ORNL/TM-2021/2208

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**September 2021**

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ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

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Nuclear Energy and Fuel Cycle Division

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Prepared by
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managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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## ABSTRACT

Advanced reactor (AR) designs differ from traditional light-water reactors in nearly every facet, including the heat transfer fluids, operating temperatures and pressures, and fuel cycle requirements. To account for these differences, significant effort will be required to ensure appropriate safeguards implementation for US-based reactors intended for global deployment. This is the third in a series of three papers that examine the facets of this issue. The first paper [1] investigates potential construction schedules for ARs to create a baseline understanding of the timeframes involved. The second paper [2] characterized the International Atomic Energy Agency (IAEA) safeguards implementation schedules for potential ARs. Finally, this paper examines gaps that exist for safeguards implementation at ARs.

New advanced reactor types are being designed, using new materials and new forms of fuel. These advances may require a shift from the traditional methodology and equipment that have been used for international safeguards. Simultaneously, modern construction methods and techniques have advanced beyond those used to build much of the existing global fleet of power reactors, allowing smaller and more efficient construction with less empty space. Furthermore, economic pressures push power reactor design and construction to the minimum possible schedule time and expedite the approach to operation, which will minimize the amount of time available before and during construction to install and verify safeguards infrastructure. Because of this combination of necessary technological maturation and schedule pressure, the international community will have a relatively short window for effective safeguards implementation before initial operation. This report provides a characterization of potential implementation issues and risks of safeguards implementation for ARs deployed internationally. Addressing these risks by using advanced communication, planning, and technology development will be essential to ensure that efficient and effective safeguards are implemented for these new designs.


## 1. INTRODUCTION

There is a diverse range of advanced reactor (AR) designs, such as pebble bed reactors, molten salt reactors, and small modular/micro reactors. These designs deviate from the traditional light-water reactor (LWR) design, operational, and nuclear safeguards requirements.

These design deviations will create implementation challenges for international safeguards in multiple areas. First, inherent differences in design will create a need for new surveillance equipment and techniques to address new challenges, such as fuel that is not constrained within fuel assemblies and the need for on-site fuel processing. Next, design differences may create size constraint challenges; AR designs strive for smaller and more efficient layout and construction methodologies. Finally, new operating modes inherent to AR efficiencies—such as multiple modules on a single site or fully remote operation—must be addressed for international safeguards.

This report provides background on these issues, as well as the International Atomic Energy Agency (IAEA) safeguards process, characterization of potential risks for international safeguards design and implementation, and ways for these risks to be mitigated.

# 2. BACKGROUND

## 2.1 PROJECT PURPOSE

This report provides an overview of the gaps between current AR construction plans and international safeguard implementation approaches. The IAEA is the organization responsible for oversight of international safeguards deployment. There is a diverse array of AR types with varying physical characteristics, some of which deviate significantly from existing reactors. Therefore, there are gaps between traditional safeguards equipment and approaches and what will be needed to quickly and efficiently safeguard ARs.

## 2.2 REACTOR AND SYSTEM TYPES

ARs face different safeguards challenges than traditional low-enriched uranium (LEU) fueled LWRs. The safeguards considerations for innovative AR designs include scalability, accessibility, and instrumentation. The following is a discussion on the considerations regarding general categories/characteristics of reactors.

### 2.2.1 SMALL MODULAR REACTORS

Small modular reactors (SMRs), including microreactors, are designed to have small footprints and to be assembled in areas where large nuclear power plants cannot be sited. This is due to SMRs' smaller grid requirements and footprint constraints, as compared to traditional LWRs. LWRs must be constructed relatively far from populated areas and require larger plots of land (e.g., ~500 acres for large LWRs). The design inherent to SMRs lends itself to advantages and disadvantages in terms of safeguards. Those are categorized below [3, 4].

- **Space requirements**: The small size of SMRs compared to traditional LEU-fueled LWRs could make finding interior space for safeguards equipment quite challenging. Moreover, retrofitting safeguards could prove more difficult because of the space constraints. One possible solution is requiring sealed systems and external monitoring. Sealed vessels are discussed further below.

- **Remote locations**: An advantage of SMRs is the ability to be placed in areas where traditional nuclear power plants cannot be sited or built. This includes remote and possibly difficult to reach areas. An advantage of remote and difficult to reach locations is an increase in cost, time, and effort for diversion. However, being difficult to reach also increases the cost of inspection, and the ability to perform short-notice inspections is diminished.

- **Transportability**: There are SMRs designed to be transported to meet power needs in various remote locations as they arise or to be returned to the manufacturer for refueling. This has the potential to increase access to the reactor, and the ability to inspect could be greatly reduced, particularly in an unsealed system. However, reactors of this size will likely require Pu, mixed oxide (MOX), or highly enriched uranium (HEU) fuel to operate. Moreover, radiation exposure concerns would likely prevent deployment and transport in populated locations.

- **Low thermal signature**: SMRs produce a thermal footprint on the scale of existing technologies used in remote locations. This can make it difficult to verify operation through satellite and remote sensing.

- **Autonomous operations**: An SMR could be placed in a remote region and operate autonomously. Autonomous operation would likely require the IAEA to develop different safeguards processes and requirements.

- **Scalability**: One advantage of SMRs is that multiple reactor units can be added to a single site over time. This leads to potential safeguards challenges, such as the following questions:

    - Can the safeguards infrastructure scale as the number of reactor units increases? Does the accessibility issue compound this problem?
    - What is the fuel cycle schedule associated with each reactor unit and how does this impact safeguards infrastructure?
    - How does the fuel cycle schedule alter the safeguards inspection schedule, and will there be enough manpower to perform the inspections?

- **Advanced fuel cycle**: For non-LWR SMRs, the fuel cycle and operations could be unfamiliar to the inspectorate. Moreover, new instrumentation may be required.

- **High-assay low-enriched uranium (HALEU)**: Many SMRs are designed to use HALEU fuel to achieve desired power outputs and increase the time between refueling. See section 4.1.

- **HEU**: Some SMRs are designed to use HEU. A reactor using uranium above 20% enrichment will certainly have greater safeguards requirements than a conventional reactor.

- **Sealed vessels**: Numerous SMRs are designed with sealed vessels. This design limits access to the core, and thus decreases the likelihood of misuse and diversion. However, this does not align with the current IAEA practice of annual physical inventory of the reactor core. This will need to be reconciled. A possible solution is to perform inventory before the reactor core is inaccessible and after the seal is broken, if it can be verified the core was not accessed in the interim.

- **Excess reactivity**: Various SMRs are designed with longer than traditional refueling intervals. This could lead to substantial surplus reactivity and burnable absorbers. As such, target material could be introduced without significantly impacting operation parameters. Neutronic management with burnable absorbers and neutronic management with target material could be similar from the perspective of an observer. This could provide for potential diversions.

- **Fuel element size**: The potential for smaller fuel elements in SMRs would require a greater number to be diverted. However, the smaller size would allow for fuel elements to be concealed more easily.

- **Spent fuel storage geometry**: For criticality concerns, the smaller fuel elements would encourage a slender vertical storage geometry (i.e., much higher than traditional height to diameter ratio) or a flatter storage geometry (i.e., much lower than traditional height to diameter ratio). Moreover, there is motivation to stack fuel and reduce the overall storage footprint. The geometry of the spent fuel storage then conflicts with current safeguards inspection requirements of a direct line of sight of fuel elements from above. An existing approach that could address this issue involves the operator packaging a set of fuel elements in a basket for easier shipping and handling, and the IAEA then placing seals on the basket at the packaging site instead of at the storage site.

### 2.2.2 FAST REACTOR SYSTEMS

Fast reactor systems are characterized by the reliance on neutrons in the fast neutron spectrum as opposed to thermal neutrons. Fast neutrons allow for more favorable cross sections; thus, once started, a fast reactor is far more efficient than a thermal neutron system. However, a fast reactor system requires more fissile material to start up. Therefore, fast reactors require different fuel and coolants than thermal systems [5].

- **Fuel**: Fast reactor systems can rely on a combination of Pu, HEU, MOX, or Trans-Uranium (TRU) fuel. Therefore, they will likely require more frequent inspection, more measurements, more monitoring, more surveillance, and more containment. Fast reactor systems will likely require hardened, secure storage for Pu, HEU, or TRU-fuel, advanced, redundant surveillance, containment and monitoring systems, and continuous, unattended non-destructive assay (NDA) to monitor fuel movements that can distinguish between fissile and fertile and non-nuclear material items. For reactors from which fresh and spent TRU-fuel assemblies are being shipped and received, new NDA techniques need to be developed for measuring Pu and actinide content [3, 6].

- **Coolants**: Use of coolants other than water, such as lead-bismuth or sodium, in fast reactor systems does not allow for traditional optical viewing of the fuel in the core or in the spent fuel storage [3, 6].

Non-destructive assay (NDA) equipment for verifying fresh prismatic fuel is the same as NDA equipment currently used. The optimization will depend on the content of the fuel [3].

### 2.2.3 PEBBLE FUELED HIGH TEMPERATURE GAS COOLED REACTORS

Pebble-fueled reactors (PBRs) are designed to operate with continually moving fuel spheres (pebbles), i.e., online fueling. This is in contrast with the uniquely identified fuel bundles found in LWRs that can only be moved during plant outages. Due to the portability of the fuel pebbles and potential use of HALEU, proposed PBR designs require different nuclear material control and accounting methods, compared to the existing US fleet of LWRs. See the reports by Durst [7], Kovacic et al. [8], and Gibbs et al. [9] for details on materials control and accounting for pebble bed reactors.

### 2.2.4 MOLTEN SALT REACTORS

Molten salt reactors (MSRs) are reactors that use molten salt as the coolant. Proposed MSRs use either solid or liquid fuel. Liquid-fueled reactors cannot be treated similarly to LWRs. The IAEA proposes the following items for consideration for the safeguarding of liquid-fueled MSRs [3].

- Integrated reprocessing and salt conditioning
- Online refueling
- Nuclear material accounting techniques and instrumentation that may not yet exist in this context for monitoring fuel flow, seals, video surveillance, triggering sensors, and NDA measurement / sampling plans.

Proposed MSR design concepts have varying physical, chemical, and isotopic composition of fresh and irradiated fuel. Operational neutron energy spectrums and breeding ratios could also significantly differ, depending on the reactor design. For example, some proposed MSRs incorporate burner reactors designed to transmute the spent nuclear fuel from LWRs or pressurized heavy water reactors, while other design concepts include breeder reactors. Additionally, some proposed MSR designs are a part of a once-through fuel cycle, while others involve chemical separation. Reactors that are designed to recycle the fuel may include on-site chemical processing or require off-site processing. Overall, there are a variety of aspects that contribute to the complete design concept of an MSR facility and each of these characteristics must be uniquely considered when implementing material control, accounting, and other safeguard measures. [10].

## 2.3 IAEA SAFEGUARDS

The objective of IAEA safeguards is

> *to deter the spread of nuclear weapons by the early detection of the misuse of nuclear material or technology. This provides credible assurances that States are honoring their legal obligations that nuclear material is being used only for peaceful purposes* [11].

A traditional safeguards approach has been employed in the design and construction of most existing power reactors and their related facilities. In practice, a state selects the site for the reactor, the type of reactor, and a design. The safeguards process does not begin until the state notifies the IAEA of their intent to build the facility. At this point, the state and IAEA conduct negotiations regarding the design, construction, and safeguards implementation. Next, the two parties agree on a facility-specific plan for construction and safeguards implementation. The final step in this approach involves the state implementing the agreed plan and requirements in cooperation with the IAEA.

## 2.4 FIRST ATTEMPTS AT SAFEGUARDS BY DESIGN IMPLEMENATION

This section summarizes select case studies of safeguards implementation, with a focus on the challenges encountered in carrying out safeguards by design (SBD) of existing power reactors (e.g., Generation III and III+ reactors) and their associated facilities. The benefits of integrating SBD at a facility include minimizing risk, reducing overall costs, improving safeguards assurances, facilitating preparation of design, expediting design verification by the IAEA, promoting innovation, and encouraging improved efficiency in the implementation of safeguards [3].

With the development and deployment of ARs, new safeguards challenges will be encountered in the form of nontraditional fuel cycles and system designs in states that may or may not have an existing nuclear program. The lessons learned from the safeguards implementation for Generation III and III+ reactors can be used as a baseline to develop potential safeguards strategies for ARs. Specifically, Generation III and III+ reactors rely on proven technologies and processes wherever possible; incorporating novel and emerging safeguards technologies poses a unique challenge to ensuring the highest degree of proliferation resistance [12].

### 2.4.1 THE ROKKASHO REPROCESSING PLANT

The first facility investigated herein, the Rokkasho Reprocessing Plant (RRP), located in northern Japan, demonstrates the importance of active and cooperative communication between a state and the IAEA during the design phase of a facility. The RRP is one of the largest safeguards projects undertaken by the IAEA; its design involves the first safeguards approach for a large commercial-scale reprocessing facility. Since there are over 50 in situ measurement/monitoring systems and approximately 70 surveillance systems at the plant, in addition to jointly used equipment and an on-site IAEA laboratory, it was critical that direct and coordinated communication between the IAEA and the state occurred during the design and construction of the facility [13].

Early in the design process, a multinational forum called LASCAR (Large Scale Reprocessing) was established to address the complex nature of safeguards implementation for the RRP. The findings of this forum inspired the early design of the plant; the following aspects were emphasized in the forum's recommendations [14].

- Early submittal of design information by the state to the IAEA
- Advanced nuclear material accountancy methods
- Containment and seals measures
- Authentication of operator instruments
- Data acquisition and transmission
- On-site inspectorate analytical laboratory

Although these insights and recommendations were valuable in the design process, the design and construction of this facility were multifaceted and spanned several decades. In its final stage, the project used a multidisciplinary management team consisting of approximately 35 members from various IAEA operations and support sections and the IAEA Seibersdorf Analytical Laboratory. Furthermore, several cost-free experts from the United States, France, Germany, UK, and Japan, consultants, contractors, and interns were involved. The wide array of experts and management involved, in addition to the timeframe of construction, greatly added to the complexity of implementing safeguards for the facility. After the development and implementation of the utilized safeguards approach, several challenges were identified that should be given special attention in future projects [14].

- **Safeguards by design are critical.** Optimization of the facility's design could have allowed for easier access for verification of material. More specifically, the following safeguards recommendations were made based on the final design.

    - Permanent installation of verifiable tank calibration systems
    - Provision of remote viewing capabilities into strategic cells
    - Improvement of the design of accountancy vessels, taking into consideration internal structures, homogenization capabilities, environmental controls, and sampling systems
    - Re-evaluation of current sampling systems and their effects on the validity of samples taken, including factors such as tamper vulnerability, evaporation, and simultaneous sampling capabilities
    - Provisions for transparency and minimization in recycling capabilities
    - Clear separation and well-defined waste handling and treatment areas
    - Installation of independently owned and controlled systems
    - Provision of easier access to the inspector regarding safeguards relevant operating information

- **Design information examination (DIE) and design information verification (DIV) procedures should be streamlined.** Although preliminary design features were provided to IAEA at a very early stage, design modifications to accommodate safeguards were difficult to implement because of the operator's contractual agreements. Also, the IAEA was not capable at this early stage to clearly outline its safeguards requirements.

- **The best available safeguards measures must be implemented.** At the time of design, the available verification measurements had inadequate sensitivity and reliability to statistically detect the diversion of a significant quantity of nuclear material or the misuse of a commercial scale reprocessing plant. Thus, enhanced safeguards measures were needed and subsequently developed to strengthen the accountancy verification activities and to provide added assurance.

Additionally, in-vessel measurement and monitoring systems capable of high-frequency random sampling / in-process analyses were installed to satisfy IAEA inventory verification and timeliness requirements.

- **Verification systems are crucial for safeguarding material.** More than 50 measuring and/or monitoring systems and approximately 70 camera surveillance systems were installed at the RRP. These systems were expensive and required many hours of labor to install and test; therefore, in the future, effort should be made to develop reliable, robust online measuring and monitoring systems with increased sensitivity.

- **Sampling and analysis procedures need improvement.** The sampling system developed and installed by the IAEA utilizes an automatic sampling authentication system that ensures the integrity of the empty and full inspector sampling vials and tracks them from the on-site laboratory to the sampling bench and back to the on-site laboratory. Although this sampling system's capacity far exceeds any system previously available, it could be improved in the future. The automated system has limited capabilities for sampling multiple vessels simultaneously, and the scheduling of samples requires significantly advanced planning which detrimentally impacts the implementation of random, short-notice sampling by the inspectors.

- **The operator/state–inspector interface must be considered during every phase of a project.** The operator, state, and IAEA should contribute to the financing and labor, with the operator carrying the largest burden. Furthermore, responsibilities for equipment development, procurement, and installation should be shared by the operator, state, and IAEA. Inspector requirements can place a heavy burden on the operator in the areas of system and process design modifications, equipment installations, adjustments to testing and calibration procedures, and schedule disruptions. Therefore, early and continuous consultation between parties should occur to minimize this burden.

### 2.4.2 CANDU REACTORS

Next, the challenges associated with recently built CANDU reactors and their unattended monitoring systems are explored. Since CANDU reactor designs now incorporate remote monitoring of online refueling, there are several safeguards implementation aspects that must be considered during their design and construction phases. An integrated fuel monitor (VIFM) is used at CANDU facilities to verify the number of bundles removed from the core when re-fueling while online [13]. The VIFM tracks and counts discharged fuel from the core of the reactor using neutron and gamma radiation detectors. Since the fuel bundles must be replaced several times a day in these pressurized heavy water reactors, the monitoring system tracks the bundles as they are loaded, rearranged in the core, and discharged to the spent fuel pool [15]. More specifically, this unattended monitoring system consists of three subsystems: the core discharge monitor (VIFC), the spent fuel bundle counter (VIFB), and a 'yes/no' monitor (VIFD). The VIFC is placed in an inaccessible area to detect irradiated fuel upon discharge from core face, the VIFB monitors strategic locations and directions in the spent fuel bundle pathway, and the VIFD determines whether any irradiated fuel has been discharged through access ports that are not part of the normal discharge path [13].

Several issues and challenges were encountered when designing the CANDU facilities and implementing the preceding safeguards systems. First, the problem of verifying spent fuel in piled spent fuel baskets was resolved by situating a verification point to an earlier part of the fuel flow where radiation monitoring and surveillance were installed. This issue was addressed and resolved by early discussion between the IAEA and the operator; the solution eliminated the need to retrofit equipment after the facility was constructed. Overall, this reduced the safeguards instrumentation installation cost burden on the operator [13].

Another safeguards implementation challenge regarding CANDU reactors surfaced in the verification of the loading of modular air-cooled storage (MACSTOR) cylinders. In the past, the inspection of MACSTOR cylinders was performed by IAEA inspectors and was a time-, energy-, and cost-intensive process. To alleviate the demand of in-person inspections, additional dedicated monitoring tubes were installed next to each of the sixteen inner cylinders in the MACSTOR system. Ultimately, the installation of these monitoring tubes was relatively easy and cost-effective; they did not impact the structural integrity or the prescribed safety requirements and security constraints [13].

Overall, the implementation of unattended monitoring systems in CANDU designs greatly reduced the cost burden on the operator and the demand of IAEA inspectors, all while maintaining safety and security.

# 3. IMPLEMENTATION CHALLENGES

## 3.1 SAFEGUARDS BY DESIGN

The IAEA expresses a desire for designers and vendors to implement SBD [3]. Historically, safeguards have been retrofitted into existing facilities as discussed above. Conversely, SBD includes safeguards considerations in each stage of a reactor's life cycle, from conceptual design through decommissioning. Two main objectives of SBD are avoiding retrofits or redesigns and making safeguards implementation more effective and efficient for the operator, state, and the IAEA. SBD is not a legal framework; however, designers and vendors who implement SBD can be more marketable to a customer in a state with safeguards obligations.

Traditionally, international safeguards agreements are negotiated between the state and the IAEA with input from the facility operator. The reactor vendors have not been directly involved, except as directed by their client. SBD for AR designs would require safeguards leadership from the reactor vendors, as in most cases there is not a confirmed client at this point in the design process. This SBD framework would be a new model for reactor vendors in the United States.

Although safeguards are not required for any reactors built in the five nuclear weapons states of the Nonproliferation Treaty (NPT) (i.e., China, France, Russia, the United Kingdom, and the United States), all five of these nations have signed voluntary offer safeguards agreements that permit the IAEA to apply safeguards to material in select eligible facilities [16]. Moreover, since the IAEA often utilizes US facilities to test new safeguard techniques, it is likely that any AR constructed in the US will be selected for safeguards implementation, in accordance with the voluntary offer agreement in place between IAEA and the US.

Assuming that there is a cost associated with additional design efforts to implement SBD, any AR vendor that intends to market its design(s) significantly within these states would put itself at a competitive disadvantage over other vendors that did not implement SBD because of the necessary increase in price to recoup these additional design efforts. Additionally, SBD implementation is recommended to begin as early as possible in the design process, such as during the preliminary design stage [17]. However, during the preliminary design stage, it is unlikely that the AR has any confirmed customers and the location of future construction of units is yet to be determined.

To address some of these challenges, there are multiple items that must be addressed; please note that this is not an all-encompassing list. First, established standards for SBD would need to be developed. These standards should be a joint effort between the IAEA, states, regulators, and designers [17]. Funding for standard development will need to be established to support these joint efforts. Next, first of a kind implementation of the SBD standards would need to be given special attention and a success framework should be established. Additional funding to cover the risks of unexpected issues would need to be secured. Establishing a firm (guaranteed) customer commitment from an NPT state in which the AR would ultimately be constructed is also essential. This state would need to agree with and buy into the SBD approach and any standards established as part of the prior implementation efforts. To complete these activities, a leadership role would need to be established for project management purposes. This could be any of the previously mentioned stakeholders, or potentially an external firm that all stakeholders agree will support the SBD implementation from a project management perspective. Using an external, neutral firm could help manage any conflicts of interest that arise between the stakeholders.

## 3.2 NON-STATIONARY FUEL MONITORING

Unlike traditional LWRs, PBRs and MSRs have non-stationary fuel. In a PBR, the fuel pebbles may be counted, verified, and segregated; however, novel accounting techniques will still need to be developed. The IAEA suggests the following safeguards for pebble fueled reactors. There should be seal and surveillance systems directed at access rather than vessels. Fuel flow monitors are required to count, verify, and discriminate between fresh, spent, irradiated, and damaged fuel, in addition to moderator pebbles. There should be seals on fresh pebble storage drums and pebble feed hoppers. NDA techniques for fresh pebble fuel casks will be the same as those currently used, and they will be complemented by surveillance, containment, and monitoring. NDA should also be optimized based on pebble fuel size, geometry, and content [3]. Overall, since the pebbles are stored in large, heavy, sealed containers, it is important to carefully consider safeguards implementation at the key points where pebbles enter and exit the fuel handling system [7, 9].

In an MSR, the fuel is not in a discrete, countable, and distinguishable form. Thus, new accounting techniques must be developed for MSRs. Although radiation monitoring equipment exists that can be used in these areas, the existing approved equipment may not be the most accurate or efficient for these new AR designs. Optimal equipment has the potential to minimize IAEA inspector burden while providing more accurate accounting information by modernizing this equipment in line with the latest AR designs.

## 3.3 PHYSICAL SPACE CONSTRAINTS

Small and micro reactors are designed with a small footprint. Therefore, there is less space for safeguards equipment. If a small or micro reactor is implemented without safeguards in mind, then it is unlikely that traditional safeguards could be retrofitted given the space constraints. It is then advised that the space for safeguards equipment be incorporated into the design. A sealed vessel design with external monitoring may be an acceptable alternative.

## 3.4 SCALABILITY FOR MULTIPLE MODULES

Many of the proposed ARs are designed to be implemented as a group of multiple modules added to a facility over time. It is possible that each of these reactor modules will have distinct refueling schedules. Moreover, it is possible that the group of modules will have shared resources. Given that each of the modules may have distinct refueling schedules, it may be that each is safeguarded separately. However, if the group of modules shares resources, then the group may need shared safeguards. In this case, the safeguards infrastructure requires the ability to scale for multiple modules being added to a single facility over time.

# 4. INTEGRATION OF NEW TECHNOLOGY

## 4.1 HIGH-ASSAY LOW ENRICHED URANIUM

HALEU fuel, which uses uranium between 5% and 20% enrichment, is a key design element in many proposed ARs. HALEU allows the attainment of desired power outputs in smaller facilities and increases the time between refueling. There are numerous sources [18] that discuss the safety, security, economic viability, and availability of HALEU.

Since the existing fleet of power reactors uses LEU (<5% enrichment), the current instrumentation and techniques for NDA are optimized for LEU fuel. This leads to the following concerns.

- Are the safeguards for a facility using HALEU different in any way from those of a facility using LEU?
- How do the existing instrumentation and techniques for NDA need to be altered for HALEU?
- Are the current methods able to provide the same level of (un)certainty with HALEU as with LEU?
- What are the safeguards considerations not directly but indirectly related to HALEU because of the higher burnup, smaller footprint, and increased refueling time?

Criticality safety should ultimately discourage a power reactor facility from pursuing fuel enriched beyond the agreed enrichment limits. So, conceivably, the primary focus for international safeguards for HALEU should be earlier in the fuel cycle, such as at fuel fabrication facilities, and the reactor facility would have to verify the delivery and take materials accounting responsibilities.

## 4.2 FULLY REMOTE OPERATIONS

It has been suggested that advanced nuclear power plants should reduce plant operations and maintenance costs through use of autonomous control systems. An autonomous control system would operate the power plant, perform maintenance, and adapt to faults automatically. Such a system could be particularly useful in the operation of an SMR in a remote region [19].

In terms of safeguards, none of the existing procedures account for autonomous control. If an AR is operated autonomously, then certainly there would be less physical access to nuclear material. However, for a reactor placed in a remote region and operated autonomously, the most apparent issue in terms of safeguards would be the ability to perform inspections. Not only would access for the inspectorate be difficult, but it could also be challenging to perform a short-notice inspection. A combination of a sealed system and a verified video feed could alleviate these concerns.

## 4.3 EMERGING SAFEGUARDS TECHNOLOGIES

Future requirements for safeguards verification will utilize innovative and/or currently under development technological solutions that will operate in different types of nuclear facilities, accounting for the increasing potential risk of the proliferation of sensitive technologies and materials. Both new (e.g., advances in present safeguards verifications techniques) and novel (e.g., innovative technologies that are already available in other branches of science but not traditionally related to nuclear safeguards) technologies must be explored. In particular, technologies that can detect undeclared nuclear activities (e.g., reprocessing or enrichment) have piqued the interest of the IAEA safeguards program. These future safeguards strategies may depend on the detection of non-traditional elements and isotopes (e.g., americium, neptunium, beryllium, and tritium) which may indicate the presence of clandestine nuclear activities. This section includes a non-inclusive list of new and novel safeguards technologies that are being investigated and researched [20].

New safeguards technologies have the capability to enhance the effectiveness and efficiency of present verification systems. These new technologies may be in their final development stages but not yet available for industrial safeguards implementation. For these technologies to be authorized for routine use, they must undergo performance, usability, and affordability assessments, in addition to stringent field testing. New sensors for nuclear material detection and characterization, process monitoring equipment/techniques, and analytical equipment are the new technology drivers. Examples of new safeguards technologies are listed and summarized below [20].

- **CALADIOM®**: Smart camera sensor that integrates behavioral and pattern analysis to enhance surveillance capabilities

- **Differential die-away self-interrogation (DDSI)**: Measures Pu in spent fuel using spontaneous fission neutrons from $^{244}Cm$

- **HF detector laser system (HFLS)**: Portable instrument for HF gas detection and enrichment activities

- **Laser item identification system (L2IS)**: Laser-based monitoring system for unique identification of $UF_6$ cylinders

- **Reflective particle tags (RFPTs)**: Reflective particles in a transparent adhesive matrix applied to detect any tampering with welds and for unique identification

- **Remotely monitored seals array (RMSA)**: Radiofrequency-based sealing system configured in a network for a large number of individual items

- **Self-interrogation neutron resonance densitometry (SINRD)**: Measures Pu in spent fuel

- **Superconducting gamma spectrometer**: Ultra high–energy resolution γ ray spectrometer for accurate enrichment measurements and Pu isotopes

- **Universal NDA data acquisition platform (UNAP)**: Standardized acquisition platform for non-destructive assay data

- **UF6 detector based on laser spectrometry (UFLS)**: On-site analytical instrument based on tunable laser diode spectroscopy for the enrichment of $UF_6$ samples

Novel safeguard technologies provide access to a wide range of methods and instruments that can support emerging and future needs. These novel safeguards include the development of methodologies that identify, document, and utilize indicators that can detect the presence of process signatures that result from specific processes. Several promising technologies currently under investigation have been identified and are described below [20].

- **Antineutrino detector**: Remotely measures Pu content, effective power, and burnup of various operating reactor cores outside their biological shield using detection of the generated antineutrinos

- **Atmospheric gases sampling and analysis**: Identifies nuclear activities (e.g., reprocessing) from a distance by the detection and analysis of airborne gaseous compounds emanating from nuclear processes

- **Fourier transform infrared (FTIR) system**: Detects the presence of molecules that have characteristic absorption bands in the infrared region

- **Laser induced breakdown spectroscopy (LIBS)**: Analyzes elemental composition and traces of solid materials by atomic emission spectroscopy to confirm past nuclear activities and the absence of undeclared activities

- **Light detection and ranging (LIDAR) system**: Senses the presence of characteristic gaseous compounds emanating from nuclear fuel cycle processes into the atmosphere from a distance

- **Microseismic monitoring**: Detects unauthorized design changes and containment breaches in final nuclear depositories

- **Nanocomposite semiconductor technology**: Enables small solid-state neutron detectors using silicon nanopillars

- **Optically stimulated luminescence (OSL)**: Measures past exposure of objects to radiation to reveal past nuclear activities and to verify integrity of containers

- **Remote sensing**: Detects and identifies the location of undeclared nuclear activity by satellite views with different spectral bands

- **Ultra-low field nuclear magnetic resonance (ULF-NMR)**: Determines the presence of $^{235}U$ in $UF_6$

Integrating these new and novel safeguards technologies could greatly improve the efficiency and effectiveness of current safeguard measures. However, there are a few considerations to be weighed if integrating some of the relevant emerging technologies listed above into ARs. Space constraints will always be an issue, especially for large equipment that requires connection to the internet and a large supply of power. Furthermore, a plan for safeguarding the actual sensors that are placed at a distance or are remotely monitored must be carefully constructed to monitor and deter tampering. Overall, there are several layers of uncertainties, safety measures, and safeguards that must be considered if and when the technologies outlined above are implemented in ARs.

## 5. RISK CHARACTERIZATION

There are several areas of major uncertainty that could cause schedule and implementation risks for AR construction and safeguard implementation. The different reactor types, as discussed earlier, each have special considerations. Newer concepts that deviate further from traditional reactor designs and layouts have a higher risk, since safeguards implementation for these designs are still in development. New construction techniques such as factory fabrication of modules—in conjunction with an expectation for smaller and more efficient plant layout and design—add an additional risk component. Meanwhile, as many nuclear newcomer nations are interested in building ARs, additional uncertainty develops from the unknown timelines for implementing the necessary regulatory and licensing processes in those states as well as developing appropriate protocols for negotiations with the IAEA.

New fuel types, changes to traditional fuel enrichments, and the possibility of fully remote operations lead to the potential need for new safeguards equipment, technology, and methodologies. Each of these areas add additional schedule risk: the timeframes to create and approve new safeguards technologies are not easily projected. Each part of the process—including layout/design, seal systems, surveillance systems, radiation monitors, remote monitoring, and fresh and spent fuel verification equipment—will need to be addressed.

These risks can be best mitigated by early and constant communication between stakeholders, including the state and the IAEA, as well as involving AR vendors in the process. Additionally, expedited development of new safeguards technologies to support new AR designs will help mitigate the expected risks. Stopgap measures, such as increased reliance on remote monitoring, may need to be developed in the interim.

## 6. SUMMARY

Proper planning for safeguards implementation is critical for the deployment of ARs internationally. The diversity of new AR types creates a unique challenge for this planning process. The ability to learn from past implementation challenges, and to address the identified risks, will be essential to ensuring smooth implementation of the international safeguards process with no or few schedule delays. Meeting schedule needs will limit required rework for states to implement changing or unknown safeguards requirements.

It is important to keep the SBD ideal in mind throughout this process, as well as lessons learned from prior implementations. The examples provided herein provide a good baseline. Finally, the impact of new challenges, including non-stationary fuel, limited physical space, multiple module plants, changing fuel enrichments, and remote operations, must be addressed by developing new processes and technologies, where needed. This approach will help address the inherent risks for AR construction and safeguards implementation.

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