear Power Plants (NPPs) for electrical power production and other applications. The advantages of SMRs arise from being simpler and modular, carrying smaller financial as well as radiological risk, being more adaptable for load following demands, factory production, and their applicability for off-grid applications. SMRs feature simplified, compact designs, which typically include built-in passive safety systems, limited on-site refueling, and provisions for remotely monitored operation and reduced on-site staffing. A number of SMR concepts have been proposed by various international companies for pre-licensing design review and eventual construction in Canada. Traditional nuclear safety and security analyses and design are impacted by the proposed advanced fuel types, their proliferation, control, and monitoring aspects. Other challenges for SMR safety and security include: geographic isolation and distribution, lack of strong thermal or radiation signatures, lack of access to core for monitoring, aqueous fuel forms, harsh environmental conditions, tools for comprehensively assessing proliferation resistance (e.g., proliferation resistant fuels), and cyber security considerations for remote monitoring/control (e.g., anomaly detection, secure data transmission, etc.). The paper discusses these considerations and describes possible strategies for these novel facets of SMR concepts

1. BACKGROUND

Small modular reactors (SMR) with power levels significantly less than the current nuclear power plants are seen as a potential ‘game changers’ for future nuclear power. They have power capacities up to 300 MWe, to as low as 3 MWe. SMRs are promoted as economically competitive alternatives to large nuclear power plants for electrical power production and other applications. The advantages of SMRs arise from being simpler and modular, carrying smaller financial risk, more adaptable for load following demands, factory production, and applicability for off-grid applications. SMRs feature simplified, compact designs, which typically include built-in passive safety systems, limited on-site refuelling, and provisions for remotely monitored operation and reduced on-site staffing.

The proposed flexibility of operations for these new designs enables a wide range of end uses, including pairing SMRs with intermittent renewable sources such as solar or wind energy to ensure grid reliability. In addition to electricity production, the energy from an SMR could be used for the production of hydrogen, for local area heating, or in industrial processes which require heat or steam.

2. MAIN SMR TECHNOLOGIES

A number of SMR concepts have been proposed by various international companies for pre-licensing design review and eventual construction in various places around the world. According to the International Atomic Energy Agency Advanced Reactor Information System (IAEA-ARIS) [1], a compilation of the SMRs, either under design, or under construction, or licensed, or operational, is given in Table 1.

TABLE 1. EXAMPLES OF PROPOSED SMR DESIGNS AROUND THE WORLD [1]

Name	Country	Organization	Status	Fuel Material	Enrichment	SMR Type
U-Battery	UK	U-Battery	Under Design	TRISO fuel	LEU	GC R
STARCORE	Canada	Starcore Nuclear	Under Design	TRISO fuel	LEU	HTGR
Micro Modular ReactorTM (MMR)	Canada	Global First Power/Ultra Safe Nuclear Corporation	Under Design	Fully Ceramic Micro-encapsulated (FCM™) fuel	LEU 9-12%	High Temperature Gas-Cooled Reactor
Integral Molten Salt Reactor-400 (IMSR-400)	Canada	Terrestrial Energy	Under Design	UF4	2-3% for start-up, 5-19% makeup fuel	MSR
European Lead Cooled Training Reactor (ELECTRA)	Sweden	Royal Institute of Technology (KTH)	Under Design	(Pu,Zr)N		LFR
Fixed Bed Nuclear Reactor (FBNR)	Brazil	Federal University of Rio Grande do Sul (FURGS)	Under Design	CERMET	5% 235U	Pressurized Water Reactors (PWR)
Integrated Modular Water Reactor (IMR)	Japan	Mitsubishi	Under Design	UO2	4.8% 235U	Integral Pressurized Water Reactor (iPWR)
Molten Salt Thermal Wasteburner (MSTW)	Denmark	Seaborg Technologies	Conceptual Design	Eutectic Sodium-actinide fluoride salt mixture	Pre-processed spent nuclear fuel (U 1.1% fissile, Pu 69 % fissile)	MSR
NuScale Power Modular and Scalable Reactor (NuScale)	USA	NuScale Power Inc.	Under Design	UO2 Ceramic Pellets	<4.95%	iPWR
Prismatic Modular High Temperature GCR (Prismatic HTR)	USA	General Atomics	Under Design	Uranium oxycarbide (UCO)	15.5% U-235	GCR
Small fluoride salt-cooled High Temperature Reactor (SmAHTR)	USA	Oak Ridge National Laboratory	Under Design	UCO	8%	MSR
Stable Salt Reactor (SSR-U)	UK	Moltex Energy	Conceptual Design	Molten Salt	<15% LEU	MSR
VVER-600	Russia	Gidropress	Under Design	UO2		PWR

Aside from boiling water reactors (BWRs) and pressurized water SMRs (PWRs/iPWRs), the advanced designs can be grouped in four different categories by fuel type, enrichment and other parameters. A brief summary for each technology is given below:

2.1. Gas-cooled fast reactor (GFR)

A GFR is a high-temperature helium-cooled fast-spectrum reactor with a closed fuel cycle [2]. This reactor technology combines the advantages of fast-spectrum systems for long-term sustainability of uranium resources and waste minimisation, with those of high-temperature systems. The high outlet temperature of the helium coolant enables to deliver electricity, heat, and hydrogen production. Currently, three GFRs are under design [1].

2.2. Sodium-cooled fast reactor (SFR)

A SFR uses low-pressure liquid sodium as the reactor coolant, thus allowing high power density with low coolant volume fraction [3]. The SFR closed fuel cycle enables regeneration of fissile fuel and facilitates actinide management. In addition, the fast neutron spectrum greatly extends the uranium resources compared to thermal reactors. Currently, nine SFRs are under design, and one is under construction [1].

2.3. Lead-cooled fast reactor (LFR)

A LFR features a fast neutron spectrum, high temperature operation, and cooling by either molten lead or lead-bismuth eutectic (LBE) [4]. These coolants support low-pressure operation, have very good thermodynamic properties, and are relatively inert with regard to interaction with air or water. These characteristics of lead as coolant, as well as the potential to exploit passively operated heat removal from lead-cooled systems supports the LFR as an advanced reactor technology to meet present and future needs. Currently, nine LFRs are under design [1].

2.4. Molten salt reactor (MSR)

The MSR is one of the Generation IV reactor system. MSRs under development include nuclear fuel dissolved in molten fluoride salt [5] as well as solid fuel with molten salt coolant. R&D efforts on MSRs are currently focused on the development of thermal as well as fast-spectrum MSR concepts (MSFR) combining the generic assets of fast neutron reactors (extended resource utilization, waste minimization) with those relating to molten salt fluorides as fluid fuel and coolant. Currently, nine MSRs are under design [1]

3. SMR DESIGNS FOR CANADA

A number of SMRs are proposed for deployment in Canada by various Canadian and international companies. These SMR concepts are promoted by private companies, and although they are in the early stages of concept development, they seem committed to taking their products to market. A few of these vendors are currently going through or about to apply for the pre-licensing review process of the Canadian Nuclear Safety Commission (CNSC).

Canadian Nuclear Laboratories (CNL), Canada’s premier nuclear science and technology organization, set the ambitious goal of siting an SMR on a CNL-managed site by 2026. To achieve this, CNL launched a request for expressions of interest to gather input and feedback from stakeholders across Canada and internationally. A total of 19 expressions of interest were received from technology developers interested in building a prototype or demonstration reactor at a CNL site. Based in part on that strong response, CNL moved forward with announcing a staged invitation process for those vendors interested in siting their demonstration unit. The invitation and evaluations are conducted independently of the CNSC’s pre-licensing vendor design review process; however, all projects are ultimately subject to Canadian regulatory requirements [6].

CNL’s invitation process is comprised of four distinct stages: Prequalification, Due Diligence, Negotiation, and Project Execution. Stage 3, Negotiation, includes preliminary, non-exclusive discussions regarding land arrangements, project risk management, and contractual terms. The fourth and final stage, Project Execution, would include construction, testing and commissioning, operation and ultimately decommissioning of the SMR unit. At present, there are four project proponents engaged in various stages (see Figure 1):

FIG. 1. SMRs being considered for Canada.

- U-Battery Canada Ltd.’s proposed SMR design is a 4 MWe high temperature gas reactor.
- StarCore Nuclear’s proposed SMR design is a 14 MWe high-temperature gas reactor.
- Terrestrial Energy’s proposed SMR design is a 190 MWe integral molten salt reactor.
- Global First Power’s proposed SMR design is a 5 MWe high-temperature gas reactor.

4. SAFETY AND SECURITY CHALLENGES

SMRs present a number of unique characteristics in comparison with large NPPs. These characteristics come about with their smaller size that potentially facilitates modularization, assembly line fabrication, reduction of financial risk profile, and opening the possibility of more flexible deployment and operation, including off-grid applications. Some of these characteristics present significant challenges for the safeguarding of SMR facilities from illicit proliferation [7, 8]. For example, alternate means will need to be found to regular physical inventory verification, which is a normal safeguards procedure, for sealed core SMRs. Hence it becomes crucial to develop the necessary safeguards and non-proliferation standards addressing various aspects, advantages, and vulnerabilities associated with SMR deployment. In this section various aspects of the challenges facing SMR designs are discussed in the context of nuclear security, safeguards and non-proliferation.

4.1. Remote locations with limited access

SMRs for remote regions could be fabricated and fuelled in a factory, sealed and transported to sites for power generation, and they can remain sealed until they are safely shipped back to the factory. This will potentially eliminate technology misuse or material diversion. The SMRs can be deployed in off-grid applications for small remote northern communities, and at mining sites. In such circumstances, being in a remote location with limited access can mitigate or reduce the likelihood of a physical attack, particularly by adversaries outside of the facility. For economic reasons, staffing for SMRs is likely to be very small, however, such that it may be difficult to have sufficient manpower present at the site to fully protect against sabotage attacks.

A number of SMR designs also propose installing the SMR core module underground. This presents further difficulty, cost, and technical challenge to access. In particular, a robust physical protection and combat plan should be prepared in case of a hostage or infiltration attempt, as security forces from outside will have difficulties accessing the facility. This can be partially eased by having the control room above ground.

Considering the fact that the SMRs will be deployed in remote regions and over a vast geographical area, development of remote monitoring capability is imperative. Non-intrusive and remote measurement techniques to collect information data for reactor components for continuous monitoring of SMRs need to be developed and incorporated in the reactor design phase [9].

4.2. Cyber security

Digital systems, increased automation, remote supervisory control and remote maintenance can be essential for driving down costs of SMRs, provided appropriate security measures are established and maintained throughout the entire SMR lifecycle from design through operation and decommissioning. Establishing a solid cyber security program up front is key to ensuring that no unauthorized changes find their way into the baseline and that the baseline does not contain any known vulnerabilities. A solid cyber security program will significantly contribute to managing risk and directing limited resources towards systems or assets based on their relative value or importance throughout their lifecycle. This is key when designing a licensable I&C architecture with its corresponding concept of operations as it establishes a foundation for regulatory review through a defined cyber security classification scheme where security risks are categorized from low to high such that appropriate zoning and controls are incorporated into the design. This also ensures that designs are not fundamentally flawed by design, such as the use of wireless or remote communications where prohibited by regulation for certain security classifications. In cases where SMR designs may be walk away safe, it may not be the regulator driving the security requirements but it will more than likely be the business case with reliability and availability requirements. In today's digital world, cyber security incidents are a reality, whether targeted or not. The cost of not preparing for such incidents will be significantly higher than the investment into the development and maintenance of a solid cyber security program from the onset.

4.3. Sealed and long-life reactor cores

Many SMR designs intend for an extended operating lifetime of the reactor core, to minimize core changes. The core design is often sealed, to facilitate secure transport and changing of the modular core. A sealed core reduces core access, particularly at the SMR site, which mitigates the consequences of any attack on the core. On the other hand, proper security measures must be maintained with due diligence over the course of the long life of the core. This approach could minimize the transportation and handling of nuclear material. Reduced core access and refuelling frequency can make nuclear material diversion more difficult. However, the current IAEA practice of physical inventory verification of the reactor core would not be possible while the core is sealed. To mitigate the lack of core access for verification, a method of reliable monitoring of nuclear material inside the sealed core will be necessary [7, 8].

4.4. Large number and distribution of SMR sites

Distributed nuclear energy generation generates power at the point of consumption. This eliminates the cost, complexity, inefficiencies and security risks associated with power transmission and distribution over long distances. SMRs lend themselves to distributed operation, as it is feasible to deploy many SMR sites over a potentially large geographic region. This has strengths and weaknesses. While the number of potential targets for security breaches grows as the number of SMR sites increases, it becomes more justifiable to employ a sizable security task force that is available to a significant network of SMR sites through dispatch centres reasonably located so as to ensure timely response in case of emergencies.

4.5. Smaller fissile inventory

SMR core loads are significantly smaller in comparison with conventional nuclear power plants. This reduces the amount of nuclear source material that would be vulnerable to theft, sabotage, or unauthorized access; this mitigates the consequences that would transpire from a successful attack. Nevertheless, when seeking to reduce the SMR facility security infrastructure in proportion to the reduction in fissile inventory relative to a standard nuclear power plant, it is important to do so in a graded approach that is informed by careful security risk analysis.

4.6. Advanced fuel cycles

For advanced fuel cycles, significant analysis is required to understand the most efficient and effective security measures. Some smaller SMR designs feature advanced/enhanced safety features including passive safety features. As many radiological consequences of safety accidents and security breaches are shared or interlinked, these advanced safety features could have a mitigating effect for the extent of required security controls and measures. The level of enrichments of proposed SMRs are given in Table 1. A few SMR designs choose high levels of enrichment in order to minimize the size, and maximize the time span of operation or decrease refuelling frequency. Thus SMR designs which will use MOX fuels and/or U-235 enrichment up to 20% will pose more proliferation challenge than traditional power reactors.

4.7. Transportation of sealed cores

It is part of the model of a number of SMR designs that the reactor core components be made on an assembly line at an off-site factory, and then be shipped to one of a number of SMR facility sites. For some SMR designs, the reactor core is shipped sealed and fully loaded with fissile material, while in other designs, fuel is inserted into the core at the SMR facility site. The factory and facility sites can even be located in different countries. Cross-border shipments will need to satisfy packaging and transport regulations of nuclear substances and dangerous goods in all countries through which the reactor core is transported. While there is operational experience for the transportation of nuclear fuel across borders and over long distances, consideration should be given towards additional issues surrounding the transportation of a sealed and fully-loaded reactor core. In particular, the core will need to be adequately protected and ensure that a sub-critical arrangement is maintained during transport. Potential challenges posed by transportation to remote locations with limited access should also be addressed. Adequate security monitoring of the reactor core will need to be maintained at all points of the transportation route.

4.8. Spent fuel management

The fuel cycle greatly impacts the handling, safeguarding, short term and long term storage of used nuclear fuel. In countries, such as Canada, with established nuclear power programmes, proposed SMRs based on current technologies would not pose any challenge for spent fuel management as long as types of fuel and enrichment levels are maintained within current parameters. SMR designs which will use MOX fuels and/or U-235 enrichment above 5% will pose more challenges; IAEA, national regulator, operators, and nuclear waste management organization should work together to put in place new or adjust solutions for spent fuel management. However, countries entering into nuclear power by deploying SMRs have need to carefully consider the spent fuel management prior to deployment [10].

5. ADDRESSING SMR CHALLENGES

“Safety by Design” and “Safeguards by Design” [11] have been applied to conventional reactors for the last 20 years or more. The inclusion of “Security by Design” [12] is a newer approach to the design and construction of a nuclear reactor in which nuclear Safety, Security, and Safeguards (3S) provisions and features are analysed and incorporated during the earliest design stages [13]. Since many of the SMRs are still conceptual or under design stage, the designers now have a unique opportunity to incorporate various safeguards and security features by design. Security by design analysis could be achieved via a fault tree approach as is done with probabilistic safety analysis and/or the consequence-based graded approach to security [14-15]. For example, early considerations can be implemented in design factors such as fuel element size, core lifetime and burnup, and excess reactivity. More about background and evolution of the SBD process, and stages in the design and construction process for a nuclear reactor are described in [16-17].

While deployment of SMRs in Canada is still several years away, CNL is building its expertise and capabilities to support the development of these technologies, and has launched initiatives that would further explore the full range of applications and mitigate foreseen challenges. Work underway at CNL includes comprehensively reviewing implications and impacts of proposed SMRs and their associated facilities, on the nuclear safeguards programs, and proposing possible technical solutions and strategies to mitigate their negative consequences. Solutions include adapting and developing fissile content verification tools for sealed cores via neutron monitoring, detection technologies to verify used fuel stored underwater, underground or in silos (e.g., diode detectors, light tube, or muon tomography) and active and passive detection techniques for SNMs applied to nuclear reactors and fuel cycle activities [18-21].

In parallel and in support of broader development of SMR technology, CNL has launched the Canadian Nuclear Research Initiative (CNRI) in 2019 August (see Figure 2). This initiative encourages SMR technology developers to propose R&D work scopes to be completed using CNL expertise and facilities on a cost-share basis.

The goal of the program is to support collaborative SMR research projects with third-party proponents in Canada to accelerate the deployment of safe, secure, clean, and cost effective SMRs in Canada. The objective of CNRI is to make CNL's technical capabilities and expert knowledge available and accessible to the SMR community in order to equip them with the technical support required to progress towards SMR deployment in Canada. Examples of approved work in the nuclear security area include evaluating the applicability of nuclear safety, security and non-proliferation technologies to the IMSR400 reactor and other SMR designs, as well as looking at opportunities to utilize CNL's existing facilities, and if necessary developing new experimental capabilities related to molten salt reactors.

FIG 2. Canadian Nuclear Research Initiative (CNRI) objective (copyright CNL).

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