SANDIA REPORT
SAND2020-4688
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Sandia National Laboratories

System Studies for Global Nuclear Assurance and Security (GNAS):

3S Risk Analysis for Portable Nuclear Reactors (Volume II) — *Conclusions and Implications*

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ABSTRACT

Growing interest in compact, easily transportable sources of baseload electricity has manifested in the proposal and early deployment of portable nuclear reactors (PNRs). PNRs are sought because they are scalable, efficient, and cost-effective for meeting energy demands in unique, remote, or contested areas. For example, Russia's KLT-40S *Akademik Lomonosov* is a floating nuclear power plant (FNPP) that successfully reached the Arctic coastal city of Pevek. It began providing power to the local grid in December 2019. While providing such key advantages as having a highly flexible power generation mechanism, FNPPs appear to directly challenge international norms and conventions for nuclear safety, safeguards, and security. FNPPs are neither a purely fixed nuclear fuel cycle activity nor a purely transportation-based nuclear fuel cycle activity. In response, Sandia's *Mitigating International Nuclear Energy Risks* (MINER) research perspective frames this discussion in terms of risk complexity and the interdependencies between safety, safeguards, and security in FNPPs, and PNRs more generally. This systems study is a technically rigorous analysis of the safety, safeguards, and security risks of FNPP technologies. This research's aims are three-fold. The first aim is to provide analytical evidence to support safety, safeguards, and security claims related to PNRs and FNPPs (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 show Sandia's ability for prompt, rigorous, and technical analysis to support emerging complex MINER mission objectives.

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ACRONYMS AND DEFINITIONS

Acronym	Definition
AC	alternating current
AP	Additional Protocol
CSA	Comprehensive Safeguards Agreement
DC	direct current
DEPO	design evaluation protection outline
DOE	Department of Energy
FNPP	floating nuclear power plant
GNAS	Global Nuclear Assurance and Security
IAEA	International Atomic Energy Agency
INFCIRC	Information Circular, International Atomic Energy Agency
LEU	low-enriched uranium
MACCS	MELCOR Accident Consequence Code System
MELCOR	Methods for Estimation of Leakages and Consequences of Releases (U.S. NRC)
MINER	Mitigating International Nuclear Energy Risks
MIT	Massachusetts Institute of Technology
MW	megawatt
N/A	not applicable
NPP	nuclear power plant
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRC	Nuclear Regulatory Commission
NWS	nuclear weapon States
OSMR	offshore small modular reactor
PNR	portable nuclear reactor
PPS	physical protection system
PWR	pressurized light water reactor
R&D	research and development
RPV	reactor pressure vessel
SFM	special fissile material
SMR	small modular reactor
SNF	spent nuclear fuel
SoO	State of origin
SoU	State of use
SQ	significant quantity
STSBO	short-term station blackout
UN	United Nations
USACE	U.S. Army Corps of Engineers

1. INTRODUCTION

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 with different levels of mobility, ranging from the Offshore Floating Nuclear Plant proposed by the Massachusetts Institute of Technology (MIT) [1] to the U.S. Army's mobile nuclear power plant conceptualized to be transported via rail, trailer, water, and air. [2]

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 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 (Figure 1) and was reported to be connected to the local power grid in December 2019 [3] and to have supplied 10GWh of electricity in January 2020 [4].

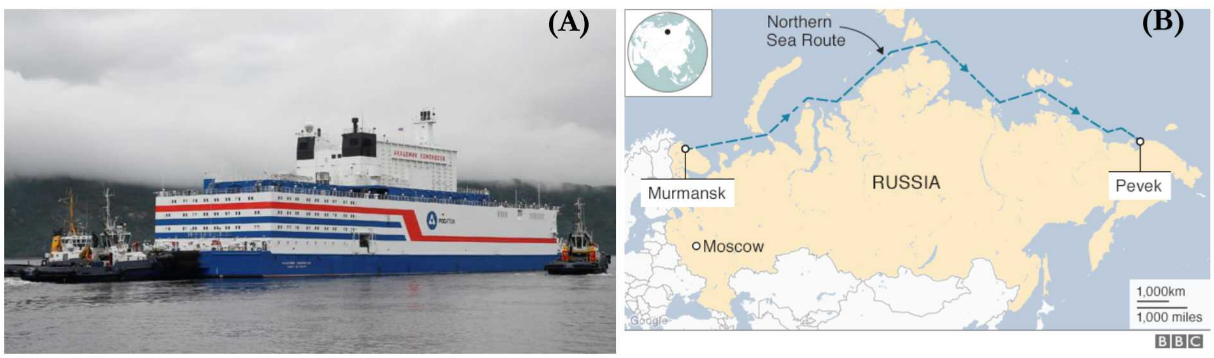


Figure 1. (A) *Akademik Lomonosov* Floating Nuclear Power Plant; (B) Route Traveled to Reach the Arctic Coastal City of Pevek, Russia (as reported by [3])

Many questions remain unanswered about PNRs and how their risks might differ from traditional, land-based reactors. For example, past incidents involving nuclear-powered vessels highlight new risks for FNPPs. [5] 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 [6], exacerbating the jurisdictional issues and raising new commercial challenges for the United States.

Sandia National Laboratories (Sandia) has been developing capabilities to address the interdependencies between safety, safeguards, and security (3S) in the nuclear fuel cycle, including a recent report on PNRs/FNPPs. [7] The implications of recent research indicate that 3S interdependent risks are inherent in nuclear fuel cycle activities and can remain unidentified when each *S* is evaluated independently. [8], [9] Sandia's *Mitigating International Nuclear Energy Risk* (MINER) research perspective frames this discussion in terms of risk complexity and the interdependencies between safety, safeguards, and security in PNRs, and FNPPs more specifically. This systems study is a technically rigorous analysis of the 3S risks of FNPP technologies.

1.1. The Portable Nuclear Reactor Context

As a representative PNR, the FNPP is not a new concept, as evidenced by the U.S. Army Corps of Engineers (USACE) MH-1A reactors. Housed on a vessel called the *Sturgis*, the 10 MW MH-1A reactor was towed to provide electricity to the Panama Canal Zone. [10] As PNRs, FNPPs have 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.

For this study, open-source data for the Russian KLT-40S reactor was adapted to provide appropriate details for technical evaluation (Appendix A of [7]). The KLT-40S is a pressurized light water reactor (PWR) based on the KLT-40 icebreaker reactor design that uses low-enriched uranium (LEU) for power generation and desalination. [3], [11] Although technical descriptions vary between sources, the consensus is that, with 121 hexagonal fuel assemblies with uranium dioxide (UO_2) fuel particles dispersed in an aluminum matrix [11], this reactor core can produce a maximum output of 150 MW of thermal energy, each reactor loop has its own steam generator and coolant pump, and the steam generators are once-through with helical coils. [12]

1.2. 3S Context and Analytical Approach

In [8] and [9], Sandia demonstrated that risk stems from interactions between technical, human, and organizational influences within various nuclear fuel cycle activities. These Sandia studies also offer three useful conclusions for evaluating risk complexity in safety, safeguards, and security for PNRs and FNPPs. First, integrated 3S approaches can help identify gaps, interdependencies, conflicts, and leverage points between 3S activities. Second, including the interdependencies between safety, safeguards, and security better aligns with real-world operational uncertainties to better describe risk complexity in multimodel, multijurisdictional systems, which fittingly describes FNPPs. Third, risk-mitigation strategies resulting from integrated 3S analysis can be designed to better account for interdependencies not included in independent *S* assessments. By extension, this framework could be used to evaluate FNPPs—and PNRs, more generally—as a systems-level whole to better characterize, evaluate, and manage increasing risk complexity.

1.3. Objectives for this MINER Systems Study

This Sandia study provides a technically rigorous analysis of the 3S risks for FNPPs. The aim of this research is three-fold. The first aim is to provide analytical evidence to support 3S claims related to FNPPs (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 show Sandia's ability for prompt, rigorous, and technical analysis to support complex MINER mission objectives.

The remainder of this volume includes these discussions:

- A summary of the challenges and insights identified in the current literature on FNPP 3S.
- Summaries of the 3S technical evaluations of FNPPs.
- Preliminary integrated 3S technical evaluation of FNPPs.
- Implications and next steps for 3S analysis of FNPPs.

1.4. 3S Gaps, Challenges, and Looking Forward

FNPPs have unique characteristics that present difficulties under current 3S approaches. The most apparent of these is that FNPPs can be transported as a complete plant in a manner that challenges conventional approaches to risk reduction. Consider an FNPP returning with spent nuclear fuel (SNF) to a dockyard for servicing and refueling, which raises questions related the appropriateness of treating an FNPP as a "traditional" transportation of nuclear material and the changing risk profiles of the nuclear material as the FNPP moves from international waters, through territorial waters, and into port. The FNPPs' selling point of portability presents deeper challenges to ensuring safe, secure, and safeguarded FNPP operations.

Also, specific challenges cut across each 3S discipline, stemming from the decision of whether to treat an FNPP as a marine vessel in transit or a fixed nuclear facility. For example, because FNPPs will be on waterways and at harbors, security scenarios might involve safety considerations from a potential radionuclide leak on a sinking FNPP. Additionally, depending on where the sinking occurs, the nuclear material in the FNPP might be practically unrecoverable (though, consider salvage ownership rights under international maritime law), presenting safeguards risks.

Given the novelty of PNRs and FNPPs, little analysis is available in the literature. Thus, investigating a systems-level analysis and incorporating the interactions between safety, security, and safeguards might more accurately address 3S challenges to provide a better framework for mitigating complexity in, and assist in developing more efficacious risk-reduction strategies for FNPP operations.

2. TECHNICAL EVALUATION SUMMARIES

2.1. Safety Analysis

2.1.1. Approach, Scope, and Key Technical and Sociopolitical Considerations

The purpose of this technical evaluation is to simulate worst-case accident sequences involving a single KLT-40S core. Even if conservatively done, quantifying such metrics informs response timelines and possible consequences from a core melt event and provides the foundation for exploring mitigations to improve FNPP safety. Additionally, this investigation attempts to locate potential interactions between safety with security and safeguards.

2.1.1.1. Tools and Methods

- MELCOR is a fully integrated severe accident analysis code that includes the thermal-hydraulic response, core degradation, material relocation, core-concrete attack, flammable gas production and combustion, and fission product release and transport behavior. [13]
- ORIGEN-ARP is an automated sequence to perform isotopic depletion, production, and decay calculations to generate the initial core radionuclide inventory. [14]

Models of both technical and nontechnical characteristics were developed to support this technical evaluation of FNPP safety. The following are the primary sociopolitical considerations:

- Using an unmitigated short-term station blackout (STSBO) scenario, which is widely considered a "worst case scenario," providing a simplification for first-order safety analysis.
- Strong social, political, and cultural forces that assume the importance of safety, inherent in commercial nuclear applications.
- Other sociopolitical considerations were mostly assumed to be inconsequential.

However, the technical considerations presented a different challenge and required developing reactor operation models from the scant technical data available in the open literature:

- Single-assembly scaling was sufficient, representing a theoretical upper bound for accidents.
- The radionuclide inventories were calculated by assuming that 5.064 kg of ^{235}U and 22.166 kg of ^{238}U (per fuel assembly) were irradiated at 1.240 MW for 3 years without downtime.
- MELCOR was designed to simulate UO_2 fuel only, not the reported UO_2-Al fuel.
- The core was modeled as three rings of five equally spaced axial levels, with decay heat partitioned across core cells with a generic PWR power profile.
- Each listed phenomenon would impact core degradation and accident sequences.

2.1.2. Key Analysis Questions

The high-level goal of the FNPP safety evaluation was to characterize the FNPP response and accident sequence under STSBO[1] conditions without operator intervention. An STSBO is the total

[1] From a security perspective, an unmitigated STSBO represents a bounding worst-case scenario in which an adversary successfully disables all safety systems and prevents any operator recovery actions.

loss of alternating current (AC) and direct current (DC) power sources and therefore all safety systems and instrumentation.

Within this technical evaluation were key analysis questions:

- What is the accident sequence for the FNPP under unmitigated STSBO conditions?
- What if any radionuclide releases are caused by the accident sequence?
- Could an adversary's sabotage increase the radionuclide release by damaging containment?

2.1.3. Key Results, Conclusions, and Implications

2.1.3.1. Key Results

- Radiological release begins at 2.29 h and is consistent with other Sandia severe accident studies for large, traditional nuclear power plants.
- In the simulation, all fuel is melted by 4.3 h, and the fuel and core material melts through the reactor vessel and into containment at 6.01 h.
- No sustained high levels of hydrogen production or reactor vessel, relief tank, or containment pressure were recorded.

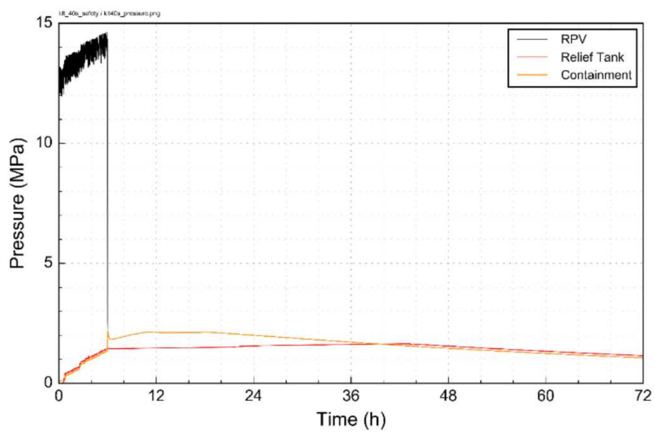


Figure 2. Simulated Fuel Characteristics: RPV, Surge Tank, and Containment Pressure Transients

2.1.3.2. Conclusions

- No gross containment failure was predicted because the comparatively large containment volume prevents overpressurization. The lack of containment failure limited the overall release.
- No significant health consequences are predicted because, at 72.0 h, only 3.7×10^{15} Bq of I and 5.2×10^{13} Bq of Cs (vs. 5.0×10^{17} Bq of iodine and 2.0×10^{16} Bq of cesium from the Fukushima accidents [15]) is predicted to be released. The release fractions are comparable to previous light water reactor accident studies that estimated no fatalities [16] [17].
- If an adversary were to disable all onboard safety systems, few mitigative actions would be possible short of sinking the FNPP outright.

2.1.3.3. Implications

- Limited physical space and weight constraints impact the type and amount of passive and active safety systems that can be on board FNPPs.
- Although no significant radiological release was identified, future safety analysis should further explore containment breaks (e.g., ablation of the floor).
- At worst, FNPPs might not have or, at best, inconsistently apply exclusion zones, creating both public health risks and security vulnerabilities that adversaries could exploit.

2.2. Safeguards Analysis

2.2.1. Approach, Scope, and Key Technical and Sociopolitical Considerations

This technical evaluation is a preliminary investigation to support the primary safeguards objective of preventing the production or diversion of special nuclear materials. This study evaluates FNPP safeguards implementation in the context of best practices for Comprehensive Safeguards Agreements (CSA) with the International Atomic Energy Agency (IAEA). Additionally, this investigation aims to locate potential points of interaction between security and safety.

2.2.1.1. Tools and Methods

- Policy-based review of practices related to the global safeguards regime and reporting considerations for each operational stage within the FNPP lifecycle.
- Material-based analysis to characterize the proliferation attractiveness of the special fissile material (SFM) inventory was performed for all identified material stages.

Risk evaluation for FNPPs also must address these significant differences in sociopolitical context to effectively mitigate new safeguards risks:

- General IAEA reporting requirements considered to be relevant to FNPPs by a State with both a CSA and an Additional Protocol (AP) in force.
- Despite well-established reporting procedures and declaration protocols, several scenarios appear to challenge the efficacy and effectiveness of current safeguards approaches.
- A scenario involving FNPPs constructed, and shipped by a nuclear weapons State (NWS) to a non-nuclear weapons State (non-NWS) does not align with conventional reporting
- Safeguard concerns include FNPPs not following historical trends, which are similar to safeguards concerns for small modular reactors (SMR).

At the heart of the international safeguards regime is the technical characterization of the nuclear material to be safeguarded, including determining the material type, form, and quantity:

- Assumption that UO_2 fuel was used with an enrichment of 18.60 mass percent U-235, with no burnable poison rods included in the core.
- A 36-month refueling interval, single loading, with full replacement of fuel assemblies.
- State of origin (SoO) is an NWS and producer of FNPP.
- State of use (SoU) is a non-NWS, is party to the NPT, has an AP in force, has no existing nuclear fuel cycle activities, and will declare FNPP procurement during the building phase.

2.2.2. Key Analysis Questions

The high-level goal of the FNPP safeguards analysis was to characterize responses to attempts to divert and process special nuclear materials. This technical evaluation included key analysis questions:

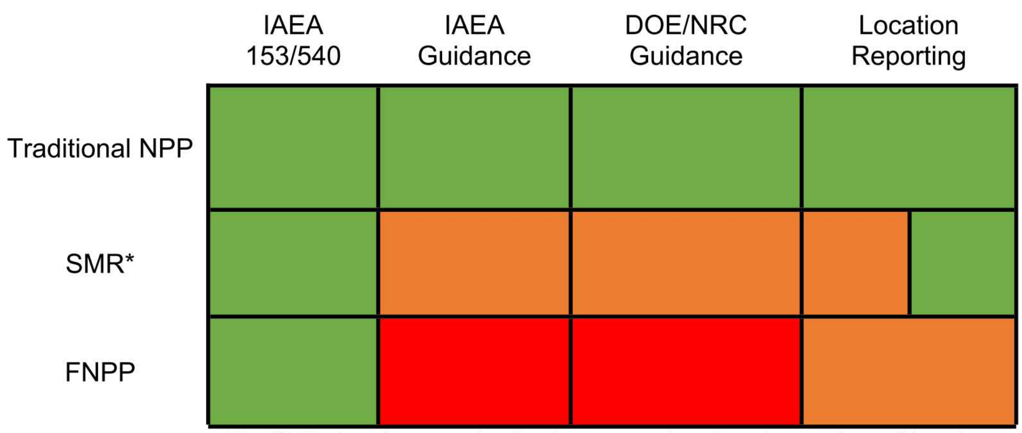
- How will the FNPP reactor operations challenge current approaches to safeguards?
- What is the proliferation attractiveness of the nuclear materials in FNPPs?

- If diversion were protracted, how many assemblies would be needed to reach a significant quantity (SQ) of material before the FNPP is returned to the SoO for refurbishment?
- Could the FNPP be used to break out of safeguards and start a weapons material production program?

2.2.3. Key Results, Conclusions, and Implications

2.2.3.1. Key Results

- Safeguards reporting by the SoU is expected, although the SoO develops and builds the FNPP.
- The ease of relocating the FNPP could make annual reporting of the facility's location inadequate because the current location might differ significantly.
- Modeling anticipated FNPP operations as individual stages helps clarify related safeguards risks and identify potential mitigation.



*For SMRs, location reporting for the construction phase is maturing and learning (orange), while the operations phase is mature and expert (green). Red indicates nonexistent or nascent.

Figure 3. International Safeguards Implementation Documentation and Guidance Maturity for Existing NPP, SMR, and FNPP Technology

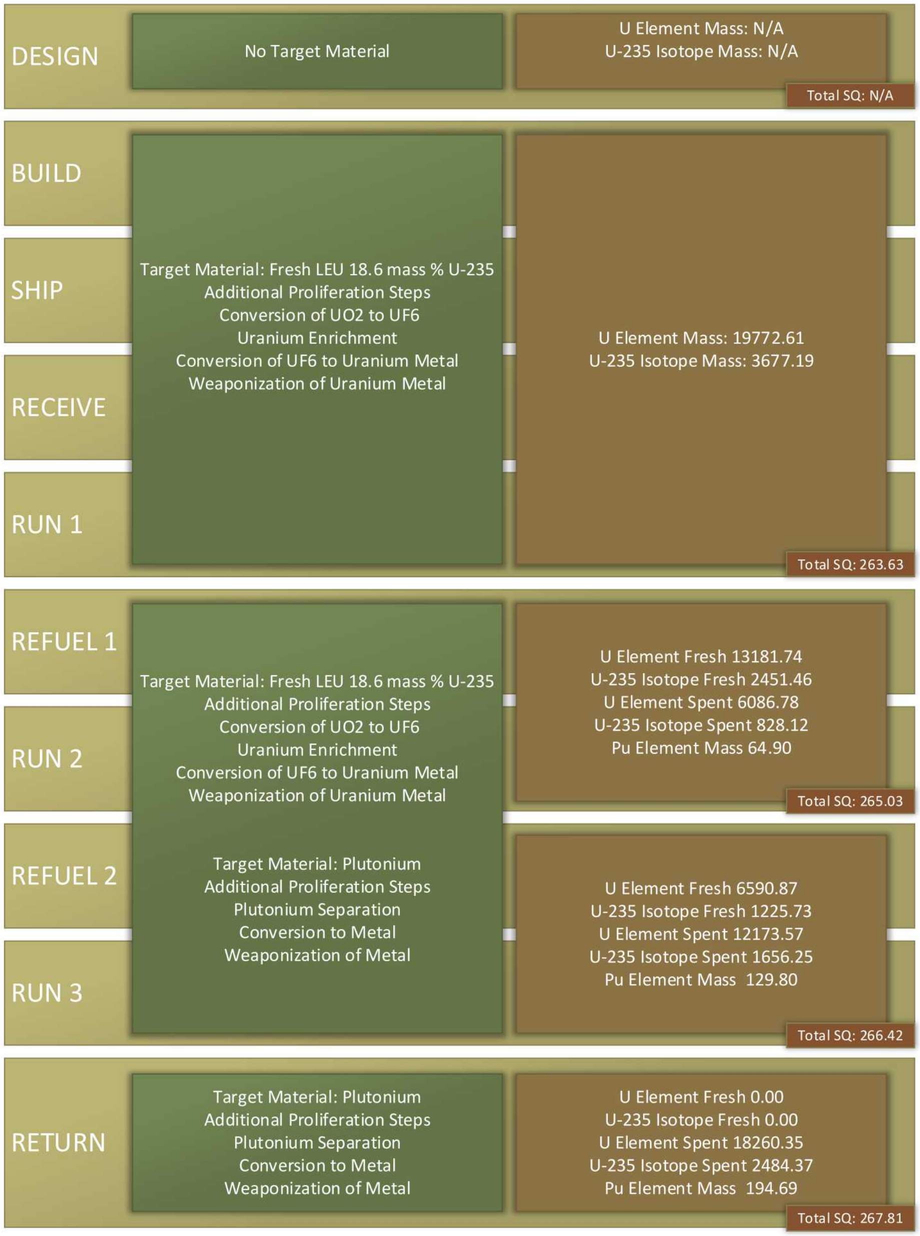


Figure 4. Nuclear Material Constituent Process Flow though the FNPP Operational Lifecycle Stages (all mass quantities in kilograms)

2.2.3.2. Conclusions

- Diversion of single assemblies is not an attractive option because each fresh assembly contains only .36 of an LEU SQ, which then would need significant additional processing.
- 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.

2.2.3.3. Implications

- Anticipated FNPP operations significantly challenge the traditional safeguards regime, necessitating renewed evaluation of the underlying assumptions of reporting expectations.
- The susceptibility of the entire FNPP vessel to be diverted, and subsequently hidden in international or transboundary waters, introduces novel "breakout" scenarios.

2.3. Security Analysis

2.3.1. Approach, Scope, and Key Technical and Sociopolitical Considerations

This technical evaluation is a preliminary investigation of FNPP security against a range of potential adversaries aiming to steal or damage nuclear materials. Because of their mobility, commercial identity, and foreign travel relative to the operating nation, traditional physical protection approaches might not address expected FNPP operations. Additionally, this investigation attempts to locate potential interactions of safeguards and safety.

2.3.1.1. Tools and Methods

- The design evaluation process outline (DEPO) method might not address the concerns raised with mobile reactors. The traditional DEPO approach is a systematic method for defining physical protection system (PPS) objectives, the design of the system, and the evaluation and redesign if necessary. [18]

Models of technical and nontechnical characteristics were developed to support this FNPP security technical evaluation, including these primary sociopolitical considerations:

- 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.
- International best practices and regulations struggle to accurately address expected the FNPP security-related operations.
- Extensive coordination among large and diverse sets of stakeholders is expected to meet response-related nuclear security objectives.

However, 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.
- 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.

2.3.2. Key Analysis Questions

The high-level goal of the FNPP security technical evaluation was to characterize the effectiveness of the PPS against adversary forces conducting various missions against an FNPP. Within this context, the key analytical questions included:

- What operational challenges facing FNPP most inhibit or enhance the effectiveness of PPS?
- How well do international best practices for PPS mitigate threats to FNPPs?

- How does the most likely adversary mission change with FNPP movement between anchor points?

2.3.3. *Key Results, Conclusions, and Implications*

2.3.3.1. Key Results

- Performance testing for off-site response should be conducted to establish response timelines, jurisdiction, and responsibilities for locations of the FNPP.
- The international community should hold discussions to establish response procedures and options for a scenario in which the FNPP is overtaken by adversaries.
- Underwater attacks are unique to FNPPs and necessitate advances in detection and delay technologies and procedures.

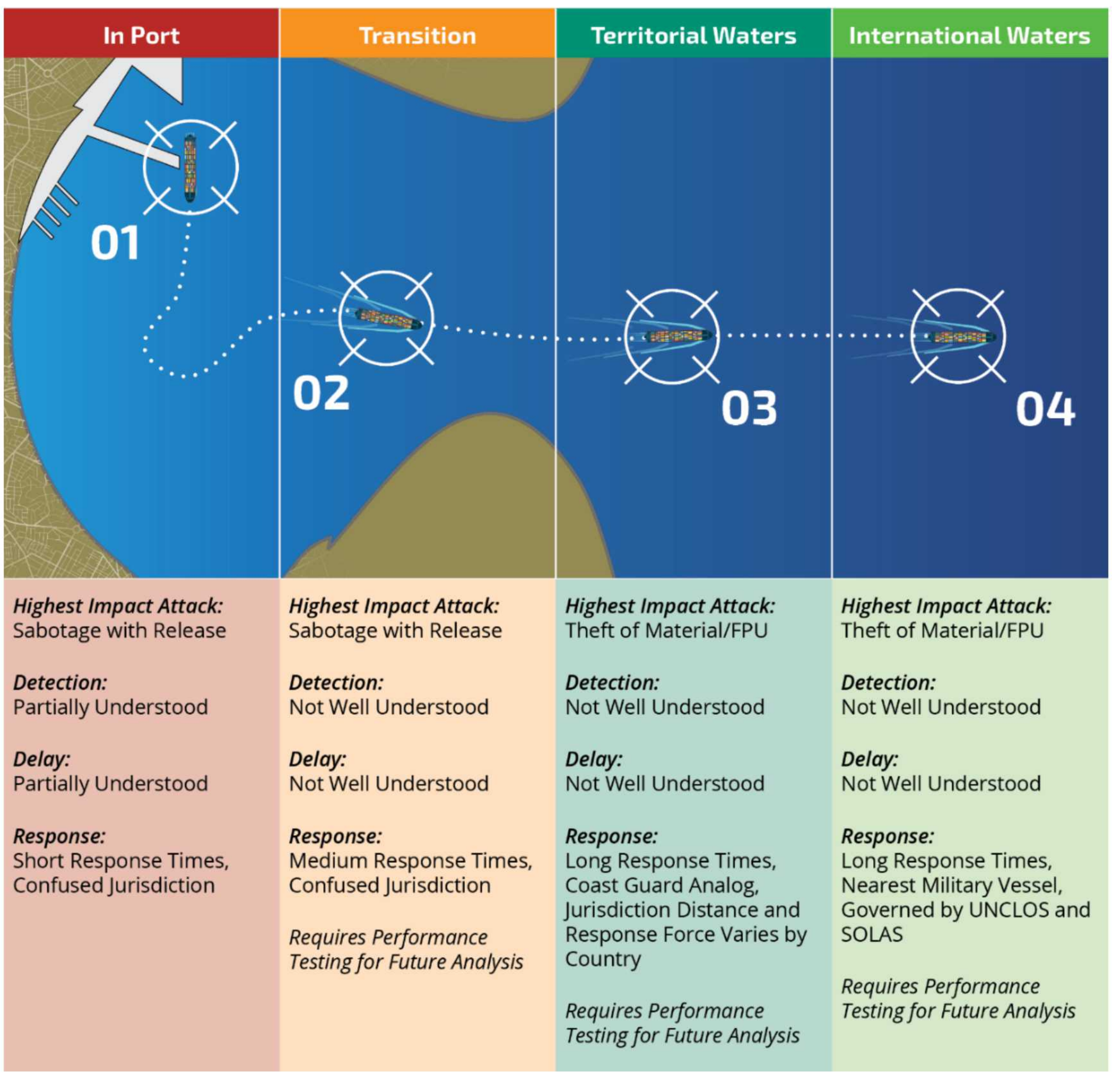


Figure 5. Key Security Challenges and Implications Mapped to the Visual Model of Key Locations of Security Concern for FNPPs

2.3.3.2. Conclusions

- 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 (for example, regional or international cooperation should occur on the authority to seize 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.

2.3.3.3. Implications

- Performance testing for detection, assessment, delay, and response systems should be conducted and guidance documents authored to account for the four FNPP locations.
- Following performance testing and upgrades, the IAEA should assemble a working group to write and establish guidance for FNPPs.
- Due to the legal concerns related to protecting—and responding to attacks on—FNPPs (e.g., sinking FNPPs in territorial or international waters), the UN should lead discussions

3. PNR/FNPP SYSTEM STUDY: 3S ANALYSIS

This technical evaluation is a preliminary 3S analysis of PNRs— FNPPs specifically—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 PNR and FNPP 3S technical evaluation is to characterize the interactions between safety, safeguards, and security mitigations across the traditional risks of concern. Within this context were the key analytical questions:

- What conflicts or leverage points exist between safety, safeguards, and security for PNRs and FNPPs?
- Where are the interdependencies between safety, safeguards, and security for PNRs and FNPPs?
- If they are interdependent, 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 in which traditional assumptions of independence did not capture likely PNR and FNPP operational realities. Although some might seem obvious, these interdependencies (Table 1) are not often accounted for in individual technical analyses, and seem to directly challenge implemented 3S regimes, as detailed in Volume I. [7]

Table 1. Potential 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.
Limits to available active and passive safety systems (weight and space)	Fewer additional potential targets and vulnerabilities	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.

3.2.1. Conclusions for PNR and FNPP 3S Analysis

- Identifying points of interdependence illustrates how the MINER 3S approach can offer higher-fidelity system analysis of increasing real-world complexity.
- The ease of moving an FNPP between multiple jurisdictions directly challenges conventional approaches to nuclear safety, safeguards, and security.
- Having multiple interpretations of international maritime law results in ambiguity regarding several key interdependencies that significantly complicate FNPP 3S mitigations (e.g., scuttling an FNPP to mitigate a safety accident introduces novel safeguards and security jurisdictional questions).
- Several identified interdependencies present significant challenges to traditional 3S mitigations for anticipated FNPP operations.
- Several interdependencies identify potential mechanisms for gaining efficiency in reducing 3S risks.
- These preliminary *qualitative* results should be validated with additional, more in-depth *quantitative* analysis.

3.2.2. 3S Implications for PNRs and FNPPs

- Significant challenges for each *S* posed by FNPPs to traditional regulatory, legal, and operational regimes support further exploration and analysis of related risk complexity.
- The interdependent impacts and implications of scuttling the FNPP should be 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.
- The implications of the potential loss of control of the entire FNPP vessel should be investigated because this scenario might give a nonnuclear state access to a fully functioning nuclear reactor, even if only for a short time.

4. CONCLUSIONS AND NEXT STEPS

Overall, this preliminary MINER 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.

4.1. Broader Implications of 3S PNR and FNPP Risk Analysis

- The ease of moving FNPPs between multiple jurisdictions directly challenges conventional approaches to nuclear safety, safeguards, and security.
- Several interdependencies significantly challenge economical and efficacious FNPP operations, but they help identify areas for efficiently reducing 3S risks.
- 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.
- 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. [8]

4.2. Next Steps for 3S PNR and FNPP Risk Analysis R&D

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

The accuracy and utility of the technical evaluation results—and the conclusions and implications in this section—depend on the accuracy, fidelity, and appropriateness of the analytical assumptions used in this study. These analytical assumptions were made to compensate for a lack of operational and technical details for PNRs and FNPPs in the open literature. Even with these data 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 the next steps toward advancing the technical understanding of 3S for PNRs and FNPPs.

5. REFERENCES

[1] J. Buongiorno, M. Golay, N. Todreas, A. Briccetti, J. Jurewicz, V. Kindfuller, D. Fadel, G. Srinivasan, R. Hannink, A. Crowle and M. Corradini, "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.

[2] J. A. Vitali, J. G. Lamothe, C. J. Toomey Jr., V. O. Peoples and K. A. McCabe, "Study on the Use of Mobile Nuclear Power Plants for Ground Operations," U.S. Army Deputy Chief of Staff, G-4, , 2018.

[3] AP News, "Russia's Floating Nuclear Plant Sails to Its Destination," *AP News,* vol. 8, no. 23, 23 August 2019.

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

[5] W. M. Arkin and J. M. Handler, "Nuclear Disasters at Sea, Then and Now," *Bulletin of the Atomic Scientists,* vol. 45, no. 6, pp. 20-24, 1989.

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

[7] A. D. Williams, D. Osborn, J. Bland, B. Cohn, C. Faucett, L. Gilbert, S. Horowitz and J. Rutkoski, "System Studies for Mitigating International Nuclear Energy Risks (MINER): 3S Risk Analysis for Portable Nuclear Reactors (Volume I) -- Technical Evaluation of Safety, Safeguards, & Security," Sandia National Laboratories, Albuquerque, NM, 2020.

[8] A. D. Williams, A. H. Mohagheghi, B. Cohn, D. M. Osborn, K. A. Jones, M. DeMenno, E. A. Kalinina, M. A. Thomas, E. R. Parks, M. J. Parks and B. A. Jeantete, "System Theoretic Frameworks for Mitigating Risk Complexity in the Nuclear Fuel Cycle," Sandia National Laboratories, Albuquerque, NM, 2017.

[9] A. D. Williams, D. Osborn, J. J. Bland, J. N. Cardoni, B. Cohn, C. Faucett, L. J. Gilbert, R. Haddal, S. Horowitz, M. Majedi and M. K. Snell, "System Studies for Global Nuclear Assurance & Security: 3S Risk Analysis for Small Modular Reactors (Volume I)?Technical Evaluation of Safety Safeguards & Security," Sandia National Laboratories, Albuquerque, NM, 2018.

[10] H. B. Honerlah and B. P. Hearty, "Characterization of the Nuclear Barge STURGIS," in *Waste Management Symposium*, Tucson, AZ, 2002.

[11] M. Dowdall and W. J. Standring, "Floating Nuclear Power Plants and Associated Technologies in the Northern Areas," Norwegian Radiation Protection Authority, Østerås, Norway, 2008.

[12] International Atomic Energy Agency, "KLT-40S," International Atomic Energy Agency, Vienna, Austria, 2013.

[13] L. L. Humphries, B. A. Beeny, F. Gelbard, D. L. Louie and J. Phillips, "MELCOR Computer Code Manuals, Vol. 1: Primer and Users' Guide, Version 2.2.9541," Sandia National Laboratories, Albuquerque, NM, 2017.

[14] M. Bell, "ORIGEN: The ORNL Isotope Generation and Depletion Code," Oak Ridge National Laboratories, Oak Ridge, TN, 1973.

[15] 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].

[16] United States Nuclear Regulatory Commission, "State-of-the-Art Reactor Consequence Analyses Project Volume 1: Peach Bottom Integrated Analysis," United States Nuclear Regulatory Commission, Rockville, MD, 2013.

[17] United States Nuclear Regulatory Commission, "State-of-the-Art Reactor Consequence Analyses Project: Uncertainity Analysis of the Unmitigated Long-Term Station Blackout of the Peach Bottom Atomic Power Station (Draft)," United States Nuclear Regulatory Commission, Rockville, MD., 2012.

[18] M. L. Garcia, Design and Evaluation of Physical Protection Systems, Burlington, MA: Butterworth-Heinemann, 2007.

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