SAFEGUARDS BY DESIGN AND ADVANCED REACTORS: OVERCOMING THE CATCH-22 TO IMPLEMENTATION

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Abstract

Safeguards by design (SBD) is vital to ensuring "safeguardability" of novel, small modular, and other advanced nuclear reactors and facility types, as well as maintaining safeguards effectiveness and efficiency for such facilities. The IAEA encourages SBD among facility designers and vendors, but it is not a requirement the IAEA can enforce and instead the onus is on industry to deliver it. However, the practical application of SBD is poorly understood for specific facility types and many advanced reactor developers are new to safeguards and often unaware of safeguards requirements. The few designers that do engage the IAEA often seek an IAEA's "seal of approval" to make designs more marketable, which the IAEA cannot give. However, the IAEA and national governments are often constrained in their ability to conduct outreach to reactor designers as this would be viewed as promoting one designer over another. This creates a scenario where the IAEA looks to Member States and industry, Member States look to industry and back to the IAEA, and industry might look back to the IAEA, if at all. The paper will describe this "Catch-22" in SBD implementation, describe some practical implications of SBD, and suggest paths forward for effective implementation.

1. INTRODUCTION

Once they are commercially deployable, small modular reactors (SMRs) and other advanced reactors bring the promise of significantly expanding access to nuclear science in technology globally. Developing States that had never considered nuclear power for electricity generation before could find themselves in a position to tap this resource. SMRs could be accessible to States with smaller electricity grids or be deployed to remote locations like mines. There are also many other potential uses for these reactors, including water desalination, heating, steam for industrial applications, fertilizer manufacturing, and hydrogen production.

SMRs have been on the horizon for some decades now, though in 2024 they seem closer to operational deployment than ever. The last supplement to the International Atomic Energy Agency's (IAEA) Advanced Reactor Information System, published in 2022, noted that there were more than 80 SMR designs under development and deployment at different stages in 18 IAEA Member States. [1] The number of SMR designs under consideration continues to increase, though not all designs will be commercially viable.

Under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), non-nuclear-weapon States (NNWSs) are required to conclude comprehensive safeguards agreements (CSAs) with the IAEA that cover "all source or special fissionable material in all peaceful nuclear activities within its territory, under its jurisdiction or carried out under its control anywhere, for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or other nuclear explosive devices." [2]

Many SMR designs are under development in nuclear-weapon States (NWSs), which are not obligated to conclude CSAs. Instead, the NWSs have voluntary offer agreements with the IAEA, by which the State offers certain facilities and locations outside facilities for verification at its discretion.

While safeguards approaches for traditional facilities are well understood, many SMRs are likely to have characteristics that might present challenges to traditional safeguards implementation. For example, many SMRs are imagined to be produced in a factory setting where the fuel is sealed inside the core and exported to recipient States (likely NWWSs) as a complete unit. As the NWS is under no obligation to allow the IAEA to verify the fuel when it is on its territory or under its jurisdiction, the IAEA could face challenges in verifying the fuel once control is transferred to the NNWS recipient if the reactor is sealed and the IAEA has not already received design information. This is further complicated because many SMR developers are not State entities but rather private start-ups.

2. THE CATCH-22 OF IMPLEMENTING SAFEGUARDS BY DESIGN

If SMRs and other advanced reactors are to propel sustainable development forward, safeguards considerations—in addition to nuclear safety and security—must be integrated into every stage of the design process, from the preconceptual phase all the way through to operation and decommissioning. The IAEA defines this practice, known as safeguards by design (SBD), as follows.

> *The integration of safeguards considerations into the design process of a new or modified nuclear facility or location outside facilities (LOF) at any point in the life cycle — from initial planning through design, construction, operation, waste management and decommissioning. The goal of safeguards by design is the improvement of safeguards implementation by addressing potential efficiency and effectiveness issues early in the design process. Safeguards by design is a voluntary process that neither replaces a State's obligations for early provision of design information under its safeguards agreement nor introduces new safeguards requirements.* [3]

Simply put, one can think of effective SBD implementation as early stakeholder engagement. However, the IAEA faces challenges in engaging with designers on a large scale, raising awareness of the benefits of SBD (including economic benefits) to both designers and potential end users, and encouraging more designers to consider safeguards early on in the design process. This is, in part, due to the large number of advanced reactor designers currently working on their own designs.

The IAEA has made efforts to address these challenges, in part through its SMR Regulators' Forum, established in 2015. However, as SMRs and other advanced reactor designs move closer towards deployment, more engagement is needed to ensure that these reactors are also safeguardable without causing costly retrofits or schedule delays. The IAEA is not in a position to reach out to initiate discussions on SBD with each individual designer, in part to a financial and human resource deficit and also because this can be viewed as the Secretariat giving preferential treatment to one designer over another. The Member State Support Programmes sometimes have similar hesitations in reaching out to individual designers.

Some reactor designers do engage with the IAEA on SBD, including on developing guidance for SMRs and other advanced reactors. Some of these designers engage with the goal of receiving a "stamp of approval" from the IAEA to make their design more marketable, but the IAEA is not able to "bless" reactor designs as such. The majority of developers of SMRs and other advanced reactors are either unaware of safeguards requirements or are not considering them.

This creates a catch-22—a paradoxical problem that resists solving because of contradictory limitations—by which the IAEA looks to the Member States and industry to implement SBD, the Member States look to industry, and industry looks back at the IAEA with none of these parties fully able to take ownership of SBD. The closer advanced reactors get to deployment without this catch-22 being addressed, the more difficult it will be for SMRs to be deployed at commercial scale.

3. WHAT ARE THE LEGAL CONSIDERATIONS FOR SAFEGUARDS BY DESIGN?

There is no legal requirement for designers to implement SBD and no government to date imposes SBD as a requirement before licensing for export. There is some question as to how the legal requirement for a State with a CSA to provide preliminary design information would be interpreted, and as to what licensing officials—both in licensing the product itself and approving export licenses—should do to promote SBD.

3.1. Provision of Design Information

Under the NPT, all NNWSs are required to have a CSA with the IAEA. One requirement of a CSA, as detailed in the modified Code 3.1 of the subsidiary arrangements associated with the agreement, is that the State must provide design information with respect to each of its facilities as soon as the decision to construct or authorise construction of a new facility is taken, whichever is earlier.[1]

This generates novel questions as concerns the export of SMRs from a NWS to a NNWS, which require consideration on a legal basis. Should a NNWS authorise construction of an SMR on its territory that would be imported from a NWS, who would provide the required early design information to the IAEA? What sort of arrangement could an importing NNWS and an exporting designer from a NWS make to ensure that the IAEA has design information as early as possible? Most relevant for this paper, what is the proper forum for those conversations?

Regardless of the answers to those questions, it would be ideal for the IAEA to have design information for SMRs long before their export, so that safeguards approaches can be conceptualised in advance, potential technical challenges can be addressed, and delays to deployment and safeguards implementation can be avoided. Reactor designers should provide conceptual design information to the IAEA as early in the design process as possible. Potential end users can create demand signals for this action in their discussions with advanced reactor designers, as well, messaging that SBD mitigates challenges for safeguards for both the designer and the end user.

3.2. Domestic Licensing

At the time of writing, no State is on record as requiring that its designers implement SBD as part of the licensing process. According to IAEA guidance, some major benefits of SBD include: minimising the risk associated with project scope, schedule, budget and licensing; reducing the cost of safeguards implementation to the operator and the IAEA; decreasing costs for State regulators; and improving safeguards assurances to the international community and the general public. Further, the "most effective option for SBD would be to have international safeguards become a standard part of the design and licensing of nuclear facilities." [4]

It is in the State's interest that SMR designers implement SBD. What are the domestic challenges that prevent States from making SBD a part of the domestic licensing process? How can those challenges be overcome and which stakeholders would need to be involved? What is the proper forum for discussion: international meetings or domestic regulatory bodies?

4. WHAT ARE THE VERIFICATION CONSIDERATIONS FOR SAFEGUARDS BY DESIGN?

There is broad agreement in the international community that SBD should be implemented. In addition to the catch-22 described above, another challenge to SBD implementation is that what it entails is often poorly understood in practice. In 2012, the Idaho National Laboratory in the United States published a paper in which the authors noted that the "concept of designing safeguards into the facility in the earliest stages includes not only the identification of IAEA equipment, but also operational parameters and procedures to accommodate IAEA verification requirements." [5]

The authors further noted that this would include, inter alia, ensuring:

- inspector access for other activities such as design information verification where facility construction and capabilities are verified against the declared design/functionality;
- minimisation of alternate nuclear material pathways to reduce verification needs;
- clear material balance area boundaries where potential losses and gains can be verified;
- access to all nuclear material streams and storage locations for verification; and
- continuity of knowledge of nuclear materials and operations. [6]

Following increased interest in the 1990s and the 2000s and a workshop held at the IAEA on "Facility Design and Plant Operation Features that Facilitate the Implementation of IAEA Safeguards", national

[1] Prior to 1992, Code 3.1 required States to provide preliminary design information for a new facility 180 days before nuclear material was introduced into a facility. In 1992, the Board of Governors approved a proposal by the Director General to modify Code 3.1 to require design information as soon as the decision to construct or authorise construction of a new facility had been taken.

laboratories in the United States published a description of a proposed model for SBD. [7] In 2023, representatives of the Westinghouse Electricity Company (hereafter “Westinghouse”) referenced that model in a paper published at a joint meeting of the Institute for Nuclear Materials Management and the European Safeguards Research and Development Association. [8]

The result of Westinghouse’s analysis was that, in the context of advanced reactor designs, the SBD model should be updated. This would include more emphasis on direct engagement between the IAEA and the designer for the provision of design information during the preconceptual and conceptual phases, rather than going through the State system of accounting for and control of nuclear material (SSAC). The Westinghouse paper also noted that SBD would benefit from direct engagement between the IAEA and the reactor designer on devising effective approaches to safeguarding SMRs.

5. WHAT ARE THE CHALLENGES TO SBD IMPLEMENTATION FOR ADVANCED REACTORS?

While there is broad agreement that SBD is a beneficial practice—especially as concerns SMRs and other advanced reactors—challenges remain to its implementation. The primary challenges are a lack of awareness among key stakeholders, primarily the reactor designers and potential end users, of safeguards requirements in general and the economic benefits of SBD in particular.

As noted above, the further towards deployment an SMR goes before the IAEA receives design information and is able to provide insight into safeguards requirements, the higher the risk becomes that the design will require costly retrofits and incur delays in the deployment schedule. This risk becomes particularly acute for the designs being developed in NWSs, which are not obligated to report to the IAEA on all nuclear activities. As many SMR designs are imagined as factory-built units with the fuel sealed inside the core before export, early dialogue with the IAEA is critical to avoiding retrofits and schedule delays, as the IAEA will need to verify the fuel in some way when in use by a NNWS.

This is not a theoretical challenge. In the 1980s, the IAEA began to contemplate the wide use of unattended monitoring systems for nuclear facilities as a way to improve both the effectiveness and efficiency of safeguards. The IAEA determined that such systems could be deployed in facilities where the cost of the system could be recovered within three years due to a reduced inspector presence and related activities in facilities. While unattended monitoring systems are widely used today, former IAEA officials noted that their installation, “while required by existing circumstances, was costly, time consuming, had considerable impact on the operator, and resulted in less than effective safeguards due to the necessary trade-offs under these less than ideal conditions.” [9]

The international nuclear governance community has the opportunity to avoid a similar situation with SMRs if it takes action now.

Another challenge to the implementation of SBD from the designers’ side is the difference in priority placed on safeguards compared to nuclear safety and security. These three disciplines, while mutually reinforcing, are often treated in silos. Advanced reactor designers often and understandably treat nuclear safety with the highest priority, followed by nuclear security, and lastly nuclear safeguards.

Between 2005 and 2008, the United States Department of Energy (DOE) conducted a comprehensive review of how safety standards were integrated in the design of nuclear reactors. At the end of this process, new standards for safety by design were adopted. [10] In 2010, the Pacific Northwest National Laboratory published a technical report detailing lessons learned from that process that could be applicable for SBD. One of the authors’ conclusions was that the internal and external drivers “for integration of safety into the design were much stronger than the corresponding drivers for institutionalizing SBD appear to be. DOE senior management was so strongly committed to the development and institutionalization of [safety by design] that the efforts could not be permitted to fail.” [11]

Lack of engagement between advanced reactor designers and the IAEA resulting in increased risk of costly retrofits and schedule delays, the siloing of considerations for safety, security and safeguards, and the lack of priority placed on safeguards by many reactor designers are challenges that the international nuclear governance community should work collaboratively to solve. Potential end users can also create demand for SBD, noting the reduced burden on operators to facilitate IAEA inspections and other verification activities if safeguards are "baked into" the reactor design.

6. WHAT ARE STRATEGIES TO ADDRESS CHALLENGES TO SBD IMPLEMENTATION FOR ADVANCED REACTORS?

As SMRs and other advanced reactors near deployment, the IAEA, national governments and non-governmental organisations can take steps to promote the implementation of SBD.

6.1. Improve Understanding of the Economic Benefits of SBD by Designers and End Users

The benefits of SBD for the effectiveness of safeguards are generally understood. What is less well understood by reactor designers and potential end users are the economic benefits of SBD. The paper noted above published by Westinghouse talks about the "business model" for SBD and notes four possible effects of safeguards on the business case for any advanced reactor design: (1) direct capital and operating cost increases; (2) additional design effort and schedule delays imposed by additional requirements on reactor systems; (3) increased uncertainty regarding the cost and time-to-market for the approved design; and (4) expansion of markets due to ability to deploy in countries requiring international safeguards. [12] As of 2023, Westinghouse concluded that the net effects of SBD were *positive* for Westinghouse's eVinci microreactor, having considered SBD from the beginning. As more reactor developers explore the economic benefits of SBD, these benefits should be widely promoted.

6.2. Leverage Support from Non-Governmental Organisations

As neutral parties, non-governmental organisations (NGOs) have a role to play in promoting SBD through research on and promotion of the benefits of SBD, and as conveners for dialogue between industry, national governments and the IAEA. The Vienna Center for Disarmament and Non-Proliferation (VCDNP) convened three workshops between April 2019 and November 2020 to discuss the unique challenges and benefits that advanced and emerging technologies pose to nuclear safeguards and export controls. Participants of that workshop series acknowledged the benefits of NGOs conducting research and dialogue activities, given their capacity to act as a "safe space" for advanced reactor developers and regulators (national, regional and international) and also to assist regulators with socialising SBD within the advanced reactor industry. [13] National governments should support the NGO community in developing strategies to increase awareness of SBD and promote its use.

6.3. Increase the Role of National Governments in Promoting SBD

While national governments take responsibility for licensing new nuclear power plants, they can do more to promote the implementation of SBD, for example, by legally requiring SBD as part of the reactor licensing criteria. [14] Moreover, national governments, including through Member State Support Programmes to the IAEA, are in a unique position to foster dialogue between SMR designers from different countries. This could come in the form of more robust support, including financially, to the IAEA's existing activities in promoting SBD, as well as by convening SMR designers in a separate forum to discuss safeguards considerations for reactors nearing deployment. The latter activity would have to be conducted such that the designers were confident that no proprietary information was at risk; as noted above, NGOs have a unique role to play as conveners to provide designers and potential end users alike an opportunity for results-oriented dialogue in a neutral place.

6.4. Increase Visibility of SBD in the IAEA's Policymaking Organs

The IAEA is a technical organisation that carries out a technical mandate in an environment that must accommodate diverging perspectives among Member States. SBD is a technical process that should be developed on a technical basis. However, political momentum can help to raise awareness of the importance of SBD. National governments and the IAEA can use the Board of Governors and the General Conference as forums for political discussions on SBD, including what Member States can do collaboratively to ensure its implementation and improve understanding of its benefits. As SBD stands to improve access to peaceful uses of nuclear science and technology, this discussion can take place both under the auspices of safeguards and technical cooperation.

6.5. Supplement the IAEA's Resources

Since the 1980s, the IAEA has run a zero-real-growth or near zero-real-growth budget, meaning that its regular budget increases from year to year to account for inflation, but not otherwise. [15] As the number of facilities and locations outside facilities required to be safeguarded increases and the budget remains static, the IAEA is increasingly turning to extrabudgetary contributions, including through Member State Support Programmes, to ensure safeguards effectiveness while maintaining efficiency. Existing efforts from the Secretariat to improve understanding of SBD and develop safeguards approaches for SMRs and other advanced reactors should be supplemented by further financial support from Member States. This is especially true for countries hoping to deploy these reactors. The United States' Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology (FIRST) programme would be one potential vehicle for this support, as well as a potential vehicle for NGOs to receive funding for additional support to IAEA activities.

7. CONCLUSION

This paper has described the importance of SBD in facilitating the wider spread of SMRs and other advanced reactors to support sustainable development, enumerated challenges to the implementation of SBD, and suggested strategies for the wider promotion of SBD. As discussed, one of the core issues in SBD implementation is that more stakeholders should take ownership of this issue, recognising the benefits to them in doing so.

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