SAFEGUARDS BY DESIGN: NUCLEAR INDUSTRY'S ROLE IN THE EFFICIENT IMPLEMENTATION OF INTERNATIONAL SAFEGUARDS

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ABSTRACT

Safeguards by Design (SBD) raises awareness among State authorities, designers, equipment providers and prospective purchasers of the importance of taking international safeguards into account when designing a nuclear facility or process. A voluntary best practice, SBD allows for informed design choices that optimize economic, operational, safety and security factors, in addition to international safeguards. It is applicable to all aspects of the nuclear fuel cycle, from initial planning and design through construction, operation, waste management and decommissioning. For new nuclear facilities, especially novel designs or processes, the earlier the discussion of safeguards the better: SBD allows for safeguards to be built 'into' the system, rather than around it afterwards. For the nuclear industry, SBD leads to more efficient safeguards implementation, meaning less burden during operations and less risk of costly retrofits during and after construction. This paper summarizes the key benefits of SBD and how the IAEA is seeking to engage the nuclear industry more effectively in SBD dialogue – particularly in two key areas: innovative reactor new-builds, and radioactive waste management. Examples of successful and ongoing SBD are also discussed.

BACKGROUND AND BENEFITS OF SBD

Safeguards by Design (SBD) is a collaborative risk-management approach whereby international safeguards considerations are integrated into the development of a new or modified nuclear facility or process, at any phase from initial planning through design, construction, operation and decommissioning. SBD is a voluntary best practice that neither replaces a State's obligations under its safeguards agreement for early provision of design information to the IAEA, nor introduces new requirements: SBD simply shifts the discussion earlier in the design process, in order to facilitate more efficient and effective safeguards implementation, at any point in the nuclear fuel cycle [1]-[8][24].

As a best practice in the nuclear industry, SBD is not new. For decades the industry's role in facilitating efficient safeguards implementation has been recognized, particularly in cases involving complex facility layouts or novel nuclear-material forms and flows. A significant example of this is the Rokkasho Reprocessing Facility in Japan, which, as the first commercial-scale reprocessing facility under comprehensive safeguards, 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 Japanese R&D support, developed a customized approach including unattended monitoring and sampling systems, and both independent and joint-use equipment [10].

Another significant early example is the unattended monitoring system (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 [11][12].

These two early examples underscore several important aspects of SBD that remain generally relevant in today's evolving nuclear industry:

- SBD is applicable to all nuclear-fuel-cycle facilities and processes (not just reactors);
- SBD is particularly important for facilities with complex nuclear-material forms and flows;
- SBD is applicable to sub-systems, processes, and components of all sizes;
- SBD is an early, mutually beneficial discussion among all relevant stakeholders; and
- SBD can involve customized equipment requiring the State's time and resources to develop.

As well, these two early examples demonstrate the main benefits of SBD, which remain valid today and apply to all stakeholders:

- SBD reduces the need for retrofitting safeguards equipment after facility construction or modification;
- SBD facilitates the use of advanced safeguards technologies, such as UMS and remote data transmission (RDT);
- SBD can involve significant State resources, but avoids future burdens;
- SBD allows the integration of cost-effective measures that would otherwise not be feasible, directly into the facility design;
- SBD facilitates the joint-use of equipment by the State and the IAEA;
- SBD facilitates the sharing of the operator's process monitoring and other operational data;
- SBD provides flexibility for upgrading safeguards measures as needed; and
- SBD facilitates harmonization of design requirements across similar technology types.

The overall benefit of SBD, then as today, is better understanding by all stakeholders of respective safeguards obligations and technical needs, and a resulting reduced risk to project scope, schedule, budget and licensing.

Beyond the notable early examples described above, SBD has tended to receive less consideration by the industry over the years. The reasons for this are varied – including perceptions that safeguards are mainly retrofitted measures following construction, perceptions that safeguards are too sensitive a topic for the design community, perceptions that safeguards can unnecessarily complicate early regulatory or design discussions seeking to accommodate safety and security requirements, perceptions that safeguards cease to apply when facility operations cease, perceptions that safeguards are less relevant to vendors based in nuclear-weapons States, or simply a lack of awareness of international safeguards obligations in the nuclear design community.

The lack of uniform attention to SBD has led to nuclear facilities requiring costly retrofits to accommodate safeguards equipment, safeguards equipment being damaged or compromised by facility operations, and in general, less cost-effective or more burdensome safeguards implementation than could have been the case. Accordingly, for many years SBD messaging by the IAEA over the years tended to focus on avoidance of these often-costly inconveniences.

Recently, increasing interest in fuel-cycle enhancement by the nuclear industry has highlighted two priority areas for effective SBD, which this paper will address in more detail:

- ***Reactor innovation:*** advanced reactors, including Small Modular Reactors (SMRs), and associated fuel-cycle facilities. The key stressor here is the novel nature of many proposed nuclear fuel and reactor designs.

- ***Back-end innovation:*** waste management (including decommissioning waste) and spent-fuel transfers to dry storage or permanent disposal. The key back-end stressor is the sheer volume of nuclear material transfers involved.

For both these areas of industry enhancement, the challenge for the IAEA in terms of safeguards readiness is meeting an unprecedented growth of new facilities and processes likely to outpace IAEA resources. For the nuclear industry the challenge is avoiding unexpected project costs and delays, often within a demanding market or timeline. Clearly, all stakeholders stand to benefit when SBD is included in the optimization of design choices alongside economic, operational, safety, and security considerations.

TYPES AND TIMING OF SBD

As a concept of engagement, SBD has broad and adaptable applicability. In its simplest manifestation it facilitates the installation of IAEA safeguards equipment (e.g., cameras, seals, detectors, supporting equipment), often involving design accommodations (e.g., wall brackets, penetrations, conduits, instrument cabinets, and sealing points). Typically, these represent minor modifications with minor cost implications when addressed in the early design phases, but significant retrofit costs once a design is finalized, or built. In the course of routine operations or maintenance, SBD reduces the probability of accidental interference with safeguards measures that would initiate follow-up activities by the IAEA (e.g., obstruction of cameras, damage to seals, shielding of detectors). In its simplest manifestation, in other words, SBD contributes to good engineering design and planning.

In its more complex manifestations, early SBD facilitates design modifications that can:

- accommodate more efficient and effective safeguards measures; e.g., facilitating customized UMS, with or without RDT of safeguards data to IAEA headquarters or field offices; or

- increase the inherent safeguardability of a facility, component, or process; e.g., modifications to the form or flow of nuclear material, container design, or facility layout that make diversion or misuse of the nuclear material more technically difficult, or make safeguards measures (e.g., seals) easier to apply.

It should be noted that enhanced safeguardability is an important aspect of proliferation resistance identified by several expert groups (e.g., GenIV International Forum and IAEA-INPRO [13][14]), and thus SBD is a key enabler of the proliferation resistance benefits proposed for many advanced design concepts.

SBD is applicable at any point in the life cycle of a facility, from design to decommissioning; however, the diverse range of SBD's applicability allows it to be broadly categorized by scope, including specific life-cycle timing and key stakeholders:

- ***Component-level SBD*****:** At the level of new sub-systems and components (including processes) within a facility, SBD ensures compatibility with the relevant facility-level safeguards approach, and optimizes the sub-system or component's inherent safeguardability if it represents novel technology (or novel to the facility/State). The SBD process at this level is typically embedded within the procurement process of an already operating facility, and is the responsibility of the operator. The key stakeholders include the technology supplier, regulator, and relevant facility personnel responsible for operations, safeguards and procurement. At this level SBD typically proceeds through official channels between the IAEA and State or regional authority responsible for safeguards implementation (SRA), including submission of a modified facility Design Information Questionnaire (DIQ). Examples include transfers to spent-fuel dry-storage, modification of fresh-fuel storage and handling systems, conditioning and disposal of contaminated-waste, and in general any maintenance/upgrades to existing components or sub-systems (e.g., spent-fuel-bay lighting upgrades).

- ***Facility-level SBD*****:** At the level of a new or modified facility, SBD ensures that an efficient and effective safeguards approach is ready for implementation when nuclear material is received, supported by a robust nuclear-material accountancy system linked to the State (or regional) system of accounting for, and control of, nuclear material (SSAC/RSAC). Key stakeholders include the technology supplier at the earliest stages, interacting with State safeguards experts and the IAEA. If early enough in the design process, this type of SBD interaction occurs prior to the onset of design-information reporting under a State's safeguards agreement, but is encouraged as a voluntary best practice (particularly for novel designs) – where possible with the support of a State's pre-licensing regulatory review process. SBD engagement of the IAEA at the earliest stages of development would involve primarily the Technical Support divisions of the Department of Safeguards, rather than Operations directly. Examples include advanced reactors (e.g., SMRs), novel fuel-fabrication and reprocessing facilities, decommissioning planning, and spent fuel encapsulation plants and geological repositories.

- ***State-level SBD*****:** At the level of the State, SBD ensures an understanding by all stakeholders of State safeguards obligations, including any new technical or legal needs related to enhancements to the State's nuclear fuel cycle, and collaborative preparation on a schedule that supports both State planning and IAEA capabilities. Key stakeholders include the relevant State authorities (including those in a third-party supplier State if applicable), facility operator, technology supplier, and the IAEA. Examples include the importing of factory-fuelled, sealed cores, new State fuel-cycle capabilities (e.g., enrichment, reprocessing), advance fuel-cycle Additional Protocol declarations (article 2a(x)), specific needs of emerging nuclear-energy States, facilitation of IAEA capabilities such as remote data transmission (RDT), random and unannounced inspections (RII, UI), and new deployment models (e.g., floating plants, distributed microreactors).

It is important to note in the above that the technology supplier is a key stakeholder, regardless of the type of SBD. This represents a paradigm shift within the nuclear industry regarding safeguards implementation – often seen as an obligation concerning only the operator, State authority, and IAEA. The nuclear industry's role during the design process is best practice (and, in many cases with advanced technology, a priority) for the efficient and effective implementation of safeguards.

CHALLENGES TO IMPLEMENTING SBD

Despite its inherent and demonstrated benefits, SBD remains challenging to implement – largely due to insufficient awareness by key stakeholders. As noted earlier, a number of perception issues have traditionally existed on the part of the nuclear industry, and these constitute the first of several 'institutional' challenges to effective SBD engagement that can be identified and mitigated:

- ***Perception challenges*****:** Cost/benefit concerns arise when the benefit to the industry (designer or operator) is not clear; i.e., when the bulk of the responsibility and burden of safeguards implementation is perceived to reside with the IAEA, then safeguards are simply not seen as an important design driver – particularly in the context of the industry's overall requirement for safe, economic operation. For the industry an investment in engineering design modification may be seen as a risk when institutional assurances (e.g., certification, guarantees, pre-approval) don't exist. Mitigation of this challenge comes through effective communication by the IAEA, through direct engagement and published guidance, of the considerable, shared risk-management benefits of effective SBD.

- ***Communication challenges*****:** The IAEA generally engages through official channels at the State level, or directly with facilities within the parameters established by safeguards agreements. The IAEA doesn't normally engage directly with specific technology designers on safeguards-related matters, and would tend to rely on third-party support or opportunities for broad-audience messaging to raise awareness of the importance of SBD. In turn the nuclear design community isn't accustomed to communicating directly with the IAEA. Mitigation of this challenge comes through effective communication and published guidance by the IAEA, increased and more effective leveraging of third-party support, engagement through the IAEA Member State Support Programme (MSSP) of the Department of Safeguards, and engagement through other Departmental initiatives of the IAEA. In the end, a direct IAEA discussion with a designer is still needed, and for this a clear understanding of terms of engagement (e.g., confidentiality, expectations, outcomes, timeframes, limitations) is required.

- ***Environmental challenges*:** Many technology designers, whether at the component, sub-system, or facility level, are based in NPT Nuclear-Weapons States (NWS), and therefore do not operate within an 'international safeguards culture', with a domestic customer base for which IAEA safeguards are generally not applied. For these technology designers, safeguards are a matter for international export for which requirements may not be clear. In turn many technology procurers are new to the industry and unfamiliar with safeguards requirements. Mitigation of this challenge comes through communication efforts and published guidance by the IAEA, and training opportunities, particularly around the safeguards needs for technology exported to countries under comprehensive safeguards agreements with the IAEA.

- ***Regulatory challenges*:** Technology designers are used to complying with the extensive regulatory requirements of their customer base, either domestic or foreign, as typically reflected in Requests for Proposal (RFPs). When international safeguards obligations are not included in such RFPs, or otherwise in the expectations of the relevant regulatory process, this can lead to a business-related reluctance to engage early on matters considered to be out of regulatory scope (and for which requirements may not be clear anyway). Mitigation of this challenge comes through communication and published guidance by the IAEA, and specifically engagement of the regulatory community and the industry to build support for the importance of including safeguards considerations in the pre-licensing and procurement process.

One notes a common theme in the above: the mitigation of all identified challenges tends to hinge upon effective communication and engagement, and thus the raising of awareness amongst all stakeholders. Accordingly, this is a tenet of IAEA efforts to facilitate effective SBD, particularly in the two priority areas of reactor and back-end innovation identified earlier. These two priority areas, and how the IAEA addresses each, are addressed the next two sections.

REACTOR SBD: ADVANCED REACTOR AND FUEL DESIGNS

Advanced reactors, including SMRs, microreactors and GenIV systems, represent new and often innovative technology and deployment models, including associated fuel-cycle facilities (e.g., fuel-fabrication, reprocessing, spent-fuel storage). For the IAEA it is essential that the capability to implement efficient and effective safeguards is ready when required, and for States under a comprehensive safeguards agreement (CSA) with the IAEA, this requirement applies to any new project utilizing nuclear material, regardless of size, technology, prototype status, location, end use, or State of origin.

While it is true that many advanced-reactor 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 – particularly where customized safeguards measures are needed. Time is 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 advanced reactors will require SBD consideration at all levels (sub-system, facility, and State):

- New fuels and fuel cycles, including those involving high-assay low-enriched uranium (HALEU), thorium, molten salts, pebble and prismatic graphite, and pyroprocessing;
- Longer refuelling cycles, on-load refuelling, and sealed cores;
- Smaller facility layouts, creating tighter, more complex spaces under containment and surveillance (C/S), with potentially significant radiation fields and other health and safety considerations relevant to in-field inspection and equipment maintenance;
- New deployment models, including factory-fueled cores, transportable and floating nuclear power plants, transnational supply of sealed cores, and remote, distributed fleets of microreactors;
- New spent fuel flow and storage configurations, including smaller items, and new physical forms (both item and bulk);
- Diverse operational end uses, including district heating, desalination, hydrogen production – possibly in combination with electricity production; and
- Non-traditional concepts of operations, including multi-unit operation with shared fresh and spent fuel management.

Accordingly, it is expected that the following aspects of safeguards implementation will be important considerations for the efficient and effective safeguarding of advanced reactors [15][16]:

- Advanced and/or customized technology such as UMS and RDT;
- Reliable, high-bandwidth, secure, remote digital connectivity;
- Containment and surveillance (e.g., seals), including the needs of factory-fuelled, transportable cores prior to shipping;
- Effective design verification, especially for complex layouts and transnational deployment;
- Multi-channel monitoring of reactor power, e.g., thermal/electric power for microreactors;
- Potential joint use of equipment, and monitoring of operator process data [15][17];
- State-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.
- Training for all stakeholders (IAEA, State authority, operator), including capacity-building needs for emerging nuclear States.

Many of these safeguards considerations have potential interactions (both synergies and conflicts) with security and safety considerations. Accordingly, it will be important to coordinate on such

‘3S’ interfaces, and where possible seek a harmonized approach that leverages commonalities among similar technology types.

The IAEA is currently engaged with several SMR designers on SBD through its Member State Support Programme, with the objective of developing preliminary assessments for safeguards implementation, including the identification (and if necessary, initiating) of any required development of new or modified technical measures [18]. Within the IAEA there is also good interdepartmental engagement aimed at coordinating SMR initiatives internally and with Member States, building on past collaborations in this area [6][14][19]-[22].

BACK-END SBD: WASTE MANAGEMENT, SPENT FUEL, AND DECOMMISSIONING

As more State nuclear programmes reach maturity there is increased activity in process-waste management, long-term spent-fuel management, and decommissioning. For each of these activities to enhance the sustainability of the nuclear industry as designed, they must include ensuring that safeguards planning optimizes cost-benefit considerations. The challenge at the back end of the fuel cycle is not only the potential use of innovative technologies and processes, but the large volume of material and financial commitment typically involved.

In the particular case of processes to condition and dispose of radioactive waste, industry misperceptions sometimes arise around the relative priority of safeguards considerations, especially given the typically low radiological concern and/or eventual inaccessibility of the nuclear material involved. It is often planned to terminate safeguards on the waste material, which requires the authorization of the IAEA based on an independent assessment of ‘practicable irrecoverability’ (stipulated in the State’s safeguards agreement). Acquiring this authorization can be problematic if nuclear material concentrations are high by IAEA standards, underlining an important role for early SBD in such planning [9][25][26].

In the case of spent-fuel management the main concern is inefficiency in the implementation of safeguards containment and surveillance (C/S) measures due to insufficient planning in facility or sub-system design (e.g., dry-storage containers), leading to additional burdens for the operator and IAEA that include health and safety issues. Best-practice examples include dry-storage systems that incorporate the needs of IAEA seals and reverification, such as MACSTOR [8].

A special case of long-term spent-fuel management involves permanent disposal in deep geological repositories (DGRs). The safeguards implications of DGRs and their associated encapsulation facilities have been discussed with Member State and IAEA experts for many years, and the first operational DGR in Finland (nearing completion) will benefit from both this generic and site-specific SBD engagement [27].

SBD engagement at the back end of the fuel cycle, as at any stage, applies at all three levels: components/processes, facilities, and State. The IAEA has published guidance to assist States in meeting their obligations as efficiently and effectively as possible with respect to spent-fuel management and decommissioning [8][23], and will soon publish guidance related to radioactive-waste management [9]. Above all, the most useful piece of SBD guidance for the nuclear industry is the importance of discussing any plans for the back end of the fuel cycle (as with any stage of the fuel cycle) with domestic and/or IAEA safeguards experts, as early as possible.

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 along with 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 both advanced-reactor development (including associated fuel-cycle facilities) and back-end activities (spent-fuel management, radioactive waste management, decommissioning). SBD also applies at any level of technology integration, from components/processes/sub-systems to full facilities, and at the level of the State fuel-cycle planning, regulation, and safeguards management. Despite successes over the decades, effective implementation of SBD faces a number of challenges based on traditional perceptions, communication barriers, design environments, and regulatory limitations. These challenges are addressed through proactive communication and engagement by the IAEA, with the support of external organizations, Member State authorities, and nuclear design organizations.

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