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Characterization of Safeguards Implementation Schedules for Advanced Reactors

S. Sabatino
C. Ball
T. J. Harrison
G. E. Hauck

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Nuclear Energy and Fuel Cycle Division

CHARACTERIZATION OF SAFEGUARDS IMPLEMENTATION SCHEDULES FOR ADVANCED REACTORS

S. Sabatino
C. Ball
T. J. Harrison
G. E. Hauck

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
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ABSTRACT

Advanced reactor designs differ from the traditional light-water reactor designs and operational requirements 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 second in a series of three reports that examine facets of this issue. The first paper (ORNL/TM-2021/2142) examines potential construction schedules for advanced reactors to create a baseline understanding of the timeframes involved. This second report characterizes International Atomic Energy Agency (IAEA) safeguards implementation schedules for potential advanced reactors. Finally, the third report (ORNL/TM-2021/2208) examines existing gaps for safeguards implementation at advanced reactors.

Modern construction methods and techniques have advanced beyond those that were used to build the majority of the existing global fleet of power reactors. Furthermore, economic pressures will push power reactor construction to the minimum possible schedule time and will expedite the approach to operation, which will minimize the amount of time available during construction to install and verify safeguards infrastructure. The combined requirements for technological maturation and tight schedule will limit the international community's time to implement effective safeguards before initial operation. This report provides a characterization of safeguards implementation schedules for advanced reactor technologies and describes the risks that accelerated construction poses to safeguards program design, development, and installation prior to reactor operation.

For the efficient and effective deployment of an international advanced power reactor, several IAEA physical safeguards measures should be considered in the facility design phase. Namely, the placement of monitoring equipment (accounting for the required space for relevant wiring/channels), video surveillance, and containment seals must be factored into the facility design. The timeframes to implement international safeguards for advanced reactors presented herein are realistic and feasible, given sufficient resources and adherence to a prescribed construction schedule. The estimated safeguard implementation schedule is highly dependent on the availability and maturity of safeguard technologies, in addition to an appropriate level of staffing and cooperation between the IAEA and the facility operator.

1. INTRODUCTION

Advanced reactor (AR) designs include the gas-cooled reactor (GCR), the molten salt reactor (MSR), and the small modular (micro) reactor (SMR micro). These designs deviate from the traditional light-water reactor (LWR) design and operational requirements. These variations will lead to departures from traditional construction pacing, requirements, and supply chains. Simplifications in design and advanced construction methods will reduce the time to deployment; this shortened construction period also shortens the amount of time available to design, implement, and begin operations for safeguards equipment, activities, and personnel. In general, design and construction efforts for advanced and microreactors will focus on decreasing construction cost, time, and effort, which in turn will impact the safeguards design and implementation schedules.

This report provides a background on International Atomic Energy Agency (IAEA) safeguards programs, stages of the design and implementation process, and characterization of potential schedules for international safeguards design and implementation based on expected accelerated construction schedules for AR technologies developed by US vendors.

2. BACKGROUND

2.1 PROJECT PURPOSE

This report provides a broad characterization of the potential safeguards implementation schedules for ARs. The IAEA is the organization responsible for oversight of international safeguards deployment. Because there is a diverse array of advanced reactor types with varying physical characteristics, all schedules are approximations to be used only to plan potential safeguards deployment.

2.2 IAEA SAFEGUARDS

The IAEA acts as the authority for international safeguards to verify the compliance of a state regarding nuclear material and activities. According to the IAEA, safeguards are necessary for the state to meet legal obligations and to help reduce the state's financial and security risks [1].

Safeguards agreements between states, regional authorities, and the IAEA fall into three main agreement categories: comprehensive safeguards agreements (CSAs), item-specific safeguards, and voluntary offer agreements. Most states have CSAs. CSAs give the IAEA the right and obligation to ensure that safeguards are implemented for all nuclear material in the territory, jurisdiction, or control of the state. The sole purpose of safeguards agreements is to verify that nuclear material is not diverted to nuclear weapons or other explosives. The United States, the United Kingdom, France, the Russian Federation, and China have voluntary offer agreements with the IAEA. These states voluntarily offer some nuclear material for the IAEA to safeguard and ensure that it is used for peaceful purposes. The offered material can be withdrawn from safeguards only under provisions in the agreement. Israel, India, and Pakistan have item-specific agreements with the IAEA. Under these agreements, specified materials and facilities have IAEA safeguards in place to ensure that the materials are used for peaceful purposes only [2].

The IAEA safeguards techniques and measures include the following [1]:

- On-site inspections by IAEA inspectors
- Material balance areas (MBAs) for nuclear material accounting
- Key measurement points (KMPs) for measuring flow and inventories of nuclear material
- Unique identifiers for nuclear material items
- Locations for surveillance, containment, monitoring, and other verification measures
- Nuclear material measurements
- Review of operating records and state reports
- Annual physical inventory verification (PIV), generally performed during facility shutdown
- Routine interim inventory verifications (monthly, quarterly, annual, or random)
- Verification of transfers of nuclear material to and from the site
- Statistical assessment of the nuclear material balance to evaluate unaccounted material
- Reactor power monitoring
- Verification of facility design for features relevant to safeguards
- Verification of the performance of the operator's measurement system

In terms of physical construction, the IAEA suggests the basic requirements for safeguards equipment include physical space, uninterruptible power, and a data transmission backbone. Moreover, safeguards equipment is updated frequently. Thus, the space in the facility should be allocated with moderate changes to the size and shape of safeguards equipment in mind. Additionally, access to stable power and secure data transmission capability throughout the facility could reduce retrofitting costs and could allow greater flexibility in future safeguards installation [1].

2.3 SAFEGUARDS BY DESIGN

The IAEA expresses a desire for designers and vendors to implement safeguards by design (SBD) [1]. Historically, safeguards have been retrofitted into existing facilities. Conversely, SBD includes safeguards considerations in each stage of a reactor's life-cycle. Those stages are conceptual design, basic design, final (detailed) design, construction, operation, and decommissioning. Two main SBD objectives are (1) avoiding retrofits or redesigns and (2) making safeguards implementation more effective and efficient for the operator, state, and the IAEA. Although SBD is not a legal framework, designers and vendors who implement SBD will likely be more marketable to a customer in a state with safeguards obligations. The IAEA proposes the SBD schedule based on stages of design, as shown in Table 1 [1].

Table 1. SBD schedule based on stages of design [1].

Stage and description	Safeguards schedule
Conceptual design The project planning period; the earliest design stage when preliminary concepts for safeguards measures might be discussed	• A designer/operator can work with the safeguards authority to ensure that the IAEA is aware of the design and can begin engagement • The IAEA might perform an evaluation of the operational process for features relevant to safeguards and may propose possible safeguards measures for consideration • The IAEA suggests preliminary considerations for a safeguards approach, and negotiations begin • The designer, the operator, and the IAEA can identify and mitigate potential safeguards risks in the conceptual design
Basic design Sub-system designs under way; basic facility design details are available, including proposed safeguards equipment and locations	• The IAEA can make a preliminary definition of MBAs and KMPs • All can consider how the design can be optimized to meet both operational and safeguards goals • The designer can assess whether the design supports the physical infrastructure necessary for safeguards instrumentation and equipment • An analysis can be performed to verify that no unmonitored opportunities for diversion or misuse exist
Final (detailed) design Detailed facility design is completed, and dimensions, equipment, and planned operations are known; it is confirmed that all systems will meet requirements with minimum interference between systems	• Stakeholders review detailed facility design • Stakeholders confirm safeguards equipment can meet requirements • Preparation of Design Information Questionnaire (DIQ)
Construction The facility is constructed according to the specifications; any changes to the facility design or safeguards equipment are assessed to ensure that safeguards performance is uncompromised	IAEA: • Conducts design verification activities • Reviews and records as-built status • Monitors installations relevant to safeguards • Confirms that safeguards equipment meets requirements
Operation The operator starts up the facility, and systems testing begins	IAEA confirms: • As-built documentation exists for design information verification and safeguards equipment • Documentation relevant to safeguards is correct • The safeguards equipment meets requirements and is operational • Safeguards equipment can be commissioned before nuclear material is introduced to test the facility operations • The first nuclear material introduced to a new facility is used to calibrate or test the safeguards equipment
Decommissioning The operator takes the facility out of operation; clean-up and dismantlement begins	IAEA: • Conducts design verification activities • Verifies the removal of nuclear material • Confirms the removal or disabling of essential equipment • Terminates safeguards on the facility

2.4 INTEGRATED SAFEGUARDS

The main legal agreement that outlines IAEA safeguards is the international safeguards agreement between a state and the IAEA, which is drafted considering the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). The NPT dictates that a non-nuclear-weapon state must have a CSA with the IAEA. A country also has the option of extending its safeguards agreement to include an additional protocol (AP) to provide the IAEA with access to nuclear fuel cycle–related locations beyond those outlined by the CSA [3].

The objectives detailed by traditional, facility-level nuclear safeguards are the timely detection and deterrence of the diversion of significant quantities of nuclear material from peaceful to nonpeaceful uses, in addition to the identification of any potential misuse of the facility for undeclared purposes (e.g., undeclared receipt, transfer, irradiation, or removal of nuclear fuel). Overall, these same detection goals apply to integrated safeguards. The IAEA defines integrated safeguards as

> *the optimum combination of all safeguards measures available to the IAEA under comprehensive safeguards agreements and additional protocols to achieve maximum effectiveness and efficiency in meeting the IAEA's safeguards obligations within available resources* [4].

One key difference between integrated and traditional safeguards is that integrated measures are applied to a country, whereas traditional safeguards are implemented at the facility level. The goals of detecting the diversion of nuclear material and misuse of the facility are still considered; however, additional measures under integrated safeguards can include the use of remotely monitored safeguards equipment, satellite image monitoring, and short-notice, random inspections. These supplementary safeguards help achieve "maximum effectiveness and efficiency" as specified in the IAEA definition of integrated safeguards above. When designing a nuclear power reactor, every facility must implement IAEA safeguards equipment, to include seals, surveillance, and radiation monitoring systems, regardless of whether the facility is subject to traditional or integrated safeguards. To this end, when a power reactor is being designed and constructed, the facility operator, state regulatory authority, and IAEA should coordinate and discuss the implementation of other measures such as remote monitoring of safeguards equipment [3].

3. SAFEGUARDS FOR REACTORS BASED ON LAYOUT

3.1 SAFEGUARDS BASICS

Advanced, or Generation IV, reactors can be placed into two main categories: (1) advanced water-cooled reactors and (2) non–water-cooled reactors. Advanced water-cooled reactors leverage proven water-based fission methods with added improvements such as simplified design, smaller size, and increased efficiency. Instead of water, non–water-cooled reactors use liquid metals such as sodium and lead, gases such as helium and carbon dioxide, or molten salts. Small modular reactors may be placed into either category, depending on the type of coolant used [5].

This section explores the differences between traditional LWRs and advanced reactors in terms of safeguards and design implications. More specifically, a high-temperature gas reactor (HTGR) with pebble fuel is used to represent advanced reactors. The pebble-bed reactor is selected as a case study because of its complexity (it requires a large amount of non-static fuel that is regularly moved around the reactor), and the availability of relevant data in published literature.

In general, safeguards equipment at reactor facilities includes:

- Video cameras in the reactor hall, above the fuel pools, and for monitoring the core
- Seals on containment penetrations and critical fuel transfer channels
- Nondestructive assay measurements of fresh and irradiated fuel

For seals, the number of units and their location are determined for each facility according to its specific design. During the design phase, an optimization process may be implemented to determine the best placement / configuration of safeguards surveillance, containment, and monitoring/measurement equipment [1]. For international facilities, accounting for nuclear material is the most important safeguard, whereas containment surveillance (seals, cameras, and radiation detection) serves as a critical complementary measure. Herein, *nuclear material accountancy* is defined as the control of nuclear material inventory changes with independent verification by the IAEA. The facility operator, in cooperation and consultation with the IAEA, defines a nuclear material balance area (MBA), which accounts for the nuclear material inventory and its changes. In practice, the facility operator and designer propose the MBA layout and structure via a schematic diagram early in the design phase. This diagram is of utmost importance, as it provides stakeholders a visualization of the issues that may arise regarding the safeguarding of nuclear material. The MBA layout diagram also indicates where safeguard measures must be implemented using equipment such as video surveillance, seals, and radiation monitoring equipment [3].

3.2 DESIGN FEATURES RELEVANT TO SAFEGUARDS

In general, when designing any nuclear reactor facility, ample space should be included to accommodate the following safeguards measures [3]:

- IAEA seal and surveillance systems
- IAEA radiation monitors
- Safe engineered access for nuclear material and design verification
- Remote monitoring and transmission of data from IAEA seal, surveillance, and radiation detection systems
- Novel and emerging safeguards measures

It is crucial that the facility design is not densely packed with equipment; nor should surveillance or monitoring areas be obstructed. Effective surveillance and monitoring of the nuclear fuel inventory locations and fuel transfer paths can be ensured by providing sufficient space in the design layout.

3.3 LIGHT WATER REACTORS

In power reactor facilities, nuclear material enters the reactor as fresh fuel, is used in the core to generate energy, is moved to wet storage at the reactor, and then is finally transported to dry storage on site or shipped to wet/dry storage facilities off site. Inventory KMPs are generally located in the fuel storage areas: fresh fuel storage, reactor core, and reactor spent fuel storage. Additionally, flow KMPs are situated to monitor critical fuel transfer processes: receipt of fresh fuel, fuel transfers from fresh fuel storage to the reactor core, irradiated fuel transfer from the reactor core to spent fuel pool and back (as applicable), transfer of spent fuel to dry storage, and spent fuel transfer/shipment from the MBA/facility [1].

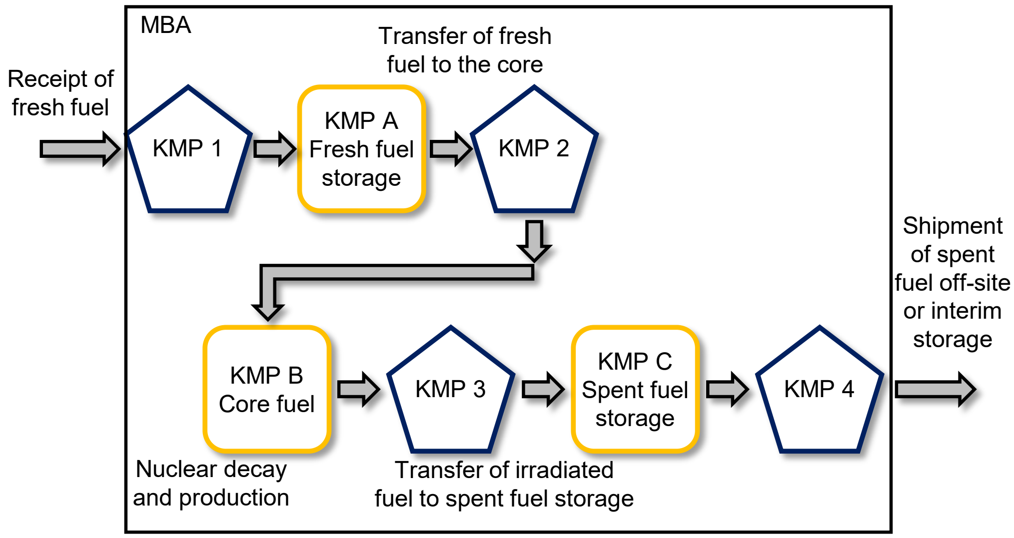

Figure 1 shows a simplified MBA and KMP layout for an LWR. Inventory KMPs (lettered and depicted as orange rounded squares) are the locations where the nuclear material is stored and made accessible for inventorying and verification by the facility operator, the state regulatory authority, and IAEA. Inventory flow KMPs (numbered and shown as dark blue pentagons) are locations where inventory changes or transfers are verified.

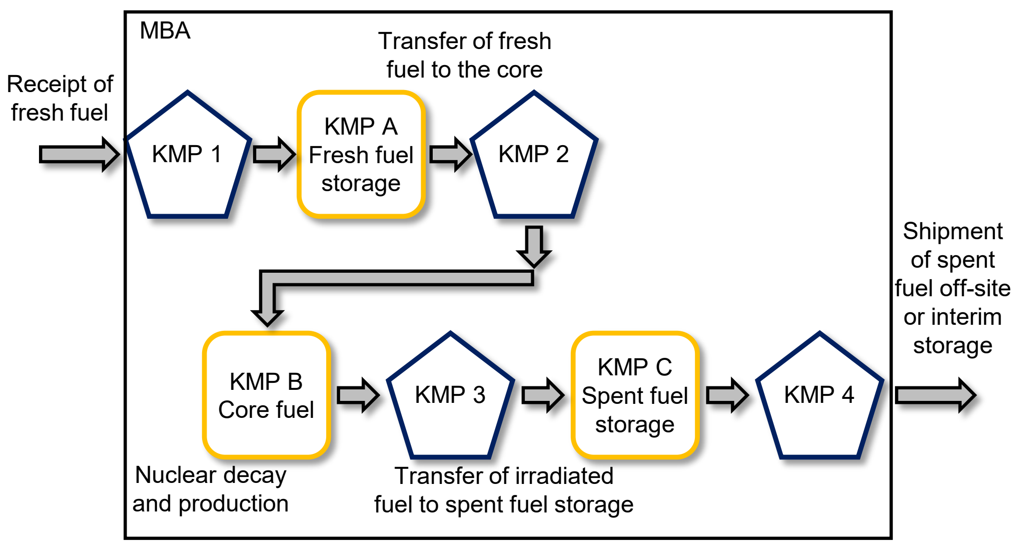

Figure 1. MBA and KMPs for an LWR (adapted from [1]).

3.4 PEBBLE FUEL HTGR

As a case study for advanced reactors, a pebble fuel HTGR was investigated. Figure 2 shows a simplified MBA layout diagram for a pebble fuel HTGR. Note that this is for the simple case of a single fresh fuel storage area, a spent fuel storage area, and a reactor core. Inventory KMPs (lettered and depicted as orange rounded squares) are where the nuclear material is stored and made accessible for inventorying / verification by the facility operator, state regulatory authority, and IAEA. Inventory flow KMPs (numbered and shown as dark blue pentagons) are locations where inventory changes or transfers are verified.

Considering this most basic layout of a pebble fuel facility, the nuclear fuel is stored primarily in the following inventory KMPs [3]:

- KMP A: Fresh fuel storage
- KMP B: Reactor core fuel
- KMP C: Reactor spent fuel storage

The following additional KMPs are anticipated for a pebble-fuel HTGR:

- KMP D: Damaged fuel
- KMP E: Graphite and used (partially irradiated) fuel
- KMP F: Post irradiation examination (PIE) area

KMPs D, E, and F are uniquely required in the case of a pebble fuel HTGR, because fuel will be stored in these areas. It is also important to note that if a facility is modular in design such that it has multiple reactor cores and/or fresh and spent fuel storage areas, then each of these areas would be considered as an additional, unique KMP [3].

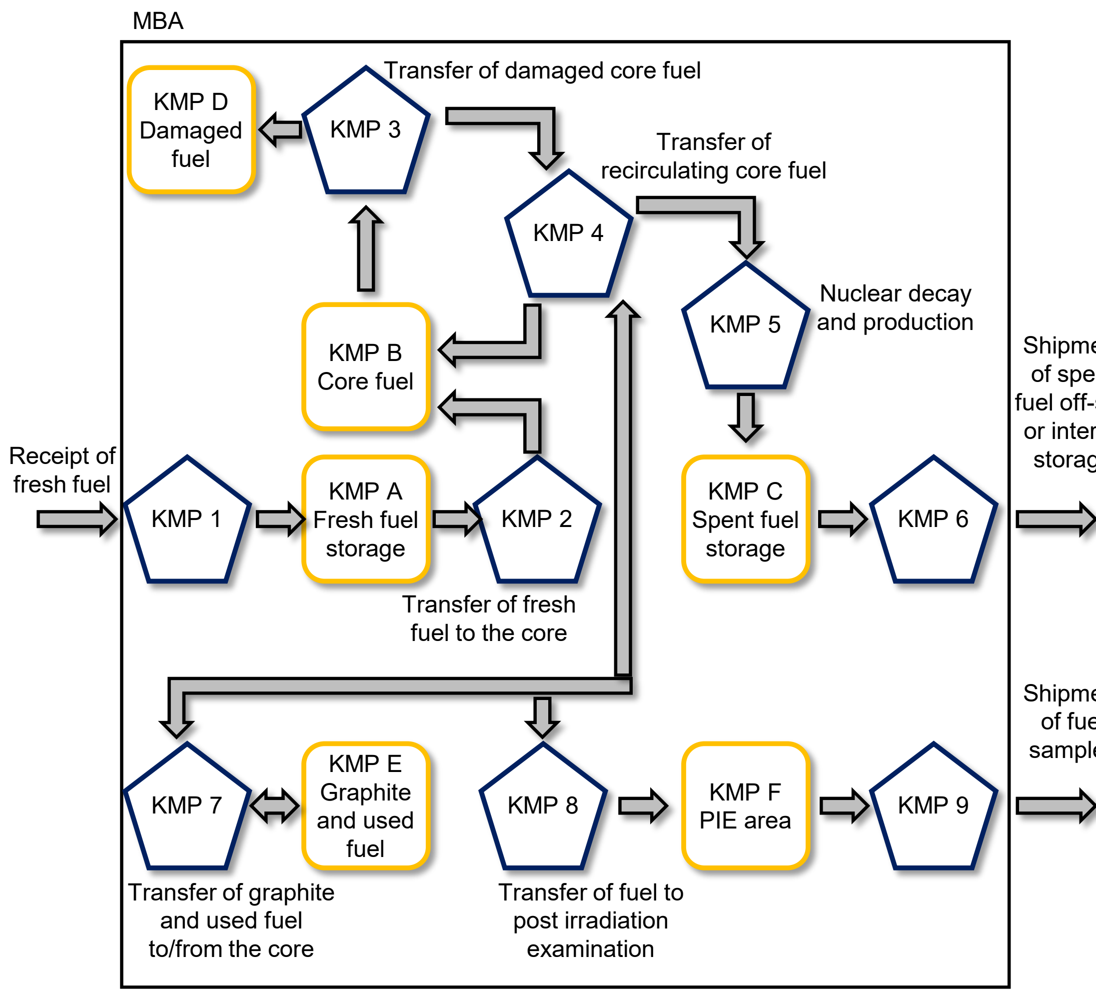

Figure 2. MBA and KMPs for a pebble fuel HTGR (adapted from Durst [3]).

To verify the fuel receipts, transfers, and shipments, the following flow KMPs are included in the MBA layout in Figure 2 [3]:

- KMP 1: Fresh fuel receipts
- KMP 2: Fuel transfers from fresh fuel storage to the reactor core
- KMP 3: Irradiated fuel transfer from the reactor core to spent fuel storage
- KMP 4: Transfer of recirculating core fuel
- KMP 5: Transfer of spent fuel to storage
- KMP 6: Spent fuel transfer/shipment from the MBA/facility
- KMP 7: Transfer of used fuel and graphite moderator to and from the core
- KMP 8: Transfer of fuel specimens to the PIE area
- KMP 9: Transfer/shipment of fuel specimens from the MBA/facility

Overall, inventory KMPs are typically covered by IAEA seal and are monitored with video surveillance systems, whereas IAEA fuel flow monitors are placed in the fuel transfer pathways between the inventory KMPs. When implementing safeguard measures at inventory KMPs, the hatches, doors, and access ports to the areas where pebble fuel is stored must accommodate IAEA seals. Additionally, there must be ample space to install IAEA video surveillance systems that have a view of the access points to the pebble fuel storage and handling areas. In summary, access to the following would likely be sealed by the IAEA and placed under surveillance [3]:

- Fresh pebble fuel storage drums and feed hoppers
- Reactor vessel service hatch(es)
- Spent pebble fuel storage area
- Damaged pebble fuel storage area
- Graphite moderator and used (irradiated) fuel storage area
- PIE hot cell
- Reactor building equipment hatch(es)

4. SAFEGAURD IMPLEMENTATION SCHEDULE

4.1 SCHEDULE ESTIMATE

Safeguards programs can vary significantly between different designs and locations, but the following broad categories of items are likely to be required for any implementation:

- Layout / design
- Seal systems
- Surveillance systems
- Radiation monitors
- Remote monitoring
- Equipment for verifying fresh fuel
- Equipment for verifying spent fuel

The layout / design activity includes reviewing the specific plant layout and logistics information and determining the equipment that will be necessary to support the safeguards program. Planning the locations of any required equipment is also included within this item.

Seal and surveillance systems (e.g., video recording devices) are two of the main required equipment categories for safeguards implementation. Radiation-based fuel flow monitors will only be required equipment for ARs that use non-static fuel, such as pebble bed or molten salt reactors. If this equipment is required, then it must be installed at the AR site after the locations are determined in the design phase.

Remote monitoring capability is highly desirable to minimize IAEA on-site resource requirements and to minimize disruptions caused by on-site inspections. However, logistics or regulatory constraints may prevent this type of capability from being included in the safeguards plan. Finally, the equipment for verifying fresh and spent fuel will vary significantly according to the fuel type, but some method of verification will be required for proper inventory accounting in accordance with IAEA regulations.

The AR construction schedule estimate previously established [6] was used as a baseline for creation of a potential safeguards implementation schedule. This schedule is included for reference with Figure 3 below. Durations are broad estimates and are scheduled within the allowable time based on the construction schedule [6]. These durations can be compressed or expanded, depending on the specific construction schedule.

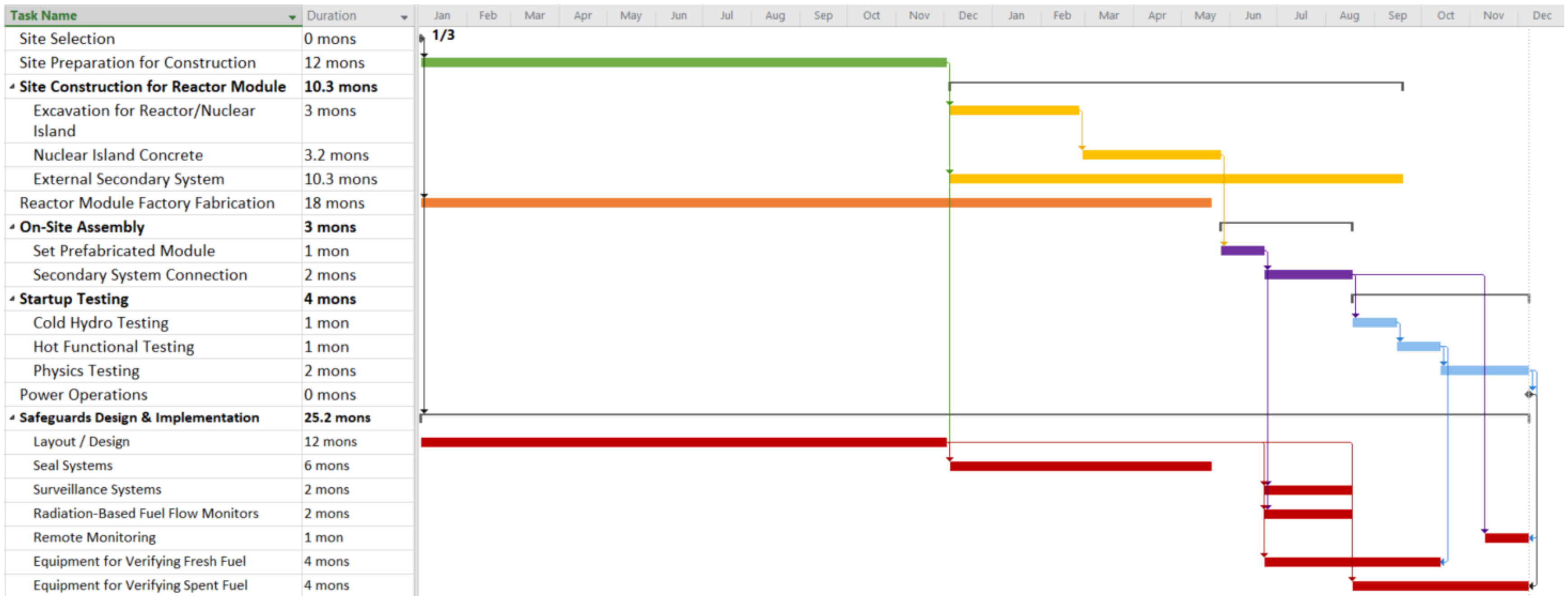

Figure 3. Potential safeguards implementation schedule for an AR with non-static fuel.

4.2 SCHEDULE RISK CHARACTERIZATION

Several risks are associated with this safeguard implementation schedule. It assumes that there is appropriate equipment available for safeguards and sufficient resources for both design and implementation. It also assumes that there are no delays in discussions or agreements between the state, IAEA, and suppliers. In reality, there are constraints; some of the equipment required for monitoring fuel flows and inventorying / verification in ARs with non-static fuel is not yet available. Similarly, the equipment for verifying fresh and spent fuel for fuel pebbles and dissolved liquid fuels may need to be created or adapted and approved via the IAEA process before it can be implemented. Moreover, the timeframes for these activities are unknown and expected to be significant. Furthermore, IAEA has limited resources, and the accelerated design and implementation schedules presented here to support rapid AR deployment may be difficult to achieve. To mitigate these risks, an interim, short-term safeguards approach may be necessary to use the existing equipment and resources before a more ideal, long-term plan can be developed and implemented.

5. SUMMARY

The broad characterization of safeguard implementation schedules is critical in the planning, development, and deployment of international advanced power reactors. In this context, the IAEA's physical safeguard measures that must be considered in the facility design and construction phases of ARs are containment seals, video surveillance, and radiation monitoring equipment. In addition, it is important to ensure that there is enough physical space available for any monitoring equipment and associated electrical wiring; this of particular concern for SMRs.

Although an accurate, detailed safeguards implementation schedule is not yet prescribed for US-based ARs, considering the generalized construction schedule developed for ARs [6] and the typical IAEA safeguards design and installation procedures, available timeframes for AR safeguards implementation are established herein. The proposed implementation timeframes are dependent on several highly variable factors, including safeguards equipment availability and maturity, cooperation between the IAEA and the facility operator, duration of facility design iterations, and adherence to a prescribed construction schedule. Overall, the design, scheduling, and implementation of IAEA safeguards is an integral aspect that must be considered in AR facility design and construction phases.

6. REFERENCES

[1] International Atomic Energy Agency (IAEA). 2014. *International Safeguards in the Design of Nuclear Reactors*, Technical Report, Vienna.

[2] International Atomic Energy Agency (IAEA). 2021. *Safeguards Agreements: IAEA*, Accessed August 27, 2021. https://www.iaea.org/topics/safeguards-agreements.

[3] P.C. Durst. 2012. *Safeguards-by-Design: Guidance for High Temperature Gas Reactors (HTGRs) with Pebble Fuel*, Idaho National Laboratory, August 2012, INL/EXT-12-26561.

[4] International Atomic Energy Agency (IAEA). 2001."IAEA Safeguards Glossary, 2001 Edition," *International Nuclear Verification Series No. 3*, Technical Report, Vienna.

[5] D. A. Arostegui and M. Holt. 2019. *Advanced Nuclear Reactors: Technology Overview and Current Issues*, Congressional Research Service, Technical Report, April 2019, R45706.

[6] G. E. Hauck, C. Ball, T. J. Harrison, and S. Sabatino. 2021. *Characterization of Potential Construction Schedules for Advanced Reactors*, Oak Ridge National Laboratory, July 2021. ORNL/TM-2021/2142