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Security, Safety, and Safeguards (3S) Risk Analysis for Portable Nuclear Reactors

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Growing interests in compact, more easily transportable sources of baseload electricity have manifested in the proposal—and early deployment—of portable nuclear reactors (PNRs). Sought as a scalable, efficient, and cost-effective option for meeting energy demands in unique, remote, or contested areas. For example, consider Russia's floating nuclear power plant Akademik Lomonosov that successfully began providing power to the Arctic coastal city of Pevek in December 2019 as a representative example.

While providing several key advantages (e.g., flexible power generation), PNRs seem to directly challenge international nuclear safety, safeguards, and security norms and conventions. Because PNRs are neither a purely fixed nuclear fuel cycle activity nor a purely transportation-based nuclear fuel cycle activity, their deployment may challenge traditional approaches to risks from nuclear security, safety, and safeguards. Research emerging from Sandia National Laboratories (Sandia) offers several useful insights for evaluating such risk complexity in safety, safeguards, and security (3S). One insight describes how integrated 3S approaches can help identify gaps, interdependencies, conflicts, and leverage points across traditional (and often isolated) 3S analysis techniques. Another insight states that including the interdependencies between 3S better aligns with real-world operational uncertainties and better describes the risk complexity associated with multi-modal and multi-jurisdictional systems. Yet another insight suggests that risk mitigation strategies resulting from integrated 3S risk assessments can be designed to better account for interdependencies not included within independent "S" assessments.

Building upon several years of similar Sandia analyses, this research further develops a systems-theoretic approach for exploring interdependencies between 3S to mitigate risk complexity in novel nuclear fuel cycle activities. As such, this paper will first offer a summary of the challenges and insights identified in the related to PNR safety, security, and safeguards. Next, the PNR safety, safeguards, and security technical evaluations are summarized. Finally, a preliminary integrated 3S technical evaluation is offered, followed by implications for 3S analysis of PNRs. The results of this analysis suggest that such a systems-theoretic framework could be used to design PNRs before deployment—and evaluate PNRs during deployment—to better account for and manage increasing risk complexity.

INTRODUCTION[1]

Historically, difficulties in siting and constructing nuclear power plants (NPPs) have been substantial barriers to nuclear energy production, particularly in regions with underdeveloped infrastructure. A recently proposed solution involves using power-generating portable nuclear reactors (PNRs) that can be moved between locations. Several nations are beginning to deploy and operate PNRs for commercial power production with different levels of mobility, ranging from the Offshore Floating Nuclear Plant proposed by the Massachusetts Institute of Technology (MIT) [3] to the U.S. Army's mobile nuclear power plant conceptualized to be transported via rail, trailer, water, and air.[4] One category of PNRs in international discussions is floating nuclear power plants (FNPPs), which are maritime vessels assembled at a shipyard, towed to and anchored at a power-generation site, and refueled after exhausting its store of

[1] This conference paper summarizes the final results of References [1] and [2].

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onboard fresh nuclear reactor fuel. An example is Russia's most recent leveraging of its nuclear-powered icebreakers to construct and operate an FNPP. Demonstrating its FNPP prowess, Russia's KLT-40S, *Akademik Lomonosov*, successfully reached the Arctic coastal city of Pevek and was reported to be connected to the local power grid in December 2019 [5] and to have supplied 10GWh of electricity in January 2020.[6]

Many questions remain unanswered about PNRs and how their risks might differ from traditional, land-based reactors. Past incidents involving nuclear-powered vessels highlight new risks for FNPPs.[7] Moreover, because they are maritime vessels, FNPPs are subject to international maritime laws, which are not necessarily compatible (nor coordinated) with nuclear regulations and best practices. Lastly, Russia is reportedly interested in leasing its FNPP to other nations [8], exacerbating the jurisdictional issues and raising new commercial challenges for the international nuclear industry.

Sandia National Laboratories (Sandia) has invested in developing capabilities to address these interdependencies between safety, safeguards, and security.[9] Sandia's *Global Nuclear Security and Assurance*[2] (GNAS) 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 research perspective centers on three useful insights for evaluating risk complexity in safety, safeguards, and security. First, an integrated 3S approach can help identify gaps, interdependencies, conflicts, and leverage points across traditional standalone safety, security, and safeguards analysis techniques. Second, including the interdependencies between safety, safeguards, and security better aligns with real-world operational uncertainties observed in multi-jurisdictional systems. Lastly, risk mitigation strategies resulting from integrated 3S risk assessments can be designed to better account for interdependencies not included in independent "S" assessments.

As a representative PNR, the FNPP is not a new concept and recently has been revisited as a way to use lower-powered reactors at sites that might not be suitable for gigawatt-scale reactors. These technologies have attractive characteristics, including increased granularity of generation (e.g., better able to align with fragile or underdeveloped electrical grids), lower core power, increased flexibility in (temporary) siting and redeployment capabilities, and significant reduction in capital and infrastructure costs. Given the novelty of PNRs in civilian nuclear energy program development, it was prudent to apply Sandia's expertise in nuclear safety, security and safeguards (individually)—and leverage its recent advances in integrated "3S" approaches—to evaluate risk complexity in PNR facilities and activities.[3]

SAFETY, SECURITY, SAFEGUARDS CHALLENGES FOR PNRs

FNPPs have numerous unique characteristics that leave questions unanswered under the current safety, safeguards, and security approaches. The most apparent of these is that FNPPs can be transported as a complete plant, which challenges the conventional approaches to risk reduction. Consider an FNPP with spent nuclear fuel (SNF) returning to a dockyard for servicing and refueling. In this case, spent fuel is transported either in a spent fuel storage room, a spent fuel pool, or within the reactor itself. For example, there is a need to understand if the risk to the SNF is fundamentally different while an FNPP is at sea versus being anchored at a generation site, given the slow speed at which FNPPs are currently planned to be transported and the continued presence of the suite of installed safety systems during transportation. Specific challenges also cut across each 3S discipline. Often, these relate to the decision

[2] The *Global Nuclear Assurance and Security* (GNAS) Sandia mission area initiative seeks to anticipate, assess, and address nuclear risks using advanced systems, technologies, expertise, and situational awareness tools.
[3] For this study, open-source data for the Russian KLT-40S [5] pressurized light water reactor was adapted to provide appropriate details for technical evaluation (see Reference [1] for more details).

of whether to treat an FNPP as a marine vessel or a fixed nuclear facility. For example, because FNPPs will be on waterways and at harbors, any security scenario that involves sinking the vessel will have attached safety considerations from radionuclides potentially leaking into the marine environment and impacting the local commercial and public interests. Additionally, depending on the location of the sinking, the nuclear material in the FNPP may be considered practically unrecoverable or may fall under maritime salvage laws, both of which present safeguards risks.

Given the novelty of PNRs and FNPPs, little analysis is available in the literature, with the primary analysis reported in a preliminary report on the "legal and institutional issues of transportable nuclear power plants" by the IAEA in 2013. [10] Thus, investigating 3S will yield useful insights for risk reduction, despite the lack of available data and documentation. Further, a systems-level analysis that incorporates 3S interactions has the potential to (1) more accurately address 3S challenges; (2) provide a better framework for mitigating complexity; and, (3) assist in developing more effective and efficacious risk-reduction strategies for expected FNPP operations.

SAFETY, SECURITY, SAFEGUARDS TECHNICAL EVALUATIONS FOR PNRs

Safety Technical Evaluation

The preliminary investigation of PNR safety focused its technical evaluation on the event of a Short-Term Station Blackout with a complete loss of all electrical power. This evaluation used MELCOR [11] 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) and ORIGEN-ARP [12] to calculate isotopic depletion, production, and decay of radionuclide inventories. In addition, this investigation identified potential points of interaction with security and safeguards.

This technical safety evaluation explored metrics related to accident sequence progression and subsequent radionuclide releases. Accident sequence metrics quantify the extent of damage to the reactor caused by an initiating event, a component or system failure that may lead to core damage. The following is a representative list of metrics used to quantitatively analyze the severe accident progression:

- Coolant levels in the reactor pressure vessel, safeguards vessel, and containment
- Maximum fuel, cladding, shroud, and supporting structure temperatures
- In-vessel and ex-vessel hydrogen mass
- Percentage of intact fuel relative to the initial core loading
- Timing of key events (e.g., initial uncovering, lower head failure)

The high-level goal of the SMR safety analysis was to characterize the FNPP response and accident sequence under unmitigated short-term station blackout conditions[4]—including identifying the related FNPP 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:

- Radiological release begins at 2.3 hours and is consistent with other Sandia severe accident studies for large, traditional nuclear power plants.
- In the simulation, all fuel is melted in the first 4.3 hours, and the fuel and core material melts through the reactor vessel and into containment at 6.0 hours.

[4] From a security perspective, an unmitigated short-term station blackout represents a bounding, worst-case scenario where an adversary has successfully disabled all engineered safety systems and prevented recovery actions. Typically, these engineered safety systems would be identified as security related target sets through vital area identification.

- No sustained high levels of hydrogen production or reactor vessel, relief tank, or containment pressure were recorded (Figure 1).

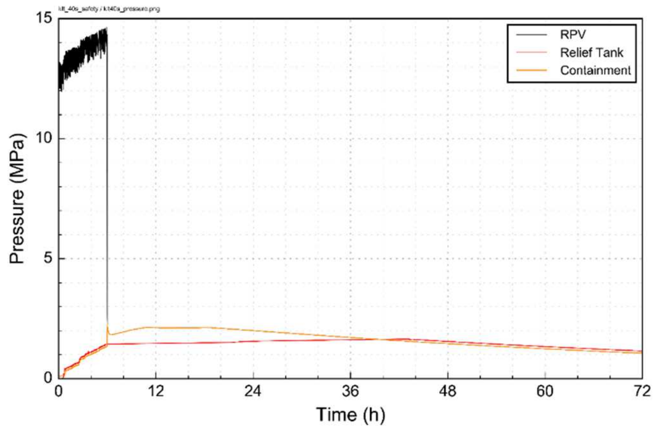

Figure 1. Simulated Fuel Characteristics: Reactor Pressure Vessel, Surge Tank, and Containment Pressure Transients

This work analyzed a conservative severe accident scenario loosely based on a single KLT-40S reactor core using a new MELCOR model created from a combination of open-source design information and a generic PWR model. Despite complete core melt, lower head failure, and containment breach, a limited radionuclide release fraction was predicted. Although no formal consequence analysis was performed for this work, a radiological release of this size is unlikely to produce any prompt fatalities but would likely contaminate the ship and its crew. FNPPs present several unique safety challenges. For example, limited space for onboard engineered safety systems presents few mitigation actions short of sinking the FNPP outright. Exclusion zones might also be problematic, as FNPPs (at worst) may not have or (at best) inconsistently apply such regulations, which creates risk to the public health and safety that an adversary could exploit. Overall conclusions for this FNPP safety technical evaluation include:

- No gross containment failure was predicted because the comparatively large containment volume prevents overpressurization. The lack of containment failure limited the overall radiological release.
- No significant health consequences are predicted: at 72.0 hours, only $3.7x10^{15}$ Bq of iodine and 5.2×10^{13} Bq of cesium (vs. 5.0×10^{17} Bq of iodine and 2.0×10^{16} Bq of cesium from the Fukushima accidents [13]).
- If an adversary were to disable all onboard engineered safety systems, few mitigative actions would be possible short of scuttling the FNPP outright.

Safety implications include accounting for how physical space/weight constraints impacts the type (and amount) of onboard safety systems and the need to further investigate containment failures (e.g., ablation of the FNPP floor). Ultimately, this analysis was a conservative first-order estimate of KLT-40S reactor safety. Additional work is necessary to more accurately quantify the impact of a KLT-40S severe accident within the scope of an integrated 3S study; including the need to obtain more detailed design information about the reactor systems, structures, and components. Despite the approximations used, the estimated radiological releases are in line with existing light water reactor studies.

Safeguards Technical Evaluation

The preliminary investigation of PNR safeguards focused its technical evaluation on attempted diversion (or production) of special nuclear materials—particularly in the context of International Atomic Energy Agency (IAEA) best practices (e.g., comprehensive safeguards agreements). This evaluation used a

Markov Chain[5]-based lifecycle stage model (Figure 2) to represent the FNPP in terms of key safeguards characteristics, such as total significant quantities [SQ] and specific diversion concerns at each lifecycle stage.

More specifically, this technical evaluation conducted a policy-based review of practices related to the global safeguards regime and reporting considerations for each operational stage within the FNPP lifecycle. A complementary material-based analysis to characterize the proliferation attractiveness of the special fissile material (SFM) inventory was performed for all identified material stages. In addition, this investigation attempts to locate potential points of interaction with security and safety.

At the heart of the international safeguards regime is the technical characterization of the nuclear material to be safeguarded. The following material type, form, quantity, and operational assumptions were investigated:

- UO_2 fuel was enriched to 18.6 mass percent U-235, with no burnable poison rods in the core
- A 36-month refueling interval, single loading, with full replacement of fuel assemblies
- State of origin (SoO) is a Nuclear Weapons State (NWS) and producer of FNPP
- State of use (SoU) is a non-NWS, is party to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), has an Additional Protocol (AP) in force, has no existing nuclear fuel cycle activities, and will declare FNPP procurement during the building phase

The high-level goal of the FNPP safeguards analysis was to characterize how related facilities respond to attempts to divert and process SNM—including describing how FNPPs challenge current safeguards approaches, determining the proliferation attractiveness of FNPP SNM, investigating ability for FNPPs so support a "break out" capability, and identifying the most vulnerable conditions for diversion for FNPPs. The results are summarized on a "per-stage" basis in Figure 2. Key results from this technical evaluation included that safeguards reporting by the SoU is expected, although the SoO develops and builds the FNPP. Similarly, the ease of relocating the FNPP could make annual reporting of the facility's location inadequate because the current location might differ significantly. In response, modeling anticipated FNPP operations as individual stages (Figure 2 & 3) helps clarify related safeguards risks and identify potential mitigation.

Most safeguards challenges identified in this study involve when and how the SOU will be responsible for reporting activities during each stage of the FNPP operational lifecycle. Evaluation of the FNPP nuclear materials inventory in standard use does not indicate any significant safeguards concerns outside those for an equivalent land-based reactor. Using LEU of almost 20 percent U-235 raises general proliferation concerns because much of enrichment to achieve weapons-grade levels as defined by the IAEA has been performed already. Further, diverting single assemblies from the system is not an attractive option for clandestine proliferants because each fresh assembly contains only 0.36 of an LEU SQ, which necessitates diverting three full assemblies for a goal quantity. Given the shortcomings in current Comprehensive Safeguards Agreements (CSA) and AP guidance for FNPPs, the cooperation of the SoO and SoU with the IAEA will significantly impact implementing safeguards with strong partnerships ensuring adequate design inspection verification and material accountancy throughout the FNPP lifecycle. Overall conclusions for this FNPP safeguards technical evaluation include:

- Diversion of single assemblies is not an attractive option because each fresh assembly contains only 0.36 of an LEU SQ, which then would need significant additional processing.

[5] Markov Chains are stochastic models of possible events in which the probability of each event depends on the previous state.

- Cases in which the SoU breaks their international treaty obligations are the most concerning for safeguards because the FNPP contains nontrivial amounts of nuclear material.
- Specific technologies that are not currently used in safeguards will need to be implemented for containment and surveillance of FNPPs, given their transportability.

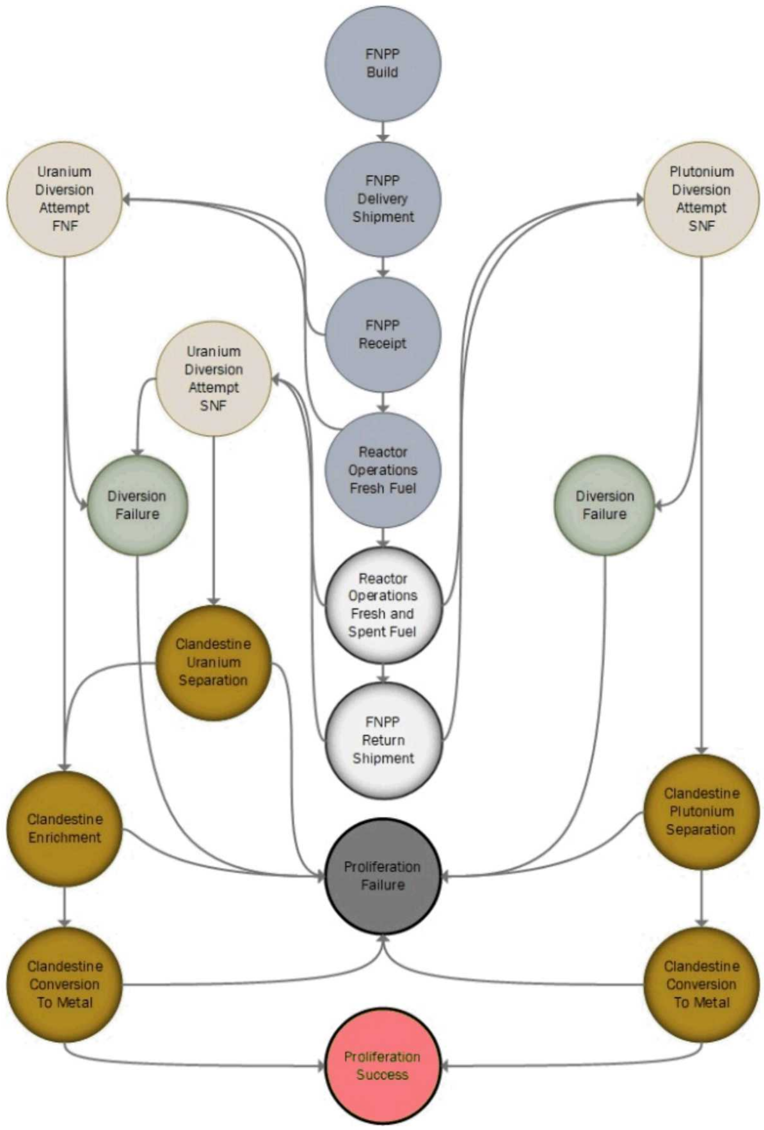

Figure 2. Markov Chain Illustrating Potential Diversions during FNPP Lifecycle

FNPP operations will challenge the traditional safeguards regime (perhaps including renewed evaluation of the underlying assumptions of reporting expectations) and accounting for the susceptibility of the entire FNPP vessel to be diverted (and subsequently hidden in international or transboundary waters) as novel "breakout" scenarios.[6] *Ultimately, this analysis was a preliminary investigation of FNPP safeguards. The FNPP's highly mobile nature, paired with its ability to store six cores of fresh and spent fuel, pose serious and difficult challenges to the safeguards and nonproliferation communities. Additional analyses will be required when additional details of the reactor's materials become public.*

[6] Appendix D in Reference [1] outlines a potential breakout use case, in which an FNPP is used to support a domestic nuclear weapons program.

Security Technical Evaluations

The preliminary investigation of PNR security focused its technical evaluation on 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.[15] The IAEA Nuclear Security Series documents were also assessed with regards to their potential ability to guide best practices and policies for the FNPP. The high-level goal of the FNPP security technical evaluation was to characterize the effectiveness of the PPS against an adversary force completing a sabotage mission. In addition, this investigation attempts to locate potential points of interaction with safeguards and safety.

Models of technical and nontechnical characteristics were developed to support this FNPP security technical evaluation, including the unique sociopolitical considerations that nuclear security best practices must align with maritime policies, such as the United Nations (UN) Convention for the Law of the Sea and International Convention for the Safety of Life at Sea. It is also noteworthy that international best practices and regulations struggle to accurately address expected FNPP security-related operations. Additionally, the technical considerations presented a different challenge and required developing security postures and anticipated operations built from international best practices:

- FNPPs will operate in one of four distinct states: in port, underway from the port, underway in territorial waters, or underway in international waters (Figure 3).
- Fresh and spent fuel and liquid waste kept onboard for the operational lifecycle of the FNPP, with sufficient storage to hold three inventories of spent fuel.
- Detection, assessment, delay, and response methodologies depend on several factors, including the geographic location and position of FNPP in the four locations.
- Three variables were used to determine unique attack scenarios for FNPPs: adversary attack goals, possible attack locations, and adversary group.

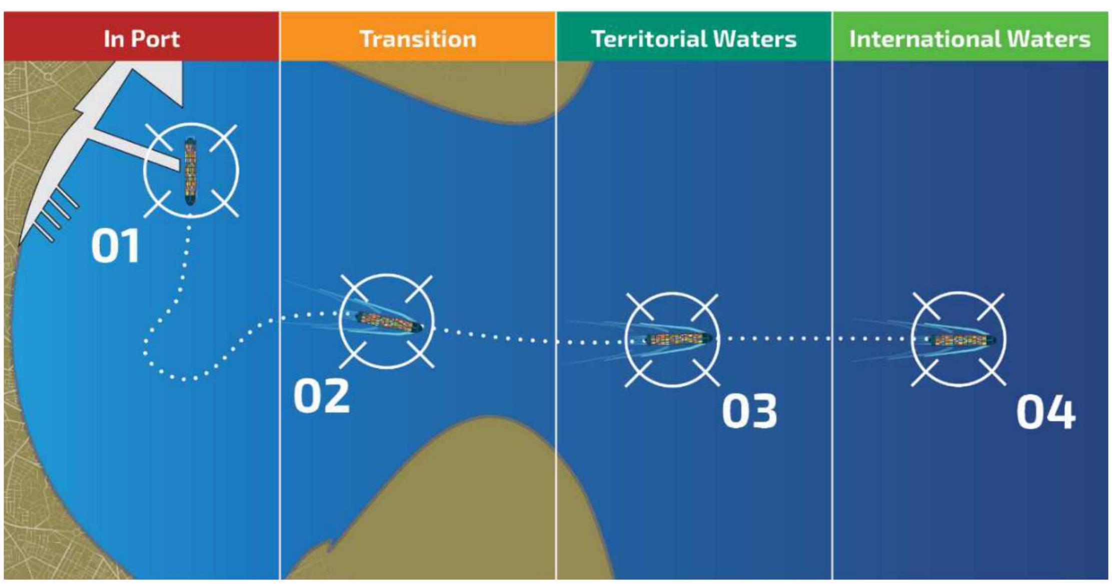

Figure 3. Key Security Challenges and Implications Mapped to the Visual Model of Key Locations of Security Concern for FNPPs

Key results from this technical evaluation include the need for performance testing for off-site response to establish response timelines, jurisdiction, and responsibilities for locations of the FNPP. Furthermore, advances in detection and delay technologies and procedures to account for possible underwater attack paths should be investigated. Sociopolitically, challenges exist between traditional nuclear security approaches and the policy implications of international maritime law. Technological shortcomings also exist in nuclear security for FNPPs. These include the need to develop—and performance test—novel detection and delay systems sufficient for the four expected FNPP locations and while the FNPP is both stationary and moving. Meeting the response objectives for FNPPs poses the most challenges to nuclear security, with a clear need to clarify stakeholder responsibilities across the four locations of expected FNPP operations (Figure 3). Overall conclusions for this FNPP security technical evaluation include:

- The expected FNPP operations identified in the scenarios will challenge conventional nuclear security approaches supported by international guidance documents.
- The response objectives for FNPPs will be challenging (e.g., regional or international cooperation regarding seizure of an FNPP in territorial or contiguous waters).
- Technological shortcomings also exist for nuclear security of FNPPs, including solutions for detection and delay as related vessels move through narrow or crowded port areas.

This technical evaluation also identifies security implications for FNPPs, including (but not limited to) the need for:

- performance testing for detection, assessment, delay, and response systems
- guidance documents authored to account for the four FNPP locations
- international cooperation (led by the IAEA) to write and establish security guidance for FNPPs
- incorporating the United Nations into these efforts due to legal concerns related to protecting—and responding to attacks on—FNPPs.

Ultimately, this analysis was a preliminary investigation of FNPP security. While these challenges may seem daunting, they also represent opportunities to define and develop new solutions, as well as procedural or system design approaches for mitigating these dynamic FNPP security risks.

INTEGRATED 3S TECHNICAL EVALUATION FOR PNRs

This technical evaluation was a preliminary 3S investigation of PNRs—and FNPPs more specifically—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 PNRs, locating where safety, safeguards, and security for PNRs are interdependent, and determining how these points of interdependence influence the key analysis questions, conclusions, and 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 FNPP operational realities. Though perhaps obvious, these interdependencies (Table 1) are not often accounted for in individual technical analyses, and may challenge individual "S" regimes, as summarized [1].

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 several interdependencies *did* present significant challenges to the ability of traditional safety, safeguards, and security mitigations for anticipated FNPP operations. These interdependencies *did* identify potential mechanisms for gaining efficiency in reducing 3S risk for FNPPs. One particular interdependence—the multiple interpretations of international maritime law for stakeholder responsibility among territorial and international waters—*did directly* challenge assumptions supporting current safety, security, and safeguards practices. By implication, such challenges support further exploration to identify specific gaps or conflicts in traditional regulatory, legal, and operational regimes. The interdependent impacts and implications of two particular events—the FNPP scuttling and potential loss of control of the *entire* FNPP—should be further explored. For example, although scuttling might prevent an initial attack from succeeding, it raises questions about how to and who would be responsible for reporting and verifying the quantities of material. Taken together, these results suggest a need—and provides a way—to initiate engagement efforts to help design PNR/FNPP facilities, systems, and activities (especially those in new nuclear countries) more capable of managing complex 3S risks.

Table 1. Points of Interdependence between Safety, Safeguards, and Security for PNRs and FNPPs.

Safety Effects	Security Effects	Safeguards Effects	Explanation
Scuttling the FNPP as a last-ditch response to an accident	Questions regarding protection responsibilities	Questions regarding reporting and accountancy responsibilities	Although large bodies of water might provide an "ultimate heat sink" to mitigate severe accidents, scuttling FNPPs poses significant security and safeguards challenges simultaneously, notably who is responsible for ensuring that the nuclear material is not accessed and used maliciously?*
N/A	Theft of the entire FNPP vessel	Potential to create a breakout capability	The potential for the entire FNPP vessel to be controlled by malicious actors, particularly in international waters, poses unique (and amplifying) security and safeguards challenges.
Weight/space limits to available active & passive safety systems	Fewer additional potential targets	N/A	Limiting the numbers and types of safety systems increases the chances of a safety incident, while simultaneously not offering new targets by which to damage FNPP operations.
Local or host site-level safety evaluation of FNPP operations	Challenges to insider threat mitigation	Increased opportunity for safeguards inspections**	Increased host site-level safety evaluations might increase operational safety while providing opportunities for safeguards inspections frequency, which simultaneously increases opportunities for insiders' malicious acts.

* Additionally, where the FNPP is scuttled will determine which laws apply regarding maritime salvage operations in territorial or international waters.
** Alternatively, if the increased host site-level safety evaluations are not used as opportunities for safeguards inspections, then the safeguards risk increases and associated opportunities for insider acts decreases.

CONCLUSIONS

Overall, this preliminary GNAS 3S analysis identifies several interesting and insightful observations regarding anticipated safety, safeguards, and security for PNRs. Given Russia's recent deployment of the *Akademik Lomonosov* FNPP and the technology's potential attractiveness, this technical evaluation provides timely implications and possible next steps. The safety technical evaluation concluded that no significant public health impacts are expected, but it also indicated that FNPPs pose unique safety challenges, given the space and weight constraints for additional mitigation. The safeguards technical evaluation described areas in which the current INFCIRC 153-based regime can help ensure that FNPPs are used for peaceful purposes. It also identified key challenges to related policy and technical mitigations. Last, the security technical evaluation identified significant challenges to current approaches, including procedural and jurisdictional ambiguity and shortcomings in technological solutions to meet traditional detection, delay, and response objectives.

From an integrated 3S perspective, the ease of moving FNPPs between multiple jurisdictions directly challenges conventional approaches to nuclear safety, safeguards, and security. As summarized in Table 1, several interdependencies significantly challenge economical and efficacious FNPP operations—but others help identify areas for efficiently reducing 3S risks for FNPPs. The identified interdependencies are subject to operations-specific contextual factors (e.g., mitigations might look different in Malaysia than in the United States), but they also must align with international maritime laws and the multiple interpretations of them. These preliminary *qualitative* results should be validated with additional, more in-depth *quantitative* analysis. As such, these conclusions and implications serve as waypoints for completing the next steps toward advancing the technical understanding of 3S for PNRs and FNPPs. The results of this analysis suggest that such a systems-theoretic framework could be used to design PNRs before deployment—and evaluate PNRs during deployment—to better account for and manage increasing risk complexity.

REFERENCES

[1] A. D. Williams, et. al, “System Studies for Global Nuclear Assurance & Security: 3S Risk Analysis for Portable Nuclear Reactors (Volume I)—Technical Evaluation of Safety, Safeguards, & Security [Official Use Only] (SAND2020--4273),” Sandia National Laboratories, Albuquerque, NM, 2020.

[2] A. D. Williams and D. Osborn, “System Studies for Global Nuclear Assurance & Security: 3S Risk Analysis for Portable Nuclear Reactors (Volume II)—Conclusions & Implications (SAND2020-4688),” Sandia National Laboratories, Albuquerque, NM, 2020.

[3] J. Buongiorno, et. al, "Offshore Small Modular Reactor (OSMR): An Innovative Plant Design for Societally Acceptable and Economically Attractive Nuclear Energy in a Post-Fukushima, Post-9/11 World," in ASME 2014 Small Modular Reactors Symposium, Washington, DC, 2014.

[4] J. A. Vitali, et, al, "Study on the Use of Mobile Nuclear Power Plants for Ground Operations," U.S. Army Deputy Chief of Staff, G-4, 2018.

[5] AP News, "Russia's Floating Nuclear Plant Sails to Its Destination," AP News, 8(23), 23 August 2019.

[6] Nuclear Engineering International, "Russian floating nuclear plant supplies 10GWh of electricity to Chukotka," Nuclear Engineering International Magazine, 27 January 2020.

[7] W. M. Arkin and J. M. Handler, "Nuclear Disasters at Sea, Then and Now," Bull. Atom. Sci, 45(6), 1989.

[8] Nuclear Threat Initiative, "Akademik Lomonosov," 9 June 2014. [Online]. Available: https://www.nti.org/learn/facilities/942/. [Accessed 15 November 2019].

[9] A. D. Williams, et. al, , "System Theoretic Frameworks for Mitigating Risk Complexity in the Nuclear Fuel Cycle (SAND2017-10243)," Sandia National Laboratories, Albuquerque, NM, 2017.

[10] International Atomic Energy Agency, "KLT-40S," 2013.

[11] L. L. Humphries, et. al, "MELCOR Computer Code Manuals, Vol. 1: Primer and Users' Guide, Version 2.2.9541," Sandia, Albuquerque, NM, 2017.

[12] M. Bell, "ORIGEN: The ORNL Isotope Generation and Depletion Code," Oak Ridge Nat. Lab., 1973.

[13] Tokyo Electic Power Company Holdings, "The Estimated Amount of Radioactive Materials Released into the Air and the Ocean Caused by Fukushima Daiichi Nuclear Power Station Accident Due to the Tohoku-Chihou-Taiheiyou-Oki Earthquake (As of May 2012)," 24 May 2012. [Online]. Available: http://www.tepco.co.jp/en/press/corp-com/release/2012/1204659_1870.html. [Accessed 18 March 2020].

[14] M. Yue, L. Cheng and R. Bari, "PRCALC - A Software Tool for Proliferation Resistance and Physical Protection Assessment: Algorithm, Modeling, and User's Guide (Draft)," Brookhaven Nat. Lab., 2008.

[15] M.L. Garcia, The Design and Evaluation of Physical Protection Systems (2nd Ed.), 2008.