Canada's Experience with Safeguards-By-Design (SBD) for Small Modular Reactors (SMR)

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ABSTRACT

Safeguards-By-Design (SBD) proports to contribute to reducing financial costs, human resource needs and shortening timelines for new nuclear reactor builds by incorporating safeguards needs into their design. Canada's experience implementing the International Atomic Energy Agency's (IAEA) equipment-based approach (EBA) for spent fuel loadings and transfers across its fleet of 19 CANDU reactors offers valuable insight into the SBD concept. The EBA process is demonstrating that having the same reactor type does not necessarily translate into a uniform approach to safeguards across each reactor site. Unique differences, such as the age of the reactor, its location and design modifications create disparity in the equipment needs and installation costs at each CANDU site. Advanced and Small Modular Reactors (SMR) are offering a renewed opportunity to pursue and benefit from SBD, not only because they are still in their design phase, but are also anticipated to be deployed rapidly and in a fleet-approach once authorized by regulators. This could eliminate design variations, which can theoretically lead to the application of identical safeguards across each identical SMR constructed. But is rapid and fleet approach deployment possible?

One factor that can cause delays is the regulatory process associated with authorizing the construction, operation, and eventual decommissioning of a nuclear reactor. The Canadian Nuclear Safety Commission (CNSC), Canada's nuclear regulator, is undertaking an SMR Readiness strategy which aims to ensure its regulatory framework, technical capacity and workforce is ready to support SMR deployment in Canada. In addition, the CNSC offers a Vendor Design Review (VDR) which is an optional service that permits the CNSC to review designs prior to a formal licensing process. A VDR ensures early consideration of safety, security and safeguards expectations, which will permit vendors to consider incorporating them into their designs prior to licensing. These efforts aim to ensure that the CNSC's licensing process does not become a barrier to new reactor deployment. Despite this effort, no regulatory licensing process can proceed at a pace which compromises safety and regulatory independence.

Moreover, different regulatory practices across different jurisdictions and the greater expectation for consultation with affected stakeholders are factors which may affect the length of regulatory licensing processes. This, in addition to other factors outside of regulatory control, may still affect the rapid, fleet approach deployment that SMR vendors are striving for. These factors merit greater discussions. Forums such as the IAEA's SBD working groups, dialogue and

cooperation between international regulators on SMR regulations, and ongoing and frequent discussion between the IAEA, regulators and SMR proponents/operators will be essential in determining if the future of SMRs will also lead to the success of SBD.

INTRODUCTION

The CNSC is preparing to license the construction of Canada's first SMR reactor, the GE Hitachi BWRX-300, set to be built by Ontario Power Generation (OPG) on the Darlington Nuclear Generating Site. Apart from the world watching the outcome of this new build, so too are other Provinces in Canada. This fact highlights predictions that dozens of new SMRs will be deployed globally, many in new entrant countries and jurisdictions. The World Nuclear Association has identified up to 30 countries that are either considering, planning or initiating nuclear power programmes for the first time [1]. Meanwhile, in Canada, the Provinces of Saskatchewan and Alberta have concluded a Memorandum of Understanding (MOU) to cooperate with Ontario and New Brunswick on modalities for facilitating the use of nuclear power [2].

The potential deployment of new nuclear reactors presents the nuclear non-proliferation community with both challenges and opportunities. The emergence of nuclear technology in new jurisdictions will require a strong nuclear regulator to implement the highest levels of safeguards, while also placing additional resource demands on the International Atomic Energy Agency (IAEA) which will be charged with safeguarding these new nuclear facilities and associated fuel cycles. Fortunately, with SMR reactor designs still being developed, there exists a unique opportunity to design-in safeguards features that can both reduce IAEA verification resource demands, and also costs and time requirements associated with introducing safeguards measures *after* a facility is constructed. This concept is commonly referred to as Safeguards-By-Design (SBD).

Once constructed, if the SMR reactor design is proven to be reliable and effective, SMR vendors propose to deploy the same, unchanged SMR reactor design in all subsequent reactor builds, in a so-called "fleet-approach" [3]. This can theoretically result in an SMR which incorporates SBD being deployed over and over again, ensuring that proven and reliable safeguards measures will be implemented equally and effectively across all the reactors, regardless of their location. This can result in ensuring that the future global "fleets" of SMRs will all meet the highest nuclear non-proliferation standards. This paper will explore this concept further.

SMRs AND NUCLEAR PROLIFERATION

As a starting point, it is important to remind readers why safeguards must be in the SMR conversation early. A major feature cited by SMR vendors and currently being explored by nuclear regulators, the IAEA and various national laboratories is that SMRs' unique characteristics reduce the risks to safety, nuclear security and even nuclear proliferation. Characteristics such as smaller fuel inventories, liquid metal or salt coolants, below-grade reactors and fuel produced from spent fuel proport benefits to safety, security and non-proliferation when compared to traditional, large-scale reactors [4]. The IAEA SMR Regulators Forum is actively addressing these claims [5]. From a nuclear non-proliferation perspective, however, if and SMR reactor uses nuclear material as fuel, and generates special fissile material as waste, it must be subject to IAEA safeguards pursuant to Article III.1 of the Treaty on the Non-proliferation of Nuclear Weapons (NPT) [6]. In Canada, SMRs will not have a legal or regulatory distinction from traditional nuclear reactors, hence will be subject to the same safeguards requirements as existing reactors. The distinction arises from the fact that SMR designs are not yet finalized. This affords the opportunity for the vendor, in collaboration with the IAEA and the national nuclear regulator to design-in safeguard features before the SMR is constructed. This can significantly reduce cost, time and resources then if these features are retrofitted into the reactor once built. Canada's experience operating large-scale nuclear reactors can shed light on what to expect in the upcoming SMR era.

CANDU REACTORS AND SAFEGUARDS EXPERIENCE

Canada has over 60 years of nuclear operating experience, with a current nuclear reactor fleet consisting of 19 Pressurized Heavy Water Reactors, otherwise known as CANDU (CANada Deuterium Uranium).

Nuclear Generating Station Name	Number of Units	Start of Commercial Operation
Pickering A	4 (2 in safe shutdown)	1971-1973
Pickering B	4	1983-1986
Bruce A	4	1977-1979
Bruce B	4	1984-1986
Gentilly-2	1 (shutdown)	1983
Point Lepreau	1	1983
Darlington	4	1990-1993

Table [7].

In addition to the CANDU reactors in Canada, there are additional CANDU reactors operating globally in Argentina, China, Republic of Korea, Romania, as well as India and Pakistan [8].

As seen in the table above, each Canadian CANDU reactor entered commercial operation at different periods across a 20-year span. This inevitably meant design changes were introduced to each reactor as operating experience was gained and utility needs varied.

Moreover, CANDU reactors present unique challenges for the application of IAEA safeguards, namely due to their use of online refuelling and heavy water moderator. Consequently, in 1978, Canada began working with the IAEA under the Canadian Safeguards Support Program (CSSP) to jointly research and develop technology that could effectively apply safeguards to CANDU reactors [9]. This effort led to the establishment of numerous surveillance and monitoring equipment to detect diversion and support nuclear material accountancy, coupled with an extensive IAEA in-person inspection regime [10]. Like anything, the IAEA safeguards system continues to evolve to incorporate new processes, technology and procedures to ensure effectiveness while improving efficiency.

In 2005, Canada first obtained the IAEA's broader conclusion, which signifies that the IAEA was able to determine that there was no indication of diversion of declared nuclear material or undeclared activities in Canada. On that basis, the IAEA can conclude that all nuclear material in Canada remained in peaceful activities. This permitted the IAEA to implement integrated safeguards, a first iteration of a State-Level Approach (SLA). The SLA expanded the IAEA's focus from just the verification of declared nuclear material and activities to include an assessment of all available information concerning a State's entire nuclear program. Under the SLA, the IAEA would no longer only rely on criteria-driven safeguards based on facility and material types, but also include a risk-informed approach. The SLA later lead to a Revised State-Level Approach (revised SLA) which is seen as a more tailored, impartial and robust approach to safeguards implementation. Under a revised SLA, the IAEA establishes an acquisition path analysis which identifies all potential pathways a state can implement should it seek to develop nuclear weapons. The IAEA established technical objectives for each path, along with specific safeguards measures and safeguards activities considered appropriate for each path and the risk it carries. Measures can include both inspections and/or containment and surveillance. For Canada, in consideration of the unique fuel cycle and the different acquisition pathways along it, the IAEA elected to rely on additional installed equipment to remotely monitor fuel movement at CANDU reactor sites. In doing so, the IAEA and the CNSC are now in the process of pursuing the CANDU Equipment Based Approach (CEBA) project for spent fuel loadings and transfers [11].

CEBA specifically targets oversight of CANDU reactor fuel transfers, including the loading of spent fuel from wet to dry storage. The project aims to expand the use of surveillance and unattended monitoring systems, which is expected to not only improve efficiency and effectiveness of spent fuel transfer verification, but may reduce the need for IAEA in-person verification of these activities, which currently involves approximately 30 unannounced inspections per year. The CEBA is currently being implemented at all operating CANDU facilities in Canada.

Early experience is already demonstrating that design differences at each CANDU reactor site is translating to different equipment needs, costs and time required to support the installment of the new IAEA equipment. The CEBA project is a good example of the high monetary, resource and time costs associated with retrofitting an existing nuclear facility with surveillance and monitoring equipment. The entire CEBA project is expected to take 5 years to fully implement and cost several millions of dollars. It requires extensive collaboration between the IAEA, the CNSC and the operators, first to identify the equipment needs, and then assess the impact of the design change required to install the proposed equipment. The equipment cannot interfere with the safety and operation of the facility, and the costs for any installation or facility modifications must be negotiated between the three parties.

The example of CEBA is a testimony to the benefits that stand to be gained if the SBD concept is applied in future SMR reactors. How would SBD be impacted in a fleet approach to deployment [12]?

SMRs AND FLEET APPROACH

Canada's Small Modular Reactor Roadmap cites SMRs as "a source of safe, clean and affordable energy" [13]. SMRs can be highly versatile, with options being explored for them to provide on-grid, off-grid electricity, along with power for heavy industry. They are also expected to be significantly less costly to construct, and given their modular design, can be deployed in a rapid, fleet-based approach [14]. In most SMR strategic plans, the use of a fleet-approach is largely touted as an economic benefit as it can drastically reduce costs and time associated with construction. The following two statements reflect this notion:

"By taking a similar approach to building a fleet of SMRs, we will deliver cost and schedule savings, and power 1.2 million homes from this site by the mid-2030s." Quote by Ken Hartwick, OPG President and CEO [15].

Once a reactor is licensed and operational, the licensing of subsequent units should be significantly more efficient provided there are no design changes. This will provide investors and operators the licensing confidence necessary to move forward with a "fleet" approach ('i.e., deploying the same technology in multiple jurisdictions), which can enhance the business case for SMRs [16].

But can a fleet-approach also prove beneficial to safeguards? As noted above, if the first of many SMRs incorporates SBD, all subsequent SMRs built, regardless of where, will also include those safeguards measures. Additionally, a fleet-approach would remove any design changes between reactors, thus negating the issues encountered under the CEBA project where design differences between CANDU reactors translates to more complex and costly safeguards equipment installation needs for each reactor site. If all SMRs have the same designs, as safeguards evolve and new surveillance and containment equipment is needed, installation costs amongst the entire SMR fleet can be predicted to be uniform and consistent across each individual reactor. But is a fleet approach really possible?

COMPLEXITY IN DEPLOYMENT

While the idea of a fleet approach is promising, many factors need to come together to ensure its success. First is the nuclear reactor licensing process. Nuclear regulators must be assured that the design meets all regulatory requirements and can operate safely and without negative impact to the environment. There is also a growing need and expectation to engage in consultation to ensure public by-in to all new nuclear projects. In Canada, the current timeline to obtain a license to operate a new nuclear reactor is approximately 9 years [17]. Factors that can impact the length of the licensing process include the completeness of the information provided in the application, the extent of the environmental impact of the proposed activity, the extent of public need to be consulted, and the satisfactory resolution of any safety issues [18]. Additionally, it is a sovereign right and responsibility of any state to undergo its own licensing and review process associated with the selection and eventual licensing of a nuclear reactor. Therefore, it cannot be assumed that the approval of an SMR in one country will automatically translate into approval in another.

Once a license is granted, reactor construction needs to be efficient. This can be impacted by several factors, such as the complexity of the reactor technology, the potential need to undertake design revisions as construction commences, the experience of the contractors and the reliability of their supply chains [19].

Lastly, environmental factors may require unique design modifications, which may impact safeguards and fleet approach from the beginning. For example, SMRs located in countries that suffer from water scarcity may require alternate means to cool the reactors compared to reactors located near bodies of water. Other geographic, environmental or seismic features may require additional design modifications, as may the proximity to or distance from population centers [20].

All these factors may result it delays, which in turn may either stall rapid, fleet deployment, or introduce design changes that affect SBD. Other factors may require an SMR to have a different design, which may result in different safeguards features than other SMRs of the same type. To further explore how SBD, reactor designs and deployment interact, frequent and collaborative discussion between SMR vendors, nuclear regulators and the IAEA should be undertaken.

SMR COLLABORATION ON SBD

The greatest advantage for SMR vendors, nuclear regulators and the IAEA is the ability to collaborate on safeguards before SMR designs are finalized. Presently, there are three major initiatives the CNSC is involved in that permit this type of collaboration.

First is the CNSC's Vendor Design Review Process (VDR). An optional pre-licensing service, the VDR process permits the vendor to submit preliminary design documentation for CNSC review. There are three phases to the CNSC's review. In Phase I, the CNSC considers the design and the vendors understanding of Canadian regulations and the CNSC's licensing expectations. Phase II examines if there are any fundamental barriers to licensing, and if there are any generic safety issues in the initial design. Phase III permits the vendor to request additional review of focus areas. Safeguards considerations are included across all three phases. The CNSC's VDR is thus an ideal opportunity for vendors to understand and consider the integration of safeguards into their SMR designs [21]. The VDR process falls within the CNSC's broader effort to ensure its readiness for SMR licensing. This includes assuring it has the appropriate technical expertise, workforce and regulatory framework to effectively conduct licensing assessments of novel SMR and advance reactors, and reduce any barriers to timely yet rigorous licensing activities.

A second area of promising collaboration is through the IAEA Member State Support Program (MSSP) task on safeguards-by-design for SMRs. SMR vendors presents safeguards-relevant information about their designs to enable the IAEA to consider safeguards approaches, equipment and techniques. Noting that many SMR designs present novel technology and unique fuels that may be more complex to safeguards (e.g., molten salt) the task aims to identify technical challenges for safeguards implementation involving these novel SMRs. It then aims to seek to develop safeguards measures, approaches and technologies that are best applicable to able to each specific SMR design, while further encouraging SBD principles. Lastly, the task will seek to test and validate the surveillance, containment, monitoring and nuclear material accountancy technologies, processes and procedures established from the collaboration to ensure their effectiveness for deployment [22].

A final forum for collaboration is through a series of MOUs the CNSC has concluded with various counterparts, notably the United Kingdom's Office of Nuclear Regulation (UK ONR), the United States Nuclear Regulatory Commission (US NRC), and the Polish National Atomic Energy Agency (PAA). It also contributes to the IAEA's Nuclear Harmonization and Standardization Initiative. The objective of these engagements is to bring together experience and expertise and seek opportunities to leverage the reviews and assessment activities of other regulators when conducting licensing activities, and where possible, conduct joint assessments when circumstances warrant. The initiative also seeks to find areas where licensing can be harmonized, and to assist in the development of new regulations for advanced technologies. The objective is to reduce SMR regulatory licensing timelines without compromising the rigor of the regulatory assessment process nor infringing on independent, sovereign review, while ensuring regulatory consistency and predictability across various jurisdictions [23].

These examples demonstrate that many platforms have been established which can actively work towards promoting the benefits of SBD and reducing barriers to deployment, namely in the area of regulatory licensing. Combined, these initiatives can be the greatest means to achieve SMR deployment which encompasses an SMR reactor that has safeguards built-in, thus assuring the promotion of the highest levels of safeguards worldwide as nuclear enters the SMR future.

CONCLUSIONS

The promise of SMR technologies is upon us, with Canada commencing licensing review of its first SMR reactor. Apart from demonstrating if the technology works, the SMR at Darlington will be a testbed for the future of SMR deployment domestically and abroad. The reactor also represents a tremendous opportunity for the nuclear non-proliferation community if the opportunity is seized and it becomes the first SMR with safeguards incorporated into its design. This prospect carries several advantages, including reduced cost, time and resource demands associated with implementing safeguards. It also has the potential to strengthen the entire global nuclear non-proliferation regime by ensuring that that highest levels of safeguards are replicated across each subsequent SMR built. Encouraging vendors to engage with the IAEA and nuclear regulators early, whilst providing them platforms where to do so are necessary ingredients for ensuring SBD are considered and ideally incorporated as SMRs move from designs to reality.

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