SAFEGUARDS BY DESIGN: SUPPORTING SUSTAINABLE SPENT-FUEL MANAGEMENT STRATEGIES[1]

J.J. WHITLOCK
International Atomic Energy Agency
Vienna, Austria
Email: j.whitlock@iaea.org

Abstract

Under the Treaty on the Non-proliferation of Nuclear Weapons (NPT), non-nuclear-weapon States (NNWS) are obliged to accept International Atomic Energy Agency (IAEA) safeguards on all nuclear material, which includes spent fuel in storage, reprocessing and disposal stages of a national nuclear fuel cycle. At every stage, the efficiency of safeguards implementation can be greatly enhanced through early discussion between the IAEA and operator or designer, reducing the subsequent burden on all stakeholders (IAEA, State authorities, and operator) during construction and operation. These discussions, known as 'safeguards by design' (SBD), facilitate the efficient application of not just traditional containment and surveillance (C/S) and verification measures, but also advanced measures based on unattended measurement systems and remote data transmission that can significantly reduce the need for in-field inspector presence. The increasing use of dry-storage solutions for spent fuel introduces specific needs for nuclear-material pre-verification and C/S measures, for which SBD is effectively applied today in minimizing operational impact. As more States look to advanced reactors and small modular reactors (SMRs) to sustainably meet their energy needs, SBD becomes a priority due to the number of advanced fuel materials, storage configurations, facility layouts, and fuel flow characteristics that are involved (including many examples of online fuelling and bulk material flow). Reprocessing stages add another layer of complexity, whether employing traditional or advanced technology (e.g., pyroprocessing), which will challenge the efficient application of safeguards if not discussed early in the planning and design stage. Geological disposal presents challenges for efficient safeguards due to the volume of nuclear material, pre-disposal verification requirements, and complexity of construction and emplacement activities. The paper summarizes the international safeguards obligations of a NNWS that translate directly to operational requirements in the handling, storage, and disposal of spent fuel – and how best practices in SBD can minimize risk and support timely deployment of new technologies.

1. BASICS OF 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 the conclusion of safeguards agreements with the IAEA. The most common type of agreement is based on the model Comprehensive Safeguards Agreement (CSA) [1], concluded by Non-Nuclear Weapon States (NNWS) under Article 3 of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). Under a CSA, a State 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 enhanced 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 related to nuclear material and activities. Verification measures include on-site inspections, complemented by containment and surveillance (C/S) techniques (e.g., seals, cameras) and information gathered through open-source and third-party sources. All safeguards-relevant information is evaluated for consistency, leading to an annual safeguards assessment for each facility, and the State as a whole.

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2. SAFEGUARDS BY DESIGN (SBD)

Typically, the development of a safeguards approach by the IAEA for a new reactor or fuel-cycle facility begins with the early provision of design information by the State to the IAEA, required under the State's safeguards agreement following a decision/authorization to construct. If the safeguards approach involves the installation of IAEA seals, camera, or other equipment, these measures have typically been retrofitted into the existing design. Over the years this has led to consideration of the efficiencies that stem from taking these safeguards needs into account earlier in the design process itself – a concept known as 'safeguards by design' (SBD).

SBD is defined as an approach whereby international safeguards requirements and objectives are integrated into the design process of a nuclear facility, from initial planning through design, construction, operation and decommissioning [3]. A voluntary best practice, SBD allows for informed design choices that optimize economic, operational, safety and security factors, along with international safeguards requirements. Importantly, 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 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:

- 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;
- Improved understanding by all stakeholders (operator, State authority, State regulator, IAEA) of each other's needs with respect to safeguards rights and obligations.

For designers of nuclear facilities located in nuclear-weapon States (NWS) under the NPT, 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, along with other customer requirements based on the national regulations and standards.

3. SBD AND SPENT-FUEL MANAGEMENT

A significant portion of the IAEA's global safeguards activities involves the verification of spent-fuel management. These activities include inspections involving both visual identification and instrumented measurement (both non-destructive and destructive, as needed), design verification during construction and operation of facilities, and – increasingly – unattended measurement systems (i.e., in-situ IAEA measurement equipment operating without inspector presence) with the potential for remote data transmission (i.e., secure transmission of safeguards data to IAEA headquarters in Vienna).

The resource requirement for the global safeguarding of spent fuel is likely to increase significantly with both expansion of the industry to support environmental sustainability goals, and expansion of spent-fuel handling in particular as facilities free up space in wet storage to facilitate continued (and possibly extended) operation. The development of advanced spent-fuel forms and processes will compound this impending resource challenge, and the potential benefits of SBD – to both timely development and efficient operation – become even more pertinent.

The following subsections explore the potential support that SBD can provide to the timely deployment of sustainable spent-fuel management strategies; in particular:

- The increasing use of *dry-storage* solutions for spent fuel introduces specific needs for pre-verification and C/S measures, for which SBD is effectively applied today in minimizing operational impact;
- As more States look to *advanced reactors* and small modular reactors (SMRs) to sustainably meet energy needs, SBD becomes a priority due to the number of advanced fuel materials, storage configurations, facility layouts, and fuel flow characteristics that are involved (including many examples of online fuelling and bulk material flow);
- *Reprocessing* facilities add another layer of complexity, whether employing traditional or advanced technology (e.g., pyroprocessing), which will challenge the efficient application of safeguards if not discussed early enough in the planning and design stage;
- *Geological disposal* presents challenges for efficient safeguards due to the volume of nuclear material, pre-disposal verification requirements, and complexity of construction and emplacement activities.

3.1. SBD and Dry Storage of Spent Fuel

The transfer of spent fuel from wet to dry storage facilities, typically co-located with a nuclear power plant (NPP), is a sound strategy for reducing the resources needed for maintaining safe and secure storage of spent fuel, while freeing up space in the wet storage needed for continued operation of the NPP. The lack of a practical option for long-term management of spent fuel in most countries today makes this intermediate storage step a necessity.

Spent fuel that is under safeguards in wet storage (i.e., at NPPs in most States) will continue to be subject to safeguards during transfer, emplacement, and subsequent storage in dry container facilities. Due to the increased difficulty of access to the spent fuel in dry storage however, the IAEA's toolbox includes a special 'Difficult-to-Access' (DtA) designation, applied solely at its discretion, that reduces the ongoing verification requirements for this nuclear material by strengthening the C/S measures (usually doubling up on the number of independent measures required; e.g., seals, cameras). Prior to transfer to dry storage under this designation, the spent fuel would typically be verified by the IAEA at a higher level than during routine inspections, as this would likely represent the last time that the material can be accessed without considerable effort and inconvenience to both the IAEA and facility operator.

The entire process of dry-storage transfer, from preparation of the spent fuel in the NPP wet storage bays through its transfer, emplacement and ongoing dry storage, involves safeguards measures and activities (and corresponding operator responsibilities) that, for an operator undertaking this process for the first time, will be new and largely unlike the safeguards implemented for years at the wet storages. SBD can therefore be effective in facilitating a smooth transition to this phase of spent-fuel management by raising awareness of new requirements, incorporating them into the planning process, and potentially facilitating the development of advanced measures that can reduce the burden on operations, the State safeguards authority, and the IAEA.

For the facility operator these aspects may include:

- Integration of the additional verification activities and schedule of the IAEA into the facility procedures to be followed in preparing spent-fuel items for transfer (including requirements for regulatory and State safeguards-authority oversight);
- Working with the IAEA and other authorities to optimize the IAEA's approach for maintaining continuity of knowledge of the spent fuel during transfer, emplacement and storage. This can include the use of seals, on-board cameras and/or radiation monitors during transfer, unattended monitoring systems and remote data transmission, radiation characterization for reverification purposes, and in general verification strategies based upon near-real-time inspections and random selection;
- Procurement of dry-storage containers that facilitate the efficient application of IAEA seals while minimizing the burden (resources, time, health and safety) to both the operator and IAEA, including an 'immobilization seal' or other measure that provides continuity of knowledge of each container's movement history – or, less ideally (in lieu of earlier SBD), working in advance with the IAEA to retrofit these safeguards accommodations into existing container designs;

3.2. SBD and Spent-Fuel Management in Advanced NPPs

The spent-fuel forms and flows in advanced and small-modular reactor facilities are as varied as the scope of these technologies now under development. In order to independently maintain continuity of knowledge of the irradiated fuel in any NPP, the IAEA needs to be capable of assessing the accuracy of operational declarations of spent-fuel burnup and location. This is typically achieved through the use of verified core-physics correlations and spent-fuel assays, facility design information verification, remote monitoring of fuel movement where necessary, C/S measures (e.g., seals, cameras) at storage locations, and direct verification of spent-fuel items by inspectors (through both visual observation and radiation detection).

For advanced reactors, the data and techniques to support safeguards will be either developed from scratch or modified from existing procedures. In either case the IAEA will require familiarity with the detailed facility layout, core operation, and spent-fuel characteristics (e.g., detailed design, burnup, time-dependent radiation signature), and will seek to optimize the type and location of C/S measures – where possible, utilizing unattended measurement systems and remote data transmission. In cases of sufficiently advanced NPP designs it may be necessary to develop bespoke IAEA measurement equipment, or make significant modifications to existing equipment. The earlier this engagement between the operator and the IAEA occurs, the better, since time will be needed to have an effective and efficient safeguards approach in place when nuclear material is first received at the NPP. This is particularly true if R&D is needed to develop new or modified IAEA instrumentation, and since such R&D often requires the support of State experts, this will require external coordination.

In most cases it will be beneficial to begin this proactive engagement at the design stage, since it is here that the most cost-effective accommodations can be made (as outlined in Section 2). It is during the engineering design phase that the incorporation of safeguards considerations with those of safety and security can best avoid any compromises between these requirements, and possibly exploit synergies (known as ‘3S’ considerations). Thus, SBD is expected play an increasingly important role in ensuring the timely deployment of advanced reactors and other innovative nuclear facilities.

SBD takes on particular importance where bulk flow (or ‘quasi’-bulk-flow) of spent fuel is involved, usually accompanied by continuous operation (i.e., online refuelling). In these cases, such as molten-salt reactors or pebble-bed reactors, the form and flow of spent fuel tends to be the most departed from conventional IAEA experience, and the requirement for new safeguards techniques and processes the most acute. Without individually identifiable items of spent fuel available for identification and verification, the IAEA may need to employ safeguards measures conceptually similar to those found in reprocessing, fuel fabrication, or other bulk-flow nuclear facilities – which tend to be more complex, resource-intensive, and dependent upon support from the facility designer and operator for development (see also the discussion in the next section).

As with some of these other types of fuel-cycle facilities, process monitoring may be required, and it may prove advantageous to make use of shared operator data in some cases – appropriately authenticated for IAEA safeguards use as necessary. At the same time the continuous operation and lack of core access in many of these designs will necessitate the use of robust, unattended measurement equipment and, if possible, remote data transmission.

Even in the case of advanced reactors with individually verifiable items of spent fuel, SBD will be beneficial in ensuring that verification activities are efficient and effective, and the need for retrofitting minimized. To support this, the IAEA has published guidance based on past experience, related to the application of C/S measures in spent fuel bays [4] (e.g., accommodation for IAEA equipment, ambient lighting levels, water clarity, storage rack design, limitations on operational activity, etc.). In the context of this guidance it’s possible to underscore specific concerns of importance to advanced and small-modular reactors that have arisen in recent SBD discussions, such as:

- Minimizing healthy and safety risks for inspectors working in a spent-fuel bay designed for minimal human presence (small footprint facilities);
- Facilitating inspection approaches that accommodate stacking of smaller spent-fuel items in the spent-fuel bay where necessary;
- Facilitating the independent distinction between fresh and spent fuel where both are stored in the same spent-fuel bay;
- Facilitating the independent identification of spent fuel when multiple modules within one NPP utilize the same spent-fuel bay.

3.3. SBD and Spent-Fuel Reprocessing

Several proposed advanced-reactor fuel cycles incorporate some form of reprocessing of spent fuel, in order to maximize resource efficiency and minimize the burden of final spent-fuel management. Any reprocessing activity is naturally challenging for safeguards as it involves nuclear material that is both highly radioactive and in bulk (non-item) form. The bulk nature usually implies statistical accounting techniques and management of process losses (in safeguards terms, 'material unaccounted for' or MUF) that must be sufficiently characterized to facilitate continuity of knowledge by the IAEA. The highly radioactive nature means that this must be achieved under difficult circumstances, typically necessitating remote handling or measurement.

Regardless of inherent challenges, the IAEA's objectives in safeguarding a reprocessing facility will be the same as with any nuclear facility: independent verification of nuclear-material accounting declarations, and continuity of knowledge. To achieve this, the IAEA will implement a number of measures including direct sampling, process monitoring (possibly utilizing shared operator data), design information verification, and C/S. The degree to which these measures are implemented will depend upon the complexity of the facility layout and chemical processes, and in general will be negotiated with the facility operator in order to minimize both the disruption to operations and the burden on the IAEA, while achieving the necessary safeguards objectives.

The IAEA has some experience with safeguarding reprocessing facilities, despite these being mainly located in nuclear-weapon States (NWS) and not under international safeguards. The most significant example is the Rokkasho Reprocessing Plant in Japan, under full IAEA safeguards that were developed with the extensive support of the designer and operator prior to operation. This level of SBD was essential for the efficient implementation of safeguards at this complex facility.

This will be no less true for advanced fuel cycles involving reprocessing, whether envisaged as integral processes within a reactor facility, or as stand-alone facilities – and particularly where advanced techniques are employed (e.g., pyroprocessing), for which there is little or no safeguards experience. The IAEA has published general SBD guidance (including best practices) for reprocessing facilities [5], which will be an important starting point for technology-specific SBD discussions – ideally initiated at the earliest possible stage of development.

3.4. SBD and Deep Geological Repositories for Spent Fuel

The end goal for spent fuel in most national fuel cycles is emplacement and long-term disposal within a Deep Geological Repository (DGR). Under current IAEA policy, both the pre-closure and post-closure phases of a DGR are subject to safeguards, due to the large volume of nuclear material involved and the fact that it cannot be considered 'practicably irretrievable' by the host State (i.e., the condition for termination of safeguards, per most States' safeguards agreements).

From the safeguards standpoint, a DGR represents a very large and complex version of a dry-storage facility as discussed is Section 3.1. Thus, the safeguards approach for a DGR will be conceptually similar to that of a conventional dry-storage facility:

- Spent fuel will have additional IAEA verification requirements prior to transfer;
- Spent-fuel transfers (from NPP to encapsulation plant, and from encapsulation plant to emplacement) will require continuity of knowledge by the IAEA;
- Viewed as a very large spent-fuel storage container, a DGR will require C/S measures applied to all credible diversion routes (e.g., surface access points), and the integrity of the containment verified (in this case, the 'geological containment' of the rock encompassing the active emplacement zone);
- Design information verification will be important in ensuring continuity of knowledge, updated as the DGR is constructed and operated.

Practically speaking, safeguarding a DGR will be one of the most challenging tasks taken on by the IAEA under its mandate. A DGR is a very large single facility (on the order of kilometres in all dimensions), most of which exists deep underground. During a DGR's extensive pre-closure phase of a century or longer, it is both an operational facility and a construction site, with dirty and dangerous conditions that are not conducive to independent inspection.

It is in every stakeholder's interest, therefore, that safeguards implementation at a DGR (and its associated encapsulation and final verification stages) be as simple and efficient as possible, while meeting the obligations of the host State under its safeguards agreement. As with reprocessing, this is a classic case for the application of SBD, and the IAEA has accordingly published guidance on this topic [6]. Also as with reprocessing, global SBD experience is very limited; however, much has been learned from the IAEA's interactions with the host State authorities, European Union safeguards authorities, NPP operator, and the designer/operator for Finland's Onkalo

DGR located near the Olkiluoto NPP, which has been under development for two decades and is soon expected to begin accepting spent fuel.

4. IMPLEMENTING SBD

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).

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 with respect to spent-fuel management [3-6]. 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.

For high-TRL technology under consideration for implementation at an existing facility (e.g., procurement of a dry-storage facility at an operating NPP), SBD interaction with the IAEA will likely be initiated through the State's normal channels of communication for safeguards implementation – i.e., via the IAEA Department of Safeguards' personnel associated with a specific State and facility. For technology under development and not necessarily involving a specific technology recipient, the designer would typically interact with the technical support side of the IAEA Department of Safeguards, the main point of contact being the Division for Concepts and Planning (SGCP).

For example, in the specific case of SMRs the IAEA Department of Safeguards initiated several years ago a dedicated Member State Support Programme (MSSP) task that facilitates SBD engagement directly with SMR designers, with SGCP 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.

More information on the IAEA's safeguards-by-design activities can be found on its website at: www.iaea.org/topics/assistance-for-states/safegaurds-by-design.

5. CONCLUSIONS

Responsible spent-fuel management is an important feature of nuclear technology, and in most countries this includes international non-proliferation obligations verified by the IAEA through the application of safeguards. Whether spent-fuel storage is temporary (wet pools), intermediate (dry storage), or long-term (deep geological repository) – and whether or not it is integrated with a recycling option (reprocessing) – the efficiency of safeguards implementation can be greatly enhanced through early discussion with the operator or designer, reducing the subsequent burden on all stakeholders (IAEA, State authorities, and operator) during construction and operation.

This process of 'safeguards by design' (SBD) presents clear benefits for deployment of any nuclear technology, but is particularly important where new forms and flows of spent fuel will be introduced in advance reactors and other fuel-cycle facilities under development.

The IAEA stands ready to support the nuclear industry in its development of sustainable spent-fuel management strategies, and has published SBD guidance that can inform proactive, collaborative efforts to minimize risk and support the timely deployment of new technologies.

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