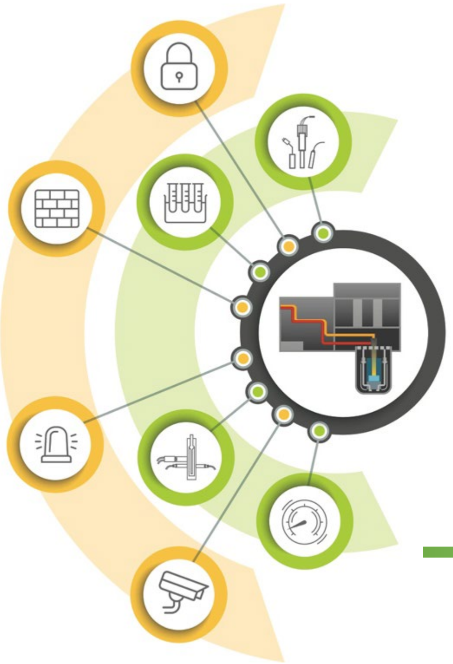

Advanced Reactor Safeguards:

Lessons from the IAEA Safeguards Domain

Prepared for
US Department of Energy

**AG Garrett, SL Garrett, RJ Marek, MR Mitchell, CR Orton, RT Otto,
T Sobolev, DC Springfels**

Pacific Northwest National Laboratory

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Executive Summary

Lessons from the International Atomic Energy Agency (IAEA) safeguards domain are relevant to U.S. advanced reactor designers for at least two reasons:

1. The IAEA has recent experience applying safeguards at advanced reactors which could provide useful case studies for designers planning nuclear material control and accounting (MC&A) systems.
2. U.S.-designed reactors can become subject to IAEA safeguards if they are exported internationally or if they are selected for safeguards under the U.S.-IAEA Voluntary Offer Agreement, as implemented through 10 CFR Part 75.

While IAEA safeguards have different objectives and may use a different mix of technical measures than domestic safeguards required by the Nuclear Regulatory Commission (NRC), both systems employ nuclear material accounting to detect if nuclear materials have been illicitly removed or misused at a facility. Understanding the synergies and distinctions between domestic and IAEA safeguards can help facility designers efficiently prepare for both sets of requirements.

This study comprises two parts. The first part discusses the relation between IAEA safeguards, domestic MC&A, and other measures such as physical protection. The second part describes lessons learned from past application of IAEA safeguards at advanced reactors. The report and the cited literature describe historical IAEA safeguards implementation, R&D, and planning considerations for these types of facilities. Significant research on IAEA safeguards for advanced reactors has been supported by the DOE National Nuclear Security Administration (DOE/NNSA) and others in the international safeguards community. The study addresses sodium fast reactors (SFRs), pebble bed reactors (PBRs), and molten salt reactors (MSRs).

Connection Between IAEA Safeguards and Domestic MC&A

As a starting point, it is important to frame the distinctions and similarities between domestic and IAEA safeguards. The NRC uses the term *domestic safeguards* to refer to measures including MC&A and physical protection that prevent non-state actors from perpetrating malicious acts involving nuclear material or facilities. This includes unauthorized removal of nuclear material (e.g., for use in an improvised nuclear device or radiological dispersion device) or the sabotage of nuclear facilities. MC&A, as one component of domestic safeguards, is used to detect and deter unauthorized removal of nuclear materials and to inform a timely and effective response to missing material. Physical protection (involving guards, barriers, surveillance, and alarm systems) is used to detect, delay, and respond to malicious acts. These measures are implemented by licensees and overseen by the NRC under U.S. law.

In contrast, IAEA safeguards confirm that State actors do not use nuclear activities under their jurisdiction to illicitly divert or produce nuclear materials for nuclear weapons in violation of international commitments. Because *State authorities* are the potential adversary, verification is performed by the IAEA, pursuant to safeguards agreements between the IAEA and each State.[1] These agreements stipulate that the State must declare nuclear material accounting data and other information to the IAEA, and IAEA inspectors verify that this information is correct and

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[1] The Treaty for Nonproliferation of Nuclear Weapons, which has been adopted by over 190 parties, requires that all Non-Nuclear Weapons States parties accept safeguards on all peaceful nuclear activities. As a result, IAEA safeguards are required for most export destinations.

complete. The information declared by the State generally originates from the domestic MC&A system, comprising a basic linkage between domestic and IAEA safeguards.

Since a notional State adversary is assumed to have control of the facility and full cooperation of the staff, physical protection and nuclear material control are not within the scope of IAEA safeguards. As a result, nuclear material accounting comprises the primary overlap between the domestic and IAEA safeguards systems. A key distinction is that the IAEA must independently verify State declarations (including taking routine measurements of nuclear material and applying its own containment and surveillance systems), whereas the NRC's focus is that licensees are meeting regulatory requirements and other obligations. Table E.1 provides an abbreviated crosswalk between domestic MC&A and IAEA safeguards. A more detailed discussion and crosswalk are found in the body of the report.

Table E.1: Abbreviated Comparison of Domestic MC&A and IAEA Safeguards

Topic	**U.S. domestic MC&A**	**IAEA safeguards**
Notional threat	Malicious subnational actor(s) from either inside or outside the facility, as described in a design basis threat.	State authorities with full cooperation of facility operator.
Legal basis	Based in U.S. law, with requirements defined in the Code of Federal Regulations and associated regulatory documents.	Defined in legally binding safeguards agreements between the IAEA and a State.
Provision of material accounting data	Provided by the licensee/facility operator to the NRC.	Provided by the State to the IAEA, likely based on operator MC&A data.
Verification goals	NRC verifies that licensee's MC&A system and practices meet regulatory requirements.	IAEA inspectors independently verify the correctness and completeness of State declarations regarding their nuclear material and activities, which includes performing measurements of nuclear material.
Regulatory or enforcement authority	The NRC has regulatory authority over its licensees and may take various enforcement measures including withholding or revoking a license if licensees do not demonstrate compliance with regulation.	The IAEA *does not* exert regulatory authority over the State or facility operators. The IAEA may report irregularities or noncompliance to Member States or the UN Security Council.
Role of nuclear material accounting	Used to detect and deter unauthorized removal and provide timely information for response to loss or removal of material.	Used to detect and deter diversion or misuse of nuclear materials. Not used for response or localization, which may lead to different material balance area structures than used domestically.

Relation to physical protection and nuclear material control	Physical protection and nuclear material control systems complement nuclear material accounting by providing additional ways of detecting, deterring, or delaying unauthorized removal. These can include administrative measures such as separation of duties or two-person rule.	Not part of IAEA safeguards. The IAEA must be able to independently detect diversions without reliance on these systems.

Case Studies from IAEA safeguards at Advanced Reactors

The IAEA has applied safeguards at sodium-cooled fast reactors and pebble-bed reactors in Japan, Germany, China, and elsewhere. The IAEA does not have verification experience at MSRs, but limited comparisons can be drawn to IAEA safeguards at reprocessing plants. The report examines case studies of the IAEA safeguards approaches used at these facilities and associated lessons learned. Some key points are described below.

- **For SFRs**: This case study examined IAEA safeguards primarily at the Monju fast breeder reactor in Japan. The IAEA safeguards approach required complex systems for identifying and maintaining continuity of knowledge of fuel assemblies along the fuel handling pathway. Such systems would probably exceed the needs of U.S. domestic safeguards, as set out in 10 CFR 74 or ANSI standard N.15-8 2009. (Existing U.S. MC&A practices for light water reactors may remain relevant at SFRs because they both use assembly-type fuel). However, if deployed in the international context, these special measurement and monitoring tools could provide added assurance regarding the location and identity of fuel assemblies. Extensive coordination would probably be required between the IAEA, the State, and the facility to implement the customized hardware and data sharing required.
- **For PBRs**: IAEA safeguards approaches for PBRs in Germany and China combined (1) item accounting for containerized fresh and spent fuel, and (2) a quasi-bulk accounting approach for the in-process pebbles. This was based around automated counting of pebbles entering/leaving the reactor, supported by containment and surveillance of the reactor and supplemental measurement or verification of pebbles. This approach does not strictly align with existing MC&A requirements for reactors or for fuel cycle facilities in 10 CFR 74; however, it does resemble an approach proposed by Oak Ridge National Laboratory in a model MC&A plan.[1] If IAEA safeguards are applied, the IAEA would likely need access to data, equipment, and locations associated with the automated pebble handling and waste discharge systems.
- **For MSRs:** There remain many uncertainties regarding MC&A requirements for future MSRs, but current MC&A requirements for Category I and II fuel cycle facilities establish requirements for measurements and process monitoring. IAEA safeguards at large aqueous reprocessing plants (which serve as a potential analog) rely heavily on attended and automated systems including process monitoring for estimating material balances, tracking solution movements, and identifying signatures of diversion and misuse. Some of these approaches merit further examination for being adapted for MC&A at MSRs.

Addressing Interfaces with IAEA Safeguards

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[1] Kovacic, Donald N.; Gibbs, Philip; Scott, Logan (2020): Model MC&A Plan for Pebble Bed Reactors. Oak Ridge National Laboratory. Oak Ridge, TN (ORNL/SPR-2019/1329). Available online at https://info.ornl.gov/sites/publications/files/pub132501.pdf.

Reactor designers who are planning for MC&A, physical protection, and other aspects of reactor design and operations might gain efficiencies from considering international safeguards during the design phase, thereby reducing the need for future modifications if a design becomes subject to IAEA safeguards. A common theme in IAEA safeguards-by-design is that special provisions may be needed to help the IAEA reach independent, verifiable conclusions, which will require a mix of inspector access to materials, special IAEA measurement and monitoring systems, or joint-use IAEA/operator instrumentation. Specific topics identified in the case studies include:

- **Sharing data or instruments with the IAEA and ensuring data security**: Advanced reactors may have instruments for fuel handling, measurement, and process control, and MC&A that could benefit IAEA safeguards. For example:
  - SFRs: Nondestructive assay and containment/surveillance systems that confirm presence, identify, attributes, or other features of fuel assemblies along fuel transfer pathway.
  - PBRs: Pebble counters and handling equipment, burnup measurement systems, or waste surveillance systems.
  - MSRs: Instruments relating to salt quantity, composition, flow, location, or other process parameters.

  It sometimes may be advantageous for both the IAEA and the facility operator to pursue joint-use of these instruments, although this introduces a need for coordinated vulnerability testing, data security, and instrument development with the IAEA.[1] A key need is ensuring that the IAEA can assure the independence of any signal used for safeguards use, for example by having an independent/encrypted IAEA signal split off within a tamper-indicating enclosure. If joint-use is not pursued, then the IAEA may need to install duplicative, IAEA-owned instruments that would need to be accommodated within the facility design and licensing process. For systems that interface directly with the reactor process, this will require increased levels of advance planning and coordination on IAEA requirements.

- **Benefits of containerization**: Because of the comparative simplicity of item verification for both domestic MC&A and IAEA safeguards, it will be useful to take advantage of containerization of nuclear material, particularly at PBRs and MSRs. This may require steps to ensure that container design and facility operations are compatible with IAEA sealing needs, that IAEA verification can occur at centralized fuel fabrication facilities, and that the IAEA can validate declarations regarding wastes (like discharged pebbles) that are placed in sealed containers through inspector access or special monitoring systems.

- **Need for enhanced containment, surveillance, and measurement capabilities:** Because IAEA inspectors must verify a facility's nuclear material inventory without relying on physical protection assumptions or other operator systems, the IAEA may have increased need for containment/surveillance systems compared to domestic MC&A. Key areas include (1) assembly flow paths for SFRs and (2) any potential sampling or takeoff points that could be used to remove nuclear materials at PBRs or MSRs. These facilities should minimize potential takeoff points and ensure that the facility design can provide for effective monitoring of these points.

- **Advanced engagement and safeguards and security by design.** A final general need area is for advance coordination and information sharing between stakeholders. As mentioned previously, the specific domestic MC&A and IAEA safeguards needs will likely vary for

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[1] K. Tolk and M. Zendel. "Considerations for Joint Use Equipment." SAND2009-8331C. https://www.osti.gov/servlets/purl/1141419.

different facility types, and domestic and international requirements will continue to evolve. Coordination at appropriate intervals involving facility designers, U.S. government stakeholders (including DOE/NNSA) and the IAEA will help identify problems proactively and help navigate interfaces between domestic MC&A and IAEA safeguards. This is particularly true for facilities such as liquid-fueled MSRs that may have especially complex MC&A systems. The IAEA and DOE/NNSA have issued reports on international safeguards by design (SBD) for a variety of relevant facility types, which can provide further guidance and considerations [1]

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[1] DOE/NNSA. (2017). Safeguards by Design Guidance Documents. https://www.energy.gov/nnsa/downloads/safeguards-design-guidance-documents

IAEA (2021). Safeguards By Design Documents. https://www.iaea.org/topics/assistance-for-states/safeguards-by-design-guidance

Acknowledgments

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Acronyms and Abbreviations

ARDP	Advanced Reactor Demonstration Program
CFR	Code of Federal Regulations
C/S	Containment and surveillance
CSA	Comprehensive safeguards agreement
DA	Destructive assay
DOE/NNSA	Department of Energy/National Nuclear Security Administration
DU	Depleted uranium
EVTM	Ex-vessel transfer machine
FNMC	Fundamental nuclear material control (plan)
HEU	High enriched uranium
HTGR	High temperature gas reactor
IAEA	International Atomic Energy Agency
ID	Inventory difference
LEU	Low enriched uranium
LWR	Light water reactor
MBA	Material balance area
MSR	Molten salt reactor
NDA	Nondestructive assay
NNWS	Non-Nuclear Weapon State
NPT	Treaty on the Nonproliferation of Nuclear Weapons
NRC	Nuclear Regulatory Commission
NWS	Nuclear Weapon State
PBMR	Pebble-bed modular reactor
PBR	Pebble-bed reactor
SEID	Standard error of the inventory difference
SFR	Sodium fast reactor
SSBD	Safeguards and security by design
VOA	Voluntary Offer Agreement

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1.0 Introduction

The U.S. nuclear industry is currently developing numerous advanced reactor concepts with plans for both domestic and international deployment. The U.S. Department of Energy promotes these efforts through coordinated programs of R&D and economic support. In FY20, DOE inaugurated the Advanced Reactor Demonstration Program (ARDP), which paves the way to deploy U.S. advanced reactors by the end of the decade.

As Nuclear Regulatory Commission (NRC) licensees, U.S. civilian reactor operators must comply with nuclear security requirements set out in federal regulation. This includes requirements for nuclear material control and accounting (MC&A) to maintain a current inventory of all nuclear material within a facility, including forms, quantities, and locations. MC&A helps to deter, detect, and respond to the loss or unauthorized removal of nuclear material, alongside other sets of nuclear security measures such as physical protection.

Certain MC&A measures and approaches used in the commercial light water reactor (LWR) fleet are expected to be ill-suited for future advanced reactor designs, for example:

- Advanced reactors using liquid or pebble fuel types are poorly suited for standard item-based accounting measures, in which fuel elements are uniquely identified, counted, and verified for integrity.
- Some advanced reactors use non-traditional refueling approaches that differ greatly from the periodic batch fueling at LWRs—for example, online fueling/reprocessing.
- Some advanced reactors have technical characteristics that would preclude the use of current verification tools or techniques. For example, irradiated reactor fuel might not be available for visual inspection due to shielding requirements or the use of opaque metal coolants. Other issues include restricted operator/inspector access due to elevated radiation fields and the immaturity of measurement systems for new fuel types.

The international community also faces nuclear material accounting challenges at advanced reactors. In addition to national regulatory requirements, over 180 countries are subject to safeguards verification by International Atomic Energy Agency (IAEA). The IAEA relies heavily on material accounting to verify that State authorities do not divert nuclear materials for illicit weapons uses. While there are significant differences between U.S. domestic MC&A requirements and IAEA safeguards, they often use similar tools and techniques to measure nuclear material and report accounting records.

The IAEA, DOE's National Nuclear Security Administration (NNSA), and other entities have developed knowledge and experience relating to IAEA safeguards at advanced reactors and analogous facilities. This includes both direct experience applying safeguards at advanced reactors and forward-looking studies to identify technology gaps, develop safeguards tools, evaluate inspection approaches, and implement safeguards-by-design at advanced reactors. Connections drawn to the IAEA safeguards domain may be useful to U.S. regulators and industry in two main ways:

- The IAEA currently applies safeguards at some types of advanced reactors—for example, sodium cooled reactors in Japan and pebble-bed reactors in China. These international experiences could provide lessons as DOE and NRC address the challenge of regulating advanced reactors in the United States.

- Some U.S. reactor designs might become subject to IAEA safeguards. This could occur under the U.S. safeguards agreement with the IAEA (a so-called ‘voluntary offer agreement’ or VOA), which is the subject of 10 CFR Part 75. It could also occur through export to non-nuclear weapons states where IAEA safeguards are compulsory. Understanding the requirements and practices of IAEA safeguards could help U.S. designers capture synergies between domestic and international safeguards through safeguards and security by design (SSBD). This has the potential to make U.S. reactor designs more attractive to foreign customers and to enhance the effectiveness and efficiency of IAEA verification.

1.1 Purpose and Scope

This report evaluates the status of IAEA practices and research (including public literature, safeguards practices, and technology/tools) relating to international safeguards at advanced reactors. The purpose is to identify areas where IAEA safeguards experience may be relevant to U.S. domestic stakeholders. The report focuses on the following themes:

1. Where are the intersections between IAEA safeguards and U.S. domestic MC&A, and what key distinctions or caveats must be accounted for when translating findings from one domain to the other?
2. What advanced reactors have been under IAEA safeguards and what can we learn from the IAEA safeguards approaches?
3. What research (ranging from scoping studies, to implementation analyses, to technology development) has been done for IAEA safeguards at advanced reactors and how can this apply to U.S. domestic safeguards or the MC&A mission?
4. Are there ways that U.S. reactor designers can account for international safeguards requirements for enhanced safeguards and security by design.

The analysis is based on a review of open literature and consultation with IAEA and domestic safeguards experts. The report is intended to be useful for (1) U.S. reactor designers, who may benefit from increased awareness of IAEA safeguards requirements for SSBD purposes and (2) programs in DOE-NE and NNSA that share similar safeguards and security interests in domestic and international domains.

1.2 Reactor Types Under Consideration

The term “advanced reactor” can refer to a variety of distinct reactor types. This report focuses on three types of reactors based on their prospects for U.S. and international deployment and their safeguards-relevant design features:

1. Sodium-cooled fast reactors (SFRs)
2. Pebble-bed reactors (PBRs)
3. Molten salt-fueled reactors (MSRs)

2.0 Comparing U.S. Domestic Measures for MC&A and Physical Protection and IAEA Safeguards

This section discusses the similarities and distinctions between (1) domestic MC&A and physical protection practices (collectively called "domestic safeguards" by the NRC), and (2) IAEA safeguards. Both systems use nuclear material accounting to verify that no material has been illicitly diverted or removed from its stated use. However, the two systems deal with fundamentally different types of threats, and as a result, have numerous technical differences.

Domestic MC&A and physical protection address the risk that **non-state** actors could perpetrate malicious acts involving nuclear material. This includes unauthorized removal of nuclear material (e.g., for use in an improvised nuclear device or radiological dispersion device) or the sabotage of nuclear facilities. Providing for nuclear security is the responsibility of a state's domestic authorities. In the United States, the NRC prescribes standards for protection, control, and accounting of nuclear materials. Licensees must meet these standards subject to NRC oversight and enforcement. One category of measures is MC&A, which is used to detect and deter unauthorized removal of nuclear materials and to inform a timely and effective response to missing material. Another category of measures is physical protection (involving guards, barriers, surveillance, and alarm systems) to detect, delay, and respond to malicious acts.

In contrast, IAEA safeguards (a form of *international* safeguards) confirm that **State authorities** do not use nuclear activities under their jurisdiction to illicitly divert or produce nuclear materials for nuclear weapons in violation of international commitments. Because the *State* is the potential adversary, verification is performed by the IAEA, pursuant to international safeguards agreements between the IAEA and the State.[i] These agreements stipulate that the State must declare nuclear material accounting data and other information to the IAEA, and IAEA inspectors verify that this information is correct and complete. The information declared by the State generally originates from the domestic MC&A system, comprising a basic linkage between domestic and IAEA safeguards.

Since a notional State adversary is assumed to have control of the facility and full cooperation of the staff, physical protection and nuclear material control are not within the scope of IAEA safeguards. **As a result, material accounting comprises the primary "overlap" between the domestic and IAEA safeguards systems.** The basic differences between domestic MC&A and IAEA safeguards are captured in Table 2 at the end of the section. Appendix A discusses common terminology used for these different systems.

2.1 NRC regulations for MC&A at power reactors

Several NRC regulations are relevant to power reactors, including:

- 10 CFR Part 50, which contains the licensing requirements for production and utilization facilities. (Power reactors are considered utilization facilities).
- 10 CFR Part 70, which contains licensing requirements for special nuclear material (such as the enriched uranium and plutonium used at a reactor).

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[i] Importantly, the Treaty for Nonproliferation of Nuclear Weapons, which has been adopted by over 190 parties, requires that all Non-Nuclear Weapons States parties accept safeguards on all peaceful nuclear activities. As a result, most export destinations for U.S. vendors would require IAEA safeguards.

- 10 CFR Part 74, which contains requirements for material control and accounting of special nuclear material.

As the principal regulation on domestic MC&A, 10 CFR Part 74 uses a graded approach that applies more stringent MC&A requirements to facilities that use nuclear material in higher categories of strategic significance. Briefly:

- 10 CFR Part 74, Subpart B contains general reporting and recordkeeping requirements that apply to all owners of special nuclear material. These require licensees to submit to the NRC periodic material accounting reports and to promptly notify the NRC of any suspected loss of nuclear material.
- Subparts C, D, and E address MC&A requirements for Category III, Category II, and Category I quantities of special nuclear material, respectively. These subparts require licensees to enact an approved fundamental nuclear material control (FNMC) plan that states how the licensee will meet the respective MC&A requirements. **However, power reactors (as utilization facilities) are specifically excluded from these requirements.** These requirements apply primarily to fuel cycle facilities and some are tailored for bulk handling operations.

Under current regulations, power reactor operators must only meet the more general reporting requirements in 10 CFR 74 Subpart B, *General Reporting and Recordkeeping Requirements*, and are not required to prepare an FNMC plan. The current Part B regulations are suited for reactors that use large, assembly-type fuel that is static, does not change form, and would be difficult for a non-state actor to handle or transport. For these reactor types, item identification and counting, rather than nuclear material measurement, is practical for most MC&A purposes. However, the current regulations may be reconsidered for certain advanced reactor types, such as pebble bed reactors and molten salt reactors, because they have nuclear material freely moving throughout the reactor and will most likely need to be treated as *bulk* material, which is not individually identified for material accounting purposes. (Pebble fuel may be “quasi-bulk” because it is countable and because some measures for pebble identification have been explored). Adapting requirements and procedures for a bulk type reactor will likely require innovative accounting methods, similar to what might be implemented at fuel cycle facilities.[i]

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[i] Additionally, some advanced reactors are considering using LEU that is enriched between 10% and 20% in U-235, which is different from the current US NPPs that use LEU enriched to less than 5% U-235. This increase in enrichment could change the safeguards and security classification from Category III to Category II, resulting in additional physical protection and MC&A requirements under Subpart D.

MC&A Practices at Current NPPs

ANSI Standard N15.8-2009 describes suitable methods for meeting the NRC's MC&A requirements at current power reactors under 10 CFR 74 subpart B. The standard is accepted by the NRC in its Regulatory Guide 5.29.

As called for in 10 CFR 74, physical inventories must be verified at least annually. The inventory method outlined in the standard centers on counting of items—such as complete assemblies or other nuclear materials (e.g., damaged fuel pieces) that have been measured and placed in a sealed container—and cross-referencing records and serial numbers. The ANSI standard also provides guidance on shipments and receipts of nuclear material, establishing internal control areas, and calculating the gain or loss of nuclear materials through irradiation. The procedures do not typically include assay of nuclear material.

As an example of how MC&A approaches may be adapted, the NRC commissioned Oak Ridge National Laboratory to develop a model FNMC for a pebble-bed reactor using Category II material.[1] The model FNMC plan outlines a "hybrid" bulk/item MC&A approach combining relevant requirements for non-reactor and reactor facilities, which serves as a reference for how MC&A might be accomplished.

It is up to each individual licensee to determine how they will meet the NRC requirements. As contemplated in the Oak Ridge report, the NRC may require advanced reactor licensees, who possess a Category II quantity of nuclear material or whose facilities have nuclear material that flows through the reactor, to prepare and submit an FNMC plan that describes how they will meet the intent of MC&A regulations contained in 10 CFR Subparts B and D. The NRC would perform MC&A inspections of these facilities to determine if the licensee's MC&A system adequately detects and protects against the loss, theft, or diversion of nuclear material.

2.2 IAEA safeguards activities at power reactors

The conduct of IAEA safeguards activities is set out in legally binding safeguards agreements (and other supporting arrangements) between the IAEA and each State. Nearly all non-nuclear weapons states have a 'comprehensive safeguards agreement' based on IAEA Information Circular 153 (INFCIRC/153). As framed in this document, the objective of IAEA safeguards is "the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection." Paragraph 29 identifies material accountancy and containment and surveillance (C/S) as the basic measures used to implement safeguards.

The State authorities must provide the IAEA with periodic reports on the locations, quantities, and use of nuclear materials and must provide access to IAEA inspectors to verify this information. The licensee's accounting system developed for domestic MC&A purposes is usually adaptable to meet the reporting requirements for IAEA safeguards purposes. The IAEA and the State will cooperate to define Material Balance Areas (MBAs, analogous to Internal Control Areas) that are used to localize nuclear material for accounting purposes. These MBAs may be larger than those defined for domestic MC&A, since IAEA safeguards are not used to localize or respond to potential losses of nuclear material or issues with the operator's MC&A system.

The frequency and intensity of IAEA inspections are designed to detect diversion of *significant quantities* of nuclear material within a specific *timeliness* goal. The IAEA selected numerical values for these variables (shown in Table 1), with the goal that the IAEA should detect diversions of weapons-relevant quantities of nuclear material before the material could be converted into a weapons-usable form. The timeliness and significant quantity values vary according to the type of nuclear material and other considerations. The IAEA uses statistical sampling plans and various types of measurements (ranging from precise destructive assay measurements, to nondestructive assay, to gross item counts) to achieve detection goals for different types of diversion or misuse scenarios.

Table 1: Representative timeliness and significant quantity goals for IAEA safeguards[2]

Material type	**Significant Quantity**	**Timeliness goal**
LEU	75 kg of U-235	1 year
HEU (unirradiated)	25 kg of U-235	1 month
HEU (irradiated)	25 kg of U-235	3 months
Pu and U-233 (unirradiated)	8 kg Pu or U-233	1 month
Pu and U233 (irradiated)	8 kg Pu or U-233	3 months

IAEA inspections must independently confirm the correctness and completeness of nuclear material accounting data without additional layers of physical protection or nuclear material control. As a result, the IAEA may perform certain types of technical measures such as nondestructive assay of fuel assemblies that are not common in domestic MC&A at reactors. Also, the IAEA reaches conclusions with respect to the *status of nuclear material* at a facility, unlike domestic regulators, its goal is not to assess the *compliance* of the operator’s practices with MC&A requirements.

IAEA Safeguards Measures at Current LWRs

For each facility under safeguards, the IAEA designs a safeguards approach that contributes to meeting the objectives of INFCIRC/153. LWRs are considered item facilities, and IAEA safeguards measures may include:

- Item counting and reconciliation of assembly serial numbers for fresh and irradiated fuel
- Use of nondestructive assay to verify gross or partial defects in fresh and spent fuel (including handheld detectors and neutron coincidence counters for fresh fuel, and fork-detectors for spent fuel stored underwater).
- Use of Cerenkov viewing devices to monitor for concealed diversion of spent fuel
- Application of seals and use of surveillance devices to detect undeclared access/movements of nuclear materials between inspections.

In addition to nuclear material accounting, containment and surveillance (C/S) are important, complementary safeguards measures used by the IAEA. C/S measures are aimed at verifying information on movement of nuclear material or preservation of the integrity of safeguards relevant data. In many instances C/S measures cover the periods when the inspector is absent, thus ensuring the continuity of knowledge for the IAEA. The IAEA implements C/S through physical containment, cameras, radiation or motion sensors, and tamper-indicating devices. The IAEA uses these systems differently than a nuclear facility operator. They are used to preserve and confirm accountancy measurements and to identify indications of undeclared movements of nuclear material. They are *not* used for nuclear material access control. Domestic facilities can also implement various administrative measures for nuclear material surveillance or control (e.g., separation of duties, two-person rule) that are not relevant for IAEA safeguards.

IAEA Safeguards for U.S.-designed reactors

U.S. designed reactors exported to NPT Non-Nuclear Weapons States (NNWS) would fall under the importing country's comprehensive safeguards agreement and would be subject to IAEA safeguards as described in Section 2.2.

The United States is a Nuclear Weapons State under the NPT and is not required to accept IAEA safeguards on all its domestic peaceful nuclear activities. However, the United States has a voluntary offer agreement (VOA) with the IAEA under which the U.S. generally makes civilian nuclear facilities eligible for IAEA safeguards. The IAEA may select these eligible facilities for safeguards if desired. One reason the IAEA might select an eligible U.S. facility for safeguards is to test new safeguards approaches before a new type of facility is deployed more broadly in NNWS. For this reason, U.S.-based advanced reactors may be of special interest to the IAEA if they were placed on the U.S. list of eligible facilities. The process by which U.S. nuclear facilities are made eligible and selected for safeguards is managed jointly by a group of U.S. agencies.

Regulations pertaining to the U.S.-IAEA VOA are contained in 10 CFR 75. Currently, the IAEA is not implementing safeguards at any U.S. power reactors.

2.3 Summary and Crosswalk of Domestic and IAEA Safeguards

The goal of this report is to identify lessons from the IAEA safeguards domain that could benefit U.S. reactor vendors. These "lessons" generally fall into two categories:

1. **Synergies between domestic and IAEA measures:** Lessons that help reactor designers and owners to develop systems that take advantage of commonalities between domestic MC&A and IAEA safeguards may promote design efficiency. This would be useful if a U.S. designed reactor is exported or if it is placed under the U.S. voluntary offer agreement.
2. **Operational experience:** The IAEA has comparatively recent experience conducting nuclear material accounting activities at certain types of advanced reactors. This experience could benefit vendor planning for domestic MC&A or international safeguards requirements.

The previous discussion highlighted the following key distinctions between IAEA and domestic measures that should be considered when applying these lessons:

- IAEA safeguards are not focused on subnational threats and instead aim to verify a State's international obligations. State authorities will have broad capabilities and access at a nuclear facility under their jurisdiction, and hence IAEA safeguards do not include physical protection or nuclear material control functions and must consider a general range of diversion scenarios.
- IAEA safeguards must be able to *independently* confirm that the State's nuclear material declarations are correct and complete, primarily on the basis of nuclear material accounting and containment/surveillance. As a result, IAEA may need to use additional/different technical measures to meet its verification goals.

Table 2 provides a crosswalk of the differences between domestic and international safeguards, based on the discussion in this section.

Table 2: Crosswalk of domestic and IAEA measures

Topic	**U.S. domestic MC&A**	**IAEA safeguards**
Notional threat	Malicious subnational actor(s) from either inside or outside the facility. Extent of capabilities defined in a Design Basis Threat.	State authorities with full cooperation of facility operator.
Legal basis	Based in U.S. law, with requirements defined in the Code of Federal Regulations and associated regulatory documents.	Defined in legally binding safeguards agreements between the IAEA and a State.
Provision of material accounting data	Provided by the licensee/facility operator to the NRC.	Provided by the State to the IAEA, likely based on operator MC&A data.
Verification goals	NRC verifies that licensee's MC&A system and practices meet regulatory requirements. This does not generally involve measurements of nuclear material to confirm operator declarations.	IAEA inspectors independently verify the correctness and completeness of State declarations regarding their nuclear material and activities, which includes performing measurements of nuclear material.
Regulatory or enforcement authority	The NRC has regulatory authorities over its licensees and may take various enforcement measures including withholding or revoking a license if licensees do not demonstrate compliance with regulation.	The IAEA <u>*does not*</u> exert regulatory authority. The IAEA may report irregularities or noncompliance to Member States or the UN Security Council.
Role of nuclear material accounting	Used to detect and deter unauthorized removal and provide timely information for response to loss or removal of material.	Used to detect and deter diversion or misuse of nuclear materials.
Relation to physical protection and	Physical protection and nuclear material control systems complement nuclear material accounting by providing additional ways of	Not part of IAEA safeguards. The IAEA must be able to independently detect diversions

nuclear material control	detecting, deterring, or delaying unauthorized removal.	without reliance on these systems.
Timeliness goals and significant quantities	These concepts are not specifically defined/used in U.S. MC&A regulation. 10 CFR 74 specifies general MC&A performance objectives for non-utilization facilities that include maintaining accurate records, protecting against and detecting unauthorized removals, resolving indications of missing material, maintaining accurate measurement systems, and aiding in the investigation and recovery of missing material.	Timeliness and significant quantity goals are defined based on assumed quantities of nuclear material needed to create a fission device and their respective conversion time. These quantities are used to define frequency and intensity of inspections.
Use of Material Balance Areas/Internal Control Areas	MBAs/ICAs are used to localize potential inventory differences, determine their cause, and inform response. As a result, MBAs used for domestic purposes may differ from those implemented for IAEA purposes.	No localization function. Often an MBA will cover entire facility.
Role of C/S and nuclear material control.	Part of nuclear material control or physical protection systems used to prevent and detect unauthorized *access,* and in some cases preserve continuity of knowledge. May be supplemented by various physical or administrative controls such as 2-person rule, separation of duties, access control/monitoring, manned portal monitors, etc.	Used to preserve continuity of knowledge and provide indications of undeclared access. C/S systems must generally be unattended between inspections. Does not have a material control or physical protection function.

3.0 Analysis Overview

The remainder of the report deals with the IAEA's safeguards experiences relevant to sodium fast reactors, pebble-bed high temperature gas reactors, and molten salt reactors. Table 3 lists advanced reactors of these types which were subject to IAEA safeguards. Notably, the IAEA does not have any safeguards experience for molten salt reactors, although it may be possible to draw some relevant lessons from IAEA experience with reprocessing plant safeguards.

Figure 1: Selected advanced reactors placed under IAEA safeguards

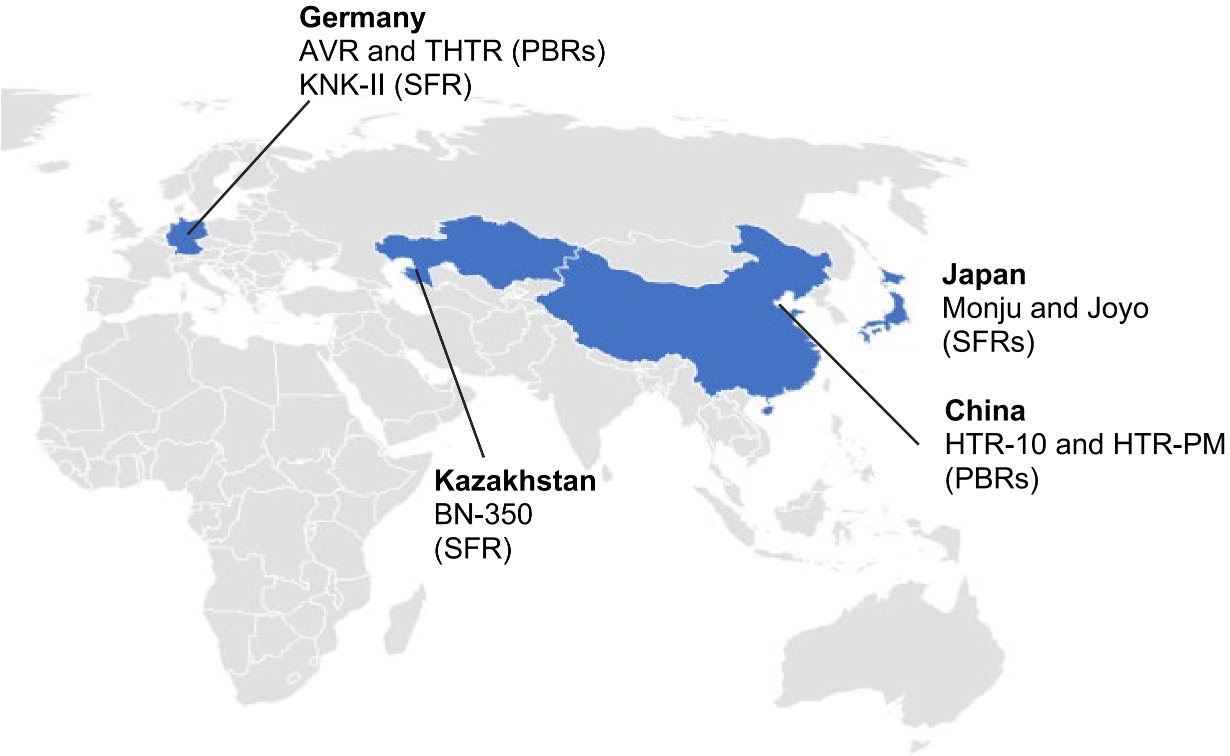

Table 3: Selected advanced reactors placed under IAEA safeguards

Type	Reactor	Country	Operation Years	Power (MWth)
SFR	KNK-II	Germany	1977-1991	58
SFR	BN-350	Kazakhstan/USSR	1972-1999	750
SFR	Joyo	Japan	1977-2007	140
SFR	Monju	Japan	1994-2010	714
PBR	AVR	Germany	1967-1988	46
PBR	THTR-300	Germany	1984-1990	750
PBR**	HTR-10	China	2004-	10
PBR**	HTR-PM	China	Awaiting operation	250
MSR*	None	-	-	-

* The IAEA has no prior experience performing safeguards at molten salt reactors.

** Both of the Chinese PBRs are selected for IAEA safeguards under China's VOA. However, the focus is on testing equipment and approaches, rather than routine verification as exists in Non-Nuclear Weapons States.

Based on a literature review and engagement with subject matter experts, the study team documented the following issues for each reactor type:

- Technology description and history of IAEA safeguards
- Reference/historical IAEA safeguards approach
- Identifying IAEA safeguards challenges and research to address them
- Relevance of findings to U.S. domestic MC&A and to U.S. reactors that might be placed under IAEA safeguards.

The report takes a different approach for MSRs due to the lack of historical IAEA safeguards experience. Specifically, the report reviews tools and techniques from other facility types that could merit further evaluation and potential use in MSR safeguards.

4.0 Sodium Fast Reactors

Over a dozen sodium-cooled fast reactors (SFRs) have been constructed and operated worldwide, including in the United States, the former USSR, the United Kingdom, France, China, India, Germany, and Japan.[3] SFRs that have operated and been subject to IAEA safeguards include: Japan's Joyo test reactor (140 MWt, operating 1977-2007) and Monju prototype nuclear power plant (714 MWt, operating intermittently between 1994 and 2010), and Kazakhstan's BN-350 (1 GWt, operating 1972-1999). Although none of these reactors are currently operating, shut-down reactors remain under IAEA safeguards until they reach a future state of decommissioning. In the United States, SFRs under development include TerraPower's Natrium reactor and GE's PRISM design.

Unlike pebble-bed and molten-salt fueled reactors, SFRs use fuel assemblies and are basically compatible with an item-centered safeguards approach like that used at LWRs. However, SFRs present unique safeguards challenges, namely:

- **Inaccessibility of fuel:** Due to the chemically reactive nature of sodium, SFRs are typically fueled using a system of air-locked transfer vessels and fuel handling equipment, greatly limiting opportunities for direct/visual access to fuel. Outside the reactor containment, fuel may be stored under sodium and a cover gas in specialized casks that further impede access. In addition, some SFRs have very long in-core residence times.
- **Visual inspection:** Visual inspection and other optical surveillance techniques are not useful for observing fuel or other items immersed in sodium, which is opaque to visible light.
- **Material types:** For IAEA verification, some SFR fuel types could challenge current nondestructive assay (NDA) techniques designed for LWR fuel. For example, some SFR designs are proposed to burn a range of transuranic wastes. Other fuels may have geometries and burnup levels very different than current LWR fuel.

Since these challenges all impact nuclear material accountancy, IAEA safeguards approaches have relied on extensive containment, surveillance, and monitoring to ensure continuity of knowledge of the fuel and to verify operator accountancy declarations.

4.1 Reference IAEA Safeguards Measures (Monju, Japan)

As the most modern SFR under IAEA safeguards, Monju Fast Breeder Reactor provides an important reference point for describing the IAEA's safeguards approach at SFRs. Monju is a 714 MW_{th} breeder reactor with a core of 198 U-Pu mixed oxide (MOX) fuel assemblies surrounded by a blanket of 172 depleted uranium (DU) blanket assemblies and a reflector composed of steel-rod assemblies. The total fuel loading is ~14 metric tons of heavy metal.[4] The fuel and blanket assemblies are each encased in a hexagonal duct with sodium inlet and outlet nozzles.[5]

Nuclear material flow proceeds in the following steps, as illustrated in Figure 2:

1. After receipt at the facility and a period of onsite storage, fresh fuel is transported to an Ex-Vessel Storage Tank. The transfer process occurs under continuous surveillance by IAEA cameras and a sequence of unattended radiation monitors. A 200-ton rail-mounted Ex-Vessel Transfer Machine (EVTM), which is depicted in Figure 3, conveys the fuel to the Ex-Vessel Storage Tank, where it is stored under sodium and an argon cover gas.

2. During semi-annual refueling outages, fresh fuel is moved into the reactor using the EVTM and various overhead/in-vessel fuel handling equipment that mates with a “rotating-plug”-type access point in the reactor core.
3. Spent fuel is removed using the same equipment and conveyed by the Ex-Vessel Fuel Transfer Machine to the Ex-Vessel Fuel Storage Tank.
4. After appropriate cooling time in the Ex-Vessel Storage Tank, the fuel is washed, sealed in steel cans, and transported underwater to a spent fuel pool.
5. Before spent fuel is removed from the facility, it is possible that the fuel assemblies could be verified again using nondestructive assay tools such as passive gamma emission tomography.

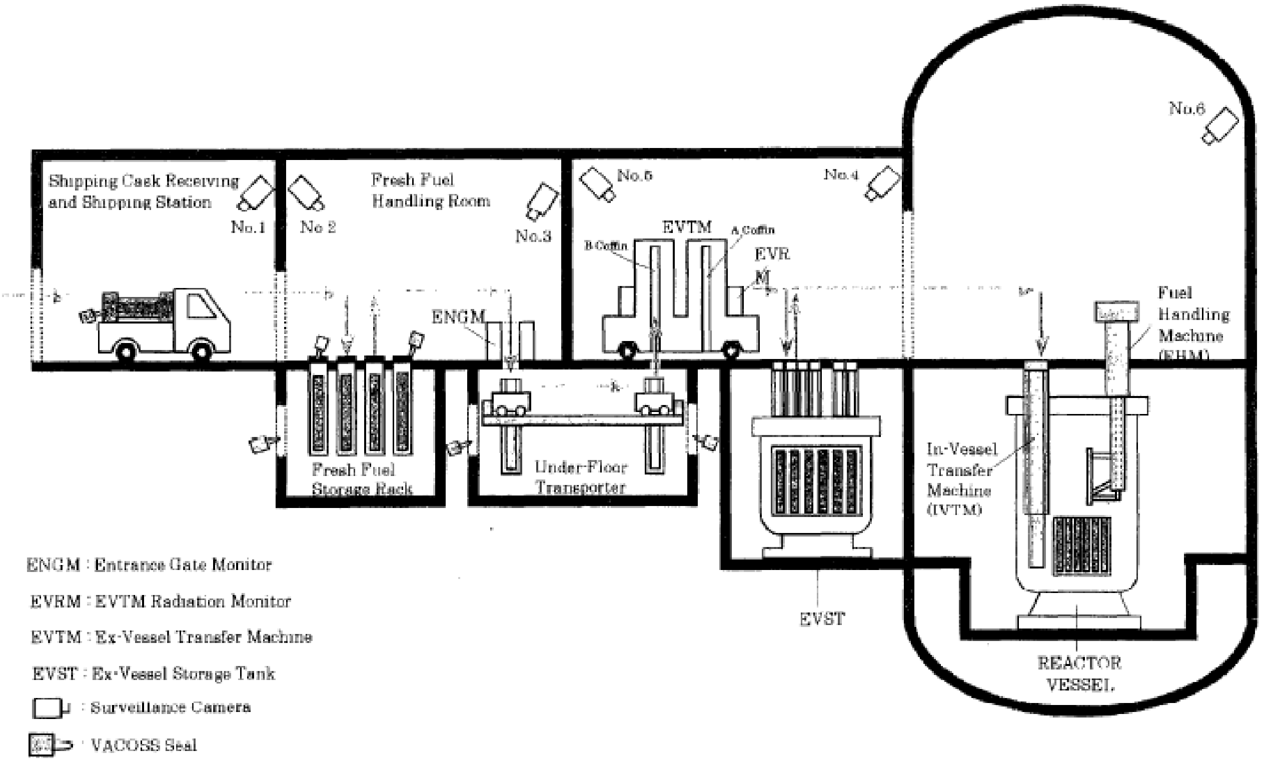

Figure 2: Fresh fuel flow paths and associated measurement and surveillance tools at the Monju Fast Breeder Reactor. Acronym Key: ENGM – Entrance Gate Monitor, EVTM – Ex-Vessel Transfer Machine, EVRM – Ex Vessel Radiation Monitor, EVST – Ex-Vessel Storage Tank. Illustration from Lu and Sanborn (2000).[6]

Under the IAEA’s safeguards criteria, the IAEA’s safeguards approach must be capable of timely detection of a significant quantity of nuclear material. Significant quantity goals and timeliness requirements depend on the type and form of nuclear material. Since Monju handles unirradiated Pu (in the form of mixed oxide fuel assemblies), the significant quantity is 8 kg Pu and the timeliness goal is 1 month.

As described above, the fuel is not accessible to inspectors for direct observation or measurement during the period of storage in the Ex-Vessel Storage Tank (before and after irradiation), during irradiation in the reactor, and during the fuel transfer sequence. Spent fuel is also inaccessible if it is loaded into steel cans for interim storage. Thus, the IAEA uses unattended measurement and surveillance tools to confirm material flows and inventories. The entire flow path uses redundant surveillance cameras and electronic seals (which digitally record opening/closing information) as illustrated in **Error! Reference source not found.**. In addition, the Monju safeguards approach uses several specially designed radiation detection instruments to assay or confirm presence of fuel, as described in Table 4. [7]

Table 4: Custom safeguards systems at Monju FBR

Instrument	Description
Entrance Gate Monitor (ENGM)	Passive neutron coincidence counter (using an array of He-3 tubes) used to assay plutonium and uranium mass in fresh fuel, allowing for partial defect detection and the discrimination between fresh MOX assemblies, DU assemblies, and other types of materials. Use of fission counters shows direction of flow.
Ex-Vessel Transfer Machine Radiation Monitor (EVRM)	He-3 neutron detectors and ionization chambers are placed alongside fuel holding locations in the EVRM to confirm the transfer of materials consistent with declared operations. The systems allow for discrimination between different irradiated and fresh fuel types.
EVST	Neutron counters and ionization chambers detect the movement of fuel into/out of the Ex-Vessel Storage Tank. The system determines the direction of movement and allows for partial discrimination of the type of fuel.
Exit Gate Monitor	Neutron counters and ionization chambers that detect movement of fuel into the spent fuel pool. The system allows for determining the direction of movement (into the fuel, out of pool) and the type of fuel.

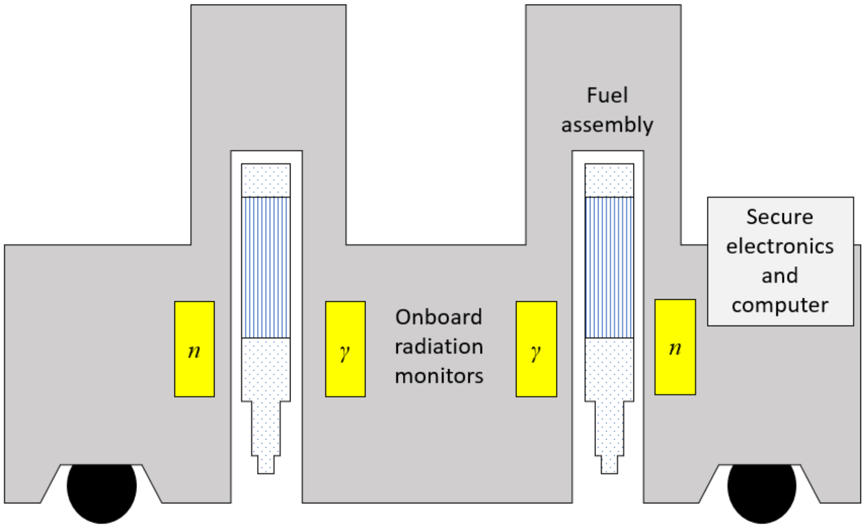

Figure 3: Schematic of Radiation Detection Equipment at the Monju Ex Vessel Transfer Machine, including ionization chambers and neutron counters surrounding fuel storage/transfer casks. Data were logged on on-board computers. (Based on: Deshimaru, et al., 1994)[8]

Initially, the monitoring systems saved their data locally to IAEA computers, which required IAEA to manually transfer data (by disk) for analysis during periodic inspections. IAEA safeguards verification therefore focused on: (1) confirming visually accessible fresh fuel and spent fuel, (2) examining operations and surveillance records to validate fuel movements, and (3) conducting design information verification to verify any changes made to the facility or to safeguards-related equipment.

Comparison to other SFRs under IAEA safeguards: Japan's sodium-cooled Joyo test reactor was constructed before Monju and used a similar IAEA safeguards approach that relied heavily on C/S and custom radiation detection tools along fuel transfer pathways. See: Hashimoto, et al. (1994). Development of plutonium fuel flow monitors for experimental fast reactor JOYO. IAEA-SM-333/51

Owing to the unique factors surrounding the collapse of the USSR and Kazakhstan's emergence as an independent Non-Nuclear Weapons State, IAEA safeguards at the BN-350 reactor focused on accounting for, sealing, and removing legacy inventories of HEU-bearing fuel, rather than routine facility operations. See: Browne, M. (2008). "Case Study: Nonproliferation activities at the BN-350 reactor, Kazakhstan." In J. Doyle (Ed): Nuclear Safeguards, Security and Nonproliferation. Amsterdam: Elsevier.

4.2 IAEA Safeguards Challenges and Research

As discussed above, the most significant challenge faced by the IAEA safeguards approach is its high reliance on C/S to validate the continued integrity of prior measurements. **Redundant and robust monitoring is essential because there may be no practical opportunities to remeasure fuel for extended periods of time if C/S fails.** This represents a significant risk for IAEA safeguards, especially since common cause failures (e.g., loss of power or lighting or data handling problems) may affect multiple elements of the C/S approach simultaneously.

- The most significant R&D contribution to this challenge from the IAEA safeguards community has been developing the specialized radiation detection and associated C/S systems at operating facilities (Monju, Joyo, and BN-350) and their incorporation into a working IAEA safeguards approach. This involved extensive coordination over many years between facility operators, regulators, other agencies, the IAEA, and experts in the United States and elsewhere. It is expected that similar approaches to monitoring material flows may be needed for IAEA safeguards at future SFRs due to the chemical and radiation hazards of transporting SFR fuel. The same basic monitoring and measurement technologies could be used, but they would need to be adapted to the facility's specific fuel design and fuel handling pathway.
- In addition, the IAEA safeguards community has conducted some strategic planning/engagement relating to SFR safeguards. Some of this strategic planning was focused on strengthening SFR safeguards approaches to enhance the safeguardability of SFRs under the former Global Nuclear Energy Partnership.[9]

Some key areas for future R&D include:

- **Efficiency and reliability of C/S:** Before the Monju reactor was shut-down, Japan and the United States were cooperating on dividing the C/S and data handling system into independent "modules" that reduced certain failure risks.[10] Future facilities can focus on the design of reliable and easy-to-use systems with simplified and automated processes for data sharing, analysis, security, and archiving based on updated information technology.

- **Improvement of unattended radiation detection systems** (like those used at Monju) for partial- or bias-defect level assays, and their development for fuels using different geometries and isotopic makeup would enhance the “material accounting” vs. “material control” aspect of the fuel handling systems and provide a mechanism for re-establishing inventories if continuity of knowledge (CoK) is lost.
- **Alternate measures for verifying spent fuel:** Some methods would be useful for uniquely identifying assemblies under sodium if CoK is lost. Ultrasonic tools for nondestructive examination have a variety of potential applications in liquid sodium environments and have been evaluated for safeguards use.[11] Another concept that has been proposed is to use special identifying markers on fuel assemblies that would allow assemblies to be counted and identified in a liquid sodium environment. Other concepts could focus on measurement of fuel assemblies after removal from sodium, but before or after they are sealed in cans.

4.3 Relevance to U.S. Domestic MC&A and Physical Protection Regulation

Since sodium-cooled fast reactors use fuel assemblies, the current domestic MC&A practices under 10 CFR Part 74 and ANSI N-15.8 2009 are generally relevant to future SFRs.[i] Under these provisions, operators periodically report information on each fuel assembly including an identifier, location, and calculated isotopic contents of these fuel assemblies. These operator systems and processes are subject to auditing by onsite NRC inspectors. The IAEA safeguards approach in place at Monju would appear to support the basic regulatory requirements for U.S. MC&A, in that it involves material measurements and surveillance that would provide a basis for auditable material balance reports by the licensee.

Certain aspects of the approach – such as the partial-defect measurement of incoming fuel assemblies and the redundant approaches to continuity of knowledge may exceed the requirements for NRC regulations. (Recall that IAEA safeguards must assume that State authorities and facility operators may be fully coordinated, allowing for a less constrained range of potential diversion or concealment strategies). However, to the extent that constant and robust continuity of knowledge is required for facility operations (including compliance with U.S. domestic MC&A or physical protection regulations) then this safeguards approach provides a proven template.

4.4 Relevance to U.S.-Designed Reactors Placed Under IAEA Safeguards

Establishing IAEA safeguards approaches for SFRs, such as Monju, has required much greater resources and coordination than establishing IAEA safeguards at light water power reactors (LWRs). This is because (1) the IAEA has less experience with SFRs than LWRs, (2) there has been a significant need to integrate safeguards equipment into the operator’s equipment and concept of operations, and (3) there are greater technical challenges for verifying materials, due to more complex fuel forms and the use of MOX fuel. Specifically, the IAEA and supporting national authorities needed to develop unique measurement systems and deploy them at appropriate places. U.S. designers who develop an SFR which will be subject to IAEA safeguards

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[i] Many SFRs use nuclear materials of moderate strategic significance (Category II). It is unknown if the MC&A regulations for power reactors, which currently apply only to LWRs using <5% enriched fresh fuel, will be updated with increased requirements for Category II material, as is the case now with fuel cycle facilities.

(under a VOA or export scenario) should take into account several considerations from previous IAEA safeguards implementation efforts.

Past practice indicates that extensive C/S systems may be needed to cover fuel transfer pathways. Example systems include surveillance cameras, seals, and radiation detection equipment. Notably, radiation detection equipment may be necessary to confirm the identity or attributes of fuel assemblies being inserted into or removed from the reactor. These tools may be particularly important in cases where visual surveillance is inadequate, such as when fuel is being moved into/out of an enclosure or container. **In some cases, these needs may have significant impact on the design requirements for certain operator-owned systems that must interface with IAEA equipment, especially systems involved in fuel handling.** These requirements can be addressed through reviewing IAEA safeguards literature to understand the IAEA's main concerns followed by interaction with national and IAEA safeguards officials during facility design.

Facility designers and operators should consider IAEA safeguards requirements when designing their own systems for monitoring nuclear materials (in-core and ex-core) **in case there are opportunities for "joint-use" equipment by the operator**, regulatory authorities, and the IAEA. In addition to monitoring for presence of nuclear fuel, other types of data streams (for example, reactor process data or overhead crane controls) might give increased safeguards assurance. The IAEA has requirements to ensure the independence and integrity of safeguards information that affect the design of joint-use systems.[12] For example, the systems may need to undergo vulnerability testing and have independent signal pathways or encrypted output for IAEA use. **These interfaces would be negotiated by the IAEA, the operator, and national regulatory authorities.**

Facility design choices can alternatively help or hinder IAEA safeguards activities. First, design choices can make certain diversion pathways less practical or more evident. For example, the Monju Ex-Vessel Fuel Transfer Machine operated on a rail track that was disassembled in between refueling events, making it easier to verify that no unauthorized fuel movements could occur.[13] Likewise, design choices can also impact the practicality of IAEA monitoring approaches. For example, providing necessary infrastructure for IAEA equipment (space, power lighting), allow clear fields of view for surveillance and enable simple authentication of joint-use equipment can greatly simplify IAEA safeguards. The IAEA provides guidance on such considerations for a variety of nuclear facility types, including nuclear reactors.[14]

5.0 Pebble-Bed Reactors

Whereas sodium fast reactors are considered item facilities for purposes of nuclear material accounting, PBRs have characteristics of both an item facility and a bulk-handling facility. The nuclear material inventory at a PBR is distributed across a large number of spherical fuel elements (known as "pebbles" as depicted in Figure 4), each of which contain on the order of 10 grams of nuclear material. A PBR core may contain hundreds of thousands of pebbles. In addition to the core, fuel elements are stored in fresh fuel canisters and spent-fuel storage areas, such as storage tanks and transport casks.[15] Fuel elements are loaded into the reactor, recycled through the core until they reach a target burnup, and discharged using automated fuel handling machines.

Figure 4: Pebble-type fuel elements[16]

Like nuclear material at a bulk-handling facility, the PBR fuel elements cannot, in general, be uniquely identified.[i] However unlike other bulk facilities, such as uranium conversion plants, the nuclear material exists as discrete, countable, objects that do not change chemical or physical properties unless the fuel pebbles are physically damaged. While the pebbles are countable, some discrepancies may accrue due to instrument malfunction or pebble damage, resulting in a nonzero inventory difference/material unaccounted for, as would exist at a bulk facility.

An important aspect for PBR safeguards is the low density of nuclear material in a large volume of fuel elements. Each element contains a gram-scale quantity of nuclear material encased in a

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[i] This has been investigated through the use of microsphere implantation for pebble identification but has not reached deployment; see: Travis Gitau and William S. Charlton. "Use of a Microsphere Fingerprint for Identity Verification of Fuel Pebbles in a Pebble-fueled HTGR." Journal of the Institute of Nuclear Materials Management 40, no. 2 (2012): 19. Further work on this concept has been conducted by Gariazzo and Chirayath (2021). "Material Control Technique Validation for Pebble Bed Reactors." (Presentation to April 2021 ARS Stakeholders Meeting) https://gain.inl.gov/SitePages/2021-April_SafeguardsAndSecurityWorkshop.aspx . Additional research has been conducted on pebble burnup discrimination, though not identification, through the use of elemental coating on the SiC layer of TRISO particles in the pebble compact; see Liu, Rongzheng; Liu, Malin; Shao, Youlin; Chen, Xiaotong; Ma, Jingtao; Liu, Bing (2017): A novel coated-particle design and fluidized-bed chemical vapor deposition preparation method for fuel-element identification in a nuclear reactor. In Particuology 31, pp. 35–41. DOI: 10.1016/j.partic.2016.05.009.

graphite ball measuring ~6 cm in diameter. While individual fuel elements might be more easily removed from a facility than an LWR fuel assembly, tens of thousands of elements need to be diverted to reach an IAEA significant quantity. This comprises many cubic meters of fuel elements.

Only a few PBRs have been subject to IAEA safeguards. The Federal Republic of Germany operated two PBRs, the AVR and THTR-300, between the 1960s and 1990s, and these reactors were subject to Germany's comprehensive safeguards agreement. A more recent South African effort starting in 1998 to develop a PBR known as the Pebble Bed Modular Reactor (PBMR) lasted roughly a decade before economic considerations shuttered the effort in 2010[17] before construction ever began. More recently, two PBRs in China have also been selected for safeguards under China's voluntary offer agreement. In the United States, X-energy has been awarded funding to build a pebble bed reactor with a planned operations date in the late 2020s.

5.1 Reference IAEA Safeguards Measures for PBRs

This section separately examines safeguards experience at German PBRs and the safeguards developments at Chinese PBRs.

5.1.1 As implemented in Germany

As mentioned above, the IAEA applied routine safeguards at two German PBRs: AVR, and THTR-300. While neither reactor has operated in recent decades, their safeguards approach still provides a relevant illustration of IAEA practices and some of the issues affecting PBR safeguards.

AVR[18] was constructed as an experimental power station for pebble-bed reactors. Located at Jülich Research Center, AVR operated from 1967 to 1988[19]. The graphite moderated, helium cooled core comprised ~100,000 pebbles and had a power level of 46 MW_{th}. AVR was used as a test reactor for pebble fuels which used uranium and thorium oxides with BISO coatings. Many of the fuel and primary system technological advances were incorporated into the THTR-300 reactor.[20,21]

The THTR power plant operated from 1983[22] to 1989[23]. The fuel elements consisted of a mixture of graphite matrix and Th-U oxide fuel particles. (The uranium component was 93% U-235). The first core contained ~359,000 fuel elements, ~277,000 graphite moderator elements and ~37,000 absorber elements. Approximately 600 fresh fuel elements were added and 600 discharged per full power day. In August 1989, it was decided to permanently shut down the THTR after ~16,000 hrs of operation.[24]

THTR-300 was designed, operated, and shut-down before the IAEA had developed specific "Safeguards Criteria" for pebble bed reactors. However, the safeguards system designed closely follows the criteria later developed. The safeguards approach was based on an evaluation of potential diversion strategies and was developed via a joint effort with the reactor operator, designer and the IAEA incorporating the IAEA's expertise.[25] The principal safeguards measures, as described in Büeker (1976)[26], Engelhardt (1978)[27] and Martin (1988)[28], were the following:

- **Fresh fuel:** The fresh fuel is verified at the fabrication facility and received at the reactor in sealed containers, which are treated as items. The identification and seals on the fuel canisters are verified or replaced periodically, and NDA attribute measurements may be performed on unsealed containers. The literature did not provide more information on the types of NDA used.

- **Fuel loading and core inventory:** Because it was not possible for the IAEA to conduct standard physical inventory verifications of the core, the core inventory was maintained by counting the insertion and removal of pebbles using counters and measurement equipment. (In some respects, this is similar to current IAEA safeguards for CANDU reactors). The counters were designed to give authentic and independent information.[29] Fresh fuel elements were counted and randomly sampled for removal and non-destructive assay by inspectors.

  Pebbles circulating in the core were discriminated by type (absorber/moderator, fully-burned fuel, partially-burned fuel) using a unique burnup measurement systems. The burnup measurement system employed a very low power reactor; the insertion of different pebble types having different reactivities would have characteristic effects on the reactor dynamics. These signals were monitored to discriminate pebble types. [30] [31] [32] The literature did not indicate whether inspectors had access to information from the burnup measurement system for safeguards use.

- **Pebble discharge and spent fuel:** Discharged elements were counted using an exit counter and then released into storage drums.
  - **Pre-equilibrium:** Only non-fuel elements are discharged. An automated NDA system verifies that drums intended for non-fuel elements do not contain fuel elements representing potential diversion.
  - **Equilibrium:** Only fuel elements are discharged. These are counted using the exit counter and loaded into drums under video surveillance and electronic seals (VACOSS seals) before removal from the site.
  - **Scraps:** Fuel elements which were discharged passed through a scrap separator to separate damaged pebbles. The damaged pebbles were stored in a semi-permanent, sealed barrel which was within the reactor core MBA.
- **C/S:** Various C/S measures are employed to ensure that all possible discharge and removal pathways are covered and that key instrumentation was not tampered with.

To summarize:

- Diversion of fresh fuel is detected through counting fuel drums, C/S, and attribute testing as needed, including sampling of fresh fuel as it is loaded into the reactor.
- Undeclared removal from the core is detected by monitoring input/output pebble counters, NDA of containers of discharged pebbles, and video monitoring of pebble discharge pathways.
- Undeclared removal of spent fuel is detected by item accounting of cylinders and video surveillance.

According to Martin, the safeguards applied at THTR-300 allowed for reasonable inspection efforts, although it required the installation and use of several unique systems to support safeguards. These basic measures are mapped to the simplified nuclear material flow diagram in Figure 5.[i]

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[i] A more detailed nuclear material flow path with safeguards measures is found in: Martin, K. "Safeguards concept for the THTR-300 Thorium High Temperature Reactor." In Nuclear safeguards technology 1986. 1987

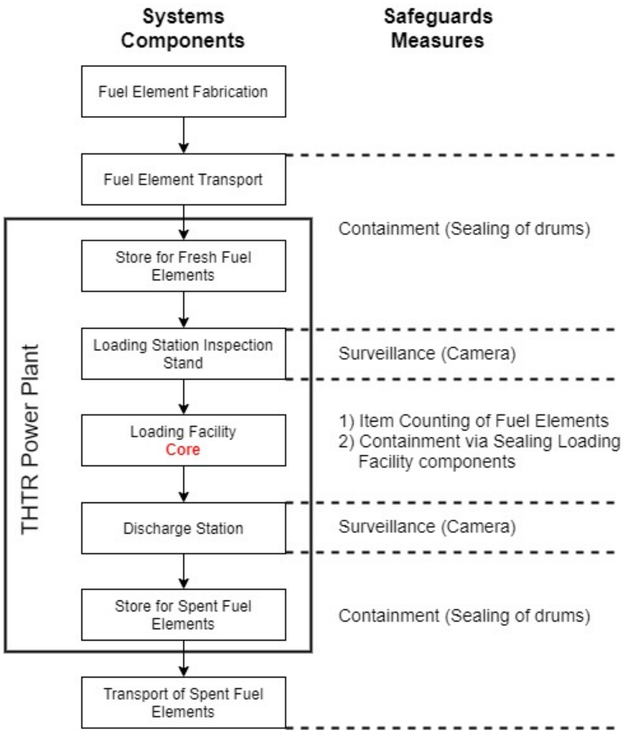

Figure 5: Safeguards System for THTR-300 Fuel Cycle. (Adapted from: Engelhardt, 1978)

5.1.2 IAEA Safeguards Development in China and Other Countries

Since the shutdown of the German PBRs, the IAEA has not performed safeguards verification at an operating PBR in a Non-Nuclear Weapons State. In the 2000s, the IAEA worked with South African authorities and the reactor designer, PBMR, Pty. to develop a preliminary IAEA safeguards concept for a planned 400 MW power reactor.[33] [34] The project was cancelled and so the approaches were never finalized or put into practice. However, the IAEA did identify specific needs including the use of independent or authenticated pebble counting/measurement systems and special monitoring and measurement provisions for spent fuel stored in large tanks (e.g., channels for monitoring the height of pebbles in storage).

The only other country to operate a PBR is China, which has constructed two PBRs. The first — called HTR-10 — is a 10 MW_{th} test reactor that first reached criticality in 2000 and is located at Tsinghua University in Beijing. The second reactor, called HTR-PM, is in Shandong Province and is awaiting the start of commercial operations. The HTR-PM power plant contains two reactors of 250MW_{th}, together driving a steam turbine with an electrical output of 200MW_e; both units use U fuel enriched up to 8.5%[35]. Over recent years, the IAEA has had growing involvement and cooperation with the Chinese operators and authorities on safeguards, and both facilities are currently listed as being under IAEA safeguards. Since China is a Nuclear Weapons State with a Voluntary Offer Agreement, the safeguards activities are primarily aimed at testing safeguards techniques, rather than performing comprehensive verification[36].

IAEA safeguards measures at the Chinese reactors are less documented than those for THTR-300. In submissions to a 2018 IAEA symposium, Chinese and IAEA authors indicated that, similar to the THTR-300, safeguards are accomplished by using a hybrid item/bulk accounting scheme, in which fresh and spent fuel are stored in sealed and/or welded containers that are treated as items[37] with unique identification numbers and stored within specified MBAs within the plant.

The bulk accounting scheme implemented at HTR-PM is pebble counting by using the pebble counters installed in the fuel handling system. The accounting of the pebbles in the reactor core and the fuel handling system is completed by the pebble counting of the inlet and outlet flows of pebbles[38], similar to the scheme implemented at THTR-300. The use of a burnup measurement system for IAEA safeguards was not detailed.

5.2 IAEA Safeguards Challenges and Research

With no recent verification experience in Non-Nuclear Weapons States, IAEA safeguards practices at PBRs are less established than at SFRs. However past IAEA practice provides a template for a hybrid bulk/item safeguards approach based around use of sealed containers for fuel outside the core, pebble counting for fuel entering/leaving the reactor, and enhanced C/S over key fuel transfer pathways. This has been demonstrated in Germany, China, and the tentative planning for safeguards in South Africa. The IAEA has developed criteria for safeguards at pebble bed reactors in states with INFCIRC/153-type agreements. These criteria are used for the planning and implementation of safeguards activities in the field and evaluating if inspection goals were fulfilled.

As with SFRs, a key feature of IAEA safeguards at historic pebble-bed reactors has been the need for some level of cooperation by the operator and State authorities to ensure the IAEA has access to necessary data and equipment. Potential need areas include:

- **Authenticated IAEA measurements for core input and discharge (including pebble counters and/or the burnup monitoring system).** This will likely require cooperation between the IAEA, the State authorities, and the facility operator. If joint use is pursued, the instruments will need to be designed to meet IAEA standards for authentication. If the IAEA establishes its own (redundant) measurement system, it would need to be incorporated into material flow paths, with potential effects for facility design, operations, and licensing.
- **Other forms of joint use instrumentation:** It may be possible to use other operator data streams (for example control rod height or reactor power) to confirm a reactor is operating as declared.
- **Appropriate C/S for the reactor process:** Reactors with limited access points to introduce or discharge nuclear material will be easier to safeguard, and all points should be covered by appropriate seals or monitoring systems.
- **Appropriate C/S for fuel storage locations:** Dual C/S will typically be necessary as it will be difficult to re-measure spent fuel pebbles stored in casks or other storage locations.

As outlined above, pebble-bed reactors face several significant verification challenges which are specific to PBRs:

- Large numbers of individual and likely non-identifiable fuel items
- Different pebble types including non-fueled moderator elements moving throughout the facility
- A quasi-continuous loading and discharge of elements (approximately 1% of the core each day)

- Variable pebble irradiation histories
- Potentially damaged or unrecoverable fuel items[i]

The IAEA has relied upon containment/surveillance to validate the continued integrity of prior measurements and robust accounting mechanisms to ensure no diversion of material. The early safeguards approach developed for the PMBR relied on process flow monitoring and new NDA techniques which needed to be developed at the time[39]. More recently, China has worked closely with the IAEA to identify and develop safeguards measures for the HTR-PM which is currently under construction. (Becker, 2018) identified the need for robust and independent fresh and spent pebble NDA verification capabilities.[40]

Research is continuing into several areas of PBR technology which will benefit safeguards for these facilities without being explicitly identified as safeguards research. Some needs remain to be resolved: including measuring final isotopic content when pebbles may have differing burnup histories or different initial enrichment levels. Technologies such as radioisotope pebble tagging, predictive pebble tracking, burnup estimation, and NDA techniques are all required for high assurance reactor operation and are active areas of PBR research and will benefit future safeguards implementation.

5.3 Relevance to U.S. Domestic MC&A and Physical Protection

Current MC&A regulations for utilization facilities are based around light water reactors that contain fuel principally as assemblies. The types of MC&A verification measures currently recognized in ANSI Standard N15.8-2009 focus on item counting. The previously discussed IAEA safeguards approaches involved storing fresh/spent fuel in sealed drums that could generally be considered as “items” once the contents were verified. This is analogous to the provision in ANSI Standard N15.8-2009 for treating damaged fuel fragments within “fuel component containers” as items on a similar basis as fuel assemblies. As a result, the extensive use of containers could significantly simplify domestic MC&A and IAEA safeguards, while maintaining continuity with current reactor MC&A practices. The safeguards approaches reviewed in this section may provide some template for these types of activities.

Fuel elements contained within the reactor core, fuel handling path or within unsealed containers may need to be handled more like bulk materials, since they are not individually identifiable. As mentioned in Section 5.2, other authors have considered the possibility that Fundamental Nuclear Material Control plan analogous to those used at bulk-handling fuel cycle facilities will need to be developed[41,42 43]. Many elements of past IAEA experience align with these plans.

5.4 Relevance to U.S.-Designed Reactors Placed Under IAEA Safeguards

As with SFRs, IAEA safeguards approaches for pebble bed reactors have required much greater resources and coordination during development than those for light water reactors. This effort is still ongoing and an active area of coordination between the IAEA and member states. Experience with THTR-300 and HTR-PM shows that there is a need to integrate safeguards equipment into the operator’s equipment and concept of operations, and in the case of THTR-300 requiring bespoke equipment for that facility. U.S. designers who develop a PBR which could be subject to IAEA safeguards should take insight from previous IAEA safeguards implementation efforts.

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[i] THTR-300 operating experience (Theymann, 1991) has shown a pebble damage rate of ~0.5%.

As with Monju, experience at THTR-300 indicates that extensive C/S systems may be needed to cover fuel transfer pathways as the core is not directly verifiable. The work to design the safeguards system and needed equipment began during the early phases of plant construction. The requirements for equipment, access and other means for implementing safeguards can be addressed through reviewing IAEA safeguards literature to understand the IAEA's main concerns followed by thorough interaction with national and IAEA safeguards officials during facility design.

6.0 Molten Salt Reactors

The IAEA has not applied safeguards to molten salt reactors and has not publicly issued a safeguards approach for future MSRs. MSRs comprise a diverse family of reactor designs with varying technical characteristics, and different types of facilities would probably require different methods for domestic MC&A or IAEA safeguards. Some key distinctions between MSR design types include:

- Fuel form (homogeneous liquid fuel, or discrete fuel elements such as pebbles or rods)
- Neutron energy spectrum (fast, thermal, other)
- Fuel cycle (including U-Pu and Th-^{233}U)
- Types of materials and strategic significance category
- Fueling strategy and forms of online salt conditioning or processing (with a key question being whether these processes yield streams of unirradiated direct-use material).

Molten salt-cooled reactors with pebble or pin-type fuel would probably have IAEA safeguards approaches similar to those at other pebble or pin-fueled reactors (like PBRs or liquid metal fast reactors). As a result, liquid-fueled MSRs are the focus of this section. The discussion of liquid-fueled MSRs is less detailed than the treatment of SFRs or PBRs for several reasons:

- The lack of an IAEA safeguards approach and operationally demonstrated safeguards tools and techniques for MSRs
- The great diversity in MSR design and operations concepts and lack of detail for early-stage reactor designs.
- The uncertainty surrounding domestic MC&A requirements for MSRs

IAEA safeguards for reprocessing plants are probably the most relevant point of comparison to liquid-fueled molten salt reactors and will be a focus of the section.

6.1 General notes on domestic MC&A for MSRs

Liquid-fueled MSRs will contain nuclear materials in bulk form (liquid fuel and waste solutions) and potentially in item form, for example, containers of fresh fuel salt or wastes that have been verified, sealed in a container, and individually identified. As with PBRs, it is not certain what specific MC&A regulatory provisions will apply to liquid fueled MSRs, because current reactor MC&A approaches are not based on this fuel type. A potential reference point is 10 CFR 74 Subparts D and E, which contains provisions for MC&A at Category I and Category II fuel cycle facilities. (MSRs may fall into these material categories). These regulations require licensees to maintain measurement systems capable of verifying nuclear material inventories and detecting and locating loss to high accuracy. For example, licensees at Category I facilities must:

- Conduct physical inventories every six months to calculate Inventory Difference (ID) and investigate cases were Standard Error of Inventory Difference (SEID) ≥ 0.1% of active inventory or where ID ≥ 3 × SEID. (10 CFR 74.59.f)
- Have monitoring capabilities to detecting 5 formula kilograms within less than 7 days or statistical trends of safeguards significance that might indicate loss or diversion. (10 CFR 74.53)

When considering MC&A requirements for future MSRs, it is important to evaluate how MSR fuel characteristics impact the credibility of different diversion/theft scenarios. Some fuel salts, especially at fast reactors, contain a high concentration of nuclear material, meaning that less volume is required to obtain the same amount of material under a given diversion scenario than would be needed with pebble or assembly type fuel. On the other hand, irradiated fuel salt drawn from an MSR may also have a higher specific activity which would make handling and transport more difficult. The feasibility of a non-state actor executing a given theft scenario will depend on the design of the reactor. (Reactors that would allow for access to high-value material with reduced radiological hazard obviously pose greater challenges). While these are primarily physical protection considerations, they will also have bearing on the ultimate types of MC&A requirements that are adopted.

6.2 Potential analogs from IAEA safeguards experience

Because they contain bulk solutions of irradiated nuclear material, reprocessing plants are arguably the closest analog to MSRs for which the IAEA has safeguards experience. The IAEA has applied safeguards at large-scale aqueous reprocessing facilities (notably the Rokkasho Reprocessing Plant in Japan) and at research-scale pyroprocessing facilities. This section evaluates the relevance of these facilities for MSR safeguards planning.

First, there are some relevant differences between MSRs and reprocessing plants. The activity and temperature of in-process MSR fuel are typically much higher than comparable inventories at aqueous, or even electrochemical, reprocessing facilities. As a result, there will be limitations on human access to parts of an operating facility, and any safeguards instruments must be designed for (1) survivability in the harsh MSR environment and (2) reliability and maintainability by both facility staff and IAEA staff, despite access constraints. Another major difference is that the facility layout and operations of an aqueous reprocessing plant are more amenable to conducing shut-downs and flush-outs of different parts of the process to support inventory measurements. It is not certain what types of flush-out operations, if any, could be supported at a commercial MSR.

A major challenge that the IAEA faced at large-scale reprocessing is the difficulty of detecting certain diversion types using standard nuclear material accounting practices. For example, the Rokkasho processing plant has a throughput of 800 metric tons/year of spent fuel (~8 metric tons of Pu), such that a 1 SQ diversion would represent only 0.1% of the facility's annual throughput. To achieve high detection probability and low false alarm rate with material accounting alone, the measurement system would need to have an error (such as SEID or σ_{MUF}) much lower than this threshold, especially when considering protracted diversions. Such measurement uncertainties and timeliness are difficult to achieve. An MSR could likewise have a very large inventory of nuclear material (including Pu and U-233), although throughput would be much less than at reprocessing plants.

As a result of these challenges, the IAEA safeguards approaches for reprocessing rely on additional measures beyond nuclear material accountancy to improve the likelihood of detection. These included enhanced containment/surveillance, near real-time accountancy for interim inventory verification, and process monitoring of different materials and equipment. Collectively, these "layers" of measures improve the effectiveness of the overall safeguards system. A similar layered approach could also increase assurances at MSRs.

6.2.1 IAEA safeguards for commercial aqueous reprocessing

IAEA safeguards for aqueous reprocessing (exemplified by the Rokkasho plant) have been described in several reports.[44] [45] [46] [47] The safeguards approach at Rokkasho is complex, and this report does not aim to give a comprehensive summary. Some elements of the IAEA safeguards approach that could be considered for use at MSR verification include:

- **Process monitoring and measurement technologies**: The Rokkasho reprocessing plant safeguards approach involves over 50 monitoring and measurement systems and dozens of IAEA surveillance cameras. Collectively, these attended and unattended systems track spent fuel assemblies that arrive at the plant, measure and monitor nuclear material-bearing solutions throughout the separations process, and verify the status of product and waste streams. These process monitoring tools work in coordination with destructive assay measurements (based on sampling), attended measurements by inspectors, design information verification, and other inspection measures. Systems potentially relevant to MSRs include: [48]
  - <u>Spent fuel and head-end verification systems</u>: These systems (including Integrated Spent Fuel Verification System and the Integrated Head-End Verification System) measure spent fuel as it arrives at the plant and is loaded into the chopping system. Similar systems could be used to track fresh fuel for MSRs. These systems measure the receipt and monitors the unloading of spent fuel assemblies using surveillance cameras and non-destructive assay (NDA) for gamma and neutron detection; assure that the spent fuel is moved to the storage pond; assure that casks are empty when leaving the area of surveillance; and maintain CoK of the inventory of spent fuel in the storage pond. They also maintain CoK of the spent fuel moving between the feeding cells and the shear cells using digital cameras, neutron detectors, and ionization chambers, and record the spent fuel identification numbers.
  - <u>Solution measurement and monitoring system:</u> This system[49] measures and monitors the solution levels, volumes, and densities using high accuracy, independent and authenticated pressure measurement devices which are connected directly to the operator's pneumatic dip tube measurement lines in the most important process vessels. IAEA computers perform data collection, evaluation of state-of health information, and authentication of data transmission. Custom software assesses the correlated measurements in different tanks and alarms if there are signs of diversion. As a result, it provides continuity of knowledge of the plutonium solutions and assists in providing measurements for nuclear material accountancy. Similar techniques could be used at MSRs for potential accountability tanks, chemical processing vessels, drain tanks, and if applicable, the primary coolant loop, to track the location, volume, and composition of liquid solutions, at the facility.
  - <u>Waste assay and tracking systems</u>**:** A vitrified canister assay system (VCAS) measures nuclear material content in the vitrified high active waste to assure that it is below a threshold value prior to being transferred to measured discards and that the waste solution has been effectively vitrified. It also records the identification of the canisters. The IAEA-controlled system is equipped with fission chambers which measure the neutrons emitted by Cm-244. The ratios Cm/Pu/U are determined in the solution by destructive assay. Additionally, ionization chambers installed on the route to and from the vitrification cell monitor that canisters are not re-submitted for measurement. A waste crate assay system (WCAS) measures the nuclear material content in the low active waste crates to assure that it is below a threshold value to be transferred to retained waste and records the identification of the crates. Digital cameras provide the ID of the crate and monitor that it

is not re-submitted for measurement. Elements of these strategies could be used for waste verifications at MSRs.

- **Extensive coordination and DIV:** The ability of the IAEA to make accurate measurements and implement effective verification relied on enhanced coordination for design information verification (DIV). For example, the IAEA was involved in the measurement of vessel volumes and the calibration of instruments. This required early and ongoing provision of data between the facility designer/operator, the State, and the IAEA. This coordination can extend to related areas like authentication of operator systems and the transmission of operational data to the IAEA. For complex facilities like Rokkasho, this information is also important to helping the IAEA plan for safeguards, conduct applied R&D, and ensure that its verification approach remains valid for a range of operational conditions.
- **Onsite analytical facilities:** Important IAEA accountancy measurements rely on destructive analyses of sampled material. To avoid costs, delays, and restrictions on sample shipment, the IAEA and Japan cooperated to host an Onsite Laboratory at Rokkasho for IAEA staff to take safeguards measurements. This also required provisions to ensure that samples for IAEA analysis could be withdrawn from the process. It is not known whether MSRs will have onsite analytical capabilities or how destructive measurements may be used for material accounting.

6.2.2 Safeguards R&D for pyroprocessing

Like molten salt reactors, electrochemical reprocessing (pyroprocessing) deals with high-temperature molten salt solutions containing irradiated nuclear materials. While much R&D has been undertaken on pyroprocessing safeguards, IAEA safeguards experience is limited, with much experience coming from the Republic of Korea (ROK). To date, the ROK has established three pyroprocessing related facilities at the Korea Atomic Energy Research Institute (KAERI) site, known as PRIDE, ACPF, and DFDF. [50] [51] [52] [53]

PRIDE is an R&D facility, handling non-irradiated depleted uranium (DU) and surrogates to develop and test key technologies for pyroprocessing prior to the development and construction of an engineering-scale facility. The facility consists of a maintenance chamber connected to a large-sized argon cell. The process involves the following main steps: voloxidation of feed material, electrolytic reduction, electrorefining, electro-winning, UCl_3 preparation; and waste salt treatment.

ACPF is an R&D facility consisting of two concrete hot cells (one containing an argon compartment) for research into the electrolytic reduction process. The ACPF process involves only one step: electrolytic reduction of oxide into metal form in the argon compartment. DFDF consists of one concrete hot cell used for the technology development of the DUPIC (Direct Use of Pressurized Water Reactor Fuel in CANDU) fuel fabrication as well as for voloxidation of irradiated PWR fuel rod cuts to produce feed material (granules and low density pellets) for the electrolytic reduction process in ACFP.

The demands for robust safeguards applied to pyroprocessing facilities require the IAEA to develop new measures/techniques to complement the more traditional safeguards systems. To meet these needs a UMS system consisting of a bus bar monitor and neutron radiation monitors, were installed in the PRIDE facility to support safeguards implementation in this facility.

The bus bar monitoring system has been designed to monitor the electrical current supplied to the electro-reduction and the electro-refining equipment via two redundant current transducers installed on the copper bus bars which supply the power to the electrolytic reducer and refiner.

The neutron portal monitoring system consists of He-3 detectors placed in two locations, one near the transfer hatch where material is brought into the argon cell and another near the electrolytic refiner. Installation of the neutron monitoring equipment was completed below the floor of the argon operating cell as the floor is constructed with metal (non-neutron absorbing). The system also has batteries in case of external main power loss, virtual private networking (VPN) hardware for secure external communications (e.g., data transfer, state-of-health monitoring) and it is installed within sealable tamper indicating enclosures. The data are remotely directed via internet to IAEA Headquarters in Vienna.

Overall, these IAEA systems are of limited utility for MSR safeguards since they are tailored to electrochemical operations (bus-bar monitor) and transport of fuel assemblies (portal monitoring). Perhaps more relevant for MSR safeguards is research on domestic and international safeguards for pyroprocessing that examines process monitoring,[54] bulk salt measurement,[55] and destructive and nondestructive assay of nuclear materials in a molten salt matrix.[56]

6.3 Lessons for domestic MC&A and international safeguards

Applying lessons from reprocessing safeguards to future MSRs is highly uncertain because there is little firm information on facility design, IAEA verification requirements, domestic MC&A approaches, and other important topics. However these experiences indicate that facility designers should be prepared to evaluate the following needs, in consultation with State authorities and the IAEA.

- **Important roles for process monitoring and measurement:** IAEA experience demonstrated the importance of process monitoring and the use of other in situ measurement tools for achieving timely, frequent measurements despite access constraints and maintaining knowledge of solution locations/transfers. Many of these needs will probably also apply at molten salt reactors, for both domestic and international safeguards. Instruments for measuring salt composition, quantities, flows, etc. are under development by DOE National Laboratories and other organizations.[57] [58] [59] [60] IAEA experience suggests that these tools could be used to create a solution monitoring system that would measure parameters for salt inventories or flows at points such as (1) fresh fuel loading, (2) transfers between the core and salt polishing systems, or (3) transfers to waste streams.
  - There is not enough information to suggest specific IAEA requirements for these instruments, other than that they would need to be compatible with IAEA data verification practices, maintenance, etc. if they were to be jointly used by the IAEA.
  - If certain instruments are needed for IAEA safeguards or domestic MC&A, they may require specific design or operational features, such as optical windows, shielding, collimators, etc. Depending on the capabilities of instruments, features such as accountability tanks or the use of batch vs. continuous transfers may aid in measurement and monitoring.
- **Potential need for onsite IAEA analytical capabilities:** It may be desirable to have salt sampling capabilities for destructive assay. If used for international safeguards, the design of this infrastructure should account for the IAEA's needs for representative, independent, and secure sampling and analysis. Design choices can also prevent sampling points from being used for diversions, including by providing for application of C/S.
- **Need for early engagement**: A consistent theme is the need for early engagement. This need was particularly great for aqueous reprocessing because the IAEA needed high-quality data on the design and volume of certain tanks and systems for accountancy and process monitoring. Similar measurements would likely be necessary at an MSR. This can be

facilitated by an engineering approach that allows advanced IAEA access for design information verification (for example, such access would be inhibited if key vessels are enclosed or modularized and the IAEA does not have access during construction).

- **Accessibility and monitoring:** The design of the containment structures that surrounding process areas can help to minimize the number of diversion pathways and facilitate monitoring of declared receipts and removals of nuclear material. However, IAEA and domestic staff will still need ways of accessing critical equipment and materials for maintenance, calibration, and design verification. Achieving this balance can be a key topic for safeguards/security by design.
- **Relevance of other safeguards measures:** A variety of measurement technologies have been demonstrated for reprocessing safeguards (ranging from bubbler systems for measuring fluid quantities to nuclear material assay techniques). While this report did not review the status of these tools for use in an MSR environment, continued instrument research, development, and demonstration will be important for translating existing techniques from reprocessing safeguards into the MSR domain.

7.0 Summary and Focus Areas

The IAEA safeguards domain provides a useful source of historical experience that facility designers can consult when planning for safeguards and security at advanced reactors. While IAEA safeguards have different objectives and may use a different mix of technical measures than domestic MC&A required by the NRC, both systems employ nuclear material accounting to ensure that nuclear materials have not been removed or misused at a facility.

As described in the report, the IAEA and national regulatory authorities have cooperated to apply IAEA safeguards at sodium-cooled fast reactors and pebble-bed reactors in Japan, Germany, China, and elsewhere. The IAEA does not have verification experience at MSRs, but limited comparisons can be drawn to IAEA safeguards at reprocessing plants. The report and the cited literature describe historical IAEA safeguards implementation, R&D, and planning for these facilities. Some key observations include the following:

- **For SFRs**: Because SFRs use assembly fuel, current MC&A practices for LWRs will remain largely applicable. The IAEA safeguards approaches at Japanese SFRs require complex systems for identifying and maintaining continuity of knowledge of fuel assemblies along the fuel handling pathway. Such systems would probably exceed the needs of U.S. domestic MC&A under ANSI N.15-8 2009. However, if deployed in the international context, these tools could provide added assurance regarding the location and identity of fuel assemblies.
- **For PBRs**: IAEA safeguards approaches for PBRs in Germany and China combined (1) item accounting for containerized fresh and spent fuel, and (2) a quasi-bulk MC&A approach for the in-process pebbles. This was based around automated counting of pebbles entering/leaving the reactor, supported by C/S of the reactor and supplemental verification of pebbles. This approach does not strictly align with certain existing MC&A requirements for reactors or for fuel cycle facilities; however, it does resemble proposed nuclear material accounting plans for these facilities.
- **For MSRs:** There remain many uncertainties regarding MC&A requirements for future MSRs, but current Cat II and Cat I MC&A requirements establish requirements for measurements and process monitoring. IAEA safeguards at large aqueous reprocessing plants rely heavily on attended and automated systems (including process monitoring) for estimating material balances, tracking solution movements, and identifying signatures of diversion and misuse. Some of these approaches merit further examination for being adapted for MC&A or other verification activities at MSRs.

Past IAEA safeguards experience is especially relevant to U.S.-designed reactors that may become subject to IAEA safeguards in the future. For domestic reactors, this could occur under the U.S.-IAEA Voluntary Offer Agreement as implemented through 10 CFR 75, although the IAEA has not recently selected any U.S. power reactors for safeguards. IAEA safeguards would also be required for any U.S. reactors exported to foreign non-nuclear weapons states.

Reactor designers who are planning for MC&A, physical protection, and other aspects of reactor design and operations might gain efficiencies from considering international safeguards during the design phase, thereby reducing the need for future retrofits or modifications. A common theme in IAEA safeguards-by-design is the need to provide the IAEA the ability to reach independent, verifiable conclusions about a facility’s nuclear material inventory. Reviewing the findings from the different reactor types, key themes include:

- **Sharing data or instruments with the IAEA and ensuring data security**: Advanced reactors may have instruments for fuel handling, measurement, process control, and MC&A that could benefit IAEA safeguards. For example:
  - SFRs: Nondestructive assay, containment, and surveillance systems that confirm presence, or identify attributes or other features of fuel assemblies along fuel transfer pathway.
  - PBRs: Pebble counters and handling equipment, burnup measurement systems, or waste surveillance systems.
  - MSRs: Instruments relating to salt quantity, composition, flow, location, or other process parameters.

  It sometimes may be advantageous for both the IAEA and the facility operator to pursue joint-use of these instruments, although this introduces a need for coordinated vulnerability testing, data security, and instrument development with the IAEA. A key need is ensuring that the IAEA can assure the independence of any signal used for safeguards use, for example by having an independent/encrypted IAEA signal split off within a tamper-indicating enclosure. If joint-use is not pursued, then the IAEA may need to install a duplicative, IAEA-owned instruments that would need to be accommodated within the facility design and licensing process. For systems that interface directly with the reactor process, this will require increased levels of advance planning and coordination on IAEA requirements.

- **Benefits of containerization**: Because of the comparative simplicity of item verification for both domestic MC&A and IAEA safeguards, it will be useful to take advantage of containerization of nuclear material, particularly at PBRs and MSRs. This may require steps to ensure that container design and facility operations are compatible with IAEA sealing needs, that IAEA verification can occur at centralized fuel fabrication facilities, and that the IAEA can validate declarations regarding wastes (like discharged pebbles) that are placed in sealed containers, through inspector access or special monitoring systems.

- **Need for enhanced containment, surveillance, and measurement capabilities:** Because IAEA inspectors must verify a facility's nuclear material inventory without relying on physical protection assumptions or other operator systems, the IAEA may have increased need for containment/surveillance systems compared to domestic MC&A. Key areas include (1) assembly flow paths for SFRs and (2) any potential sampling or takeoff points that could be used to remove nuclear materials at PBRs or MSRs. These facilities should minimize potential takeoff points and ensure that the facility design can provide for effective monitoring of these points.

- **Advanced engagement and safeguards by design.** A final general need area is for advance coordination and information sharing between stakeholders. As mentioned previously, the specific domestic MC&A and IAEA safeguards needs will likely vary for different facility types, and domestic and international requirements will continue to evolve. Coordination at appropriate intervals involving facility designers, U.S. government stakeholders (including DOE/NNSA) and the IAEA will help identify problems proactively and help navigate interfaces between domestic MC&A and IAEA safeguards. This is particularly true for facilities such as liquid-fueled MSRs that may have particularly complex MC&A systems. The IAEA and

DOE/NNSA have issued reports on international safeguards by design (SBD) for a variety of relevant facility types, which can provide further guidance and considerations.[i]

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[i] See: DOE/NNSA. (2017). Safeguards by Design Guidance Documents. https://www.energy.gov/nnsa/downloads/safeguards-design-guidance-documents, and:
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Appendix A – Selected Terminology

Confusion of terminology can pose challenges in discussing the interfaces between IAEA safeguards and domestic measures like MC&A or physical protection. This appendix summarizes usage of key terms by organizations such as the NRC and the IAEA.

- **Domestic safeguards**: The NRC uses this term in reference to NRC and licensee systems "aimed at ensuring that special nuclear material (SNM) within the United States is not stolen or otherwise diverted from civilian facilities for possible use in clandestine fissile explosives and does not pose an unreasonable risk owing to radiological sabotage. The users of the special nuclear and certain quantities of byproduct material apply safeguards to protect against sabotage, theft, and diversion, including physical protection of facilities and/or special nuclear material at both fixed sides and during transportation and material control and accounting for special nuclear material."
- **Material control and accounting (MC&A):** MC&A is a term used by the NRC to denote one component of the NRC's domestic safeguards program. According to the NRC: "MC&A regulations ensure that the information collected by the licensee about SNM is accurate, authentic, and sufficiently detailed to enable a licensee to 1) maintain current knowledge of its SNM and 2) manage its program for securing and protecting SNM… The MC&A component of the larger safeguards program helps ensure that SNM within a licensed facility is not stolen or otherwise diverted from the facility."
- **Material control:** According to the NRC, **"**material control means the use of control and monitoring measures to prevent or detect loss when it occurs or soon afterward."
- **Material accounting:** According to the NRC, "Material accounting is defined as the use of statistical and accounting measures to maintain knowledge of the quantities of SNM present in each area of a facility. It includes the use of physical inventories and material balances to verify the presence of material or to detect the loss of material after it occurs, in particular, through theft by one or more insiders."
- **Physical protection:** According to the NRC, "physical protection (also called physical security) consists of a variety of measures to protect nuclear facilities and material against sabotage, theft, diversion, and other malicious acts."
- **IAEA safeguards** are defined by the IAEA as: "A set of technical measures applied by the IAEA on nuclear material and activities, through which the Agency seeks to independently verify that nuclear facilities are not misused and nuclear material not diverted from peaceful uses." *IAEA safeguards* is sometimes used interchangeably with the term **international safeguards**, which may also include verification systems involving other organizations (such as regional agencies like Euratom or the Argentine-Brazilian Agency for Accounting and Control of Nuclear Material).
- **Nuclear material accountancy** is a term used by the IAEA Department of Safeguards that refers collectively to nuclear material accounting practices implemented by the facility operator and the State and in addition their independent verification by the IAEA as part of IAEA safeguards.
- **Safeguards by design (SBD)** is defined by the IAEA Department of Safeguards as "an approach whereby early consideration of international safeguards is included in the design process of a nuclear facility, allowing informed design choices that are the optimum confluence of economic, operational, safety and security factors, in addition to international safeguards."

- Because the unqualified term “safeguards” can refer to either domestic or international measures in different contexts, the terms **Safeguards and Security By Design (SSBD); Security By Design, or Safety, Security, and Safeguards (3S),** refer to design approaches that explicitly include nuclear security topics such as physical protection and domestic MC&A within their scope, potentially alongside IAEA safeguards.
- **Nuclear security** is defined by the IAEA Division of Nuclear Security as “the prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material, other radioactive substances or their associated facilities.” Domestic safeguards activities such as physical protection and MC&A are included within nuclear security. However “nuclear security” also includes topics such as the interdiction of nuclear material smuggling that are outside the scope of “domestic safeguards.”

Note: In addition to the international verification role played by the IAEA Department of Safeguards, other IAEA organizations (principally the Division of Nuclear Security) provide guidance, standards, training, and technical support related to nuclear security. The terminology used by the IAEA for these domestic nuclear security functions sometimes differs from the terminology used by the NRC. For example, the IAEA uses the term “**nuclear material accounting and control (NMAC)**” instead of “MC&A.” The IAEA does not generally use the terms “domestic safeguards” or “safeguards” in reference to domestic physical protection and nuclear material accounting and control activities.