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

Adam D. Williams[1], Doug Osborn[1], Rossitza Homan[1], Katherine A. Jones[1], Elena A. Kalinina[1], Amir H. Mohagheghi[1]

[1]Sandia National Laboratories, Albuquerque, NM, USA, [adwilli; dosborn; rhoman; kajones; eakalin; ahmohag]@sandia.gov*

ABSTRACT
New analytical approaches are desired to effectively manage the growing complexity of safety, security and safeguards (3S) threats to the nuclear fuel cycle (NFC) in today's dynamic environment. As NFC global infrastructure expands within this multifaceted threat environment, increasingly complex risks emerge—a risk space impeccably captured in the 3S challenges of transporting spent nuclear fuel (SNF) via multimodal transportation routes between countries around the world. This research hypothesizes that an integrated, 3S analytical approach to SNF transportation risk results in design, implementation and evaluation benefits. Given that the extant 3S literature is primarily conceptual, this research develops a scientific and technically rigorous 3S approach to assessing, managing, mitigating and reducing the complex risks of SNF transportation. Traditional SNF transportation evaluation methods for 3S are challenged by uncertainties related to ignoring interdependencies, by stochastic assumptions of environmental factors and by time independent domain risk mitigation strategies. In contrast, this proof-of-concept paper utilizes system-theoretic approaches and dynamic risk assessment frameworks to model SNF transportation and demonstrates how to assess, manage, mitigate and reduce complex risks of SNF transportation with a time dependent, dynamic control theoretic complex system model. Leveraging the growing applications of the system theoretic process analysis (STPA) and dynamic probabilistic risk assessment (DPRA) methods, this paper outlines the gaps, interdependencies, conflicts and leverage points between SNF transportation 3S often overlooked by traditional methods that rely on analyzing each 'S' in isolation. This preliminary characterization of the multifaceted risk space facing SNF transportation and complex system model evaluation of risk mitigation strategies is based on a notional, international SNF transportation scenario (e.g., SNF crossing geopolitical borders). Preliminary results indicate that system-theoretic analysis of SNF transportation as a complex, socio-technical system is better able to mitigate the risk complexity of SNF transportation in international environments. As more countries obtain nuclear fuel cycle capabilities, the greater the need for a comprehensive framework for identifying and mitigating the complex risks of transporting SNF in a dynamic 21st century context—and the more powerful this 3S analytical framework for ensuring the responsible expansion and management of nuclear energy programs.

INTRODUCTION
The recent creation and development of new nuclear programs (e.g., United Arab Emirates and Vietnam) and increasingly popular 'fuel take back' agreements as incentives for new nuclear energy programs suggests a significant increase in the amount of spent nuclear fuel (SNF) to be transported—including transfers of SNF casks between transportation modes (e.g., road to rail to water) and across geopolitical or maritime borders. Further, this increases the likelihood that safety, security and safeguards mitigation resources and regulations along approved international SNF transportation routes will be inconsistent.

Though limited in number, real cases suggest an increase in complexity for future international SNF transportation and motivate this research. For example, consider the spring 1996 shipment of spent highly enriched uranium (HEU) fuel from a research facility in Bogota to the Colombian coast for shipment back to the U.S. as part of a global program to swap HEU for low enriched uranium in research reactors. Decisions regarding this SNF shipment had to include mitigations for such complexities as strained governmental relationships between Colombia and the U.S., high guerilla activity during a period of severe civil unrest and navigating road, rail or air travel infrastructure in various states of disrepair.[1] In addition, the 2005 agreement between Moscow and Tehran for SNF from Iran's Bushehr nuclear power plant to be transported back to Russia may also involve diverse risks.[2] Simply looking at a world map suggests that these cases introduce a new, more complex set of risks, including overlaps in risk mitigation responsibilities (e.g., at ports or harbors) and conflicting objectives (e.g., national regulations for labeling hazardous materials on transportation pathways), for the international shipment of SNF.[3] Lastly, the U.S. National Academies of Science recently stated a need for an

> integrated evaluation of the threat environment, the response of packages to credible malevolent acts, and operational security requirements for protecting spent fuel and high-level waste while in transport.[4, p 8]

Given that current SNF transportation analyses heavily emphasize safety, lightly touch security and typically ignore safeguards [5], current analysis techniques for mitigating these risks may be insufficient. In response, this study evaluates the potential improvement in complex risk mitigation in SNF transportation from a system-theoretic, integrated 3S perspective over traditional risk assessments that evaluate safety, security and safeguards risks individually.

BACKGROUND

Recent interest in how to integrate safety, security and safeguards[1] (3S) prompted multiple studies from both international and domestic organizations, including Sandia National Laboratories. Past efforts at exploring integrated 3S approaches include, but are not limited to:

- analyzing the possible integration of 3S into the design of nuclear facilities [6];
- characterizing the current state of 3S integration at U.S. nuclear power plants [7];
- integrating 3S into international nuclear infrastructure improvement programs [8];
- proposing a conceptual systems approach to integrating 3S within the broader context of a civilian nuclear energy program [9]; and,
- describing 3S as a preliminary framework for coordinating the safety, security and safeguards regulatory requirements and combining the results of individual analyses.[10]

More recent efforts to characterize integrated 3S approaches have extended these preliminary studies, but still remain as conceptual offerings. One recent example incorporates the relatively novel 'by-design' concept to offer a comprehensive design approach called safety, security, and safeguards by design ('3SBD').[11] By leveraging the conceptual 3S overlaps in regulations,

[1] Safety, security and safeguards will be referred to as 'characteristics' in this paper, and their associated analysis methods will be referred to as 'characteristic-specific risk analysis techniques.'

procedures and instrumentation, 3SBD offers such potential resource savings for nuclear utilities as using data gathered on a shared video surveillance platform for perimeter monitoring (security), providing continuity of knowledge (safeguards) and detecting hazardous scenarios (safety).[11] A second recent example uses traditional risk management approaches to integrate the 3S by effectively pairing sabotage with safety and theft with safeguards.[12] The vulnerability evaluation simulating plausible attacks (VESPA) compares quantified severity and likelihood of potential consequences—described in terms of the similarities and synergies between sabotage/safety and theft/safeguards—and evaluates the severity of pre-defined scenarios, regardless of the associated safety or security origin.[12] Both of these recent approaches mention, but offer no mitigations for, the increase in complexity from 3S analysis.

Considering SNF transportation as a complex socio-technical system offers a new paradigm by which to characterize and mitigate increasing risk complexity. One such effort, dynamic risk analysis, offers a time-dependent evaluation of the consequences (for both people and the environment) of system failures in terms of continuous improvement and risk management.[13] Because risk stems from interactions between technical, human and organizational influences within a complex system, reducing risk for specific scenarios or components may prove insufficient. Therefore, there is a need to evaluate the system as a whole to adequately characterize, evaluate and manage increasingly complex risk.[13] Two particular system-theoretic approaches have shown promise in mitigating complex risk: dynamic probabilistic risk assessment (DPRA) and system theoretic process analysis (STPA).

A dynamic probabilistic risk assessment (DPRA) methodology provides a 'bottom-up' framework for evaluating the integrated 3S concept. Current approaches to probabilistic risk assessment (PRA) use the conventional event-tree/fault-tree methodology and requires pre-specification of event order occurrence—which may vary significantly in the presence of uncertainties.[14] Manual preparation of input data to evaluate the possible scenarios arising from these uncertainties and their execution using serial runs may lead to errors from faulty or incomplete input preparation and infeasible run times. In response, a methodology has been developed for DPRA analysis using dynamic event trees (DETs) that removes these limitations with systematic and automated assessment of possible scenarios arising from the uncertainties [15] and allows for a seamless transition for an integrated 3S analysis without using the practice of linearly combining results from individual safety, security and safeguards risk analyses. DPRA employs developed DETs for a seamless transition from a safety-to-security-to-safeguards analysis. In extending DPRA to include seamless integration of the 3S, assessment of uncertainties is performed in a 2-loop process. This 2-loop process will allow evaluation of epistemic (e.g., arising from the model) and aleatory (e.g., arising from stochasticity of the processes) uncertainties in a systematic and coherent fashion. In the DPRA research framework, the output from a safety code will provide input to a security code, whose output will subsequently provide input to a safeguards code—with the order of their implementation varied to explore why any differences may have occurred.

Similarly, the system theoretic process analysis (STPA) argues that managing the complex risk on security, safety and safeguards of international SNF transportation can be seen as eliminating, minimizing or mitigating migration into states of higher risk. STPA is a top-down analytical processes that provides a rigorous, structured mechanism for linking specific design details to supporting overall system objectives.[16] This traceability provides both (non-probabilistic) resource justification for complex risk mitigation and a metric by which to compare and validate proposed measures to improve the complex risk mitigation of international SNF transportation. STPA's analytical prowess is based on abstracting real complex system operations into hierarchical control structures and functional control loops.[16] Within the constraints provided by higher levels in a hierarchical control structure and loop, a controller issues a control action—based on its current process model—to an actuator. This actuator manipulates a controlled process based on the control action. The completion of this controlled process is registered by a sensor. This sensor information becomes feedback that updates the controller's process model regarding the original control action. STPA uses control loops to derive control actions designed to prevent migration into system states of higher risk and consists of two major steps [16]:

- '**Step One**': rigorously identify possible violations of control actions that lead to system states of higher risk (including, when incorrect control actions are issued; required control actions are not issued; control actions are provided too early or late; or control actions are stopped too soon (or too late) to be adequately enforced); and,
- '**Step Two**': derive specific scenarios, based on observed or regular system operations, that could cause the theorized control action violations (identified in Step One) to occur.

As such, STPA suggests utility in redefining the complex risks associated with security, safety and safeguards of international SNF transportation as identifying requirements and enforcing control actions to avoid system states of higher (or unnecessary) risk.

The proposed DPRA and STPA methodologies have the potential to provide justification into integrated 3S research areas, evaluate the potential 3S benefits over characteristic-specific risk analyses and characterize an overall complexity metric.

RESEARCH FRAMEWORK

This research hypothesizes that integrated 3S approaches for mitigating complex risks are improvements over traditional, isolated characteristic risk analysis techniques. Using a complex risk framework to capture the interdependence of safety, security and safeguards, the focus becomes less on emphasizing instrumentation or policy reliability and more on how the interaction of system components work to allow the SNF to successfully complete the route from origin to destination. As such, this research assumes that each characteristic (and their interdependence) is an emergent, system-level property—not just a compounded reliability of characteristic-specific components along a particular SNF transportation path.

Past studies using STPA [16][17] and DPRA [14][14] suggest that this systems-theoretic perspective is able to provide an enhanced level of risk mitigation (e.g., reductions in safety hazard, security vulnerability and safeguards violations) over traditional characteristic-specific analysis techniques. Thus, this research framework will apply each of these analysis techniques to evaluate the complex risk for a hypothetical case of international SNF transportation.

To develop an adequate hypothetical international SNF transportation case study that meets the standards of single case research design [18], details were leveraged from real-world SNF transportation cases to develop an unclassified, hypothetical SNF transportation case, including country, cask, transportation mode and transportation route selection details. These case parameters were translated into a complex systems model, inclusive of all aspects of transportation along an approved route (e.g., border crossings and changes of transportation mode), but not loading/unloading operations at the point of origin/destination. The systems model of the hypothetical transportation case considers the nominal sphere around the transport vehicle (including dedicated response vehicles if appropriate) and provides a platform for risk minimization analysis of interacting social and technical components.

As such, the STPA research framework will be used to evaluate the risk of each characteristic in isolation. More specifically, individual safety, security and safeguards hierarchical control structures will be developed to accurately reflect the related entities in the SNF transportation system and their responsibilities. Examples of entities and related responsibilities include:

- the national nuclear regulator establishing cask thermal output standards (e.g., safety);
- the shipping organization initiating locks on the transport vehicle (e.g., security); and,
- border inspectors confirming cask seals against manifest information (e.g., safeguards).

Similarly, system-level requirements (e.g., desired limits on system behavior) and supporting control actions (e.g., component specifications) will be generated based on each characteristic's hierarchical control structure. A representative set of these requirements and control actions for each characteristic will then be evaluated with STPA to logically and rigorously identify opportunities for violation (e.g., how the system can migrate toward states of higher risk). From this output, specific categories of risk for each characteristic (STPA step 1) and specific scenarios or paths of concern (STPA step 2) will be identified.

Then STPA will be used to analyze an integrated 3S description of international SNF transportation case (Figure 1). Following the same process as described above, a 3S hierarchical control structure will be constructed, including certain elements of the characteristic-specific models. The process of constructing this model—deciding what and how to include various characteristic-specific entities and responsibilities—alone is likely to help highlight and identify gaps, interdependencies, conflicts and leverage points between safety, security and safeguards. This 3S control structure will produce system-level risk mitigation requirements and associated control actions. The control actions identified will not be categorized *a priori* (e.g., a 'safety requirement'), but will be stated in terms of component specifications necessary to constrain overall system behavior within desired limits—and away from higher risks. A representative set of these 3S requirements and 3S control actions will then be analyzed with STPA for possible violations. These 3S control actions (and related violations) will be compared directly to the characteristic-specific control actions (and related violations) to identify additional gaps, interdependencies, conflicts and leverage points. As such, it is vital that the selected set of requirements and control actions broadly cover both the wide range and depth of influence of risks of concern in order for the comparative analysis to yield useful, generalizable results. Further, this selection is a key component of the overall research agenda as careful selection will provide opportunities for supplemental comparison with output from the parallel DPRA analysis.

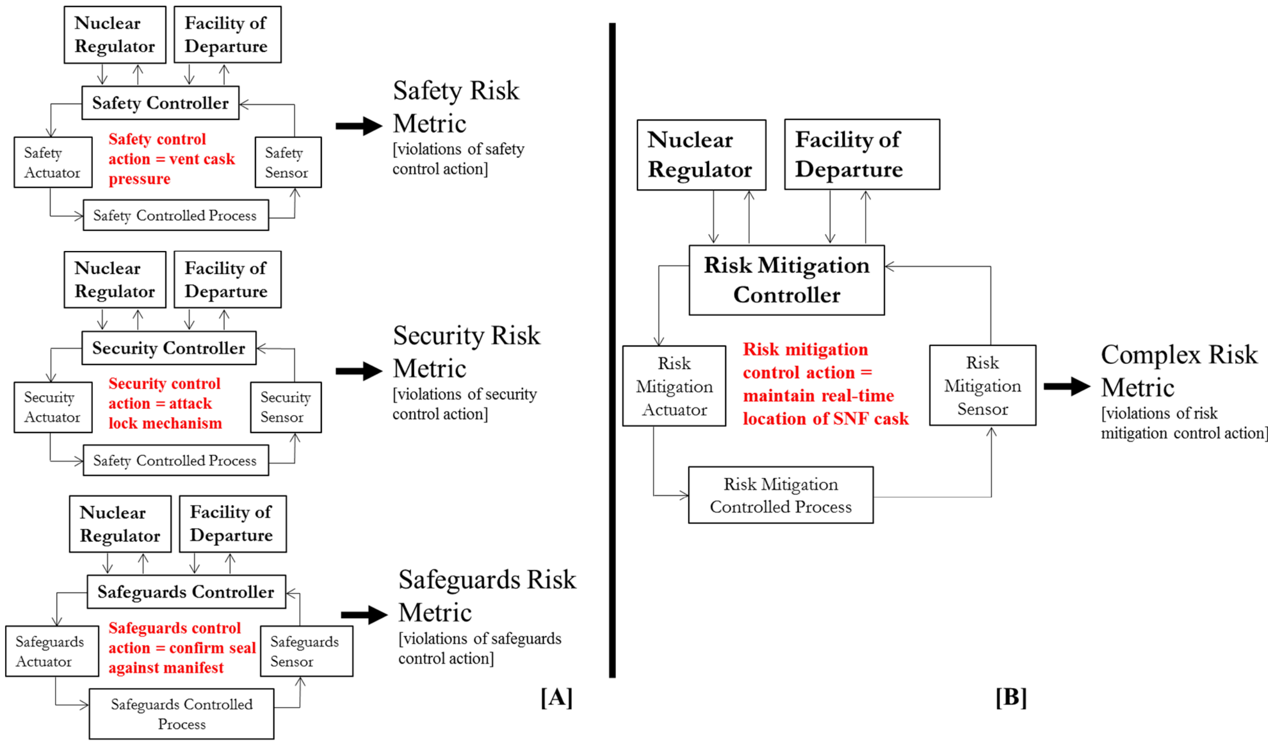

Figure 1. Illustration of the STPA research framework, via representative control loops for individual characteristic [A] and 3S complex risk [B] STPA analysis.

Working in parallel, the DPRA research framework will generate the baseline risk mitigation identified by evaluating isolated characteristics via traditional SNF transportation analytical techniques. More specifically, the safety analysis will use RADTRAN—an internationally accepted program and code for calculating the risks of transporting radioactive materials. The security analysis will be conducted using a SNL-specific application of a commercial code called the Scenario Toolkit and Generation Environment (STAGE) that has been used across a range of applications.[19][20] STAGE (from Presagis International) is a computer combat model composed of database, mission, script, scenario and run time editors that use logic based behavior models and its own artificial intelligence package (AI.implant) to simulate complex behaviors, intelligent reactions and dynamic path planning on a flexible platform. Lastly, because not software code currently exists for SNF transportation safeguards, this analysis is expected to include a modified version of the Separations & Safeguards Performance Model (SSPM), augmented by Origen for source term generation. SSPM is a Matlab Simulink platform-based transient reprocessing plant model that tracks mass and volumetric flows of special nuclear materials through all physical steps in a given process (e.g., UREX or PUREX), monitors inventory differences within and across material balance areas and includes a moveable 'diversion' component for testing system reaction to material loss.[21] Origen is an Oak Ridge National Laboratory-developed point depletion and decay computer code for simulating nuclide compositions of materials developed for generating spent fuel and nuclear waste characteristics. The output from each of these analyses will form the baseline data against which to evaluate the utility of the DPRA integrated 3S method.

The DPRA-based analysis will then evaluate an integrated 3S approach by interrelating the inputs and outputs of the software codes described above. Here, the integration will occur using the Analysis of Dynamic Accident Progression Trees (ADAPT) software which has been linked to various system-level models.[15] The ADAPT code was developed by the Ohio State University as part of a SNL Laboratory Directed Research and Development (LDRD) project to generate dynamic event trees (DET). ADAPT will be used as the controller and scheduler to link RADTRAN, STAGE and SSPM because it can determine possible scenarios (e.g., complex risks) based on the branching and stopping rules provided by varying uncertainty and input parameters. In addition, ADAPT can keep track of scenario likelihoods and graphically display the DETs, as well as all simulator output figures of merit as a function of time. ADAPT will not only provide a mechanism for addressing the 3S interdependencies by linking the characteristic-specific risk analysis codes in a novel manner, it also will provide the opportunity to vary the order in which the codes are run. This will allow additional research and sensitivity analysis on the order in which the codes are linked, in order to better reconcile potential differences in the output. As with the STPA analysis, selection of the figures of merit to evaluate is vital in order (1) provide a clear comparison to the output from the characteristic-specific risk analysis and (2) provide opportunities for comparison with output from STPA.

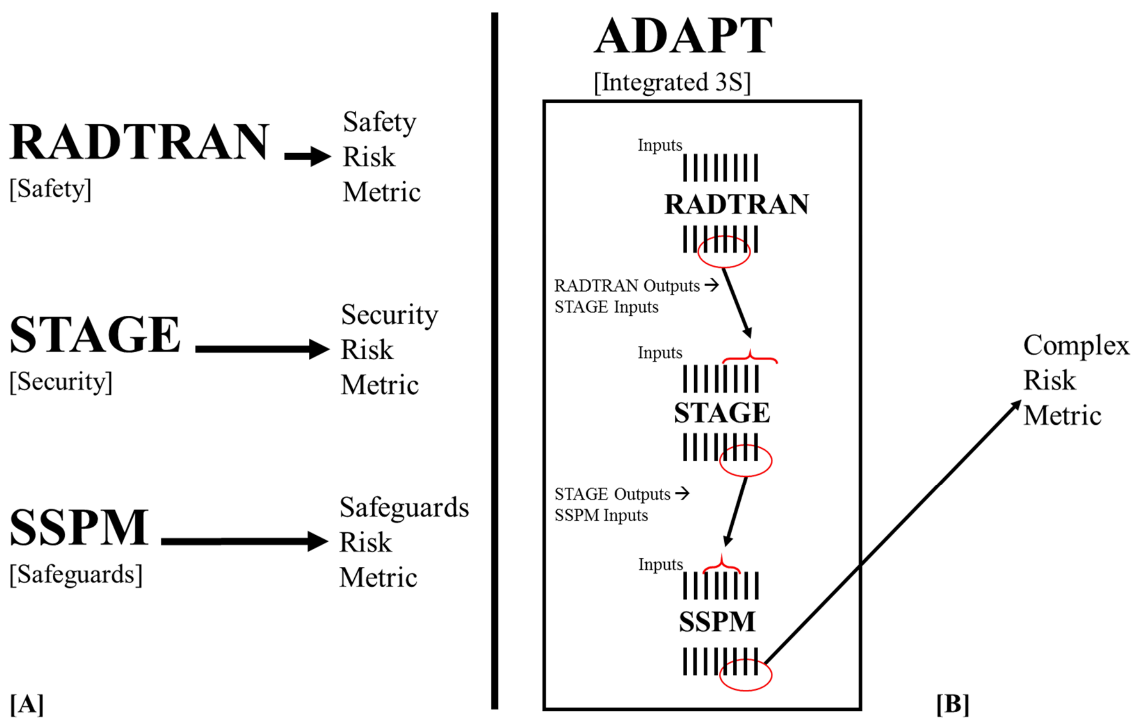

Figure 2. Illustration of the DPR research framework, via representative individual characteristic-specific risk analyses [A] and 3S complex risk [B] ADAPT analysis.

PRELIMINARY RESULTS

Preliminary research provided a set of useful insights regarding complex system perspectives and an integrated 3S approach to international SNF transportation. In particular, the inability to assess safeguards-related risks is a significant gap, one that is accentuated when considering the potential inconsistency in safeguards responsibilities along a specified SNF route may increase system-level risk by providing opportunities for state diversion pathways if resources are not available to maintain adequate (or provide timely detection of broken) continuity of knowledge. And, where these inconsistencies increase the time required to conduct inspections at various points of authority transfer along a route, interdependence is demonstrated as security capabilities may be stressed (and overall system risk increased) by the delay(s). Other potential interdependencies include authorized speeds that SNF transportation vehicles may use (e.g., safety analysis mandates a speed slower than security analysis suggests) or cask structural integrity degradation from applied tamper-indicating devices (e.g., safeguards needs influencing safety analysis). While some interdependencies can lead to conflicts between characteristic-specific requirements (e.g., safety mandated communication of the transportation route to local stakeholders along a route, despite the security mandate to enforce 'need-to-know' information control policies), a systems perspective can help translate these into opportunities to identify leverage points. For example, ensuring that emergency medical skills and supplies are present in the SNF escort vehicles (e.g., safety leveraging security)—either by cross-training response force personnel or imbedding medical personnel in response force units.

Thus, one of the clear merits of evaluating SNF with an integrated 3S approach is that complex risk is better characterized in terms of emergent system behavior(s) than compounded probabilities from each characteristic-specific risk analysis. The DPRA research framework demonstrates this in its ability to evaluate different orders of linking the traditional characteristic-specific risk analysis codes, as well as the input and output variables shared across them. In so doing, the DPRA analysis will be able to identify risks that would not be captured by simply running the characteristic-specific risk analysis codes in series and linearly combining their outputs. Some additional insights resulting from establishing the DPRA framework include:

- the analytical uncertainty values used for Origen (e.g., a safeguards figure of merit) directly influence source term calculation (e.g., a safety figure of merit);
- the determination of figures of merit (and their resultant interactions) to be used to link the various characteristic-specific analysis codes has not been done; and,
- there is a need to be precise in expanding definitions for (and what parameters are included in) 'epistemic' and 'aleatory' uncertainty for security and safeguards.

Similarly, the STPA research framework further demonstrates this by characterizing risk as emerging from the completion (or violation) of control actions that interact with other system components to avoid (steer toward) states of higher risk. Defining risk mitigation as a system level property, the STPA 3S analysis offers an expanded solution space for redesigning or replacing control actions to enforce desired component specifications and emergent system behaviors. Some additional insights resulting from establishing the STPA framework include:

- a need to adequately characterize and evaluate different resources and expectations in each characteristic along an SNF transportation route;
- specific scenarios of concern can be potentially 'binned' into categories of risks to be mitigated and help evaluate the benefit of the 3S analytical results; and,
- there is a need to clearly characterize and evaluate points of operational or procedural confusion (e.g., specific inspection protocols) along international SNF shipment routes.

Moving forward, key figures of merit will be identified that connect across characteristics—with those evaluated to have significant influence on the overall system risk included in a comprehensive measure of complex risk. This comprehensive risk metric is likely to include:

- elements that consistently emerge from ADAPT analysis, regardless of the order in which characteristic-specific risk analysis codes are employed;
- STPA generated descriptions of system states of higher risk; and,
- measures of nuclear material lost and land area contaminated.

By characterizing risk in this manner, associated risk mitigation strategies will be cross-cutting (e.g., not scenario dependent) between safety, security and safeguards and better serve the overall system goal of successfully transporting SNF internationally from origin to destination.

SUMMARY

The expected significant increase in international SNF transportation—and its associated increases in complexity—suggest that risks associated with SNF transportation should be considered more than dose consequences, as well as new consequences of concern like state diversion of SNF and land contamination from any SNF transportation-related release. The emerging research framework seeks to expand beyond linear combinations of characteristic-specific risk analyses, using DPRA and STPA to explore gaps, interdependencies, conflicts and leverage points of an integrated 3S approach. Next steps for this research project include:

- down select figures of merit for 3S analysis (e.g., input and outputs in DPRA and security requirements and control actions for STPA);
- demonstrate proof-of-concept analyses of DPRA and STPA 3S approaches on a hypothetical international SNF transportation case;
- develop a framework and metrics for comparing the risk description and mitigation of the 3S approaches vs characteristic-specific risk analyses (for both DPRA and STPA); and,
- apply the 3S approaches to real SNF transportation cases (if available).

Ultimately, this research will use a time dependent, dynamic control theoretic complex system model to provide both new approaches to define and mitigate increasingly complex risk and methodologies to generate strategies to assess, manage, mitigate and eliminate the complex risks of SNF international transportation.

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