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Security, Safety, and Safeguards (3S) Risk Analysis for Small Modular Reactors

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Small modular reactors (SMR) are increasingly emerging as an efficient and effective method to meeting growing energy demands worldwide. Because the global community has a growing aversion to cost and schedule overruns traditionally associated with the current fleet of commercial nuclear power plants (NPP), SMRs are attractive, viable alternatives because they offer a significant relative cost reduction to current-generation NPPs. In addition, popular claims for SMRs indicate certain benefits for safety and security that seemingly challenge long-established regulatory regimes and procedural norms. Yet, the new physical layouts, procedural design, and increased digitization of proposed SMRs may challenge traditional approaches to nuclear security, safety, and safeguards (3S)-related risk.

Research emerging from Sandia National Laboratories (Sandia) offers three useful conclusions for evaluating risk complexity in safety, safeguards, and security of nuclear fuel cycle activities. First, integrated 3S approaches can help identify gaps, interdependencies, conflicts, and leverage points across traditional safety, security, and safeguards analysis techniques. Second, including the interdependencies between safety, safeguards, and security better aligns with real-world operational uncertainties and better describes the risk complexity associated with multi-model, multi-jurisdictional systems. Third, risk mitigation strategies resulting from integrated 3S risk assessments can be designed to better account for interdependencies not included in independent "S" assessments.

Recent Sandia research has applied these conclusions to investigating risk complexity in SMRs. More specifically, this research provides technically rigorous analysis of the safety, safeguards, and security risks of SMR technologies and an introduction to a systems-theoretic approach for exploring interdependencies between the technical evaluations. This paper will first offer a summary of the challenges and insights identified in the current literature on SMR safety, security, and safeguards. Next, the SMR safety, safeguards, and security technical evaluations are summarized. Finally, a preliminary integrated 3S technical evaluation is offered, followed by implications for 3S analysis of SMRs. By extension, this framework could be used to evaluate SMRs as a "systems-level" whole to better characterize, evaluate, and manage increasing risk complexity.

INTRODUCTION[1]

Globally, the development of small modular reactors (SMR)[2] is of interest to utilities and governments as an efficient and effective method to meet increasing energy demands (for both electricity generation and water desalination) and calls for "carbon-free" energy programs. Coupled with a growing aversion to the large capital outlays traditionally associated with the current fleet of commercial nuclear power plants (NPP), SMRs are attractive because of their smaller operational footprint and unique design features. SMRs will generate substantially less energy than the current nuclear, thereby offering a significant relative cost reduction to current-generation nuclear reactors—increasing their appeal around the globe. This

[1] This conference paper summarizes the final results of [1] and [2].
[2] The authors are aware that there are multiple technologies that could be considered "small modular reactors"—including some currently in operation. For this report, when "small modular reactor" or "SMR" is used, we are referring to the recent emphasis on light water reactor-based concepts and designs for localized power generation.

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includes countries with stated interest in purchasing (e.g., Saudi Arabia [3] and Jordan [4]) and selling (e.g., South Korea [5] and the U.S. [6]) SMRs.

SMRs also differ from the operating Generation II NPP fleet in that they have a variety of *passive* (e.g., no additional energy is necessary for initiation) safety features intended to provide adequate core cooling to delay (or prevent) core damage in the event of a short term station blackout. When combined with the small core size and lower power density design characteristics, the passive safety systems may provide an inherent degree of resilience to beyond design basis events not typically seen in traditional light water reactors. This shift in focus from engineered active safety systems in the current reactor fleet to passive safety measures in SMRs has potential implications beyond safety. For example, the change in the safety case has the potential to affect security and safeguards characteristics of reactor sub-systems assumed in traditional analytical approaches. Further, the safety, safeguards, and security of SMRs—presumably like any nuclear fuel cycle activity—are increasingly *interconnected*, which, in the words of former Deputy Director-General for Safeguards at the International Atomic Energy Agency Olli Heinonen

> *Safeguards, security, and safety* are commonly seen as *separate areas* in nuclear governance. While there are technical and legal reasons to justify this, they also *co-exist and are mutually reinforcing*. Each has a *synergetic effect on the other…* For instance, *near real-time nuclear material accountancy and monitoring systems* provide valuable information about the location and status of nuclear material. This in turn is useful for *nuclear security* measures. Similarly, such information enhances *nuclear safety* by contributing as input to critical controls and locations of nuclear materials. [7] (Emphasis added)

Sandia National Laboratories (Sandia) has invested in developing capabilities to address these interdependencies between safety, safeguards, and security.[8] Sandia's *Mitigating International Nuclear Energy Risks*[3] (MINER) research perspective reframes the discussion around the risk complexity for nuclear fuel cycle activities to provide a new way to explore these interdependencies. This Sandia study offered three useful conclusions for evaluating the 3S risk complexity:

- integrated 3S approaches can help identify gaps, interdependencies, conflicts, and leverage points across traditional safety, security, and safeguards analysis techniques;
- including the interdependencies between safety, safeguards, and security better aligns with real-world operational uncertainties observed in multi-jurisdictional systems; and,
- risk mitigation strategies resulting from integrated 3S risk assessments can be designed to better account for interdependencies not included in independent "S" assessments.

Given the (likely) important role that SMRs will play in the future of civilian nuclear energy program development, it was prudent to apply Sandia's world-class expertise in nuclear safety, security and safeguards (individually)—and leverage its recent advances in integrated "3S" approaches—to evaluate risk complexity in SMR facilities.[4]

SAFETY, SECURITY, SAFEGUARDS CHALLENGES FOR SMRs

In general, the largest number of—and more rigorous technical analysis for—SMRs in the published literature are related to safety, particularly those that explore the concepts of "inherent safety" or "passive

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[3] The *Mitigating International Nuclear Energy Risks* (MINER—formerly that *Global Nuclear Assurance and Security* (GNAS) mission area) initiative seeks to confidently anticipate, assess, and address nuclear risks—including novel and 'over-the-horizon' issues—worldwide using advanced systems and technologies, expertise, and situational awareness systems/tools.
[4] The Sandia research used a hypothetical SMR facility, whose detailed technical description can be found in [1].

safety systems" of SMR designs. This is in contrast to traditional light water reactor safety systems which are considered "active" in the sense that they require mechanical or electrical input to function. Nearly all SMRs incorporate inherent and passive (or, those that *do not* require external mechanical or electrical inputs to function) safety features that serve to prevent system failures and mitigate potential accidents.[9][10][11][12] The passive safety systems have several advantages including operation independent of emergency power and the elimination of the need for the auxiliary feedwater subsystems in the traditional NPP fleet. Furthermore, the simplified design of the passive safety systems increases their reliability. Examples of these safety systems include passive condensers (e.g. NuScale Power Module), gravity-driven injection (e.g. mPower), and heat removal via natural convection through the containment liner (e.g. the South Korean SMART reactor).[9]

The published literature on safeguards for SMRs is neither as substantive as that for safety and is highly conceptual. Several studies identified challenges to the traditional International Atomic Energy Agency (IAEA) comprehensive safeguards agreement-based regime posed by the unique characteristics of SMRs. For example, [13] indicated that low thermal signatures, the number of units per site, long life of reactor core, enrichment needs, surplus reactivity, and spent fuel storage geometry challenge the current safeguards paradigm. Other studies added low/infrequent refueling rates, decommissioning issues, fissile material inventories, coolant opacity, and fuel shuffling between co-located reactors.[13]14][15] In response, much of the SMR safeguards literature argues for variations of the "safeguards-by-design" concept, where technical and procedural elements to increase diversion difficulty nuclear materials are incorporated into basic engineering steps for facility operations.[14] Yet, a realistic understanding of how to implement safeguards at SMR facilities is still unknown—suggesting that safeguards for SMR facilities are likely to rely on existing guidance.

Similarly, the scant published literature related to security at SMRs is limited and does not extend beyond making assertions on security efficacy that scale linearly with geographic footprints of traditional NPPs versus proposed SMR facilities. Other literature further supports reduced security expenditures because of the proposed underground siting for SMRs, the long refueling intervals (that limit access to fresh and spent fuels in transit), and because of new passive safety systems.[16][17][18] In response, the literature identified the "security-by-design" concept as the appropriate path forward to mitigate these impacts on traditional security paradigms.[19] While some studies argue for a reduced security profile for SMRs, one study counters by noting that other vital facility operations— balance of plant systems like turbines and condensers—will likely still be above ground and need adequate protection.[20]

Reviewing this SMR-related literature revealed several key challenges. The first major challenge relates to the common economic arguments for SMR safety, safeguards, and security—namely the ability to still achieve the same levels of risk reduction when resources available for safety, safeguards, and security are reduced. A second challenge is the applicability of current safety, safeguards, and security approaches—including both technical analysis and best practice rules-of-thumb—to SMRs. For example, how can passive safety systems be modeled in traditional probabilistic risk assessment (PRA)-based techniques. A third challenge is the lack of robust and appropriate regulatory regimes to bound risk SMRs.

SAFETY, SECURITY, SAFEGUARDS TECHNICAL EVALUATIONS FOR SMRs

Safety Technical Evaluation

Sandia's technical evaluation was a preliminary investigation of safety at SMR facilities in the event of a Short Term Station Blackout with a complete loss of all electrical power. This evaluation used MELCOR [21] to model severe accident progression(s) (including thermal-hydraulic response, core degradation, material relocation, core-concrete attack, hydrogen production/combustion, and fission product release/transport behavior), ORIGEN-ARP [22] to calculate isotopic depletion, production, and decay of radionuclide inventories, and MelMACCS [23] to generate source terms from MELCOR output to calculate radionuclide activities. More specifically, this technical evaluation focused on four safety scenarios were on different pathways to/repercussions from short-term station blackout conditions (Table 1). In addition, this investigation identified potential points of interaction with security and safeguards.

Table 1. Summary description of safety evaluation scenarios.

Scenario Number	Summary	Containment Status
1	Total loss of on/off-site power with disabled passive safety systems (e.g., reference accident sequence and baseline release estimate)	Intact, fully functional
2	Total loss of on/off-site power with disabled passive safety systems with lowered pressure thresholds	Degraded, still functional
3	Direct containment breach by including a 2 foot diameter hole[5] (e.g., an upper bound on any radiological releases)	Breached
4	Total loss of on/off-site power with functional passive safety systems (e.g., a best-case scenario with some accident mitigation)	Intact, fully functional

The high-level goal of the SMR safety analysis was to characterize the SMR plant response and accident sequence under unmitigated short-term station blackout conditions[6]—including identifying the related SMR accident sequences (and resultant radionuclide releases), describing potential impact of a sabotage act on these accident sequences, and determining the effectiveness of passive safety systems. Key results from this technical evaluation included that:

- Passive heat removal systems have a dramatic effect on accident progress (e.g., core uncovering is delayed for an additional 35 hours beyond the other safety scenarios)
- Accident progressions for scenarios 1, 2, and 3 are nearly identical, and scenario 4 exhibits zero radiological releases due to passive heat removal systems
- Assuming intact containment, fractional releases for all classes are less than $1x10^{-4}$ (except for the Xe class at $< 4x10^{-1}$)

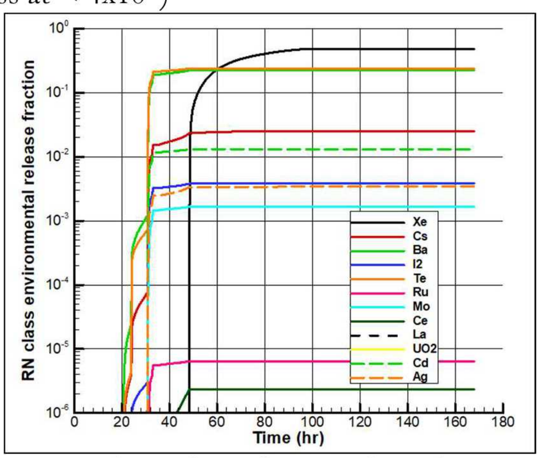

Figure 1. RN class release fraction for safety scenario 3

These results suggest that this hypothetical SMR has a good degree of safety (assuming an intact containment structure) and support the argument that the small core sizes and low core power densities of SMRs can slow severe accident progression and helps mitigate beyond design basis accidents. By

[5] Representative of a saboteur successfully using a shape charge.
[6] From a security perspective, an unmitigated short-term station blackout represents a bounding, worst-case scenario where an adversary has successfully disabled all safety systems, prevented recovery actions, and eases sabotage mission completion.

extension, this safety technical evaluation illustrates how passive safety systems challenge the assumption that if the adversaries can hold a control room for a predetermined time that damage to the reactor core *has occurred*. Similarly, the relatively small size of the radiological releases suggests the need to develop a new metric for safety—potentially shifting from release thresholds toward metrics based on offsite health effects. Lastly, because all non-passive safety systems simulations predict a slow accident progression (e.g., first environment releases did not occur until about 20 h), an immediate offsite response may not be necessary to prevent a release (if containment is intact).

Safeguards Technical Evaluation

Sandia's safeguards technical evaluation was a preliminary investigation of safeguards at SMR facilities in the event of an attempted diversion (or production) of special nuclear materials—particularly in the context of International Atomic Energy Agency (IAEA) best practices. This evaluation used PRCALC, a Markov Chain[7] (Figure 2)—based software package, to model nuclear facilities in terms of normal and diversion stages, characteristics of the reactor assemblies (in units of assemblies per significant quantity), applied safeguards measures (called *extrinsic barriers*), and the *intrinsic barriers* of the material/processes associated with a given operational stage. [24] More specifically, six Safeguards scenarios were generated by varying whether traditional safeguards were implemented, the number of SMRs onsite, whether wet or dry spent fuel storage, and total material quantity (Table 2.). In addition, this investigation attempts to locate potential points of interaction with security and safety.

Table 2. Safeguards scenario characteristic summaries.

Scenario	# of Reactors	Safeguards
1	1	Yes
2	1	No
3	2	Yes
4	2	No
5	10	Yes
6	10	No

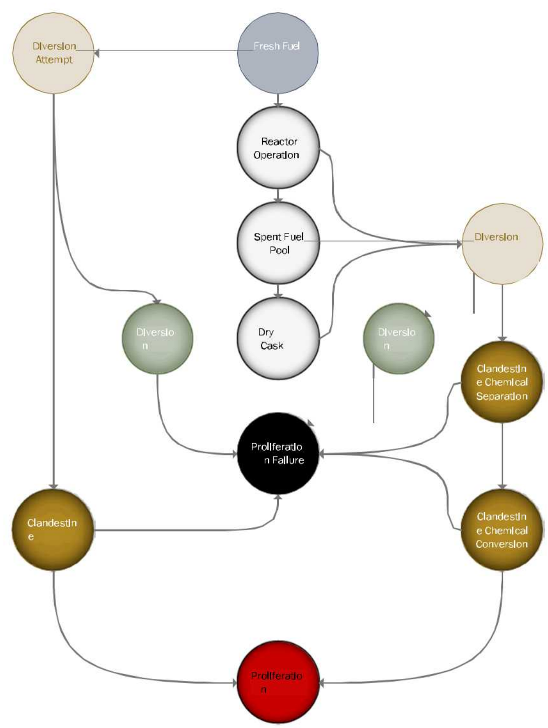

Figure 2. PRCALC Markov-model for Safeguards scenario 1

[7] Markov Chains are stochastic models describing sequences of possible events in which the probability of each event is only dependent on the previous state.

The high-level goal of the SMR safeguards analysis was to characterize how related facilities respond to attempts to divert and process SNM—including determining the baseline probability of proliferation success without specific safeguards interventions, investigating the probability of proliferation success when a safeguards program is in place, describing the effect of multiple reactor modules at one site on the probability of proliferation success, and identifying the most vulnerable states for diversion for SMR facilities. Key results from this technical evaluation included:

- The proliferation of U-235 is less probable with a longer timeline than that of Pu, primarily due to the difference in the probability of detection
- Of the Markov stages evaluated (Figure 2), the spent fuel pool stage had the highest proliferation probability and the fresh fuel arriva/reactor operations stages had the lowest
- Preliminary analysis indicates the initial loading of one reactor for weapons grade Pu production would yield approximately three significant quantities or 22kg[8]

These results suggest that, while intrinsic barriers and technical difficulties for SMRs can significantly impede the probability of proliferation success, additional safeguards elements can further reduce the likelihood of proliferation success. Similarly, the PRCALC simulations illustrated an increased concern —in terms of key proliferation metrics—from additional nuclear material present in multiple reactors at a single facility. Ultimately, this technical evaluation indicated that the safeguards impact of a single SMR (under normal operating conditions) was on par with other electricity-generating nuclear facilities. Conversely, an increase in SMR reactor production globally may challenge the international nuclear safeguards regime (for example: what is the impact of 50, 100, or 200 operating SMRs— particularly in terms of e.g., SNM production or amount of material under safeguards. Lastly, the technical evaluation suggested that introducing DO_2 into an SMR core *may* shift the neutron energy spectrum up and increase the efficiency of breeding Pu, directly challenging traditional safeguards.

Security Technical Evaluations

Sandia's technical evaluation was a preliminary investigation of security at SMR facilities in the event of adversary sabotage for a range of physical protection systems (PPS) capabilities. This evaluation used the Design Evaluation Process Outline (DEPO) analytic approach to describe physical protection system (PPS) effectiveness in terms of its ability to detect, delay, and initiate a response to adversary actions against a nuclear facility—including adversary pathway diagrams and timeline analysis. [25]

Table 3. Adversary Mission Summary Table.

Adv. Mission	**Initiating Event**	**Path Summary**	**Deviations from the DBT[9]**
1	Breach with vehicle bomb	Use truck bomb to destroy control room, *then* attack auxiliary control room	+ Ammonium nitrate vehicle bomb (~1T TNT)
2	Gain access with counterfeit badges	Pass through personnel portal, *then* take over main/auxiliary control rooms	+ Active non-violent insider (network privileges)
3	Insider escorts into facility	Pass through personnel portal, *then* take over main/auxiliary control rooms	+ Active non-violent insider (control operator)
4	Overt attack on entrance portal	Kinetic attack on entrance portal, *then* take over main/auxiliary control rooms	None

[8] For a more detailed explanation, please see Appendix C of [1].

[9] For full hypothetical design basis threat, please see [1].

More specifically, the scenarios considered for this analysis consisted of combinations of four different adversary missions (Table 3) and three different (e.g., low, medium, high) security posture levels (Figure 3). Any adversary breach of the control room is considered a loss for the physical protection system. In addition, this investigation attempts to locate potential points of interaction with safeguards and safety.

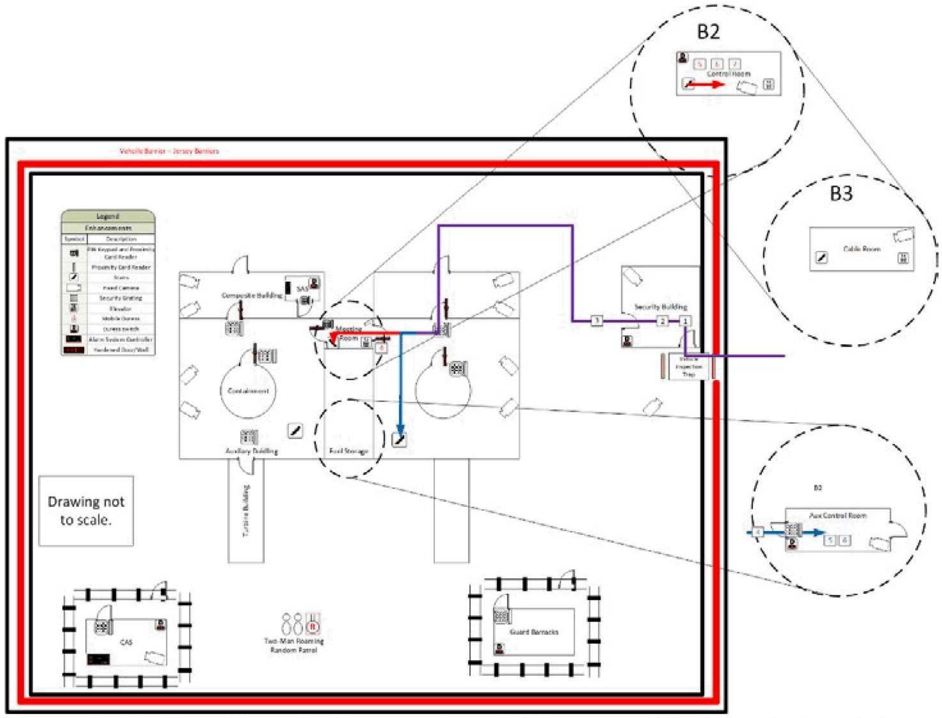

Figure 3. Medium Security Posture Level Adversary Missions 2, 3 and 4.

The high level goal of the SMR security technical evaluation was to characterize the effectiveness of the PPS against an adversary force completing a sabotage mission—including determining the effectiveness of SMR-related PPS against a notional DBT with a sabotage mission, deriving the cumulative probability of detection for different PPS configurations, and identifying the CDPs for different PPS configurations. Key results from this technical evaluation include:

- No critical detection point existed for any *low security posture*-based scenario
- Critical detection points existed for onsite response for all *medium* and *high security posture*-based scenarios
- Critical detection points existed for offsite response only for adversary missions 1 and 4 against *high security posture*-based scenarios

These results suggest that the existence of critical detection points on adversary timelines indicates that the vault doors are minimally sufficient to delay adversary sabotage missions. In addition, only two scenarios (adversary mission 1 and 4 for the high security posture level) experience both onsite and offsite response to fully achieve a denial response strategy. The results of this technical evaluation indicated that sole reliance on offsite response to deny adversary sabotage missions is insufficient, despite the associated facility operational cost savings—which directly challenges popular arguments for cost-efficiency from cutting onsite response. Lastly, passive safety systems *may* represent a new/novel target and set of adversary pathways to sabotage SMR facilities (e.g., passive heat removal systems as non-traditional targets).

INTEGRATED 3S TECHNICAL EVALUATION FOR SMRs

Sandia's technical evaluation was a preliminary 3S evaluation of SMR facilities based on the interactions identified in the individual safety, safeguards, and security technical evaluations. The high level goal of the SMR 3S technical evaluation was to characterize the interactions between safety, safeguards, and security mitigations across the traditional risks of concern—including identifying the conflicts and/or leverage points between safety, safeguards, and security for SMRs, locating where safety, safeguards, and security for SMRs interdependent, and determining how these points of interdependence influence the key analysis questions, conclusions, and insights from the individual technical evaluations.

Focusing on *interactions* between technologies, processes, and procedures related to safety, safeguards, and security mitigations identified several instances where traditional assumptions of *independence* did not fully capture likely SMR operational realities. Though seemingly obvious, these interdependencies (Table 4) are not often accounted for in individual technical analyses.

Table 4. Points of Interdependence between Safety, Safeguards, and Security for SMRs.

Safety Effects	Security Effects	Safeguards Effects	Explanation
Passive vs. active safety systems	New potential targets, vulnerabilities, and needed mitigations	N/A	Reliance on passive safety systems reduces the chances of a safety incident, *while simultaneously* changing the possible targets by which to damage SMR operations
Physical separation of reactor trains	Requires greater movement of adversaries to sabotage plant	Potential to conceal sections of facility from inspections	Tradition of physically separating trains to reduce common cause failures in safety *simultaneously* increases the distance attackers would need to travel to sabotage a plant AND increases the complexity (and footprint) of the plant layout—thereby making it easier for a proliferator to guide an inspector around sections of a facility
Challenges operator actions during a severe accident	**Strict access control procedures**	Can provide assurance to safeguards inspector that rooms have not been entered inappropriately	Access control both provides an additional barrier to overcome and limits the opportunity for insiders *while simultaneously* increasing assurance of appropriate safeguards-related access AND challenging the ability for emergency personnel to respond to accidents
N/A	Increases attractiveness of material storage locations	**Consolidation of locations storing nuclear material**	Reducing the number of locations where nuclear material is stored or processed minimizes the opportunity of proliferators to divert materials *while simultaneously* increasing the attractiveness of individual location—and, perhaps, requiring more security
N/A	Improved insider threat mitigation*	**Increased frequency of safeguards inspections**	Increased safeguards inspections frequency (including surprise inspections) reduces opportunities for diversion *while simultaneously* increasing the difficulty for an insider adversary to perpetrate a malicious act
* There is another possible interpretation of this security/safety interaction—that by allowing inspectors more frequent access, they gain more knowledge of the facility, including its security posture, which increases opportunities for inspector to be an insider adversary.			

This 3S technical evaluation concluded that identifying these points of interdependence can offer higher fidelity system analysis of increasing real-world complexity. In addition, the results suggested that all but one interdependence *did not* present significant challenges to the ability of traditional SMR safety, safeguards, and security mitigations to achieve operational goals. These interdependencies *did* identify potential mechanisms for gaining efficiency in reducing safety, safeguards, and security risks. One particular interdependence—the need to adequately secure passive safety systems in order to ensure their utility—*did directly* challenge popular claims associated with arguments about inherent safety and reduced security costs for SMRs. By implication, some interdependencies—like passive safety systems as new vital security areas— identify gaps or conflicts that need to be mitigated to improve SMR facility operations. Similarly, some interdependencies—like physical separation of trains—identify gaps or leverage points that need to be optimized to improve SMR facility operations. Taken together, these results suggest a need—and provide a way—to reprioritize engagement efforts to help design SMR facilities, systems, and activities (especially those in new nuclear countries) more capable of managing complex risks.

CONCLUSIONS

Overall, this preliminary MINER 3S technical evaluation partially supports popular safety, safeguards, and security claims for SMRs. Moreover, these results support calls for "by-design" approaches to address risk complexity in SMRs—particularly in regards to the how interdependencies may impact the efficacy of "inherent" or "passive" safety systems. These preliminary interdependencies are subject to additional nuance contingent upon operational-specific details (e.g., mitigations *may* look different in Jordan than in the U.S.). The accuracy and utility of the technical evaluation results—and the conclusions and implications in this section—are dependent on the accuracy, fidelity, and appropriateness of the analytical assumptions used in this study. Even with the lack of detailed operational and technical limitations, the analytical assumptions were carefully discussed and benchmarked (where possible) against related data or subject matter expertise. Thus, our conclusions and implications serve as waypoints for completing next steps toward advancing the technical understanding of safety, safeguards, and security for SMRs. By extension, this integrated 3S framework could be used to evaluate SMRs as a "systems-level" whole to better characterize, evaluate, and manage increasing risk complexity.

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