A PATH TOWARD LEVERAGING THE BENEFITS OF SAFETY, SECURITY, AND (INTERNATIONAL) SAFEGUARDS (3S) FOR ADVANCED & SMALL MODULAR REACTORS(A/SMRS):
Summary of the Institute of Nuclear Materials Management's Workshop on Advanced Reactor 3S

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Abstract

Efforts to improve knowledge and application of interfaces between safety, security, and (international) safeguards—the so-called 3S—are important for advanced and small modular reactors (A/SMR). Having been addressed across technical meetings and professional conferences, the nuclear materials management professional community is seeking to leverage the anticipated benefits of 3S. To continue this discussion, in February 2024 the Institute for Nuclear Materials Management (INMM) convened the Advanced Reactor 3S workshop in Albuquerque, New Mexico. The workshop welcomed over 70 safety, security, and safeguards professionals from government, academia, and industry. Participants heard from over 20 expert speakers, and further discussed potential 3S engineered solutions and "by-design" concepts to address interfaces. The two-day workshop brought together the experience of the INMM community to describe the current state-of-the-art—and investigate potential future solutions—regarding 3S for A/SMRs. Workshop participants also provided insights into how effectively the INMM supports current 3S efforts, where 3S gaps, challenges, and needs exist, and recommendations on what INMM should do to support future 3S efforts. The present paper synthesizes the 3S-related thoughts, concerns, key needs, and opportunities identified by the INMM community—and offers potential pathways for A/SMRs to leverage the benefits of 3S interfaces.

1. INTRODUCTION

Compared with the current fleet of large nuclear power plants, advanced and small modular reactors (A/SMRs) will likely offer additional opportunities to leverage safety, security, and (international) safeguards (3S) interactions and interfaces for enhanced performance and overall risk reduction. Anticipated to produce a significant shift in nuclear power generation, A/SMR operations will likely need to move beyond the traditional lessons learned and best practices that are related to conducting safety, security, and (international) safeguards at traditional nuclear power facilities. Despite significant R&D being invested in advanced reactor designs—with the intent to bring these technologies to domestic and international markets as soon as possible—there are apparent R&D gaps related to 3S interfaces across the various stages of A/SMR lifecycles. Better characterizing and leveraging 3S interfaces seem well poised to better address the challenges facing A/SMRs. Additional benefits of addressing 3S interfaces and interactions include navigating new technologies, developing novel control strategies, reducing complex risk profiles, and aligning with nascent licensing processes toward more optimal A/SMR operations. Continuing efforts to improve 3S integration are increasingly important to the nuclear materials management community, as indicated by IAEA Deputy Director General and Head of the Department for Nuclear Safety and Security Lydie Evrard who asserts that

> With many SMRs still being in an early design stage, there is a unique opportunity to comprehensively integrate all three elements of safety, security and safeguards – the so-called 3S concept – in the design of innovative reactors [1]

Though a larger number of such offerings have occurred over roughly the last 10 years, Table 1 highlights the international venues hosting 3S-related discussions since 2023. Common to these discussions is the desire to

focus on how 3S interfaces and interactions can enhance—not overwrite or ignore—the capabilities of each "S" domain. For example, the 2023 U.S. Nuclear Regulatory Commission "3S Workshop: Advanced Reactors and Fuel Fabrication" emphasized *increasing awareness of the development of appropriate methodologies and tools to address future challenges in the interdependencies between the individual 3S domains*.

TABLE 1. SUMMARY OF INTERNATIONAL 3S-RELATED EVENTS, 2023—PRESENT

Event Dates	Event Name	Host Org.
Oct. 2024	International Conference on Small Modular Reactors & their Applications (Group C)[A]	IAEA
Feb. 2024	Advanced Reactor 3S (Safety, Security, and Safeguards) Workshop[B]	INMM
Dec. 2023	3S Workshop: Advanced Reactors and Fuel Fabrication[C]	NRC
Sep. 2023	Interregional Workshop on 3S by Design in Small Modular Reactors[D]	IAEA

[A] For more details: https://www.iaea.org/events/smr2024; [B] For more details: https://inmm.org/page/AdvancedReactors3S; [C] For more details: https://www.nrc.gov/docs/ML2406/ML24065A009.pdf ; [D] For more details: https://nucleus.iaea.org/sites/smr/SitePages/Event-details.aspx?EventID=EVT2301206

Despite this momentum, these discussions seem to be missing a complementary focus on technical and systems perspectives—leaving the nuclear materials management professional community seeking additional insight into how to leverage the anticipated benefits of 3S.

2. 3S WORKSHOP LOGISTICS & DATA COLLECTION

To continue this discussion, in February 2024 the Institute for Nuclear Materials Management (INMM) convened the Advanced Reactor 3S (Safety, Security, and Safeguards) workshop in Albuquerque, New Mexico. (NOTE: A more detailed description is provided in [2].) The INMM seeks global peace, security, and prosperity through the advancement of scientific knowledge, technical skills, policy dialogue, professional capabilities, and best practices related to nuclear and radiological materials. To this end, the institute is a professional society dedicated to the safe, secure, and effective stewardship of activities using nuclear and radioactive materials.

TABLE 2. SUMMARY OF INMM'S ADVANCED REACTOR 3S AGENDA

Session [Interfaces]	Keynote Speaker [*Organization*]	Presenters' Organizations
I [Safety/ Security]	Alison Hahn, Office Director Nuclear Reactor Deployment [*U.S. Department of Energy*]	• Sandia National Lab. • Univ. of New Mexico • Enercon
II [Security/ Safeguards]	Jorge Navarro, Senior Technical Advisor for Analytics and Innovation, Office of International Nuclear Security [*National Nuclear Security Administration*]	• Sandia National Lab. • Rhinocorps • Los Alamos National Lab
III [Safeguards/ Safety]	Ruth Smith, Deputy Director, Office of International Safeguards [*National Nuclear Security Administration*]	• Sandia National Lab. • Oak Ridge National Lab.
IV [Safety/ Security/ Safeguards]	Kirsten Laurin-Kovitz, Associate Laboratory Director, Nuclear Technologies and National Security [*Argonne National Laboratory and Coordinator, Advanced Nuclear Security, Waste & Energy R&D (ANSWER) Working Group*]	• Sandia National Lab. • IAEA • Idaho National Lab. • Abilene Christian Univ.

The INMM Advanced Reactor 3S Workshop convened professionals to fill the need for a dedicated dialogue on technical and systems solutions for 3S interfaces and interactions. In an effort to balance the desired emphasis on technical or systems approaches for 3S with anticipated challenges and emerging complexity, this workshop decided to structure around the different permutations of "2S" interactions. In this manner, the workshop was oriented toward discussions on specific, tangible, actionable, and clear examples of how to identify interfaces. The associated 2S anecdotes helped navigate the process of identifying, categorizing, and prioritizing interfaces—potentially as either gaps or conflicts to overcome or as opportunities to leverage [3]. Workshop speakers and session chairs were selected by a small technical committee to further support—and bring a diversity of perspectives to—the overall technical and systems focus of the workshop. Table 2 (which summarizes the overall workshop agenda) highlights the broad subject matter area(s) of expertise and the past experience in 3S-related engagements represented in the cross-cutting set of participating organizational representatives.

In addition to facilitated discussions across the full range of INMM equities for interactions and interfaces, the structure and orientation of this 3S workshop also provided an opportunity to gather data to better situate future 3S-related needs and opportunities in more realistic contexts. Data Set 1 consisted of the notes taken by each session chair and the workshop chairman to provide insights on 3S topics characterized in their respective areas of expertise. In addition to SME interpretation of each session, specific quotes capturing key elements of the 3S discussion were also recorded (examples are provided in the middle column of Table 3). To capture insights into broader perspectives of the INMM community on 3S topics, Data Set 2 consisted of participant feedback collected after each session on potential advantages, most likely opportunities, most interesting opportunities, and hindrances or obstacles for each set of interfaces for advanced reactors (see the right-hand column of Table 3).

TABLE 3. OVERVIEW OF DATA SETS 1 & 2 FROM INMM'S ADVANCED REACTOR 3S WORKSHOP

Workshop Session [Interfaces]	Data Set 1 (*emphasis* added)	Data Set 2 (raw count/total session responses)
I [Safety/ Security]	• "*Risk-informed applications* have improved safety…by *focusing on what matters most*" • "safety and security boundaries of operation rest on '*context of intentionality*'"	• *Potential Advantage*: reduced costs (4/22) • *Likely Opportunities*: create more data (3/22) • *Interesting Opportunities*: modelling/simulation (3/22) • *Obstacles*: (lack of) regulations (8/22)
II [Security/ Safeguards]	• "safeguards and security don't matter *without a functioning…* nuclear facility" • "[we need] deep and early conversations on interactions…*more than a one hour talk*"	• *Potential Advantage*: by-design options (3/13) • *Likely Opportunities*: by-design options (3/13) • *Interesting Opportunities*: modelling/simulation (3/13) • *Obstacles*: lack of experience (3/13)
III [Safeguards/ Safety]	• "We need to [be] *open to solutions that look different* than what 'I' came up with" • "[3S] is all tradeoffs… *things will be missed* by prioritizing individual perspectives"	• *Potential Advantage*: expand passive safety (1/4) • *Likely Opportunities*: robotic solutions (1/4) • *Interesting Opportunities*: new data types (2/4) • *Obstacles*: uncertainty in risk measures (2/4)
IV [Safety/ Security/ Safeguards]	• "if we do each '2S' well, we will get 3S as a by-product • "By-design [needs]…to learn [to] *balance between design uncertainty and 3S functions*"	• *Potential Advantage*: reduced costs (2/11) • *Likely Opportunities*: by-design options (3/11) • *Interesting Opportunities*: ACU's MSRR (4/11) • *Obstacles*: (lack of) regulations (4/11)

These data sets were collected to elicit perspectives from across the INMM community to help identify a "roadmap" for advancing 3S capabilities as a set of realistic, objective, and empirically developed next steps and opportunities for foundational, practical, and regulatory 3S solutions.

3. 3S WORKSHOP DATA ANALYSIS: TOWARD A 3S PATH FORWARD FOR INMM

Reviewing the information provided in Data Sets 1 and 2 produced several emerging themes related to 3S options, opportunities, needs, and challenges discussed by workshop participants. Though a relatively small sample size, the spread of the 75 workshop participants across research, academic, government, regulatory, and industry stakeholders represents a reasonable mapping to the broader professional community related to 3S domains. As such, any insights from these data sets are likely generalizable, appropriate, and beneficial for advancing the dialogue on technical and systems 3S solutions—particularly in supporting A/SMR deployment.

The Data Set 1 results help characterize several different interpretations for 2S and 3S interfaces. For example, Session I discussions included the "connected concept" of risk (including intentionality) for safety and security, the need for mutually congruent metrics of performance, and several key challenges anticipated with A/SMR safety and security operations. Session I ended with a collective brainstorming session highlighting the need to mitigate data scarcity for interface performance evaluation, as well as shifted the conversation for interfaces to reduce in A/SMR-related decision making. Similarly, Session II reiterated the need for useful metrics to describe interface performance and discussed the (near-term) importance for moving interface (and "by-design") conversations from concept to practice. The Session II brainstorming also introduced the paramount need to contextualize all 3S-related systems or technical solutions in the operational experience—identifying a recurring theme where interface opportunities should "start with the [A/SMR] facility engineering team."

Day 2 began with Session III conversations revolving around the themes of risk (e.g., reconciling different interpretations of tolerance and significance), communication (e.g., resolving ambiguous interface terminology and poor interaction with interface solutions), and technology (e.g., developing solutions [like wireless communications] consistent with operational limitations and requirements). The associated brainstorming session used the example of wireless communications as an exemplar of how creativity and innovation across the interface trade space is necessary and must balance against different performance expectations in each "S" domain. Lastly, Session IV situated this 3S workshop within the 2023 United Nations Climate Change Conference or Conference of the Parties of the UNFCCC (COP 28) pledge to "commit … [to the] highest standards of safety, sustainability, security, and non-proliferation" in response to desires to triple nuclear energy by 2050. Session IV conversations expanded the dialogue, offering the sentiment "if we do each '2S' well, we will get 3S as a by-product" as an example of how incremental and transformational improvements are necessary. The concluding brainstorming session articulated the need for balance between increased integration and maintaining certain S-domain specific capabilities, to identify multiple 3S interface champions, to demonstrate early 3S-associated benefits for A/SMR operations, and to consider better incorporation of 3S into A/SMR lifecycle planning (via discussions on inclusion in "pre-licensing" mechanisms for A/SMRs, for example).

As a by-product of the wide-ranging stakeholder perspectives represented in the speakers and session chairs, there was no clear consensus on potential advantages, likely, or interesting opportunities for 3S interface solutions for A/SMRs. The most popular response garnered from the participant feedback related to the obstacles to 3S interfaces, including the current lack of interface-related regulations (8 of 22 responses in Session I, and 4 of 11 responses in Session IV). A similar challenge is crystalized by one participant who stated how the presentations "[often] represented one 'S' primarily (mostly security) with the second 'S' as a secondary" and posed the timely (and pertinent) question: "how can we bring balance" to interface discussions. Yet, the largest 3S opportunity in Data Set 2 related to incorporating interfaces earlier into A/SMR design processes, with calls for more "by-design" opportunities (3 responses each in Sessions I, II, and IV) and more modelling/simulation capabilities (3, 6, and 1 responses in Sessions I, II, and III, respectively). Other opportunities that garnered significant discussion at the workshop included leveraging new data sources for characterizing 3S interface performance, creating human capacity development mechanisms for 3S interface expertise, developing new "risk-informed" methods, and advancing A/SMR marketability via 3S interface optimization.

This INMM Advanced Reactor 3S Workshop received extremely positive feedback from the participants and identified several key takeaways for interface discussions, including: 3S benefits that will result from enhanced communications between *all* A/SMR stakeholders (e.g., vendors, operators, newcomers, etc.), "radical collaboration" between "S" domain experts, and sustaining current levels of interest in developing (and deploying) mutually agreeable 2S or 3S solution. (NOTE: Again, a more detailed description is provided in [2].)

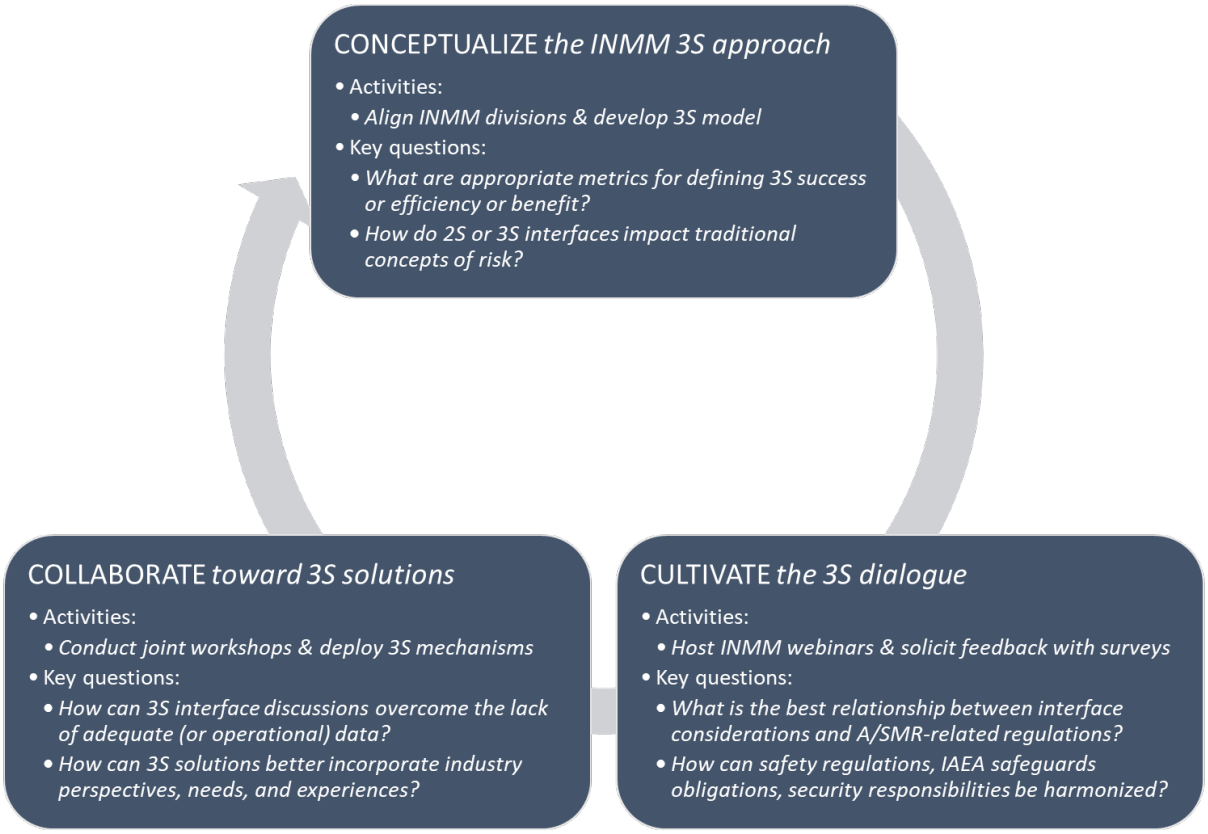

FIG. 1. INMM Roadmap for advancing technical and systems 3S interface solutions, mapped to key questions emerging from the Advanced Reactor 3S Workshop (and explained more in [2]).

Emerging from this 3S workshop—and subsequent evaluation and discussions within executive leadership—was a roadmap describing processes that INMM can take to manifest cutting-edge 3S interface thinking into tangible solutions to bolster A/SMR deployment. In an attempt to incorporate the temporal and complex dynamics associated with 3S interface considerations for A/SMRs, the INMM roadmap (FIG. 1) reimagines a generic feedback loop in terms of conceptualizing, cultivating, and collaborating. Within this roadmap, the INMM will *conceptualize* across internal technical divisions to craft an institute-endorsed approach for characterizing 3S interfaces. Next, the institute will *cultivate* a sustained, meaningful dialogue via webinars and community-feedback mechanisms aimed at describing foundational, practical, and regulatory features to guide exploration into 3S interface opportunities for A/SMRs. Lastly, INMM will *collaborate* through joint events and exploration activities to deploy and demonstrate 3S solutions for A/SMR contexts. Following this "conceptualize—cultivate—collaborate" roadmap will better position INMM to execute "radical collaboration" and "embrace discomfort" called for in the workshop—ultimately resulting in a consensus 3S interface approach that helps generate useful solutions across the nuclear material management community for enhancing responsible operations and reducing risk in nuclear energy activities.

Consider, for example, how another paper presented on the 2024 IAEA *International Conference on Small Modular Reactors and their Applications* demonstrated "radical collaboration" emerging from this workshop. Discussions between a presenter and the keynote speaker emerging from Workshop Session III resulted in the presentation "Applying 3S Lessons: Using Safety Concepts to Develop 'Risk-Informed Safeguards' for Small Modular Reactors" (Abstract 365), which explores the concept of "risk-significance" for enhancing safeguards performance. In this way, the INMM workshop created the opportunity space for representatives of different A/SMR-related support programs to meet, engage, and explore potential solutions to 2S and 3S interface issues. Given that representatives from many such U.S. government support programs (summarized in Table 4) participated in the Advanced Reactor 3S Workshop, INMM seems positioned to create additional opportunities to serve as the conduit for similar 3S interface opportunities in the future.

TABLE 4. SUMMARY OF U.S. PROGRAMS OFFERING 3S-RELATED SUPPPRT PROGRAMS

US Government Stakeholder	A/SMR-Related Objectives	Website [*Contact Information*]
NNSA Office of International Nuclear Security (NA211)-International Nuclear Security for Advanced Reactors (INSTAR)	• Improve security of U.S. A/SMRs via security by design • Build nuclear security capacity • Strengthen the global nuclear security regime for A/SMRs	https://nuclear-nexus.anl.gov/ [*INSinfo@nnsa.doe.gov*]
NNSA's Office of Conversion (NA231)-Proliferation Resistance Optimization (PRO-AR/FC)	• Minimize the production of special nuclear material while maintaining performance • Employ cutting-edge modelling techniques • Develop resources for a nonproliferation approach during the design phase	https://nuclear-nexus.anl.gov/ [*Online contact form*]
NNSA's Office of international Safeguards (NA241)-Advanced Reactor International Safeguards Engagements (ARISE)	• Integrate safeguards early in the design process • Develop safeguards approaches and concepts to facilitate regulatory harmonization • Collaborate with the IAEA (& other stakeholders) to mitigate A/SMR nonproliferation challenges	https://nuclear-nexus.anl.gov/ [*sbd@nnsa.doe.gov*]
U.S. Department of Energy's Office of Advanced Reactors (NE-52)-Advanced Reactor Safeguards & Security	• Support domestic deployment of A/SMRs by mitigating safeguards and security roadblocks • Apply national laboratory R&D to address near-term challenges A/SMR vendors face in meeting physical/cyber security and accounting requirements for U.S. construction	https://energy.sandia.gov/programs/nuclear-energy/safety-security-and-safeguards-for-advanced-nuclear-power/advanced-reactor-safeguards-and-security/ [*bbcipit@sandia.gov*]
U.S. Nuclear Risk Reduction's Office of Nuclear Reactor Regulation-Division of Advanced Reactors and Non-Power Production and Utilization Facilities (DANU)	• Develop & implement risk-informed and performance-based approaches to licensing for A/SMR non-power production and utilization facilities (NPUF) • Conduct design & initial licensing reviews for A/SMRs • Support international coordination programs for A/SMR & NPUF oversight	https://www.nrc.gov/about-nrc/organization/nrrfuncdesc.html#dsnu [*Unavailable*]
U.S. Department of State's Office for Cooperative Threat Reduction-Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology (FIRST)	• Establish A/SMR programs with the highest standards for security, safety, & nonproliferation, • Leverage next generation nuclear innovations and technologies in their sustainable energy plans • Deepen A/SMR through government, industry, national laboratory, and university engagements	https://www.smr-first-program.net/ [*Online contact form*]

Building on the current momentum in 3S interfaces, the INMM roadmap (FIG. 1) can serve as the connective tissue between US government program A/SMR focus areas (Table 4) to spearhead the development of mutually beneficial, resilient, and reinforcing foundational, practical, and regulatory 3S solutions.

4. INSIGHTS FOR RADICAL COLLABORATION BETWEEN INMM AND IAEA

Building on the idea of radical collaboration from the workshop, there seems to be mission- and vison-related similarities between the INMM and the IAEA. More specifically, the INMM's aim to ensure "safe, secure and effective stewardship of nuclear and other radioactive materials and related technologies" directly complements the IAEA's efforts in "planning for and using nuclear science and technology for various peaceful purposes." Despite some organizational differences, several opportunities for advancing the state-of-the-art in 3S interface evaluation exist related to the INMM roadmap for enhanced engagement with the IAEA, including:

- Mutual participation in 3S-related events (e.g., IAEA representatives continued participation in INM webinars or workshops, as well as potential INMM representative participation in IAEA technical meetings or consultancy meetings).
- Informal, topical dialogues on 2S or 3S interface issues (e.g., INMM and IAEA domain and interface experts can have focused discussions-under Chatham House Rules—toward meaningful steps forward).
- IAEA can continue to share its global perspective for 3S solutions with the INMM community (e.g., keynote speakers at conferences).
- INMM can host focused workshops on IAEA 3S-related documents or recommendations to cultivate more concrete 3S solutions (e.g., INMM events provide opportunities for structured brainstorming on interface implementation issues).

Through such opportunities, the deep technical expertise and capabilities of INMM can merge with the IAEA's knowledge of the "pulse" of international nuclear energy dynamics to accelerate the deployment of A/SMRs.

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