



# Toward a New Approach to Risk Complexity in the Nuclear Fuel Cycle



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Adam Williams (SNL) & Mercy DeMenno (SNL)



# Outline

- Introduction
- Traditional Approaches to Risk
- Complex Risk Conceptualization
- Complex Risk & SNF Transportation
- Summary & Conclusions

- Safety, security & safeguards (3S) challenges to the nuclear fuel cycle (NFC) are growing & evolving
  - Can emerge from asymmetries in nuclear energy program capabilities or today's dynamic environment
  
- This represents an increasing **complexity** in the **risk** associated with NFC activities
  - Some degree of risk is inevitable
  - Risks become significant for practitioners when they prevent the completion of desired nuclear fuel cycle activities
  
- Example: the multi-modal & multi-jurisdictional nature of international transportation of spent nuclear fuel (SNF)
  - The complexities involved in the international transportation of SNF have been shown to challenge traditional risk reduction in
    - Security
    - Safety
    - Safeguards

# Introduction

- In response, we offer a broader concept: **complex risk**
- Complex risk includes the pressures & dynamics that prevent completion of desired objectives
  - For SNF transportation, the total risk encompasses (& is not limited to) traditional descriptions of safety, security or safeguards risks
- This concept expands upon traditional engineering approaches to risk by:
  - Accounting for social, political & technical contexts
  - Emergence of system-level risk resulting from component-level interactions

# Traditional Approaches to Risk

- SNF transportation suggests **2 challenges** to the extant engineering literature on risk
  - (1) Emphasis on defining risk as a function of probability & consequence
  - (2) Micro-to-macro risk extrapolation limitations
  
- Further, the extant literature does not explain how low-risk components can interact non-linearly to result in higher risk system-level behaviors
  - Example: how one state's overly conservative nuclear safety policies can slow the SNF convoy road transportation speeds to levels that increase the security risk beyond designed limits

# Traditional Approaches to Risk

- This review highlights the need for a broader conceptualization of risk that can:
  - Inform an approach to risk analysis that is data-pluralistic
  - Avoid the limitations of purely probabilistic approaches
  - Support new risk frameworks for overcoming the micro-macro extrapolation issue

IName [ref] (Emphasis)	Summary	Advantages	Disadvantages	Analytical Gaps
<b>“Set of Triplets” (Risk Definition)</b>	<ul style="list-style-type: none"> <li>• Probability &amp; consequence over a given set of scenarios: Risk = <math>\{(s_i, p_i, x_i)\}, i=1,2, \dots, N+1</math></li> </ul>	<ul style="list-style-type: none"> <li>• First level definition is computationally simple &amp; visually accessible via risk tables or risk curves</li> <li>• Accounts for multi-dimensionality of consequences &amp; incomplete information</li> <li>• Definition used by NRC</li> </ul>	<ul style="list-style-type: none"> <li>• Requires comparability in measures of consequence</li> <li>• Acknowledges subjectivity in probability assessment, but does not incorporate social-psychological elements of risk</li> </ul>	<ul style="list-style-type: none"> <li>• Limited data plurality, unclear how to incorporate qualitative measures</li> <li>• Presumably could be applied to each “S” in isolation (assuming data could be standardized within analysis) but does not provide for interaction/feedback</li> </ul>
<b>Complexity Theory &amp; the Management of Risk (Risk Management)</b>	<ul style="list-style-type: none"> <li>• Risk is emergent, rather than mechanistic &amp; as such risk managers should view organizations as ecologies, not machines</li> </ul>	<ul style="list-style-type: none"> <li>• Provides a framework for using complexity theory for risk management in complex systems</li> <li>• Identifies the factors that cause complex systems to “drift” into failure or success</li> </ul>	<ul style="list-style-type: none"> <li>• Does not provide a definition of risk not an actionable framework for risk analysis nor address issues related to data plurality</li> </ul>	<ul style="list-style-type: none"> <li>• Proposes a solution—diversity—which may not be feasible in the 3S context given the relative lack of centralized control &amp; repeat players</li> </ul>

<sup>[1]</sup> Options: Risk definition (quantitative, qualitative, both), risk management, risk analysis & risk communication.

<sup>[2]</sup> Only analytical gaps vis-à-vis 3S analysis of SNF international transportation included.

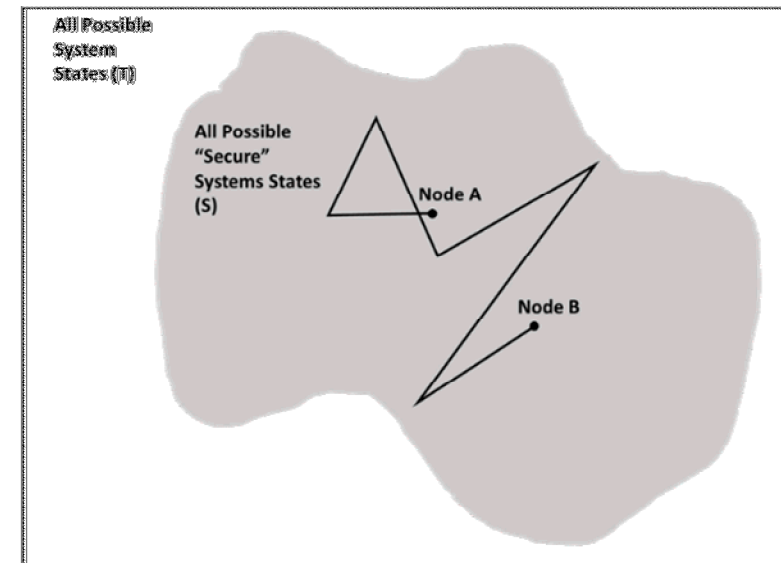
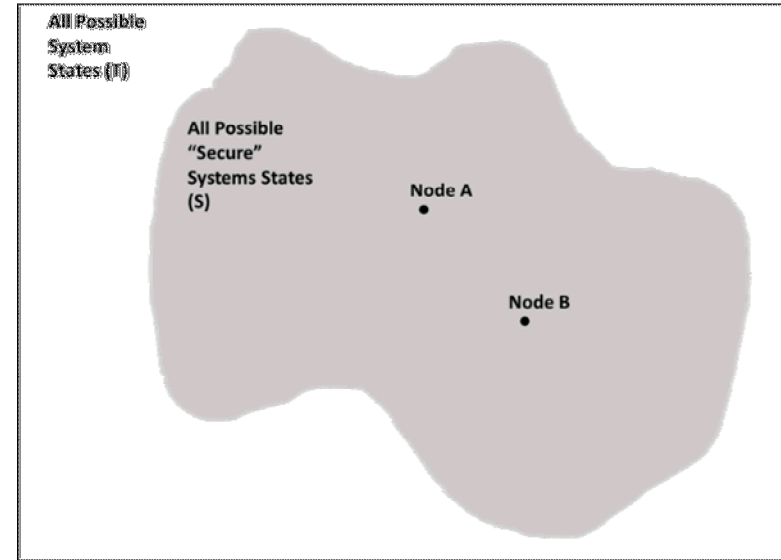
# Complex Risk Conceptualization



- Complex risk is necessarily highly contextual
  - In operational reality, risk encompasses all the pressures, objects, and dynamics that may oppose the completion of system-level goals or existence of desired system-level behavior
  
- For example, Weaver (1948) describes 'risky behaviors' in terms of :
  - **Complexity**: the logical, albeit unforeseen, pathway leading the risky event
  - **Randomness**: the accuracy describing interactions along the logical pathway
  - Conclusion: need a way to evaluate 'risky behaviors' that are organized & highly complex
  
- Potential solution found in the tenets of complexity & systems theories augment engineering approaches to risk
  - Interdependence
  - Emergence
  - Hierarchy
  - Control
  
- Risk goes beyond the probabilistic calculation of technical component reliability to include descriptions of how social dynamics influence resultant behavior(s)

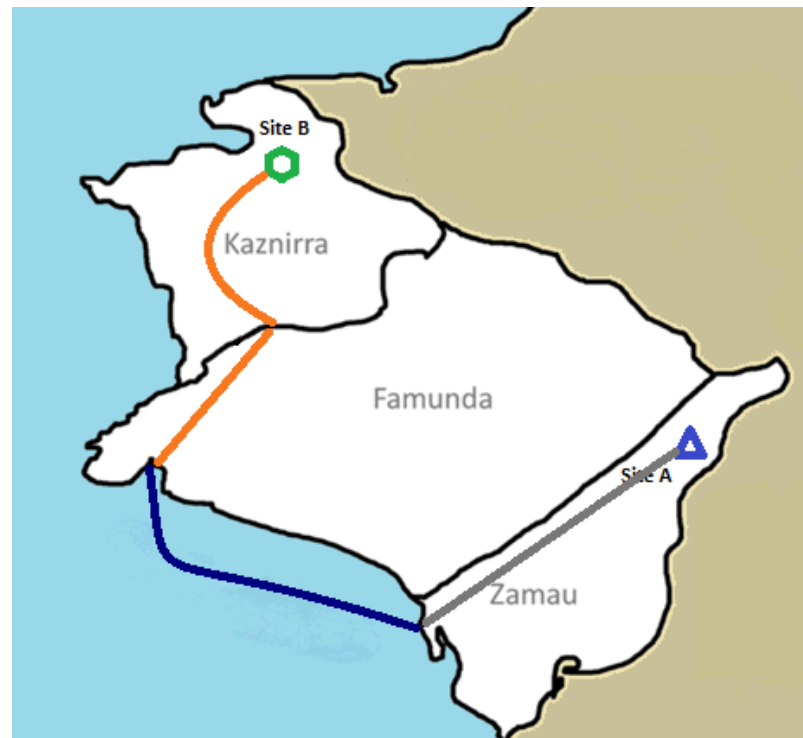
# Complex Risk Conceptualization

- Results in a “state space” description of where **complex risk** is conceptually a function of:
  - Distance from the current state within the secure space to the nearest boundary
  - Speed at which forces are pulling/pushing the system toward the boundary
  
- Security system states defined by high-level security requirements
  - These requirements are implemented in different social, political & technical contexts
  
- A system may exist at different places in the secure space at different points in time:
  - **Top Graphic:** Relatively secure because both Node A & Node B are centrally located (not near a boundary) within the secure space
  - **Bottom Graphic** Not as relatively secure, despite the centrality of Nodes A & B, due to multiples points that approach the boundary of the secure space
  
- **Complex risk** is dynamic & the risk profile involves both
  - Point estimates of risk
  - All system states between the point estimates



# Complex Risk & SNF Transportation

- For demonstration, consider a hypothetical international transportation of SNF case
  - This example involves the physical transportation of SNF from an origin facility in Zamau (mature nuclear program), through the intermediary country of Famunda (immature nuclear program), to a destination facility in Kaznirra (mature nuclear program)
- For simplicity, this demonstration will focus on the “organized complexity” of **providing security for the SNF while it travels via rail car to the Port of Zamau:**



# Complex Risk & SNF Transportation



- Various levels of resources exist to provide security for the SNF as it travels along this route
  - In this case, each country agrees that it will provide security & emergency response, as necessary, for the SNF cask while it is transported within its borders
  
- Per the **complex risk** concept:
  - System goal: stay within the secure space (S)
    - Boundaries of which defined by tenets in CPPNM
  - Operational goal: physical transportation of the SNF without disruption to selected/approved routes, timelines & operations
  
- This operational goal sets **2 individually necessary & jointly sufficient** conditions:
  - The transportation of SNF material from the origin facility to the border crossing
  - Meeting the operational conditions, which in this case are defined as utilizing the selected & approved routes, timelines & operations

# Complex Risk & SNF Transportation



- This conceptualization enables a richer understanding of pressures, objects & dynamics influencing risky behaviors
- For this example, consider how the SNF
  - is successful transported under the desired operational conditions [C]
  - might be successfully transported, but riskier than anticipated (e.g., route deviation) [A]
  - not successfully transported, though requirements meet operational conditions, (e.g., inaccurate translation) [D]
- Thus, **complex risk** encompasses pressures, objects & dynamics which prevent the completion of the desired system objective [C]

		Was the task completed?	
		Y	N
Were the operational conditions met?	N	SNF moved from Country A to Country B, but deviated from the selected and approved routes, timelines, and operations [A]	SNF not moved from Country A to Country B, as a result of deviation from selected and approved routes, timelines, and operations [B]
	Y	SNF moved from Country A to Country B, utilizing the selected and approved routes, timelines, and operations [C]	SNF not moved from Country A to Country B, despite utilizing the selected and approved routes, timelines, and operations [D]

# Complex Risk & SNF Transportation



- Analysis summary:
  - **(S)** is the system objective (stay in the secure space defined by CPPNM)
  - **(C)** operational objective is the physical transportation of SNF from an origin to destination without disruption
  - **(Z)** security incident (adversary attempt to access SNF cask) of unknown probability that can prevent (C)
  - Logic: meeting the system objective (S) increases the probability of meeting the operational objective (C) assuming some incident (Z)
- Complex risk manages its consequences while reflecting the pressures, objects & dynamics on completion of (C)
  - Likely impossible to mitigate the likelihood of (Z),
- For this example, the route from the origin facility in Zamau to the Famunda/Kaznirra border crossing consists of five transportation legs ( $L_{1-5}$ )
- Risk varies throughout the route & across the scenarios for two reasons:
  - (1) Each transportation mode has an inherent level of risk which is outside the control of operators
  - (2) Countries have autonomy in deciding how to implement the high-level security requirements that compose the secure space

# Complex Risk & SNF Transportation

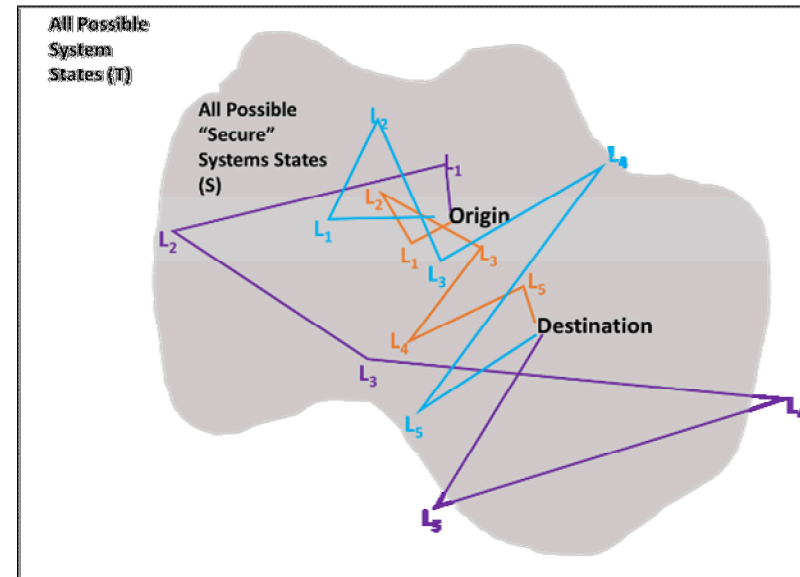


- The high-level security requirement is ‘**provide armed escort**’
- Zamau has three approaches to meet this high-level security requirement:
  - Special forces (high security)
  - Contract security forces (medium security)
  - Local law enforcement (low security)
  - NOTE: each of these are sufficient to meet the high-level requirement, but varies in the operational level of security
- Famunda has two approaches to meet the high-level security requirement:
  - Contract security forces (medium security)
  - Local law enforcement (low security)
  - Famunda might also choose to not meet the high level security requirement thereby violating the tenets of the CPPNM
- The inherent risk of each leg & the country implementation approaches for the security requirements produce three hypothetical scenarios (orange, blue & purple) with three distinct risk profile

SNF Transportation Route Legs	Country	Implementation Approach to Meet High-Level Security Requirement: Armed Escort		
		Orange Scenario	Blue Scenario	Purple Scenario
Origin	Zamau	n/a	n/a	n/a
Movement on rail line (L <sub>1</sub> )	Zamau	Special forces	Contract security forces	Local law enforcement
Transfer rail to barge (L <sub>2</sub> )	Zamau	Special forces	Contract security forces	Local law enforcement
Movement on barge (L <sub>3</sub> )	Zamau	Special forces	Contract security forces	Local law enforcement
Transfer barge to truck (L <sub>4</sub> )	Famunda	Contract security forces	Local law enforcement	Nothing
Movement on truck (L <sub>5</sub> )	Famunda	Contract security forces	Local law enforcement	Nothing
Arrival at border crossing with Kaznirra	Famunda/Kaznirra	n/a	n/a	n/a

# Complex Risk & SNF Transportation

- **Orange scenario:** both Zamau & Famunda meet the high-level security requirement with their most secure implementation strategies
  - **Result: this scenario is quite secure** throughout the route (as depicted by its relative centrality in the secure state (S))
    - Complex risk → high probability of meeting the operational objective given a potentially disruptive security incident
- **Blue scenario:** both Zamau & Famunda meet the high-level security requirement with their moderately secure implementation strategies
  - **Result: this scenario is moderately secure** throughout the route (as depicted by two legs approaching the boundary of the secure state (S))
    - Complex risk → moderate probability of meeting the operational objective given a potentially disruptive security incident
- **Purple scenario:** both Zamau & Famunda meet the high-level security requirement with their least secure implementation strategies
  - **Result: this scenario is least secure** throughout the route (as depicted by several legs outside the secure state (S) boundary)
    - Complex risk → lowest probability of meeting the operational objective given a potentially disruptive security incident



# Summary & Conclusions



- **Complex risk** is a function of:
  - Distance from the current state space location to the nearest boundary
  - Speed at which forces are pulling/pushing the system toward the boundary of the secure space
  - Those pressures, objects & dynamics which prevent completion of the physical transportation of the SNF without disruption to selected/approved routes, timelines & operations
  
- SNF transportation case yields several insights on the utility of the complex risk concept:
  - (1) Distinguishes those sources of risk that can be controlled (i.e., defining high level security requirements, implementing high-level security requirements) from those sources of risk that cannot be controlled (i.e., security incident (Z), inherent risk associated with various modes)
  - (2) Identifies aspects risk variability stemming from implementation (e.g., choice of armed escort type) versus inherent aspects of risk (e.g., riskiness of various transportation modes)
  - (3) Highlights the need for greater attention to scenarios in which the system objective is not completed, but for reasons other than violating the specified conditions
  
- Though further research is necessary, this **complex risk** concept is aimed to support new frameworks & analytical techniques to more effectively capture the increasing complexity facing NFC activities