Proceedings of the INMM & ESARDA Joint Virtual Annual Meeting
August 23-26 & August 30-September 1, 2021

ADVANCED REACTOR DEPLOYMENT: U.S. SAFEGUARDS AND SECURITY CHALLENGES*

Benjamin B. Cipiti
Sandia National Laboratories
P.O. Box 5800, MS 0747, Albuquerque, NM 87185-0747

ABSTRACT

The U.S. Department of Energy established the Advanced Reactor Demonstration Program (ARDP) in 2020 to help support initial deployment of advanced reactors in the United States. The Advanced Reactor Safeguards (ARS) program area was established as part of ARDP to help address near term challenges that vendors face in meeting domestic Material Control and Accountability (MC&A) and Physical Protection System (PPS) regulatory requirements. The ARS program seeks to remove roadblocks to reduce regulatory uncertainty, utilize the latest technologies and approaches, and optimize safeguards and security costs. Many of the challenges in the U.S. stem from regulatory requirements that were built around large light water reactors. Often, existing MC&A and PPS requirements are not applicable to small reactors and different designs. The ARS program focuses on six key challenge areas for advanced reactors: develop a robust and cost appropriate PPS, examine high assay low enriched uranium regulatory issues, develop MC&A approaches for pebble bed reactors, determine MC&A and PPS requirements for microreactors, develop MC&A approaches for molten salt reactors, and leverage international interfaces. Research conducted in the ARS program helps vendors with these aspects of their designs and promotes Safeguards and Security by Design. In addition, the work helps inform the Nuclear Regulatory Commission (NRC) and new rulemaking that applies to these types of reactors. Initial findings and lessons learned are presented in addition to ongoing work.

INTRODUCTION

The U.S. and other countries around the world have seen a resurgence of interest over the past decade in the development of advanced reactors. Due to the challenging economics of building large plants, many of the new designs are smaller, modular, potentially safer, and follow Generation-IV reactor design concepts. Smaller designs have also made it easier for venture and private capital to fund these efforts. Many of the vendors recognize the importance of Safeguards and Security by Design (SSBD), or the consideration of safeguards and security requirements early in the design process.

In a more general sense, SSBD includes early consideration of both the state's regulatory requirements as well as international requirements, depending on the country. The Advanced Reactor Safeguards (ARS) program, funded through the Office of Nuclear Energy within the U.S.

---

* SAND2021-9053C, Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

Department of Energy, funds research and development to support advanced reactor vendors with U.S. domestic safeguards and security requirements.

Existing regulations for safeguards and security in the U.S. were written for large Light Water Reactors (LWRs), and some of the requirements are not suited to smaller, advanced reactor designs with differing fuels and coolants. While new reactor designs can be licensed under the existing regulations, advanced reactor vendors will likely need to use exemptions which increases uncertainty and time in the process. The ARS program is supporting research to help the vendors with their Material Control and Accounting (MC&A) and Physical Protection System (PPS) approach.

BACKGROUND

In the U.S., the requirements for physical protection of plants and materials is outlined in the Code of Federal Regulations (CFR) 10 CFR Part 73 [1]. MC&A requirements are outlined in the Code of Federal Regulations (CFR) 10 CFR Part 74. The regulations follow a graded approach depending on the category of the facility. In addition, Parts 50 and 52 have historically been used in the licensing of reactors and contain additional guidance.

The Nuclear Regulatory Commission (NRC) is currently going through rulemaking to make licensing more flexible and performance-based to cover different types of reactor designs and to provide additional options for meeting protection requirements [2,3]. The new NRC rulemaking provides the vendors with additional options for optimizing the PPS footprint. Following the new rulemaking, the licensee may be able to reduce the minimum number of armed responders, have a secondary alarm station off-site, and rely on local law enforcement to interdict and neutralize the Design Basis Threat (DBT). The licensee will need to show that the off-site dose can be kept below a certain threshold at the site boundary for any security-related event. Various options are provided, but the rulemaking is still progressing, so specific details will not be presented here.

The new rulemaking may also provide more clarity on MC&A approaches for advanced reactor vendors. Advanced reactors that use traditional solid fuel assemblies use item accounting for control of nuclear material—assemblies are treated as individual items. The large size and handling requirements of a full assembly make theft difficult. For advanced reactors with differing fuel forms, the MC&A approach is less clear.

The ARS program is focused on U.S. deployment, and U.S. vendor needs are a key driver for identifying safeguards and security challenges. Many of the vendors have aggressive deployment schedules. The Nuclear Energy Institute (NEI), Electric Power Research Institute (EPRI), and NRC have also been excellent resources for engagement with vendors and discussing regulatory concerns.

The research in the ARS program is meant to be as broadly applicable to reactor vendors as possible, as opposed to examining a particular design. That being said, there are differences in the necessary approaches depending on the general class of the reactor. Much of the work in the ARS program will be focused on a particular class of reactors but will still be useful to all vendors within that class.

ARS THRUST AREAS

The ARS program has focused on six thrust areas over the past two years based on identified needs. These thrusts are expected to change with time as challenges are solved new issues are identified. The following sections provide an overview of each thrust area and highlight key results from the work.

Develop a Robust and Cost Appropriate PPS

The traditional PPS approach for large numbers of on-site responders may not be appropriate for smaller and safer reactor designs. While maintaining a larger protective force on-site can be absorbed in the cost for large power producers, large numbers of on-site responders may be both inappropriate and cost-prohibitive for smaller reactors. Microreactors in particular seek alternatives to drastically reduce the on-site presence required.

The new NRC rulemaking will provide options to allow reactor vendors to take credit for their enhanced safety systems and smaller source terms. However, new approaches should be demonstrated through modeling and simulation. A key goal of the ARS program is to provide design alternatives with performance metrics to provide options for advanced reactor vendors.

In addition, PPS technologies are constantly improving. New technologies, increased automation, and improvements in machine learning and artificial intelligence allow for new control and protection strategies. This is balanced by the fact that new technologies also change the threat landscape. PPS designs need to be robust, yet flexible to anticipate changing future threats. Security by Design is a key goal in the development of PPSs—security needs to be considered early in the design process so that costly plant retrofits or operational contingencies are not needed later.

Initial work has evaluated PPS upgrades to increase delay time for advanced reactors so that they may depend on local law enforcement resources [4]. Both path analysis and force-on-force adversary modeling tools are being used to examine new approaches that reduce the number of on-site staff and extend delay substantially. Various PPS upgrades have been considered including additional external facility walls, mantraps on exterior doors, additional hallways and doors inside of the facility, the use of slippery agents and obscurants, and the addition of hardened fighting positions for on-site responders. Current and future work is expanding the analysis to look in more detail at specific reactor classes including pebble bed, microreactor, and sodium cooled fast reactors. Additional PPS technologies will be considered, and both theft and sabotage scenarios will be evaluated.

The Deliberate Motion Algorithm (DMA) is being evaluated to reduce upfront capital costs for detection [5]. This algorithm uses multiple sensors and a multi-artificial intelligence algorithm to distinguish deliberate motion from nuisance alarms (such as from wildlife or wind at a reactor site). This technology may be able to replace costly Perimeter Intrusion Detection and Assessment Systems (PIDAS). Its use may be particularly useful for microreactor sites that are trying to drastically reduce their PPS footprint.

Reactor vendors may also be able to take credit for long accident progression from a sabotage event. If an adversary sabotages a system but the operator can recover the reactor (either through on-site responders or local law enforcement), or maintain off-site dose below a threshold, the vendor can still meet licensing requirements. This approach requires more analysis since it involves blending accident progression timelines (typically from Safety analyses) with force-on-force adversary modeling. Current and future work is evaluating credible scenarios and timelines and analyzing PPS response.

Examine High Assay Low Enriched Uranium Regulatory Issues

Many advanced, small, and microreactor vendors in the U.S. are planning to use high assay low enriched uranium (HALEU). The main advantage is that it allows the fuel to last longer (reduced refueling intervals) and allows for higher power from smaller cores. However, the use of HALEU will have implications on the regulatory requirements.

Current work is examining the policy and regulatory challenges faced in domestic safeguards for the use of HALEU. The quantity of HALEU possessed in advanced reactors will be Category II special nuclear material under NRC regulations. NRC is currently planning to make licensing decisions for facilities possessing Category II materials on a case-by-case basis. The NRC staff plans to use the technical basis from the rulemaking on Enhanced Security of Special Nuclear Material, which was cancelled in 2018, to inform their licensing decisions, but this situation creates uncertainty for vendors, operators, and other prospective license holders. One of the goals of the current work in the program is to provide more clear guidance on the licensing approach for different classes of advanced reactors. The work is also examining how HALEU fuel is treated prior to loading, start up, and during refueling operations. Long term spent fuel storage on site is also being examined.

Future work will transition recommendations to individual reactor design categories to produce guidance for each major design type, which would then be available to assist vendors/operators. Future work may also generate generic guidance for physical protection of HALEU and check for consistency across the fuel cycle (including fuel fabrication facilities and transportation).

Develop MC&A Approaches for Pebble Bed Reactors

The ARS program is addressing both the MC&A regulatory approach and new technologies that may help with accountancy or operator monitoring in PBRs. Research on the regulatory approach focuses on providing guidance to vendors on how to meet MC&A requirements. Recent work has developed a preliminary MC&A approach for pebble bed reactors (PBRs) but identified a number of gaps [6]. Most of the needed work related to MC&A revolves around pebble receipt, the pebble handling systems, and storage of spent pebbles. This initial work was used as a basis for additional R&D which will help the vendors. Figure 1 shows the potential organization of the material balance area (MBA) structure in a PBR. Three sub-MBAs are included: fresh fuel storage, the reactor loop, and spent fuel storage.

For PBRs there are several areas where additional research is needed: packaging and handling, pebble counting systems, reactor inventory approaches, and fuel burnup measurements. Reasonable progress has been made on packaging and handling for both fresh and spent fuel. Some of the vendors have current design efforts underway to increase the capacity of spent fuel containers. For pebble counting and indexing systems, which will be critical to accurate physical inventories of the reactor vessel, only preliminary information seems to be available, and vendors are still designing and testing these systems. For the reactor inventory approach, a much more detailed discussion is needed to integrate operations, safeguards, and security requirements. For burnup measurements, multiple activities have been identified across industry, universities, and national labs, but the technology readiness level of these technologies needs to be increased.

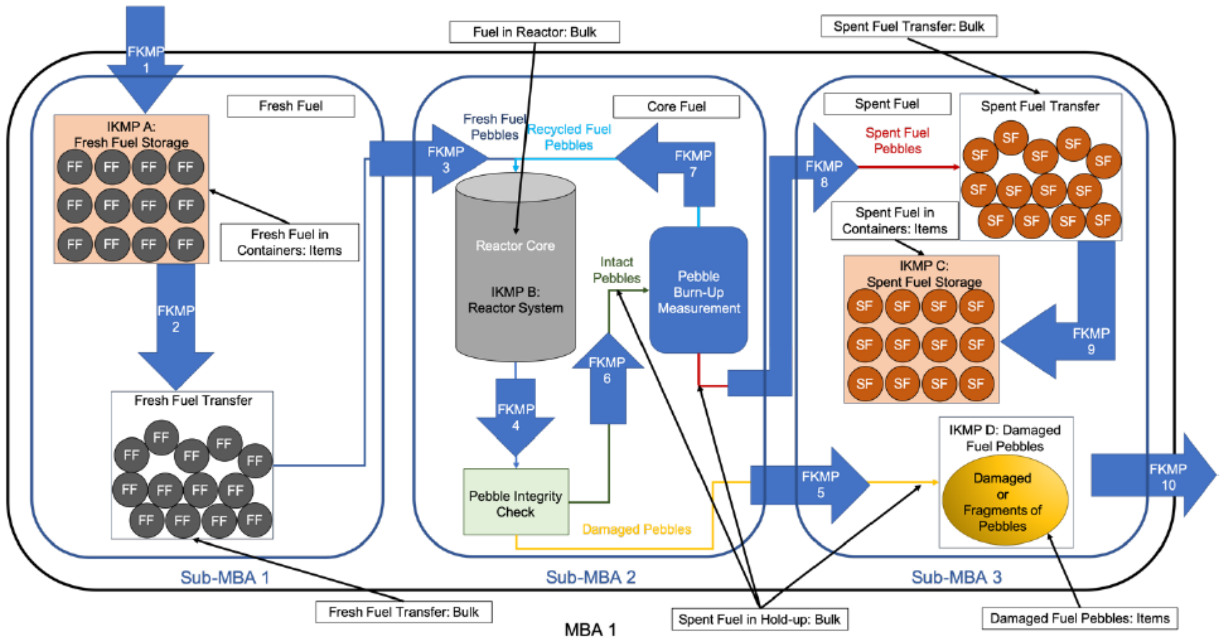

Figure 1. Nominal MBA structure for a PBR

Pebble bed reactors are unlikely to require nuclear measurements on each pebble for MC&A since the quantity of nuclear material per pebble is very small. However, the operator needs to measure burnup in order to better utilize the fuel. They have a strong economic incentive to recycle the pebbles until their burnup limit is reached, and the burnup will vary depending on the path the pebble takes in the core. There also may be interest in unique identifiers for pebbles of different enrichments and/or to help keep track of the number of passes better.

Current research is exploring a combination of placement of inert microspheres in different types or batches of fuel pebble and an ultra-sound-based optical system to image the microspheres as a recognizable fingerprint [7]. Figure 2 shows the microspheres that can be placed in the outer layers of a fuel pebble. Though this approach to safeguarding large pebble-bed-type reactors has been proven conceptually feasible, the work described herein is to experimentally validate and progress the design which may be of use for MC&A and process control. The work is being completed jointly at the Pebble Bed Test Facility (PBTF) in Texas A&M University's Thermal-Hydraulic Research Laboratory.

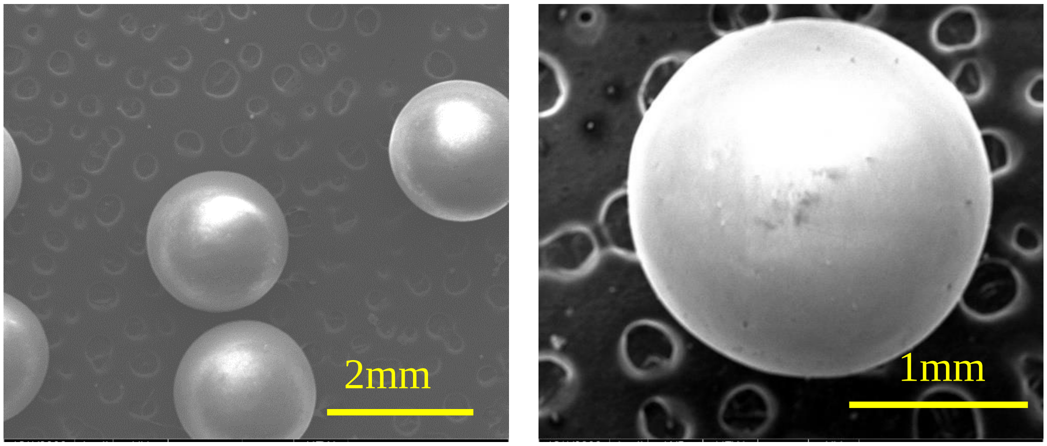

Figure 2. Micrograph images of inert microspheres [7]

Machine Learning (ML) approaches are also being considered as part of the MC&A system for PBRs. ML may be applied to containment and surveillance systems to better track the fuel with specific applications that include: enabling verification of pebble inventory in the reactor core and spent fuel containers, improving accuracy and reducing measurement in spectral analysis related to burnup measurements, remotely monitoring reactor power based on neutron measurements, and using tomography imaging to identify a unique signature in each pebble. The current work is focused on improving the accuracy of spectral analysis in burnup measurements. An initial version of the algorithm has been developed, and a test dataset is being created through modeling and simulation.

Determine MC&A and PPS Requirements for Microreactors

Microreactors present new challenges to MC&A and PPS due to their very small size compared to traditional LWRs. A significant challenge the vendors face is in meeting regulatory requirements in cost-efficient ways. Whereas the MC&A and PPS costs for an SMR are likely to be a small fraction of the total cost of the reactor, microreactors may have disproportionally higher costs.

Current work is creating a two-step framework focusing on safeguards and security that should be useful and impactful to microreactor vendors. The framework will help vendors assess both advantages and gaps in their design concept against U.S. NRC licensing requirements and regulations in relation to domestic safeguards. By partnering with the NRC, the research will ensure that both vendors and the NRC have the tools and information necessary to communicate during licensing activities. Ultimately, the two-step framework will help inform vendors prior to submission of the domestic safeguards portion of the licensing application. The framework will influence vendors to produce a highly safeguarded and secure reactor licensing/siting case with minimal impact on costs, resources, deployment, and NRC staff effort.

The ARS program has also examined potential use or need for MC&A measurements throughout the microreactor's lifecycle [8]. A sealed core type of design would be treated as an item at the reactor site, which significantly simplifies the MC&A approach. However, current work is exploring if measurements may be needed at the fabrication facility prior to shipment of module/core or when received by a processing facility. The microreactor's own in-core neutron instrumentation may also provide valuable data.

Physical protection requirements for microreactors will require more work since there are different attack scenarios to consider for the small size. Microreactors generally have different heat transfer mechanisms. Theft of the entire unit will be considered in future research, and this work will tie into the physical protection modeling work described previously

Develop MC&A Approaches for Molten Salt Reactors

Liquid fueled reactors (MSRs) have unique features that result in additional MC&A challenges. MSRs are similar to bulk processing facilities, such as reprocessing, since the nuclear material is not contained in discrete fuel assemblies and instead contained in a molten salt solution. However, the liquid fuel is very hot radioactively, which influences the regulatory requirements. MSR designs can have continuous fuel feeds and removals, constant depletion and decay, and non-stationary fuel inventories. The technical work is divided into development of the MC&A approach and measurement technologies that may be used as part of the approach.

Current work is evaluating MC&A design concepts for MSRs and communicating with the NRC to outline MC&A considerations. Two general approaches to MC&A have been considered: a "black box" approach - comparable to LWRs, and a process monitoring approach. Initial communication with the NRC has suggested that components of a process monitoring approach is favorable to the regulator while a pure black box approach would be unfavorable.

A dynamic simulation capability that produces isotopic concentrations and other operational data (temperatures, pressures) for a user defined system-wide model has been developed. This is needed for future work in order to better understand the radioactivity of molten salts as a function of time—self-protection and the difficulties of handling molten salts need to be taken into account when designing systems to monitor for material loss.

Safeguards performance modeling is being used to evaluate how proposed systems can track nuclear material and detect material loss [9]. Traditional inventory difference (ID) calculations, which are required for bulk handling facilities, are being examined. Initial work has found that the large buildup of actinides like Pu in a MSR lead to high absolute uncertainties on the quantification of Pu. This is simply due to the limit of measurement technology, even assuming sampling and high precision destructive analysis. Figure 3 shows the standard error of the inventory difference of Pu, σ_{ID}, as a function of time in a molten salt reactor. The growth of Pu in the salt over time lead to high errors which can make detection of material loss challenging.

Measurement technologies for MSRs are also being evaluated. On-line optical spectroscopy, flowing voltammetry measurements, and non-destructive analysis (NDA) techniques are being considered to account for actinides in molten salts. Optical spectroscopy-based monitoring tools are mature and commercially available but must be adapted to the harsh molten salt environment [10]. A separate effort is developing flow-enhanced electrochemical sensors to provide mass accountancy, corrosion, and salt health monitoring for MSRs [11]. Past work on electrochemical sensors has been designed for non-flowing conditions. For deployment to flowing systems such as pumped loops and thermal convection loops, designs use shrouding to isolate the sensing electrodes from any prevailing flow. This instrument is being tested on the Modular Flow Instrumentation Testbed (MFIT) at Argonne National Laboratory. Non-destructive characterization of fissile material and waste streams at MSRs may also be of interest due to the high radiation environment of the material [12]. Both high-purity germanium and ultra-high-resolution microcalorimetry are capable of quantifying important nuclides, and each have unique advantages due to efficiency or energy resolution. Results suggest that direct quantification of important actinides in fuel salt may be possible by NDA for a sampling loop in an operating MSR or for salt samples.

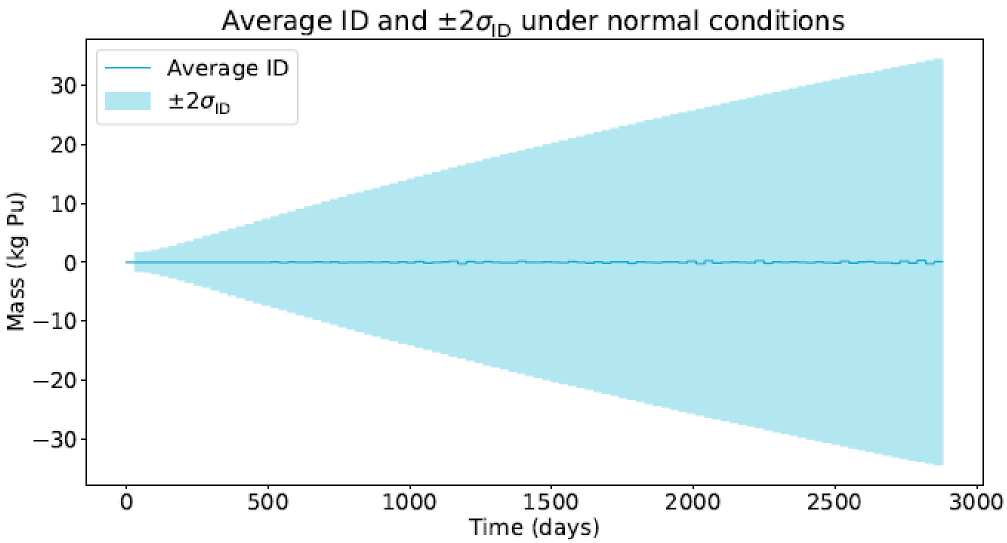

Figure 3. Standard error of the inventory difference in a MSR as a function of time [9]

Leverage International Interfaces

While the focus of the ARS program is to help vendors meet domestic MC&A and PPS requirements, most vendors are also interested in international deployment. From a SSBD perspective, it is useful for vendors to consider both domestic and international requirements in the design of their facilities. The ARS program is coordinating research with related program areas that fund research on international safeguards and security. Experience, techniques, and R&D from the International Atomic Energy Agency (IAEA) international safeguards domain are being evaluated to aid in developing domestic MC&A approaches for advanced reactors.

The Office of Nuclear Energy has been a long-time supporter of the Generation-IV International Forum. The Proliferation Resistance and Physical Protection (PR&PP) working group examines safeguards and security aspects of the various advanced reactor designs, facilitates the practice of SSBD for advanced reactor designs, and assures that analyses are an aid to informing decisions by policy makers. Recently, the PR&PP working group has focused on updating the six advanced nuclear reactor system white papers which analyze the six GIF systems from a PR&PP viewpoint. These efforts are support through the ARS program and will help provide insight to advanced reactor vendors.

CONCLUSIONS

The ARS program provides R&D to support advanced nuclear reactor vendors with domestic MC&A and PPS requirements. The goal of the program is to reduce regulatory uncertainty, help vendors develop robust protection systems, and provide approaches to MC&A and PPS design to help optimize costs. In order to support aggressive vendor timelines, the research in the program is focused on near-term deliverables, and most of the work will achieve significant milestones at the end of the current calendar year. The research in the program is expected to turn over regularly as new research gaps are identified.

ACKNOWLEDGEMENTS

This paper summarizes work funded through the U.S. Department of Energy Office of Nuclear Energy.

REFERENCES

1. NRC Regulations, Title 10, Code of Federal Regulations. 2021. https://www.nrc.gov/reading-rm/doc-collections/cfr/.
2. "Rulemaking for Physical Security for Advanced Reactors," NRC Docket ID: NRC-2017-0227, Nuclear Regulatory Commission (2019).
3. "Preliminary Proposed Rule Language: Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors," NRC Docket ID: NRC-2019-0062 (2020).
4. A. Evans et al., "U.S. Domestic Small Modular Reactor Security by Design," SAND2021-0768, Sandia National Laboratories (2021).
5. J.R. Russell et al., "Deliberate Motion Analytics Fused Radar and Video Test Results," SAND2021-5413, Sandia National Laboratories (2021).
6. D. Kovacic et al., "Advanced Reactor Safeguards: Nuclear Material Control and Accounting for Pebble Bed Reactors," ORNL/SPR-2020/1849, Oak Ridge National Laboratory (2021).
7. C. Gariazzo, "Investigations to Create and Identification Method for Pebbles of an Advanced Nuclear Reactor," Advanced Reactor Safeguards Program Report, Argonne National Laboratory (2021).
8. R.K. Weinmann-Smith et al., "Material Control and Accounting Regulatory and Technical Considerations for Microreactors," LA-UR-20-30489, Los Alamos National Laboratory (2020).
9. N. Shoman & M. Higgins, "Considerations for NMA of Molten Salt Reactors," American Nuclear Society Summary, not yet published (2021).
10. A. Lines et al., "Evaluation of Optical Techniques for Molten Salt Reactor Materials Control and Accounting," Pacific Northwest National Laboratories, PNNL-30360 (September 2020).
11. N. Hoyt, E. Stricker, and C. Moore, "Design and Construction Progress for the Modular Flow Instrumentation Testbed and Associated Sensors," Argonne National Laboratory, M3RS-20AN0401112 (September 2020).
12. M. Croce et al., "Experimental Validation of Nondestructive Assay Capabilities for MSR Safeguards," Advanced Reactor Safeguards Program Report, Los Alamos National Laboratory (2020).