SMR Development and Safeguards by Design in Canada

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ABSTRACT

In recent years, small modular reactors (SMRs) have gained wide interest in the nuclear industry around the world. In Canada, SMRs are considered as an advanced technology to meet energy requirements and reduce greenhouse gas emissions. Currently more than 10 SMR designs have been proposed in Canada with potential deployment to on-grid, and remote off-grid areas. Natural Resources Canada engaged stakeholders across Canada to develop a roadmap on the future of SMRs to support SMR development. Global First Power has filed a licence to prepare site application to build a Micro Modular Reactor at Canadian Nuclear Laboratories, and in January 2022, Ontario Power Generation announced its selection of the GE-H BWRX-300 SMR to be built at Darlington site.

In the proposed SMRs, various novel fuel forms, designs, and deployment models are pursued by the vendors. These new features of SMRs may introduce challenges to safety, security, and safeguards due to limited operational experience with these reactors. To address these potential challenges, the Canadian Nuclear Safety Commission (CNSC) issued a discussion paper on SMRs in 2016 and optimized regulatory framework to regulate the SMRs in future. The CNSC also offers a pre-licensing vendor design review (VDR) as an optional service in which the safeguards by design (SBD) principle is applied by vendors in the SMR designs. Currently, nine vendors have applied such VDR on their SMRs. The CNSC encourages the vendors to apply the SBD approach and engages the IAEA and vendors to ensure that safeguards is considered in their SMR's design and the regulatory requirements can be met in the operating of these SMRs. This paper discusses the SMR development, pre-licensing VDR, potential safeguards challenges, and the application of SBD in Canada.

INTRODUCTION

In recent years, small modular reactors (SMRs) have gained wide interest in the nuclear industry around the world. This global renewed interest in SMRs is mainly driven by both the energy needs and reducing greenhouse gas emission to Net-Zero Emissions (NZEs) by 2050 [1].

The importance of reducing the green house emission has been recognized and actions have been taken worldwide. In Canada, the Canadian NZEs Accountability Act became law on June 29, 2021 to ensure Canada's commitment to reduce emissions by 40-45% from 2005 levels by 2030 and achieve NZEs by 2050 [2]. In order to meet these goals, Canadians need to look to all forms of clean energy to replace energy produced from fossil fuels which is currently estimated to be more than 20% of the total energy in Canada [3]. As a result, it is recognized that nuclear energy is needed to achieve Canada's NZEs and in particular SMRs have been identified as a promising technology for this. The novel features of SMRs such as modular designs and various energy output (3 to 300 MWe) could be suited for off-grid, remote, or industrial applications such as mining companies and northern areas to transition away from using diesel while lowering cost.

SMR INDUSTRY DEVELOPMENT

In Canada, the Government of Canada has recognized the great potential of SMRs to meet the NZEs goals and is committed to working with the industries, provinces, and territories to enable deployment of SMRs. Great developments have been recently made in Canada regarding SMRs including the development of a SMR road map, action plan, industry feasibility report, and two SMR projects which have been launched.

In 2018, Natural Resources Canada (NRCan) brought together provincial and territorial governments, industry, utilities, and other interested stakeholders to explore the opportunity of SMRs. Through a series of expert working groups, and workshops held across Canada, a roadmap has been developed on the direction for the possible development and deployment of SMRs in Canada. In the published roadmap, three major areas of application are being considered [4]:

- On-grid power generation, especially in provinces phasing out coal in the near future. Utilities want to replace end-of-life coal plants with non-emitting base-load plants of similar size. Larger SMRs are likely to align to this application.
- On- and off-grid combined heat and power for heavy industry. Oilsands producers and remote mines would benefit from medium-term options for bulk heat and power that would be more reliable and cleaner than their current energy sources. Small or medium SMRs are likely to fit this need.
- Off-grid power, district heating, and desalination in remote communities. These currently rely almost exclusively on diesel fuel, which has various limitations (e.g., cost, emissions). Renewables and batteries can mitigate these limitations to some extent for residential power, but may not supply building heat, nor are they likely to offer reliable bulk energy to open up economic development. Very small SMRs may address these needs.

In the roadmap, it was estimated that the potential value for SMRs in Canada will be $5.3B between 2025 and 2040 and it is believed that Canada has one of the world's most promising domestic markets for SMRs. This was based on the identified on- and off-grid combined heat and power for heavy industry, such as mineral processing, resource extraction, and 24 current and potential off-grid mines in Canada that might be suitable for SMR deployment, as one of the three potential applications for SMRs in Canada.

In 2020, NRCan released Canada's SMR action plan describing ongoing and future efforts to develop SMR science and technology, and the role of SMRs in clean electrification and energy [5].

In 2021, a report on "Feasibility of Small Modular Reactor Development and Deployment in Canada" as released by Canadian nuclear industry. This report was prepared by Ontario Power Generation (OPG), Bruce Power, NB Power and SaskPower for the governments of Ontario, New Brunswick and Saskatchewan. This report indicated that energy generated by SMRs in Ontario and Saskatchewan is expected to be economical compared to other low-carbon alternatives and could be used to support reduction in carbon emissions and meet new energy demands. The choice of SMR technology and speed of commercialization will play a significant role in the cost of deployment. For off-grid applications, such as remote mines or communities, SMRs need to be economically competitive with diesel generation (i.e., including the cost of fuel and transport), and SMRs could potentially reduce energy costs for remote sites and communities with electricity demands between 10 and 20 MW. For smaller communities (e.g., those with demands of 3 MW),

the costs are near break-even. As with on-grid applications, the choice of technology and speed of commercialization will depend on the cost of SMR deployment and its ability to compete with diesel [6].

In 2022, a strategic plan for the deployment of SMR was also released by the Governments of Ontario, New Brunswick, Saskatchewan and Alberta. The plan builds on the SMR feasibility study released by the provincial power utilities in 2021 by identifying key actions that provinces can take to enable a decision on whether to proceed with SMRs. Following a decision to proceed, it outlines further actions to support the deployment of SMRs [7].

In July 2022, OPG and X-energy signed a framework agreement to seek opportunities for the decarbonisation of high-temperature industrial applications through the deployment of the Xe-100 SMR in Canada [8].

In August 2022, the Invest Alberta Corporation (IAC) signed a Memorandum of Understanding (MOU) with Canada's Terrestrial Energy Inc (TEI) to support commercialisation of TEI's Integral Molten Salt Reactor (IMSR) generation IV SMR plant in western Canada [9]. In January and March 2023, the IAC also signed a MOU with X-Energy Canada and ARC Nuclear Canada Inc., respectively, to develop economic opportunities supporting the potential deployment of the Xe-100 SMR and ARC-100 within the province [10].

As results of these developments, two SMR projects have been recently launched in Canada. In November 2020, Ultra Safe Nuclear Corporation – Power (USNC-Power) announced the signing of a Project Host Agreement (PHA) for the company's initial deployment site in Canada. USNC-Power and OPG formed a joint venture, referred to as Global First Power (GFP), to implement (build, own and operate) USNC's Micro Modular Reactor (MMR) high-temperature gas-cooled reactor technology at Atomic Energy of Canada Limited's (AECL's) Chalk River Laboratories (CRL) site, managed by CNL. In December 2021, OPG selected GE Hitachi (GEH) to supply its BWRX-300 SMR for the Darlington site. GEH is working to deploy this SMR there as early as 2028. In January 2023, GEH, OPG, SNC-Lavalin and Aecon inked a commercial contract for a 300 MW SMR at OPG's Darlington new nuclear site.

On 25 March 2022, SaskPower also selected the BWRX-300 for potential deployment in Saskatchewan in the mid-2030s [11]. SaskPower is currently exploring two sites in Saskatchewan for potential SMR development. In addition, the Saskatchewan Research Council signed a MOU with Westinghouse Electric Canada in June 2022 to advance the study of their very small modular reactors, eVinc micro-reactor (Up to 5 MWe), in Saskatchewan and this SMR could be developed as early as 2030 [12].

In New Brunswick, NB Power is currently working with ARC Canada and Moltex for its potential SMR development adjacent to the existing CANDU unit at Point Lepreau. NB Power is currently exploring designs for the ACR-100 (100 MW sodium-cooled fast reactor), and Moltex's Wasteburner or SSR-W (300 MW stable salt reactor) and Waste to Stable Salt facility (WATSS) [13]. In November 2022, the Belledune Port Authority in New Brunswick announced plans to pursue a project for deployment of the ARC Clean Energy Inc. SMR, the ARC-100, as part of a future expansion at the northern New Brunswick port [14].

In the development of SMR designs, research and development projects have been carried out by SMR vendors. Canadian Nuclear Laboratories is providing science and technology services to support governments, industry, vendors and inviting demonstration SMR projects.

The SMR developments in Canada have been supported and invested by both provincial and federal governments.

In June 2018, the New Brunswick provincial government committed $10 million to help establish New Brunswick as a leader in the field of research and development of SMR technology [15].

In October 2020, the Government of Canada invested $20 million to support TEI's SMR development [16].

In February 2021, New Brunswick government announced continuation of its partnership with ARC Canada by supporting its next phase of technology development with the establishment of another round of funding totaling $20 million [17].

In March 2021, Moltex received funding of 50.5 million from Canada's Strategic Innovation Fund and Atlantic Canada Opportunities Agency to advance the company's molten salt reactor and spent fuel recycling technology in New Brunswick [18].

In October 2022, the Canada Infrastructure Bank (CIB) is committing $970 million in debt financing toward the SMR being developed by OPG [19]. The CIB-financed phase 1 work covers all preparation prior to nuclear construction, including project design, site preparation, procurement of long lead-time equipment, utility connections, digital strategy and other project management costs.

Very recently in February 2023, the Canadian government has launched an "Enabling Small Modular Reactors Programme" which will provide $29.6 million over four years. It will be used to develop supply chains for SMR manufacturing and fuel supply and security, and to fund research on safe SMR waste management solutions [20].

SMR REGULATORY DEVELOPMENT

The Canadian Nuclear Safety Commission (CNSC) is Canada's independent nuclear regulator and regulates the use of nuclear energy and materials to protect health, safety, security and the environment. As the regulator of nuclear activities and materials in Canada, the CNSC is maintaining and improving a state of readiness for regulatory review of licence applications for SMR projects and regulating SMRs in Canada using an objective based safety framework that can be applied to different reactor technologies [21].

Currently more than 10 SMR designs have been proposed in Canada in which various novel fuel forms, designs, and deployment models are pursued by the vendors. These new features of SMRs differ from Canada's current CANDU reactors in terms of the technologies and deployment models, combined with limited operating experience with these technologies, and can introduce potential regulatory challenges. To address these potential challenges, the CNSC is actively working to further enhance the existing regulatory framework as experience is gained from new technologies for SMR regulatory readiness.

In 2011, CNSC published RD-337 - *Design of Small Reactor Facilities* which sets out the requirements of the CNSC for the design of new SMR facilities.

The CNSC has engaged with the public about SMRs through the web and publication of discussion paper DIS-16-04, *Small Modular Reactors: Regulatory Strategy, Approaches and Challenges,* in 2016 [22] that helped to enhance regulatory clarity and framework to regulate the SMRs in future.

In 2019, CNSC developed a supplementary information document, REGDOC-1.1.5, *Supplemental Information for Small Modular Reactor Proponents*, to further clarify SMR implications on safety and control measures expected in a licence application. The CNSC also published its *Strategy for Readiness to Regulate Advanced Reactor Technologies* [23] in December 2019. This advanced reactor readiness report describes the CNSC's strategy for addressing the challenges of regulating advanced reactor technologies and prioritizing its regulatory efforts, and outlines how the CNSC is prepared to address regulatory challenges like those presented by new technological advances in reactor designs, and new deployment and operational models. The CNSC's regulatory readiness strategy for new advanced reactors is built upon three fundamental pillars involving eight areas (figure 1):

- A robust but flexible regulatory framework that provides a sound basis upon which regulatory decisions can be made and enforced.
- Risk-informed processes by which the regulatory framework is applied.
- A capable workforce with sufficient capacity and technical expertise, operating within an agile work organization.

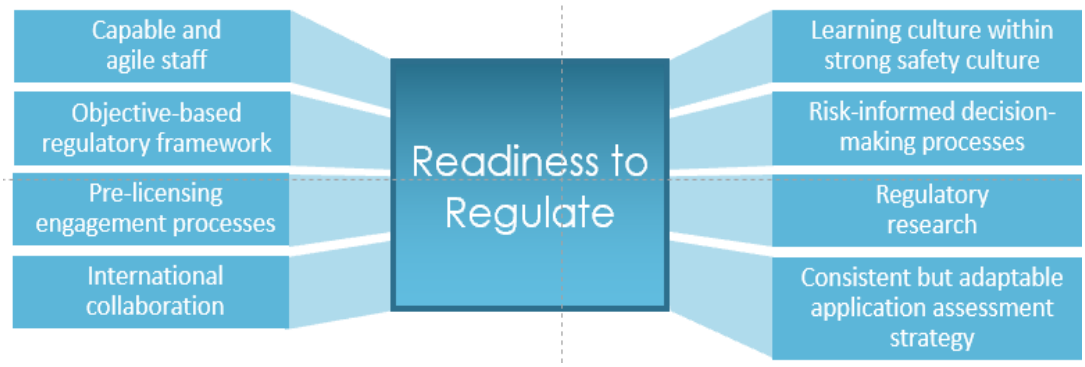

Figure 1. CNSC's readiness to regulate SMRs in Canada.

In addition, as part of the CNSC's overall regulatory framework planning and periodic review cycle, regulatory documents applicable to nuclear power plants are being reviewed for SMR specific considerations and clarified as needed to reflect emerging operating experience. Through the improving and optimizing of regulatory framework, CNSC is ready to license and regulate SMRs in Canada.

CNSC PRE-LICENSING VENDOR DESIGN REVIEW

The CNSC also offers optional pre-licensing engagement with potential applicants and pre-licensing VDR service. The VDR process, which takes place prior to the licensing process,

provides an early opportunity for vendors of a reactor technology to engage with the CNSC and to seek clarity on the regulatory requirements and the expectations of their designs, and to enable the identification and resolution of safety, security, and safeguards issues in advance of the formal licensing process for SMR licensing applications. Currently the CNSC is engaged in nine vendors in different phases of the VDR process as summarized in Table 1.

Table 1. Status of the CNSC's Current Pre-Licensing Vendor Design Reviews

Vendor design review service agreements in force between vendors and the CNSC					
Vendor	**Name of design and cooling type**	**Approximate electrical capacity (MW electrical)**	**Applied for**	**Review start date**	**Status**
Terrestrial Energy Inc.	Integral Molten Salt Reactor	200	Phase 1	April 2016	Complete
			Phase 2	December 2018	Complete
Ultra Safe Nuclear Corporation	MMR-5 and MMR-10 High-temperature gas	5-10	Phase 1	December 2016	Complete
			Phase 2	June 2021	Assessment in progress
ARC Nuclear Canada Inc.	ARC-100 Liquid Sodium	100	Phase 1	September 2017	Complete
			Phase 2	February 2022	Assessment in progress
Moltex Energy	Moltex Energy Stable Salt Reactor Molten Salt	300	Series Phase 1 and 2	December 2017	Phase 1 completed
SMR, LLC. (A Holtec International Company)	SMR-160 Pressurized Light Water	160	Phase 1	July 2018	Complete
U-Battery Canada Ltd.	U-Battery High-temperature gas	4	Phase 1	Pending	Project start pending

GE-Hitachi Nuclear Energy	BWRX-300 boiling water reactor	300	Phase 2*	January 2020	Complete
X Energy, LLC	Xe-100 High-temperature gas	80	Phase 2*	July 2020	Assessment in Progress
Westinghouse Electric Company, LLC	eVinci Micro Reactor solid core and heat pipes	Up to 5 MWe	Phase 2*	January 2023	Assessment to Start in 2023

*Phase 1 objectives will be addressed within the Phase 2 scope of work.

The primary purpose of a vendor design review is to provide feedback to the vendor about how the vendor is addressing Canadian regulatory requirements and CNSC expectations in its designs. Therefore, this process provides opportunity for the early identification and resolution of potential regulatory or technical issues in the design process so that any potential fundamental barriers can be addressed in a future licensing process. However, a VDR does not result in any decision by the Commission under the *Nuclear Safety and Control Act*. The VDR process is composed of three distinct phases, corresponding with the level of design details. For more Information on the CNSC's Pre-licensing VDR, please refer to REGDOC-3.5.4, Pre-Licensing Review of a Vendor's Reactor Design. The details of review criteria and phased review can also be found in reference [23].

When an applicant submits an application for a licence to construct and/or operate a facility using the vendor's design completed with the pre-licensing VDR process, the CNSC will initiate the licensing process with the applicant and leverage the results of the VDR in the conduct of licensing activities.

Currently a few SMR licensing projects have been carried out at CNSC. In 2019, GFP submitted a site preparation licence application to CNSC for the USNC's 15 MW thermal MMR high-temperature gas-cooled reactor technology at AECL's CRL site with a tentative timeline for site preparation beginning in mid-2023. The CNSC is currently conducting an environmental assessment under the Canadian Environmental Assessment Act for this project. In addition to holding a nuclear power reactor site preparation licence for the Darlington New Nuclear Project, OPG submitted a Licence to Construct (LTC) application to the CNSC in October 2022 to construct a SMR adjacent to the existing CANDU units at Darlington based on GEH's BWRX-300 design. OPG's LTC application is currently under CNSC's review and assessment. OPG has also submitted a preliminary design information questionnaire for the new facility to the IAEA for review.

SAFEGUARDS BY DESIGN FOR SMRS

In addition to the pre-licensing VDR process, the CNSC accepted an IAEA task, SBD for SMRs, under the Member State Support Program in 2019. This task enables the vendors to discuss safeguards matters with the IAEA in the development of SMR designs and aims to:

- Identify the key technical challenges for safeguards implementation involving SMRs, and steps that can be taken to support incorporating SBD principles into SMR designs in the early stage.
- Enable the IAEA to be adequately prepared to safeguard these facilities, and
- Contribute to better understanding and awareness of safeguards needs by States and industry, avoiding potential challenges in safeguards implementation.

The CNSC is working closely with the IAEA and vendors in the development of SMR designs. Under this task, the CNSC provides preliminary design information to the IAEA and organizes SBD meetings with the IAEA and vendors to review their designs, identify challenges and impacts on safeguards, and discuss safeguards approaches and implementation strategies, and incorporating safeguards considerations and requirements in the SMR designs in the early stage. Activities that have been completed to date include:

- Encouraged all vendors to apply the SBD approach in their design of SMRs.
- Obtained and provided preliminary design information to IAEA for three SMRs including TEI's IMSR-400 design, Moltex's SSR-W300 and the associated Waste to Stable Salt (WATSS) facility, and X-Energy's Xe-100.
- In 2021, five virtual trilateral (i.e., IAEA, CNSC, Vendor) SBD meetings were held to discuss safeguards considerations and approaches in the design of TEI and Moltex's SMRs.
- A SBD meeting was held to discuss the design for X-Energy's SMR in 2022, and
- In December 2022, progress review meetings have been held to further discuss safeguards matters with the development of TEI's SMR designs.

These SBD discussion meetings have provided opportunities for the vendors to present the details of designs at both system and component levels and discuss directly with the IAEA about safeguards considerations, approaches, and measures. It has also facilitated the IAEA and the CNSC to better understand the SMR technologies, design features, potential challenges in future safeguards implementation, and develop preliminary safeguards approaches and equipment for safeguarding these SMRs once deployed. The comments and feedback provided by the IAEA have also facilitated the vendors to consider safeguards requirements in their further development of the SMR design and ensure safeguards can be effectively implemented in these facilities once deployment.

As the designs of SMRs are still evolving in Canada, it is expected that the task of SBD for SMRs will continue to be associated with vendors' design developments.

CONCLUSION

In conclusion, SMRs have been developed in Canada, and a few SMR projects have recently been launched by Canadian nuclear industry in the past a few years. The regulatory framework has been improved and ready for the CNSC to regulate SMRs including pre-licensing VDR and licensing projects to ensure safe construction and operation of SMRs in Canada. The CNSC continues to work with IAEA, provincial governments, and Canadian nuclear industry for the developing and deployment of SMRs. In addition to safety and security by design, the CNSC will continue to encourage vendors and applicants to apply the safeguards by design principle in the design of SMRs, and will work with the IAEA, vendors, and applicants to develop safeguards approaches

and measures for SMRs to ensure effective and efficient safeguards implementation in a cost-effective manner at Canadian SMR facilities.

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