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Intermediate Results from a System-Theoretic Framework for Mitigating Complex Risks in International Transport of Spent Nuclear Fuel

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ABSTRACT

The challenges surrounding the safety, security and safeguards (3S) of international transportation of spent nuclear fuel (SNF) in today's dynamic environment demonstrate growing risk complexity surrounding the nuclear fuel cycle (NFC). Interdependencies between 3S risks and dynamic (and emergent) effects on risk make the use of traditional risk analysis methods challenging. In response, this research evaluated the ability of system-theoretic frameworks to better assess, manage, mitigate, and reduce the complex risks associated with international SNF transportation. Invoking two analysis techniques, the gaps, interdependencies, conflicts, and leverage points resulting from an integrated 3S SNF transportation analysis are evaluated to determine any potential benefit over traditional methods that rely on analyzing each 'S' in isolation. The first analysis technique, dynamic probabilistic risk assessment (DPRA), uses dynamic event trees to systematically evaluate scenarios arising from various sources of uncertainty to characterize the risk complexity of international SNF transportation. The second technique, system theoretic process analysis (STPA), incorporates system and control theory to evaluate complex systems as hierarchical control structures in order to characterize international SNF transportation risk complexity in terms of emergent system properties. These novel analysis techniques provide the basis for a robust and technically rigorous evaluation of integrated 3S approaches to understand and mitigate complex risk.

This paper reports intermediate results from both the DPRA and STPA analyses including:

- Explanations of how each analysis technique was used to develop an integrated 3S technique,
- The processes by which isolated and integrated analyses were conducted, and
- The comparison rubric used to identify and assess gaps, interdependencies, conflicts, and leverage points.

This paper then describes and illustrates the relationship between these analytical results and a new 'complex risk metric' aimed to better characterize risk management related to international SNF transportation. The intermediate results suggest that (1) integrated 3S approaches do offer enhancements to mitigating the complex risk associated with international SNF transportation, and (2) DPRA and STPA offer system-theoretic frameworks better able to mitigate the growing risk complexity within (and across) the NFC in a dynamic 21st century environment.

INTRODUCTION

The challenges surrounding the safety, security and safeguards (3S) of international transportation of spent nuclear fuel (SNF) in today's dynamic environment demonstrate growing

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risk complexity surrounding the nuclear fuel cycle (NFC). Current research efforts at Sandia National Laboratories (SNL) are exploring system-theoretic, integrated 3S frameworks for managing risk complexity in the NFC. This research invokes two novel analysis techniques – dynamic probabilistic risk assessment (DPRA) and system theoretic process analysis (STPA) – to evaluate the gaps, interdependencies, conflicts, and leverage points resulting from an integrated 3S SNF transportation and determine any potential benefit over traditional methods that rely on analyzing each ‘S’ in isolation. Benefits from such an integrated 3S perspective have been shown for security [1], safety [2], and safeguards [3] analyses.

Interdependencies between 3S risks and dynamic (and emergent) effects on risk make the use of traditional risk analysis methods challenging. For example, consider the need to reconcile the competing safety (e.g., transport via truck vs. commercial air freight) and security (e.g., avoiding guerilla controlled roadways) risks related to the 1996 shipment of spent highly enriched uranium (HEU) fuel from a Columbian research facility to the United States [4]. Similarly, risk complexity is evident in the logistics necessary to support the 2005 agreement between Moscow and Tehran for SNF transport from Iran’s Bushehr nuclear power plant to Russia [5]. Whether from multi-modal or multi-jurisdictional complexity, operational risks associated with the international transportation of SNF suggests the need for a new perspective of risk. In response, this research developed and evaluated the ability of system-theoretic frameworks to better assess, manage, mitigate, and reduce the complex risks associated with international SNF transportation.

RESEARCH DESIGN & FRAMEWORK

At the highest level, this research is designed to explore the hypothesis that integrated 3S approaches are improvements for managing complex risks in the NFC over traditionally isolated ‘S’ approaches. Consider a broad meaning of the term ‘improvements’ that includes the ability to identify operational risks missed (gaps), illustrate interactions between risks and mitigations (interdependencies), characterize oppositional forces in operational risks (conflicts), and capture natural redundancies or compensatory effects to mitigate risks (leverage points). This research consists of three broad thrusts. First, the development of a DPRA-based approach for 3S risk analysis. Second (and in parallel), the development of a STPA-based approach comparing 3S versus individual ‘S’ analyses. Lastly, the creation of a new concept, coined ‘complex risk,’ to capture the interdependence of safety, security and safeguards risks within an operational context.

DPRA analyzes the evolution of various scenarios that results from various possible paths between initiating events and possible end states. DPRA is a ‘bottom-up’ technique that statistically evaluates simulation run-based data from deterministic approaches to generate insights about risk. To do this, DPRA employs dynamic event trees for the systematic and automated assessment of possible scenarios arising from uncertainties within the complex system model. In this manner, DPRA is capable of better accounting for both epistemic (e.g., arising from the model) and aleatory (e.g., arising stochasticity in the complex system) uncertainties to provide higher fidelity analytical conclusions for complex system analysis [6]. More specifically, the DPRA research thrust uses the Analysis of Dynamic Accident Progression Trees (ADAPT) software [7] to generate dynamic event trees and evaluate risk in complex applications. Within this research thrust, ADAPT is used as an overall scenario scheduler to coordinate the complex system model-related inputs and outputs between three different software codes (that support traditionally isolated 'S' analysis):

- **RADTRAN**, an internationally accepted program and code for evaluating the safety risks of transporting radioactive materials [8]; (Copyright: SNL 2006)
- **Scenario Toolkit and Generation Environment (STAGE)**, a SNL-specific application of a commercial modeling and simulation program for evaluating security risks in terms of physical protection system effectiveness [9]; and,
- **PRCALC**, a Markov Chain-based code (developed by Brookhaven National Laboratory) for evaluating various risks associated with safeguarding nuclear materials [10].

Here, ADAPT's edit and branching rules coordinate how the output from RADTRAN are inserted as inputs into STAGE, whose outputs are subsequently input into PRCALC (e.g., Figure 1 [A] & [B]) with the order of implementation varied to explore any differences that may arise. Ultimately, the DPRA research thrust is based comparing the outputs of each traditionally isolated 'S' code simulation with its 3S complex risk (e.g., ADAPT-influenced) counterpart.

STPA explores system-level behaviors by looking at how requirements and desired actions interact to either mitigate or potentially increase states of risk that can lead to unacceptable losses. STPA is a 'top-down' process that links specific design details to high-level objectives using such key tenets of systems and control theory as hierarchy, emergence, interdependence, and feedback. To do this, STPA abstracts real complex system operations into hierarchical control structures and functional control loops (e.g., Figure 1 [C] and [D]). Within the constraints provided by higher levels in the hierarchical control structure, STPA uses control loop logic to analyze how control actions (designed for desired system behaviors) may interact to drive the complex system into states of higher risk [11]. STPA's underlying logic suggests redefining the complex risks associated with the 3S of international SNF transportation as identifying requirements and enforcing control actions to avoid system states of higher (or unnecessary) risk. Similar to the construct of the DPRA thrust, the STPA thrust is based on comparing the states of increased risk identified in the traditionally isolated 'S' analysis with its 3S complex risk counterpart.

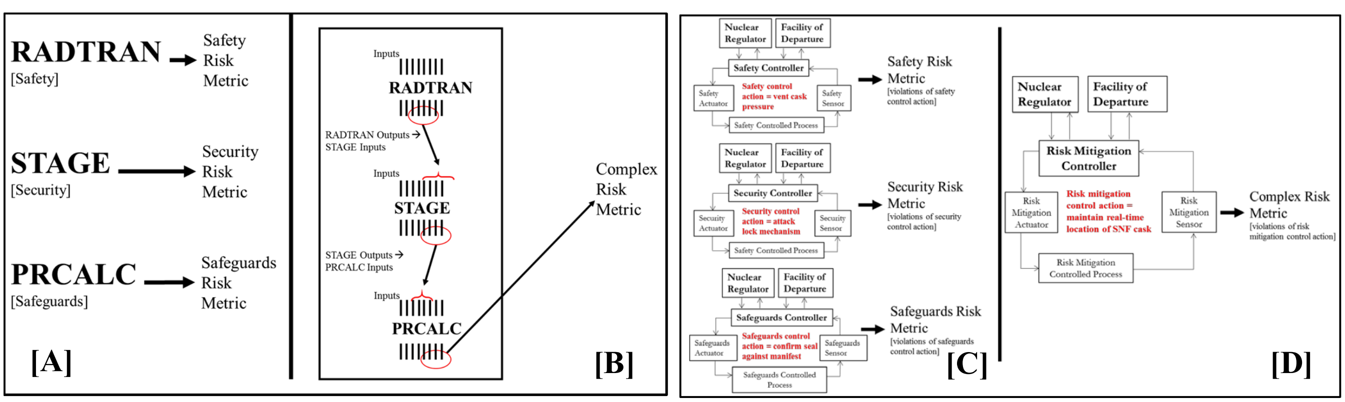

Figure 1. Illustration of the DPRA [A, B] and STPA [C, D] research thrusts – including representative traditionally isolated 'S' [A] and [C] vs. 3S complex risk [B] and [D] analyses.

The third research thrust focuses on developing a new concept of risk that better incorporates operational complexities (i.e., the interdependence of safety, security and safeguards risks) within the international transportation of SNF. To explore how risk is conceptualized across various academic disciplines ranging from engineering to organization science to cognitive psychology, a working matrix compares various approaches to risk definition, quantification, assessment, and management. What emerged is a state-space description of risk that grounds engineering risk in systems and complexity theory to better identify and illustrate causal mechanisms driving risk. Ultimately, the 'complex risk' concept is aimed to more efficiently and effectively capture (and mitigate) the increasing complexity facing NFC applications and support integrated 3S analytical techniques. (Though not discussed in in this paper, please see Reference [12] for more details.)

To support data collection for this research, a real-world SNF transportation case was developed using a hypothetical international SNF transportation case that includes regional, geopolitical, country, cask, transportation mode, and transportation route selection details. The case description (and related scenarios for evaluation) were consistent with the standards for a single case study research design [13]. A regional map of the hypothetical SNF transport case study is shown in Figure 2. Regional map (and route) of a hypothetical SNF transportation.Figure 2. (NOTE: A more complete description of this case study is provided in [1], [2], and [3]), and includes a transportation route that consists of:

- SNF cask loaded from the storage site (Site A) in Zamau onto a rail car for transporation to the Port of Zamau where it is loaded onto a barge;
- SNF cask travels via international waters to the Port of Famunda in the southwest corner of the country where it is loaded onto a heavy-haul truck; and
- SNF cask travels by road through western Famunda, across the border, and across interior Kaznirra to Site B.

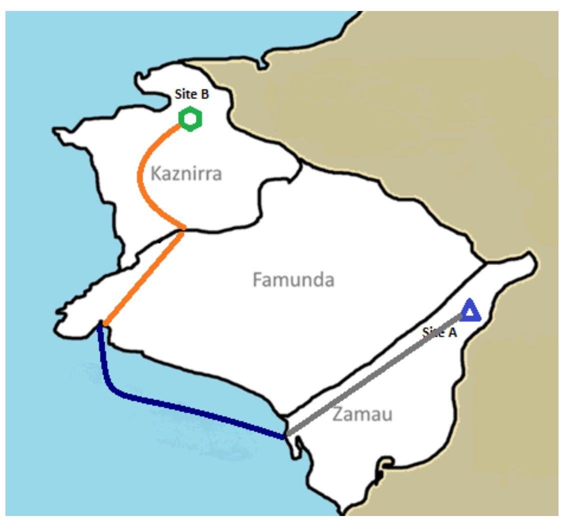

Figure 2. Regional map (and route) of a hypothetical SNF transportation.

The details contained within this case description and scenarios of concern were briefed before a panel of subject matter experts from a range of disciplines (including spent fuel transportation, spent fuel management, nuclear safety, nuclear security and nuclear safeguards) SNL. This audience indicated no glaring mistakes, omissions, or flawed logic within either the case description or scenarios. Further, per the relatively low track class (standards dictating railroad track quality) of Zamau's expansive railway network (i.e., gray portion of the SNF transportation route in Figure 2), and the fact that train derailments are the most common type of rail incident [14], the first scenario for analysis included such an event.

INTERMEDIATE RESULTS

Within the DPRA research thrust, efforts to identify and quantify elements of risk from international SNF transportation have resulted in the development of a maturing framework for linking RADTRAN, STAGE, and PRCALC with ADAPT. DPRA's 'bottom-up' approach requires a specific scenario for analysis as a way to evaluate how branching and editing rules influence changing uncertainty throughout the simulation for a selected derailment scenario. This scenario provides analytical flexibility, as the cause of the derailment could be accidental (due to poor rail track quality) or intentional (resulting from adversary sabotage at a known time and location to support a secondary attack on the SNF). This chosen scenario has the advantage of having relatively clear delineations between safety, security, and safeguards concerns in different time-based phases of the scenario. Phase 1 is the derailment itself, which is an accident scenario that previously has been studied as a standalone safety case [2]. After the accident scenario, Phase 2 involves a potential security event where adversaries attack the stopped SNF shipment (leveraging the damage and confusion caused by the accident on the security forces) in order to gain access to the SNF canister. Following the accident and the attack, Phase 3 of the analysis investigates the safeguards implications of a successful attack on the SNF canister. As such, the scenario evolves through time, and ADAPT transitions between RADTRAN, STAGE, and PRCALC to evaluate the DPRA approach for an integrated 3S analysis.

Further, each of these three phases of the scenario timeline have been analyzed with their respective software code. For Phase 1 using RADTRAN, the derailment accident was modeled for 12 different SNF configurations among burnups and fuel ages [2][3] for two fuel types (pressurized water reactor (PWR) and boiling water reactor). The resulting release fraction analysis, shown in Table 1 illustrates how such consequences could be amplified when accounting for Phase 2.

Table 1. RADTRAN release fractions[1] related to safety risk for the train derailment scenario [2].

Group	Release Fraction		Total Release Fraction	Aerosol Fraction	Respirable Fraction	Total Respirable
	From Rods	From Cask				
Gas	0.12	*M*x0.8	*M*x0.096	1	1	*M*x0.096
CRUD	1	0.001	0.001	1	0.05	$5*10^{-5}$
Particle	*N*x $4.8*10^{-6}$	*M*x0.7	*N*x*M*x $3.36*10^{-6}$	1	0.05	*N*x*M*x $1.68*10^{-7}$
Volatile	*N*x $3.0*10^{-5}$	*M*x0.5	*N*x*M*x $1.5*10^{-5}$	1	0.05	*N*x*M* $7.5*10^{-7}$

[1] More specifically, for particles and volatiles (from rods to cask): *N* times higher than in NUREG-2125 [16]; Gases, particles, and volatiles (from cask to environment): *M* higher than in NUREG-2125 (M<N); *M* and *N* depend on the attack severity (i.e., evaluated by STAGE).

Similarly, STAGE evaluated Phase 2 as a characteristic attack on the SNF cask by a small, well-equipped adversary force. Here, the number of adversary attackers and response force members were varied; the first to indicate the uncertainty in actual attack details, and the latter to model the potential incapacitation of response force members from the derailment. Table 2 [A] and [B] illustrate how the probability of neutralization and average time on the task by an adversary changes across the difference configurations modeled which provides insight into where ADAPT can insert RADTRAN outputs as inputs into the STAGE analysis.

Table 2. STAGE generated output measures related to security risk for the train derailment scenario.

[A] Average P_N					[B] Average Time on Task (%)				
		Responders					Responders		
		2	4	8			2	4	8
Adversaries	3	43.4%	100.0%	100.0%	Adversaries	3	85.6%	56.4%	60.7%
	5	47.5%	96.0%	100.0%		5	82.7%	72.9%	68.5%
	7	19.2%	65.0%	93.0%		7	90.5%	87.1%	86.1%

Lastly, PRCALC analyzed Phase 3 as an assumed successful elimination of the response forces by the adversaries, who then aim to divert a quantity of special nuclear material from the SNF cask and replace several fuel rods with dummy rods. The time varying probabilities of diversion failure and proliferation success probabilities (i.e., represented in the PWR configuration with 25-year aged with 60 GWD/MTU burnup in Figure 3) are attributable to the amount of Pu in the transport cask, and the model selection of a fixed intrinsic barrier that does not cause significant delay to proliferation [3]. Again, the selection of this particular intrinsic barrier indicates how ADAPT can insert STAGE outputs as inputs into the PRCALC analysis.

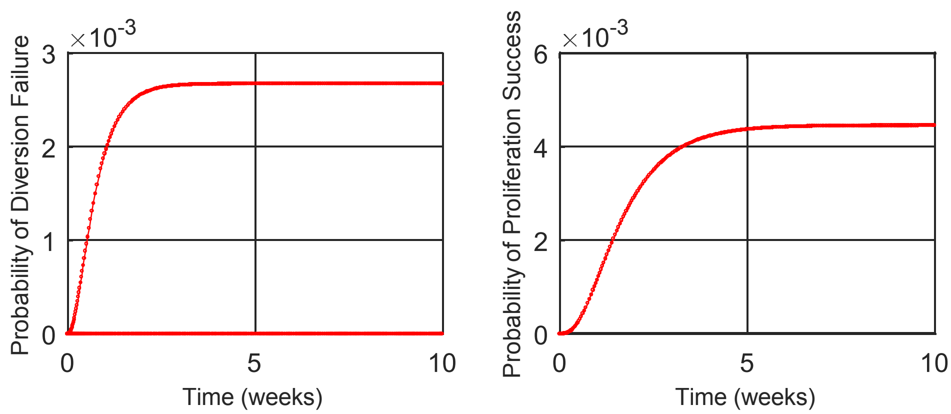

Figure 3. PRCALC generated output measures related to safeguards risk for the train derailment scenario [3].

From here, the DPRA thrust focused on determining conditions where the scenario may branch between different potential evolutions for the integrated 3S analysis. This analysis begins at the derailment (Phase 1) with RADTRAN, which does not have dynamic capabilities, and travels forward in (simulated) time. Branching in Phase 1 cannot be based on conditions that develop during the simulation, therefore ADAPT is used to perform branching similarly to a classical event tree, where the analysis is split along predefined junctions. These branches include:

- Between different fuel characteristics (i.e., different fuel configurations affect the consequences in RADTRAN and STAGE differently, and also contain different quantities of fissionable material which influences PRCALC); and,
- With the size of the accident (e.g., the more severe the accident, the greater potential for radioactive release and the more difficult for the response forces to perform in STAGE).

Because Phase 2 uses the dynamic software code STAGE, branching can occur at specific instances in time, and result in multiple possible paths. Here, such conditions that define this branching include:

- Between adversaries being state-sponsored or non-state actors (e.g., assumptions of greater financial and technical capabilities for the former influence both STAGE and PRCALC analysis); and,
- On the wreckage and habitability of the area around the cask (e.g., the terrain immediately around the canister may include different levels of hazards blocking access to cask or to engaging the adversaries).

Lastly, Phase 3 uses the results from the STAGE analysis (itself informed by the RADTRAN analysis), evaluates attackers that are state-sponsored with the goal of diverting spent fuel and efforts at detection by IAEA inspectors; where the associated branching occurs in relation to the different states in the PRCALC Markov model. The current status of the DPRA thrust rests on re-engineering ADAPT into a multiple-simulator analytical tool the leverages the core function of the software to take a template version of an input file and replace values of specified parameters within that input file at each branching point within the analysis. As such, for the DPRA thrust of the 3S analysis, ADAPT both determines the new input values of parameters when the analysis branches and which simulator needs to be used. This branching includes conditions such as:

- The amount of fuel previously dispersed through the derailment in Phase 1 and a potentially successful attack in Phase 2 (e.g., fuel dispersed into the environment through accident or sabotage will neither be present for accountancy nor be available for diversion); and,
- The time necessary to return the cask to either the origin site or to an alternative inspection location (e.g., time delays from restoring the cask to a condition acceptable for transport and repairing the rail line before safeguards inspections can occur).

For the STPA thrust, SNL created a series of hierarchical control structures to reflect how various actors interact to give rise to the emergent system properties of 3S for international SNF transportation; first as individual complex systems models and then as an integrated 3S model. STPA's 'top-down' approach requires both overall system objects and a set of unacceptable system-level losses. For the international transportation of SNF, the mission is to physically move SNF from an origin facility to a destination facility without disruption (unplanned or otherwise) and to selected and approved routes, timelines, and operations. Here, the set of unacceptable losses includes human serious injury or loss of life (L1), environmental contamination (L2), significant damage to infrastructure (L3), significant loss of revenue (L4), reputational/ professional confidence (L5) and non-adherence to IAEA obligations (L6).

The underlying logic of STPA suggests that, if the system migrates into one of these states of increased risk, one additional external event could lead to a high-level system loss. For example, if there is unauthorized access to the SNF during the transport, the shipment could experience a loss; whether from the intentional use of explosives or an unintentional derailment. For both of these instances, if the unauthorized access had been prevented (through technical, administrative and/or systemic controls), then the shipment is less likely to experience a loss. Table 3 illustrates a representative set of states of increased risk aligned with their safety, security, and safeguard functions. It is interesting to note that this research has also identified essential states of increased risk that does not fit directly into one of the columns and, therefore are missed by isolated analysis of risk. Two examples of such '3S-based states of increased risk' include the uncoordinated implementation of operational concept(s) of operations, and operational emergency plans.

Table 3. Representative set of states of increased risk (and their related losses) for STPA analysis of international SNF transportation.

System States of Increased Risk			**Related Losses**
Increased **hazardous** state [Safety]	Increased **vulnerable** state [Security]	Increased **proliferation** state [Safeguards]	
Unplanned radiological release from the cask	Unauthorized access of cask	Loss of 'continuity of knowledge' of SNF material status	L1, L2, L3, L4, L5, L6
N/A	Unauthorized access of transportation vehicle	Loss of 'continuity of knowledge' of SNF location	L1, L4, L5, L6
Population/individual normal operations exposure limits exceeded	Transportation vehicle stopped longer than expected	N/A	L1, L2, L3, L4
N/A	Transportation vehicle traveling slower than scheduled	Untimely reporting of SNF arrival	L1, L2, L3, L4, L5, L6
Unconstrained movement of the cask (runaway cask)	N/A	N/A	L1, L2, L3, L4, L5
N/A	Unverified transfer of armed security responsibility	N/A	L1, L2, L3, L6
Transportation vehicle exceeds regulated speed limits	N/A	N/A	L1, L2, L4
N/A	N/A	Untimely reporting of SNF removal	L5, L6

A representative subset of these states of increased risk were selected for further STPA-based analysis with some directly aligned to either safety, security, or safeguards and others transcending the conceptual boundaries between these emergent system properties. In Table 4, the states of increased risk marked with an asterisk (*) identify a unique capability of STPA for 3S analysis. Namely, these three states are identified as conceptually similar (e.g., leading to the same set of losses), suggesting their associated system requirements are interdependent.

The representative control actions associated with each state of increased risk then become the analytical focal points for the STPA thrust. As such, each control action was evaluated rigorously and systematically in STPA to identify how they could possibly be violated; including from interactions with other control actions. Per STPA, system states of increased risk result when incorrect control actions are issued, as well as when required control actions are not issued; provided too early, too late, or out of order; or, stopped too soon or engaged too long [11].

Because these possible control action violations are directly traceable through their associated states of increased risk back to unacceptable losses, they provide a rich data set by which to compare STPA to traditionally isolated approaches to safety, security and safeguards with an integrated 3S approach. In addition, SNL have explored the use of network theory as way to interrogate the different individual 'S' and integrated 3S hierarchical control structures; specifically, looking to better understand the role of interactions across safety, security, and/or safeguards control actions expected of the same controller.[2] The current status of the STPA thrust revolves around the meta-comparative analyses of both control action violations and hierarchical control structures across individual and 3S control actions.

Table 4. Representative set of states of increased risk, related system requirements and controller actions for STPA analysis of international SNF transportation.

Emergent Property	State of Increased Risk	System Requirement	Representative Control Action [Specific Controller]
Safety	Unplanned radiological release from the cask*	All radiological release(s) from the cask must be planned & verified	An airtight seal [Cask]
			Physical assessment of cask contents conducted in appropriately sealed facility [Inspector]
	Transportation vehicle exceeds regulated speed limits	Transportation vehicle must always abide by posted, regulated speed limits	Throttle governor stops acceleration once at 55mph [Transportation Vehicle]
			Adhere to posted speed limits [Driver]
Security	Unauthorized access of cask*	Unauthorized individuals must not access the cask	Engage locking mechanism [Cask]
			Check credentials of inspectors of the cask [Local Law Enforcement Agency]
	Unverified transfer of armed security responsibility	Any transfer of armed security must be verified	Confirm scheduled time for security responsibility transfer [Transportation Security Operations]
			Communicate process for transfer of armed security responsibilities [Competent Security Authority]
Safeguards	Loss of 'continuity of knowledge' of SNF material status*	Accurate SNF material status must be maintained at all times	Transmit GPS location of SNF [Cask]
			Submit confirmation of physical inventory verification within 24 hours [Inspectors]
	Untimely reporting of SNF removal	All reporting of SNF removal must be reported with IAEA guidelines	Record manifest of SNF removed from inventory [Facility of Departure]
			Submit confirmation of removing SNF into inventory within 48 hours to IAEA [State Authority for Safeguards]

SUMMARY & CONCLUSIONS

Both DPRA and STPA are novel analysis techniques that support current SNL research toward a robust and technically rigorous evaluation of integrated 3S approaches to mitigate complex risk within the NFC. Evaluating a hypothetical case description and scenario for international SNF transportation, which is both grounded in operational realities and accepted by a diverse panel or relevant SMEs, provides rich data sets to support the research objectives. For the DPRA thrust, the use of dynamic event trees (via the ADAPT software code) allows for traditionally isolated analysis tools for safety, security and safeguards to be interwoven in a manner more aligned with operational realities. For the STPA thrust, comparing possible control action violations generated from different hierarchical control structures better incorporates multi-faceted interactions often seen in complex environments. Together, the 'bottom-up' and 'top-down' analysis techniques reduce and potentially illuminate the gaps, interdependencies, conflicts and leverage points between safety, security and safeguards in international SNF transportation.

[2] For more details, see Reference [15].

Additionally, this research supports a new 'complex risk' conceptualization where the focus moves away from emphasizing technology or policy reliability and toward managing the interaction(s) of system components and allow SNF to successfully complete the route from origin to destination. Next steps in this research include a linking of RADTRAN, STAGE and PRCALC with ADAPT, defining realistic branching rules, more deeply probing differences in control action violations, and formalizing the 'complex risk' concept into a usable framework. These intermediate results suggest that (1) integrated 3S approaches do offer enhancements to mitigating the complex risk associated with international SNF transportation, and (2) DPRA and STPA offer system-theoretic frameworks better able to mitigate the growing risk complexity within (and across) the NFC in a dynamic 21st century environment.

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