# safeguards by design: preparing for small modular reactors

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**Abstract**

Safeguards are a set of technical measures applied by the IAEA on nuclear material and activities, through which the IAEA seeks to independently verify that nuclear facilities are not misused, and nuclear material not diverted from peaceful uses. States accept these measures through the conclusion of safeguards agreements with the IAEA, applicable for most States to all nuclear source and special fissionable material in all peaceful nuclear activities within the State’s territory, under its jurisdiction, or carried out under its control anywhere. The IAEA’s capability to implement safeguards on new nuclear technology must be ready before the technology is deployed. The innovative and evolutionary technologies proposed in several small modular reactor (SMR) designs will introduce unique safeguards challenges. This suggests the need for early awareness of the technology designs, requiring direct engagement with design companies – a challenging prospect given the IAEA’s limited resources and the number and variety of SMR designs currently in development. The process of early consideration of safeguards in the design process is known as safeguards by design (SBD). SBD can not only avoid costly retrofitting of safeguards equipment or modified facility features after construction, but also potentially improve the efficiency and effectiveness of safeguards implementation throughout the life of a facility – thus reducing the burden on all stakeholders (operator, State authorities, IAEA) during operation. To manage the SBD process for SMRs, the IAEA has initiated tasks with several Member State Support Programmes that allow direct engagement with SMR design companies, with the goal of facilitating timely deployment and efficient, effective safeguards implementation during operation. The paper will summarize the status of this project, including lessons learned, next steps and future needs, as the IAEA works with Member States to jointly prepare for the timely and secure deployment of SMRs.

## Iaea safeguards

Safeguards are a set of technical measures applied by the International Atomic Energy Agency (IAEA) on nuclear material and activities, through which the IAEA seeks to independently verify that nuclear facilities are not misused, and nuclear material not diverted from peaceful uses. States accept these measures through safeguards agreements with the IAEA, the most common type being a Comprehensive Safeguards Agreement (CSA) [1], concluded by Non-Nuclear Weapon States (NNWS) as an obligation under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). A State under a CSA accepts IAEA safeguards on all nuclear material in all peaceful nuclear activities within its territory, under its jurisdiction, or carried out under its control anywhere. Most States have also concluded an Additional Protocol to their CSA, which provides the IAEA with broader access to information about the State’s nuclear-related capabilities, activities, and plans [2].

Safeguards facilitate an independent assessment of the correctness and completeness of a State’s declarations to the IAEA related to nuclear material and activities. A State’s declaration for a new facility includes the provision of early design information as soon as a decision to construct or to authorize construction has been taken (whichever is earlier), increasing in detail during construction and updated through the life of the facility as it is modified and eventually decommissioned. All safeguards-relevant information is evaluated for consistency, informing an annual safeguards assessment for each facility and the State as a whole. Safeguards measures include on-site inspections and design information verification, complemented by containment and surveillance (C/S) techniques (e.g., seals, cameras) and information gathered through open-source and third-party sources.

## SAFEGUARDS BY DESIGN (sbd)

A State’s obligation under a CSA begins with the early provision of design information to the IAEA following a decision/authorization to construct a new nuclear facility, enabling the IAEA to begin its development of a facility-specific safeguards approach. At this relatively late stage of facility design, a safeguards approach that involves the installation of IAEA seals, cameras, or other equipment would typically require retrofitting of these measures into the existing design. To avoid these potentially expensive retrofits and other associated inefficiencies, efforts are made to take safeguards needs into account earlier in the design process itself – a concept known as ‘safeguards by design’ (SBD) [3].

SBD is defined as an approach whereby international safeguards requirements and objectives are integrated into the design process of a nuclear facility (or location outside facilities, if applicable), from initial planning through design, construction, operation and decommissioning [4]. SBD is a voluntary best practice that facilitates optimization of economic, operational, safety and security factors, along with international safeguards requirements. SBD neither replaces a State’s obligation for early provision of design information to the IAEA under its safeguards agreement, nor introduces new requirements. The IAEA has developed SBD guidance that spans the nuclear fuel cycle [4]-[11].

The avoidance of costly retrofitting mentioned above is one of several potential benefits of SBD, which together reduce the burden of safeguards implementation for all stakeholders during the many years of operation of a facility [4]:

* More efficient/optimized in-field inspections, reducing the time and effort of IAEA inspections that require preparation and participation by the facility, State authority, and IAEA;
* Potential incorporation of advanced safeguards technologies, such as unattended monitoring systems and remote data transmission, that can increase both the efficiency and effectiveness of safeguards verification;
* Reduction of costly retrofitting of IAEA equipment;
* Facilitation of IAEA shared use of operator equipment or information (if applicable);
* Increased flexibility for future installation of safeguards equipment as activities evolve;
* Minimization of conflicts and leveraging of synergies with safety and security needs;
* Reduction of risk to the cost, scope and schedule of new facility deployment; and
* Improved understanding by all stakeholders (operator, State authority, State regulator, IAEA) of each other’s needs with respect to safeguards rights and obligations.

Particularly for designers of nuclear facilities located in Nuclear-Weapon States (NWS), awareness of international safeguards tends to be low since civilian nuclear activities in these States are generally not subject to IAEA safeguards. Nevertheless, since many companies intend to export their nuclear technology to States where it will be subject to IAEA safeguards, it is important that this significant recipient-State obligation be taken into consideration, together with other customer requirements based on the relevant national regulations and standards.

## safeguArds challenges presented by smrs

The IAEA has been applying safeguards to reactor facilities for over half a century. While the technology and policies for applying safeguards has evolved significantly in this time, the same cannot be said of reactor technology itself – especially from the point of view of safeguards requirements. This situation is now changing, on a large scale and relatively quickly.

Today almost a hundred small modular reactor (SMR) designs are under development [12], many representing either innovative reactor technology (and related fuel-cycle facilities), or new concepts of operations applied to smaller, often evolutionary, versions of conventional reactor technology. In either case the IAEA will need to develop new safeguards approaches, and be ready to implement these as soon as nuclear material is received on site and enters facility nuclear material accountancy and control (NMAC). The development of a new safeguards approach typically begins once early design information is declared to the IAEA, which has typically allowed sufficient time since (a) reactor build projects have tended to last a decade or longer, and (b) safeguards approaches have often been based upon those already developed for similar technology. Neither of these factors can be counted on with the development of SMRs, since technology is both new and quicker to build.

While it is true that many of the SMR concepts and associated fuel-cycle processes proposed today have been discussed, tested, or even prototyped within the global nuclear R&D community for decades, few have had any significant level of international safeguards applied. The IAEA therefore has little practical safeguards experience with most of the novel concepts, and both time and resources will be needed to prepare for these – particularly where customized safeguards measures are needed. Time and resources are exactly what SBD facilitates, by initiating the necessary technical discussions early in the process; the resources will necessarily come from both the IAEA and supporting States (e.g., industry, academia, or R&D community).

The following innovative features of SMR technology will present new challenges for the IAEA in the development of safeguards approaches [3]:

* New fuels and fuel cycles, including those involving high-assay low-enriched uranium (HALEU), thorium, molten salts, pebble and prismatic graphite, and pyroprocessing: these represent new or previously limited-use technology that the IAEA will need to fully understand and be able to effectively verify independently;
* Longer refuelling cycles, on-load refuelling, and sealed cores: these will potentially challenge the IAEA’s need for independent continuity of knowledge, and require the of seals and unattended monitoring;
* Smaller facility layouts: these will potentially create tighter, more complex spaces for IAEA containment and surveillance (C/S) measures, with potentially significant radiation fields and other health and safety considerations relevant to in-field inspection, design verification, and equipment maintenance;
* New deployment models, including factory-fuelled cores, transportable and floating nuclear power plants, transnational supply of sealed cores, and remote, distributed fleets of microreactors: these will potentially challenge the resources and policies of the IAEA under existing safeguards implementation models (e.g., transnational supply of seals cores would necessitate design verification in the supplier State, involving a significantly different safeguards agreement if the supplier State is a NWS);
* New spent fuel flow, storage configurations, and physical forms (both item and bulk): these can potentially lead to verification challenges for the IAEA, for example if smaller irradiated nuclear material items are stacked in storage pools, or if re-frozen irradiated bulk fuel or irradiated pebble fuel is stored in containers;
* Diverse operational end uses, including district heating, desalination, hydrogen production – possibly in combination with electricity production: these diverse energy streams will all need to be monitored by the IAEA since together they provide safeguards-relevant information related to declared operation status; and
* Non-traditional concepts of operations, including multi-unit operation with shared fresh and spent fuel management: these can potentially lead to a significant increase in IAEA resources needed to implement traditional safeguards approaches, even if the fuel technology itself doesn’t represent a radical departure from past conventions (e.g., integral LWR designs).

## Aspects of safeguArds that will potentially be important for smrs

Given the challenges listed in the previous section, it is clear that the following aspects will potentially be important in achieving either efficiency or effectiveness (or both) of safeguards implementation for future SMRs:

* Advanced and/or customized technology such as unattended monitoring systems (UMS) and remote data transmission (RDT): these enable safeguards-relevant information to be received remotely by the IAEA, potentially reducing the number on-site inspections and allowing real-time monitoring (note: customized monitoring technology will necessarily be developed with Member-State support and in some cases require years of R&D effort);
* Reliable, high-bandwidth, secure digital connectivity: this is a State infrastructure element that facilitates the use of remote monitoring of IAEA equipment (notably, an infrastructure element not necessarily in place in areas currently under consideration for remote SMR operation, and one with potential synergies with safety and security);
* Containment and surveillance (e.g., seals), including the needs of factory-fuelled, transportable cores prior to shipping: this will enable the IAEA to maintain continuity of knowledge of reactor core designs that have been verified at the factory (whether shipped fuelled, or separately to the fuel charge);
* Effective design information verification, especially for complex layouts and transnational deployment: this will potentially require multi-State negotiation to allow access, as well as design considerations to allow efficient facility access for design information verification;
* Multi-channel monitoring of reactor power, e.g., thermal/electric power for microreactors: this will be important where multiple output energy streams are utilized, such as electricity plus process heat;
* Potential shared use of operator equipment, and monitoring of operator process data [13][14]: this can potentially increase the cost-effectiveness of safeguards measures since nuclear material data are acquired by the operator anyway as part of facility operation and NMAC; for the IAEA to makes use of this information, however, it would need to be authenticated such that there is certainty in its provenance;
* National-level concerns such as nuclear-material transfers, transnational supply arrangements, access to remotely-deployed facilities, enhancement of State fuel-cycle capabilities, and cyber infrastructure and security: these are policy and infrastructure aspects that fall more to the State to address, than the operator.
* Training for all stakeholders (IAEA, State authority, operator), including capacity-building needs for emerging nuclear States.

It is additionally important to note that many of these safeguards aspects have potential interactions (both synergies and conflicts) with security and safety considerations. Accordingly, it will be important to coordinate on such interfaces, and where possible seek a integrated approach that leverages commonalities among similar technology types.

## challenges in applying safeguards by design

SBD is not a new concept. In the past the benefits of early planning for safeguards implementation have been recognized when a new technology was ‘different’ enough to draw attention to its potential safeguards challenges. A significant example is the Rokkasho Reprocessing Facility in Japan, which, as the first commercial-scale reprocessing facility in an NNWS, was the subject of extensive collaborative safeguards development in parallel with its design and construction, starting in the late 1980s. The IAEA, working closely with the facility operator, State authority and R&D community, developed a customized approach that included unattended monitoring and sampling systems, and use of both IAEA and shared-use equipment [15].

Another early example is provided by the unattended monitoring systems (UMS) and other customized technical measures developed for PHWR facilities starting in the late 1970s with Canadian R&D support. In this case the on-load-refuelling of the CANDU design necessitated the incorporation of customized core-discharge monitors and bundle counters in the standard facility design, providing continuity of knowledge of the fuel flow despite its inaccessibility for physical inspection prior to the spent fuel bay [16][17].

What’s new today is the sheer number of new reactor designs under development, the shortened timescale with which many of them will either be prototyped or fully brought to market (requiring IAEA safeguards in either case if built in an NNWS), and the fact that many developers are non-government entities, often located in an NWS, with low awareness of customer-State obligations under international safeguards – or a perception that these obligations do not impact the design phase significantly.

It is crucial, therefore, that awareness of the needs of international safeguards be raised within the SMR design community, particularly if significant design modifications can potentially reduce the cost and burden of safeguards implementation during operation, and especially if new IAEA instrumentation is required to be developed (requiring Member-State support).

Raising this awareness is challenged by a number of factors however:

* The IAEA lacks a direct channel for initiating communication with SMR designers (particularly at the earliest stages of design when greatest SBD potential exists) since this usually entails direct engagement of a private entity, and a perception of favourable treatment within a highly competitive field of designers;
* There is no ‘engineering standards’ document for safeguards (only ‘best practices’) – a situation that arises since safeguards approaches themselves are determined on a case-by-case basis subject to IAEA policy and assessment;
* Designers themselves lack a uniform understanding of safeguards requirements, as these are not widely taught in the nuclear engineering curricula, have traditionally not impacted design, and particularly within nuclear-weapon States have had low visibility due to the lack of IAEA safeguards implemented in operating facilities;
* Many nuclear designers are new to the industry, often relatively small with a limited scope of capabilities;
* Safety and economics are priority design drivers: safeguards is typically not seen as a design driver at all, of relevance toward the end of a build process when nuclear accountancy preparations are underway;
* Inconsistent licensing practice means that some regulators will engage in pre-licensing reviews of new facilities under development where safeguards considerations are included, but many will not; and
* Many SMR designers have confidentiality concerns with the early sharing of proprietary and commercial information with the IAEA.

## implementing sbd at the iaea

The challenges of implementing SBD can largely be mitigated through awareness, and thus SBD is fundamentally a process of raising awareness about safeguards obligations early in the design stage of nuclear technology development – and optimizing these end-user needs with safety, security, and other design considerations. The relevant design processes are any that arise during the lifecycle of a facility, from initial design through decommissioning, and can involve either new facilities or modification of existing facilities (e.g., addition of dry storage capability).

For the designer, SBD is a voluntary process that begins with knowledge of international safeguards and their implementation at relevant facility types. For this the IAEA guidance documents provide a good starting point [4]-[11]. A recommended practice is to involve a safeguards subject-matter expert (SME) in the design process, directly or as a review component. Safeguards SMEs, if not available internally, can often be found in national nuclear labs, nuclear consultant companies, the national nuclear regulator, or of course through consultation with the IAEA.

For the technology recipient (e.g., host State, operator), SBD is also a voluntary process that can optionally be initiated through the procurement process – for example as a specification for consideration of international safeguards and their interfaces (potential conflicts/synergies) with safety and security design requirements.

The SBD process itself is a graded design review involving, at minimum, design experts and a safeguards SME – the level of detail generally dependent upon the technical-readiness level (TRL) of the technology. At any TRL the IAEA (Department of Safeguards) is available to engage in such discussions, which can range from informal discussion to detailed assessment. At the early stage of development of a project this engagement would typically not constitute a design declaration under a State’s safeguards agreement, but rather take the form of a voluntary technical consultation at the discretion of the designer and/or technology recipient.

In recognition of the particular need for SBD in the preparation for SMR deployment, as outlined in this paper, the IAEA initiated in 2018 a dedicated Member State Support Programme (MSSP) task that facilitates SBD engagement directly with SMR designers, with the Division of Safeguards Concepts and Planning (SGCP) acting as the main point of contact but involving other internal experts as needed. The process is voluntary and initiated by the State and technology designer.

To date the MSSP task on “SBD for SMRs” has been accepted by nine support programmes – in South Korea, Russia, France, Canada, Finland, China, the UK, USA, and Belgium – and discussions with other support programmes are underway. Through this process the IAEA has been able to engage directly with designers representing a wide scope of SMR technologies, including floating nuclear power plants, integral PWRs, molten-salt reactors, micro-reactors, and pebble-bed high-temperature gas-cooled reactors. The goal of each MSSP task is the development of an internal, technology-specific IAEA safeguards technical report (STR), co-authored with the technology designer, that outlines the necessary information for implementing a sound and cost-effective safeguards approach. The report would serve as a starting point for the development of such an approach by the IAEA once a State declaration of construction is received that is based on the technology in question.

Depending on the level of design development, it is plausible that this process would also lead to identification of potential design modifications or new instrumentation development that would assist the IAEA in implementing cost-effective safeguards, and at the same time minimize the burden of safeguards on facility operations.

Additionally, the IAEA Department of Safeguards collaborates internally with other IAEA Departments as needed to raise awareness with Member States of SBD and its potential interactions with safety and security. This has included engagement with the Department of Nuclear Energy on a wide range of technical topics such as fusion systems and waste management, in addition to many SMR-related activities including those under the Milestones Approach[[1]](#footnote-2) and INPRO[[2]](#footnote-3) (International Project on Innovative Nuclear Reactors and Fuel Cycles). Engagement with the Department of Nuclear Safety and Security has focused on elaborating the various interactions (i.e., the potential conflicts and synergies) between safety, security and safeguards. Engagement with the IAEA’s Office of Legal Affairs (OLA) has focused on addressing various legal issues related to implementing safeguards under various safeguards agreements and technology supply scenarios, and facilitating discussions with vendors and national authorities. Interdepartmental collaboration on Member State engagement initiatives includes the SMR Platform[[3]](#footnote-4), SBD Working Group, NHSI[[4]](#footnote-5) (Nuclear Harmonization and Standardization Initiative), and the SMR Regulators Forum[[5]](#footnote-6).

## lessons learned and next steps

The last five years have seen a significant increase in general awareness of SBD and its potential benefits, within both the industry and the IAEA. This stems from activities under the IAEA’s MSSP tasks on “SBD for SMRs”, as well as increased engagement both internally (described above) and externally through a number of Member-State industry, regulatory, and government networking initiatives.

The MSSP tasks themselves have advanced, albeit at a slower rate than initially expected as they are driven largely by the capacity of the industry to engage. SBD, as a voluntary, awareness-raising activity, can easily shift in priority compared to other pressing R&D and administrative matters. SBD discussions are nevertheless underway with many SMR designers, with progress ranging from near completion of a final safeguards technical report, to preliminary interaction. The number of MSSPs and designer organizations involved in these tasks has also grown recently as general awareness expands.

The following are some general observations and lessons learned during the SBD process thus far:

* Some designer organizations perceive a risk associated with confidentiality of design information; this has been addressed through assurances of strict information handling protocols at the IAEA – i.e., treating SBD design data as highly-confidential information (similarly to other such safeguards-relevant Member-State information), including data storage only on the IAEA’s secure internal network, limitation of meeting participants, and if necessary destroying data held at the IAEA once the SBD engagement has concluded;
* Another perceived risk is the financial exposure faced by a designer organizations when it supports early safeguards R&D (e.g., potential design modifications, potential development of new IAEA safeguards instrumentation) – particularly given that specific customers may not have been identified yet, safeguards approaches and policies themselves may change, and ultimately safeguards are the legal responsibility of the operator and not the designer; this has been addressed through assurances that investments in safeguards preparation can lead to an improved vendor product through reduction of operational and State burdens, with minimal risk since safeguards agreements are determined primarily by the IAEA in consultation with States, and do not vary significantly from State to State in terms of types of measures and activities employed;
* Broad engagement of industry can be as useful as bilateral engagement with designer organizations: the U.S. support programme in particular, while limited from nominating specific companies for engagement with the IAEA due to perceptions of favourable treatment (similar to the IAEA’s own limitations mentioned in Section 5), has facilitated general engagement of its industry and R&D community with the IAEA leading to better understanding by all stakeholders, and in some cases subsequent bilateral engagement initiated by designer organizations themselves;
* SBD engagement with an SMR designer organization outside of am MSSP task, while less desirable (due to the lack of the MSSP’s facilitating framework), remains possible, providing that transparency is maintained as to the nature of the engagement (e.g., at the designer organization’s initiative) and appropriate non-disclosure and other terms of engagement are concluded;
* IAEA resources currently committed to SBD engagements with SMR designer organizations are appropriate for the current level of interaction; however, should industry and Member-State interest substantially increase these resources will need to be internally addressed; it may be necessary to address SBD matters more broadly by technology stratum (e.g., all molten-salt technologies, all prismatic graphite microreactors) through targeted activities, and to ‘triage’ SBD requests – based upon technical readiness level (TRL) for example – to optimize the IAEA’s interaction.
* The regulatory community can significantly facilitate SBD interaction through pre-licensing reviews that consider safeguards requirements and their potential interactions with safety and security – particularly since there is often hesitation within the industry to take action not prescribed or otherwise encouraged by the relevant nuclear regulatory body;
* Although safeguards approaches themselves are confidential and facility-specific, many generic aspects and best practices of safeguards preparation exist that can be shared within the industry and regulatory community, potentially accelerating deployment through more efficient and better-prepared safeguards implementation; thus, engagement of these stakeholders through harmonization initiatives such as NHSI and the SMR Regulators Forum is valuable.
* Some Member States have expressed concerns that the consideration of interfaces between safety, security, and safeguards can potentially lead to confusion as to the degree of integration between these separate legal domestic and international frameworks; this has been addressed through awareness-raising initiatives that underscore the limited scope of such integrated technical considerations (i.e., purely an engineering-design practice with no bearing on governing legal frameworks).

Regarding next steps, the IAEA will continue to engage SMR design organizations through primarily the MSSP tasks, but also direct engagements where MSSP tasks are not available. Internal resource needs will be monitored and adjusted accordingly. These activities are expected to lead to a number of technology-specific internal reports on potential safeguards application that would serve as useful starting points for the development of safeguards approaches once construction projects are declared to the IAEA. At that time, operational safeguards sections at the IAEA would then ideally have access to a reference document representing pre-agreed concepts by all stakeholders (including identified gaps such as customized instrumentation R&D that may have already begun to be addressed), and a facility developer, operator, and State authority that are fully cognizant of the safeguards needs of the planned technology (including potential interactions with safety and security). As always, the actual safeguards approach at that time will be developed by the IAEA at its own discretion, in consultation with the SMR-hosting State and facility owner/operator as needed.

## sUMMARY

SBD is a demonstrated approach to collaborative risk-management in the design of any new or modified nuclear facility or process, which optimizes safeguards implementation with the consideration of economic, operational, safety, and security factors, and reduces the resulting burden to all stakeholders. A voluntary best practice, SBD applies at any stage of the nuclear fuel cycle, and any phase of a facility’s life cycle – but is a priority today for SMRs. Despite successes over the decades, effective implementation of SBD faces a number of challenges based on traditional perceptions, communication barriers, design environments, legal and technical factors, and regulatory limitations. These challenges are addressed through proactive communication and engagement with the IAEA, supported by external expert organizations, State authorities, and nuclear design organizations as needed. A dedicated Member State Support Programme project allows a number of Member States to facilitate a direct SBD conversation with SMR designers, which to date involves nine separate Member States and a wide variety of SMR technologies. A number of lessons have been learned to date that will facilitate a more efficient, more broadly subscribed and better understood process going forward.

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