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System Studies for Global Nuclear Assurance & Security: 3S Risk Analysis for Small Modular Reactors (Volume II)—*Conclusions & Implications*

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System Studies for Global Nuclear Assurance & Security: 3S Risk Analysis for Small Modular Reactors (Volume II)
Conclusions & Implications

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Abstract

Coupling interests in small modular reactors (SMR) as efficient and effective method to meet increasing energy demands with a growing aversion to cost and schedule overruns traditionally associated with the current fleet of commercial nuclear power plants (NPP), SMRs are attractive because they offer a significant relative cost reduction to current-generation nuclear reactors—increasing their appeal around the globe. Sandia's Global Nuclear Assurance and Security (GNAS) research perspective reframes the discussion around the "complex risk" of SMRs to address interdependencies between safety, safeguards, and security. This systems study provides technically rigorous analysis of the safety, safeguards, and security risks of SMR technologies. The aims of this research is three-fold. The first aim is to provide analytical evidence to support safety, safeguards, and security claims related to SMRs (Study Report Volume I). Second, this study aims to introduce a systems-theoretic approach for exploring interdependencies between the technical evaluations (Study Report Volume II). The third aim is to demonstrate Sandia's capability for timely, rigorous, and technical analysis to support emerging complex GNAS mission objectives.

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1. INTRODUCTION

Globally, the development of small modular reactors (SMR)[1] 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. SMRs are attractive because of their smaller operational footprint, unique design features, and relative cost reduction (as compared to current-generation nuclear reactors)—especially around the globe. This includes countries with stated interest in purchasing (e.g., Saudi Arabia [1] and Jordan [2]) and selling (e.g., South Korea [3] and the U.S. [4]) SMRs.

Whereas traditional light water reactors often rely on active safety systems, SMRs typically employ passive safety systems that do not rely on mechanical or electrical input. When combined with the small core size and lower power density design characteristics, the passive safety systems provide an inherent degree of resilience to beyond design basis events not typically seen in traditional light water reactors. Popular claims for SMRs indicate certain benefits for safety and security that seemingly challenge long-established regulatory regimes and procedural norms.

Sandia National Laboratories (Sandia) has invested in developing capabilities to address the interdependencies between safety, safeguards, and security in the nuclear fuel cycle—including a recent report on SMRs.[5] Implications of recent research argue that safety, safeguards, and security interdependent risks (1) are inherent in nuclear fuel cycle activities and (2) can go unidentified when each "S" is independently evaluated [6]. Sandia's Global Nuclear Assurance and Security[2] (GNAS) research perspective reframes the discussion around the "complex risk"[3] of SMRs to address interdependencies between safety, safeguards, and security. Given the (likely) important role that SMRs will play in the future of civilian nuclear energy program development, it is prudent to identify key challenges and insights to guide Sandia's efforts to support future U.S. government policy goals.

1.1. The *Small Modular Reactor* Context

For this study, a hypothetical SMR facility in [6] was adapted to provide appropriate technical details while protecting sensitive or proprietary information. A brief summary—for context—is summarized here (with additional details provided in Appendix A of [5]).

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[1] 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.

[2] The Global Nuclear Assurance and Security (GNAS) mission area seeks to lead the nation in enabling the U.S. government to confidently anticipate, assess, and address nuclear risks worldwide using advanced systems and technologies, expertise, and situational awareness systems/tools. To continue the success of addressing these complex GNAS issues, anticipating Sandia customer needs, and building internal Sandia capabilities, this project seeks to leverage currently developed cross-Center collaborative experiences. Specifically, this initiative focuses on evaluating challenges in the Global civilian nuclear energy enterprise by considering novel and 'over-the-horizon' issues to identify and prepare appropriate Sandia responses for the U.S. Government.

[3] "…***complex risk*** accounts for the emergence of risk resulting from interactions among security, safety, and safeguards risks and mitigations." [7, p. 41, emphasis added]

The hypothetical Stalfgar Nuclear Power Plant (SNPP) represents the first use of an SMR facility to be linked to a desalinization plant. For analysis purposes, this power plant has been operating for a range (e.g., 2, 12, 59) years without incident. This plant is considered critical infrastructure for the nation of Poscatu, and not only provides electric power for residential and industrial use but is a necessary supplier of electricity for desalinization. SNPP is the only commercial reactor that has ever operated in Poscatu, and it remains the only commercial facility that is under the purview of Poscatu's regulatory agency.

SNPP has two reactors, where the reactor building consists of two above-grade and five below-grade stories. Nuclear fuel is to the Nuclear Receiving building where the fuel is inspected before being transferred to a fuel vault in the Fuel Service & Maintenance building. During a refueling period for either reactor, the spent fuel is removed from the core and sent to a shared spent fuel pool in the Fuel Service & Maintenance building. Spent fuel remains in this pool for a minimum of 10 years, is then loaded into a canister and cask, and is moved to the Cask Storage Area.

The reactor building is a reinforced concrete structure designed to protect the reactor from design basis accidents and threats. This building also houses four large water tanks equally-spaced around containment intended to provide a passive source of natural circulation cooling for several days following a station blackout event. These tanks are located in the Storage rooms surrounding the containment structure. Two out of four passive heat removal systems are sufficient to maintain core integrity in the event of a station black out (SBO).

1.2. Safety/Safeguards/Security (3S) Context & Analytical Approach

In [6], Sandia researchers argued that risk stems from interactions between technical, human, and organizational influences within a complex system. This Sandia study also 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. By extension, this framework could be used to evaluate SMRs as a "systems-level" whole to better characterize, evaluate, and manage increasing risk complexity.

1.3. Objectives for this GNAS Systems Study

This Sandia study provides technically rigorous analysis of the safety, safeguards, and security risks of SMR technologies. The aim of this research is three-fold. The first aim is to provide analytical evidence to support safety, safeguards, and security claims related to SMRs (Study Report Volume I). Second, this study aims to introduce a systems-theoretic approach for exploring interdependencies between the technical evaluations (Study Report Volume II). The third aim is to demonstrate Sandia's capability for timely, rigorous, and technical analysis to support complex GNAS mission objectives.

The remainder of this volume includes:

- A summary of the challenges and insights identified in the current literature on SMR safety, security, and safeguards;
- Summaries of the safety, safeguards, and security technical evaluations of SMRs;

- Preliminary integrated 3S technical evaluation of SMRs; and,
- Implications and next steps for 3S analysis of SMRs.

1.4. Challenges and Insights from a Literature Review

Reviewing the scant literature on safety, safeguards, and security for SMRs [5] revealed several key gaps and challenges. The first major challenge relates to the common arguments that safety, safeguards, and security for SMRs will be less expensive. The specific challenge is being able 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. A third challenge is the lack of robust and appropriate regulatory regimes to bound acceptable safety, safeguards, and security risk for this new technology.

This review also identified two major gaps in published SMR-related studies. The first is the legacy of evaluating safety, safeguards, and security as independent aspects of SMR-related risks. Current trends across all NPPs (e.g., increased digitization of safety-critical systems) combined with the unique features of SMRs (e.g., reliance on passive safety systems) are not adequately addressed when evaluating safety, safeguards, and security in isolation. The second major gap is the lack of technical evaluation-based evidence to validate safety, safeguards, and security claims for SMRs. The literature made claims based on *inferences* from established best practices in nuclear safety, safeguards, and security for SMRs—which does not lend credibility to the implied benefits of this new nuclear energy technology.

2. TECHNICAL EVALUATION SUMMARIES

2.1. Safety Analysis

2.1.1. Approach, Scope, & Scenario Description(s)

This technical evaluation is 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. In addition, this investigation attempts to locate potential points of interaction with security and safeguards.

Tool(s)/Method(s):

- **MELCOR**: a fully integrated severe accident analysis code, that includes the thermal-hydraulic response, core degradation, material relocation, core-concrete attack, hydrogen production/combustion, and fission product release/transport behavior [8]
- **ORIGEN-ARP**: an automated sequence to perform isotopic depletion, production, and decay calculations to generate the initial core radionuclide inventory [9]
- **MelMACCS**: a program to generate source terms from MELCOR output to calculate radionuclide activities [10]

Scenarios: To address these questions, four safety scenarios were on different pathways to/repercussions from short-term station blackout conditions (Table 1).

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[4] (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

2.1.2. Key Analysis Questions

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.[5]

Within this technical evaluation, key analysis questions included:

- What is the accident sequence for the SMR under unmitigated short-term station blackout conditions?
- What, if any, radionuclide releases occur as a result of the accident sequence?

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[4] Representative of a saboteur successfully using a shape charge.

[5] 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 any operator recovery actions, and makes completion of a sabotage mission significantly easier.

- Could adversary sabotage increase the radionuclide release by damaging containment?
- What effects, if any, will a functional passive safety system have on the accident sequence and/or radionuclide releases?

2.1.3. Key Results, Conclusions, & Implications

Key Results:

- 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 1×10^{-4} (except for the Xe class at $< 4\times10^{-1}$)

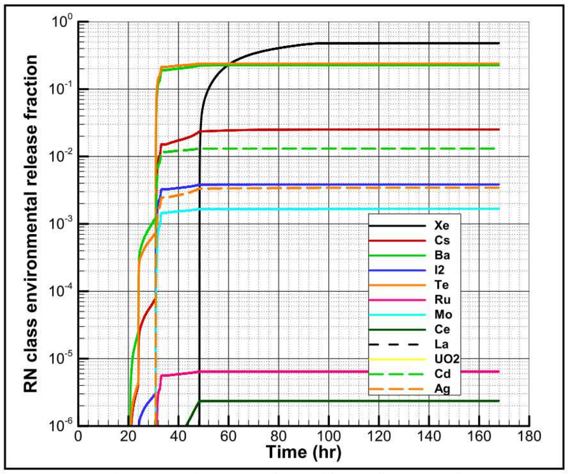

Figure 1. RN class release fraction for Safety scenario 3.

Conclusions:

- MELCOR simulations suggest that the hypothetical SMR has a good degree of safety (assuming an intact containment)
- Results support 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

Implications:

- 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*
- The relatively small size of the radiological releases suggests the need to develop a new metric for safety—shifting from release thresholds and toward offsite health effects
- All non-passive safety systems simulations predict a slow accident progression (e.g., first environment releases did not occur until about 20 h)—suggesting an immediate offsite response may not be necessary to prevent a release (if containment is intact)

2.2. Safeguards Analysis

2.2.1. Approach, Scope, & Scenario Description(s)

This technical evaluation is a preliminary investigation of safeguards at SMR facilities in the event of an attempted diversion (or production) of special nuclear materials (SNM) in the context of International Atomic Energy Agency (IAEA) best practices. In addition, this investigation attempts to locate potential points of interaction with security and safety.

Tool(s)/Method(s):

- **PRCALC**: a software package that uses Markov Chains[6] to model nuclear facilities in terms of normal and diversion stages, characteristics of the reactor assemblies (in units of assemblies per SQ), applied safeguards measures (called *extrinsic barriers*), and the *intrinsic barriers* of the material/processes associated with a given operational stage [11]

Scenarios: To address these question, six Safeguards scenarios were generated by varying whether traditional safeguards were implemented for a different number of SMRs onsite (Table 1.)—thereby varying the total material quantity in the SMR facility and assuming both wet and dry spent fuel inventory represents a 60 year design life of the reactor.

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

2.2.2. Key Analysis Questions

The high-level goal of the SMR safeguards analysis was to characterize how related facilities respond to attempts to divert and process SNM.

Within this technical evaluation, key analysis questions included:

- What is the baseline probability of proliferation success without specific safeguards interventions?
- What is the probability of proliferation success when a safeguards program is in place?
- What is the effect of multiple reactor modules at one site on the probability of proliferation success?
- What are the most vulnerable states for diversion for SMR facilities?

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

2.2.3. *Key Results, Conclusions, & Implications*

Key Results:

- 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 1), the spent fuel pool stage had the highest probability of proliferation and the fresh fuel arrival and 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[7]

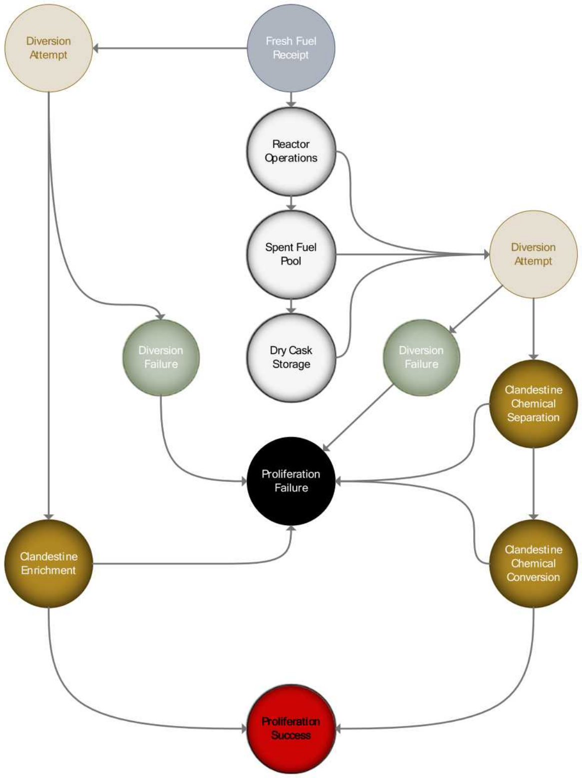

Figure 2. PRCALC Markov-model for Safeguards scenario 1.

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[7] For a more detailed explanation, please see Appendix C of [5].

Conclusions:

- With no safeguards in place, intrinsic barriers and technical difficulties for SMRs alone can significantly impede the probability of proliferation success
- PRCALC simulations illustrated an increased concern —in terms of key proliferation metrics—from additional nuclear material present in multiple reactors at a single facility

Implications:

- Safeguards impact of a single SMR (under normal operating conditions) in this analysis is negligible
- 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)
- 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

2.3. Security Analysis

2.3.1. Approach, Scope, & Scenario Description(s)

This technical evaluation is a preliminary investigation of security at SMR facilities in the event of adversary sabotage for a range of physical protection systems (PPS) capabilities. In addition, this investigation attempts to locate potential points of interaction with safeguards and safety.

Tool(s)/Method(s):

- **Design Evaluation Process Outline (DEPO)**: an analysis approach that describes 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 [12]

Scenarios: The scenarios considered for this analysis consisted of combinations of four different adversary missions (Table 2) and three different (e.g., low, medium, high) security posture levels. In support of the bounding assumption that adversaries are seeking to sabotage the SMR facility, any adversary breach of the control room (or auxiliary control room) is considered a loss for the physical protection system.

Table 3. Adversary Mission Summary Table.

Adv. Mission	Initiating Event	Path Summary	Deviations from the DBT[8]
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	Pass through personnel portal, *then* take	+ Active non-violent

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[8] For full hypothetical design basis threat, please see [5].

	into facility	over main/auxiliary control rooms	insider (control operator)
4	Overt attack on entrance portal	Kinetic attack on entrance portal, *then* take over main/auxiliary control rooms	None

2.3.2. Key Analysis Questions

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. Within this context, the key analytical questions included:

- What is the effectiveness of SMR-related PPS against a notional DBT with a sabotage mission?
- What is the cumulative probability of detection for different PPS configurations for the above?
- Where are the CDPs for different PPS configurations for the above?

2.3.3. Key Results, Conclusions, & Implications

Key Results:

- 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

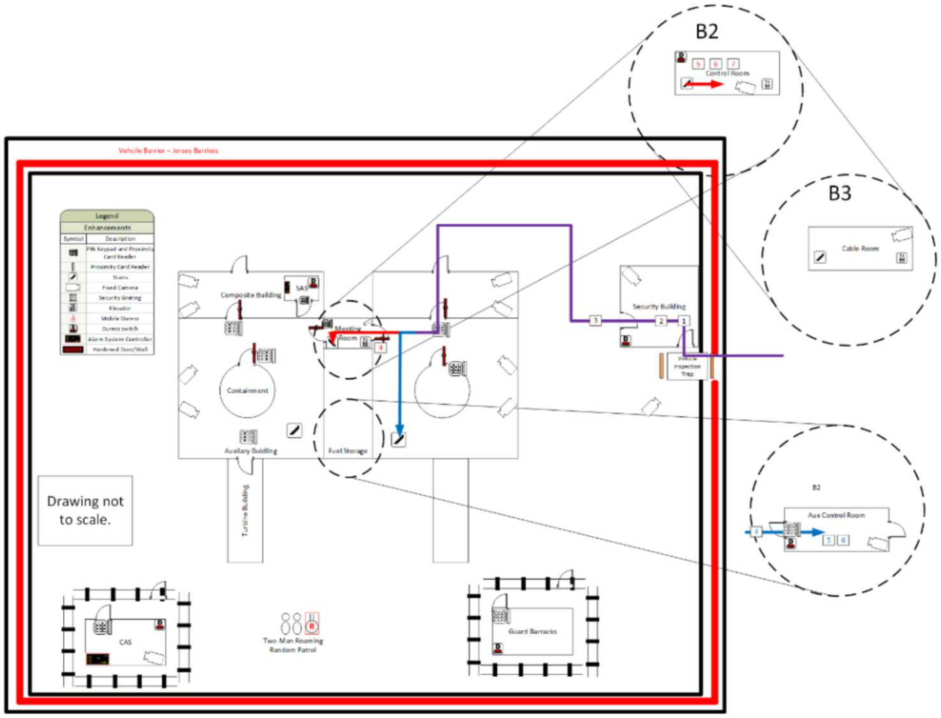

Figure 3. Medium Security Posture Level Adversary Missions 2, 3 and 4.

Conclusions:

- Existence of critical detection points on adversary timelines indicates that the vault doors are minimally sufficient to delay adversary sabotage missions
- 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

Implications:

- Sole reliance on offsite response to deny adversary sabotage missions is insufficient, despite the associated facility operational cost savings
- Results challenge popular arguments for cost-efficiency from cutting onsite response
- 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)

3. SMR SYSTEMS STUDY: 3S ANALYSIS

This technical evaluation is a preliminary 3S evaluation of SMR facilities based on the interactions identified in the individual safety, safeguards, and security technical evaluations.

3.1. Key Analysis Questions

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. Within this context, the key analytical questions included:

- What are the conflicts and/or leverage points between safety, safeguards, and security for SMRs?
- Where are safety, safeguards, and security for SMRs interdependent?
- And, if they are, how do these points of interdependence influence the key analysis questions, conclusions, and insights from the individual technical evaluations?

3.2. Key Insights

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 3) 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	N/A	Reliance on passive safety systems reduces the chances of a safety incident, *while simultaneously* offering new targets by which to damage SMR operations

	mitigations		
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 avoid a direct pathway 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.

3.2.1. Conclusions of SMR 3S Analysis

- Identifying these points of interdependence illustrates how the GNAS 3S approach can offer higher fidelity system analysis of increasing real-world complexity
- One particular interdependence—the need to adequately secure passive safety systems in order to ensure their utility—directly challenges popular claims associated with SMRs
- None of the other interdependencies presented 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
- These preliminary, primarily *qualitative* results should be validated with additional, more in-depth *quantitative* analysis

3.2.2. 3S Implications for SMRs

- 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
- Some interdependencies—like physical separation of trains—identify gaps or leverage points that need to be optimized to improve SMR facility operations
- These results suggests a need—and provides 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

4. CONCLUSIONS AND NEXT STEPS

Overall, this preliminary GNAS 3S analysis partially supports popular claims regarding safety, safeguards, and security for small modular reactors. The safety technical evaluation supported popular claims regarding the benefits of passive safety systems in many SMR designs, but also identified additional considerations that challenge the "silver bullet" connotation of such passive safety systems. While the safeguards technical evaluation supported generic claims on the suitability of the current INFCIRC/153-based framework, it identified some novel challenges to this legacy regime from the unique characteristics of SMRs. Lastly, the security technical evaluation challenged the possibility of adequately protecting SMR facilities with reduced security posture levels, despite common assumptions that smaller geographic and operational footprints equate to a reduced need for security.

4.1. Broader Implications from 3S SMR Risk Analysis

- Calls for "by-design" approaches for security and safeguards in SMRs support further application of the GNAS 3S analytical framework for risk complexity in SMRs
- The efficacy of "inherent" or "passive" safety systems may be challenged by interdependencies within unique SMR facility designs
- 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 identified interactions define the relationships necessary for more in-depth, quantifiable evaluation via such systems-theoretic approaches as dynamic probabilistic risk assessment or systems-theoretic process analysis [13]

4.2. Next Steps for 3S SMR Risk Analysis R&D

- Apply the GNAS 3S analytical framework within each of the above technical evaluations (including the effects of a radiological release on each "S")
- Expand this GNAS 3S evaluation to include more specific contextual factors in a set of use cases based on *likely* or *reported* geopolitical interest in pursuing SMRs
- Use the GNAS 3S analytical framework to scope *potential* engagement opportunities with international colleagues exploring SMR facilities

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. The use of analytical assumptions was driven by the lack of operational and technical details for SMRs in the open literature. Even with these data limitations, the our 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.

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