ABSTRACT

PRINS, MOLLY. A Probabilistic Risk Assessment for the Transportation of Department of Defense Micro Reactors with the Effects of an Accident on the Surrounding Population (Under the direction of Dr. Mihai A. Diaconeasa).

In the late 2010s, the Department of Defense (DoD) began research into the employment of mobile nuclear power plants (MNPP) with the purpose of providing electrical energy to remote locations during peace and war. Project Pele, an MNPP prototype designed to build and test advanced nuclear power plant engineering, provides comprehensive strategic capabilities information to decision makers. Nuclear reactor system probabilistic risk assessments (PRA) are vital to describing operational safety measures during operation and in the event of an accident. Risk assessments are especially critical with MNPPs due to their complex design and unique ability to move locations. This thesis describes Project Pele in order to conduct a PRA MNPP transportation framework through multi-mode event tree analyses. Four transportation event trees are developed from exhaustive research on accident causes and results. The event trees also provide insight into radionuclide release with associated transport determined by using RADTRAN. Contextual analysis is presented via a case study demonstrating effects of radionuclide release due to a MNPP accident during transportation. The proposed framework integrates a probabilistic perspective on transportation of spent fuel accidents and the effects on water, providing a unique aspect of MNPP employment to decision makers for Project Pele.

A Probabilistic Risk Assessment for the Transportation of Department of Defense Micro Reactors with the Effects of an Accident on the Surrounding Population.

by

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DEDICATION

To my Army friends who always sent me coffee money, my NC State friends who always grabbed coffee with me, and my parents who always supported me. It takes a village and I'm glad you're in mine.

BIOGRAPHY

Molly attended the United States Military Academy from 2013-2017, earning a BS in Interdisciplinary Science with an engineering focus on Nuclear Engineering. Upon graduation, Molly commissioned into the US Army Corps of Engineers at the rank of Second Lieutenant. She began her Army career in as a Platoon Leader with the 11th Engineer Battalion at Camp Humphreys in the Republic of South Korea. Molly's next assignment was at Fort Campbell, Kentucky. She served as the Battalion S$ within the 326 Brigade Engineer Battalion as part of 1st Brigade, 101st Airborne Division. She transitioned from that role to the position as Company Executive Officer for Bravo Company, 326 Brigade. While at Fort Campbell, Molly was selected to transfer within the Army to the Nuclear Counter Weapons of Mass Destruction Functional Area (FA52). Molly moved to Fort Leonard Wood, Missouri to attend her Captain's Career Course and was simultaneously accepted into North Carolina State University's Department of Nuclear Engineering to study towards a Master of Science. She was admitted into the Probabilistic Risk Assessment Group in Fall 2021 under the direction of Dr. Mihai A. Diaconeasa. Upon completion of her degree at NC State, Molly will return to the US Army where she currently holds the rank of Captain.

ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to Dr. Mihai A. Diaconeasa for his guidance and patience for the past two years. I am lucky to have him as my advisor and under his direction, I have been successful in completing this Master of Science program. I am extremely grateful to my colleagues in the PRA Group who helped me learn nuclear engineering and explore Raleigh. I would also like to thank my fellow FA52 officers and other members of the United States Department of Defense for their assistance in my research and professional life. Finally, I would like to thank my friends and family for their continuous support no matter the time or day.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. Introduction

1.1 Background and Motivation

Energy consumption and delivery is a strategic risk for military operations. The logistical complexities and expenses of supporting Forward Operating Bases (FOBs), expeditionary bases and remote bases, constrain planning and operations. The United States Department of Defense (DoD) is one of the largest consumers of energy in the world, using approximately 30 terawatt-hours of electricity per year with predictions of significant increases in the future [1, p. S-1]. Currently, field operating, and expeditionary base electrical power is provided by diesel generators requiring constant refueling due to their limited fuel storage capability. The modern and future battlefields are filled with technologies requiring large amounts of energy and storage capabilities. The DoD needs technology that allows for a smaller reliance on local power grids, portable generators, and logistical fuel packages to run operations.

Moving logistic packages with limited security are easy targets for enemy attacks. Logistic packages containing vital supplies are transferred via four types of transportation with truck transportation being the most dangerous in recent military conflicts. During Operation Enduring Freedom (OEF) and Operation Iraqi Freedom (OIF), 52% of casualties were from attacks during transportation missions [2, p. 3]. During OEF and OIF, 70% to 90% of logistical packages were made up fuel and water to FOBs and expeditionary bases. The fuel demand on installations within Afghanistan for installation energy (structural electricity) was approximately 40% to 60% [3, p. S-2]. Base operations fuel dependency constrains operational and strategic advances forcing DoD to really look into more reliable and continuous energy sources.

In 2016, the DoD requested a Defense Science Board (DSB) study on FOB energy systems. The results of the study were that the use of wind, solar and hydro for energy sources would neither

adequately meet current demands nor reliably produce enough energy across many locations and seasons [4, p. 28]. The DSB assessed that nuclear power in the form of modular reactors more than adequately provides the necessary amount of power for current and future needs [4, p. 30]. The DSB results kick started DoD mobile micro reactor interest, funding, and research.

1.2 Micro Reactors

During the 1950s the United States Army and Air Force designed, tested, and deployed small nuclear reactors. Of the 10 reactors, six were intended for maneuverability and ranged up to 10MWe (megawatt thermal). In particular, the ML-1 reactor was designed as a mobile low power plant with power up to 3.3 MWe, using highly enriched uranium (HEU) fuel with a water moderator and nitrogen coolant. The Army Nuclear Power Program (ANPP) created full-scale mockups of the reactor and power conversion package to mimic ML-1 exact specifications. The mockups were used to determine transportability while providing valuable information towards reactor modifications.

1.2.1 Project Pele

Project Pele is an outcome of the 2016 DSB study with an objective to design, build and demonstrate a prototype mobile microreactor producing 1 to 5 MWe (megawatt electric) using high-assay low-enriched uranium (HALEU). In April 2022, the Office of the Secretary of Defense's Strategic Capabilities Office (SCO) published a record of decision (ROD) promoting a final construction and demonstration for the prototype. The decision approved the proposed actions and manufacturing facilities. The approved proposed action consists of microreactor fabrication at an offsite commercial facility using stockpiled HEU converted from a metal to an oxide. The HEU is down blended into HALEU then fabricated into tri-structural isotropic (TRISO) fuel [5, p. 22522]. The 2022 ROD states BWX Technologies, Inc. (BWXT) and the Nuclear Fuel Services,

a subsidiary of BWXT, are responsible for down blending the HEU, fabrication of the TRISO fuel and construction of the microreactor prototype.

The demonstration of the microreactor prototype will occur at Idaho National Laboratory (INL) producing "reliable electric power for an electrical grid that is separate" from the public electrical grid [6, p. 22522]. Additional activities include demonstrating microreactor mobility, an example of safe disassembly and transportation of the spent nuclear fuel (SNF).

1.2.2 TRISO Fuel

The Tri-structural Isotropic (TRISO) fuel pebble has a core spherical fuel kernel made up of uranium, carbon, and oxygen. There are three outer layers that are made up of carbon and ceramic based material layers. These layers prevent the release of the inner radioactive fission products. The use of TRISO fuel is extremely popular in advanced high temperature reactors (HTRs) [7, p. 2]. Each layer of the TRISO fuel pebble serves a different purpose; the inner layer accommodates gaseous fission products, the middle layers provide load-bearing support and the outer layer is barrier for fission products [7, p. 4]. The layers make TRISO fuel very reliable. According to an NRC technical report describing the SiC layer testing, failure occurred at "approximately one per 52,000 particles in the irradiation testing and one per 15,000 particles at 1600°C testing following irradiation [7, p. 10]." The fraction failures during the tests were less than or equal to 3.6×10^{-5} during irradiation and less or equal to 1.7×10^{-4} and 1.3×10^{-3} when tested at 1600°C and 1800°C, respectively [7, p. 10]. Figure 1 provides the TRISO fuel pebbles, particles and fit within the graphite fuel blocks.

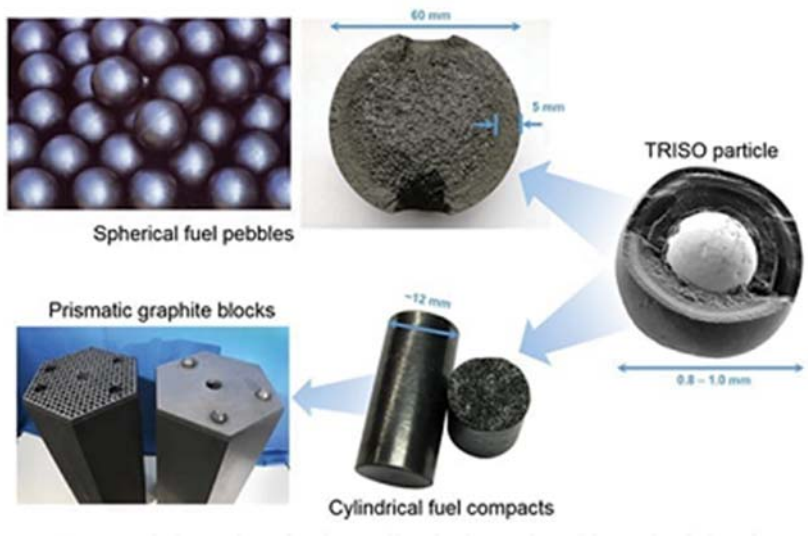

Figure 1. TRISO Fuel Schematic [8]

1.2.3 Reactor Design

The BWXT microreactor is set to be a high-temperature gas-cooled reactor (HTGR) that will be transported in shipping containers. The design is made up of multiple 20-foot long, ISO-compliant shipping containers [9]. The on-site reactor assembly process is designed to be operational within 72 hours with a seven-day shutdown, cool down, disconnection and removal [9]. A key objective for the reactor is the ability to move to various locations safely and rapidly by air, road, rail and sea. Figure 2 depicts the overall concept of transportation from a study on the use of mobile nuclear power plants. Idaho National Laboratory requirement testing is anticipated to last three years. Figure 3 displays the Idaho National Laboratory potential test site design. The design shows four containers in orange as well as a shielding structure in gray over the microreactor and power conversion modules.

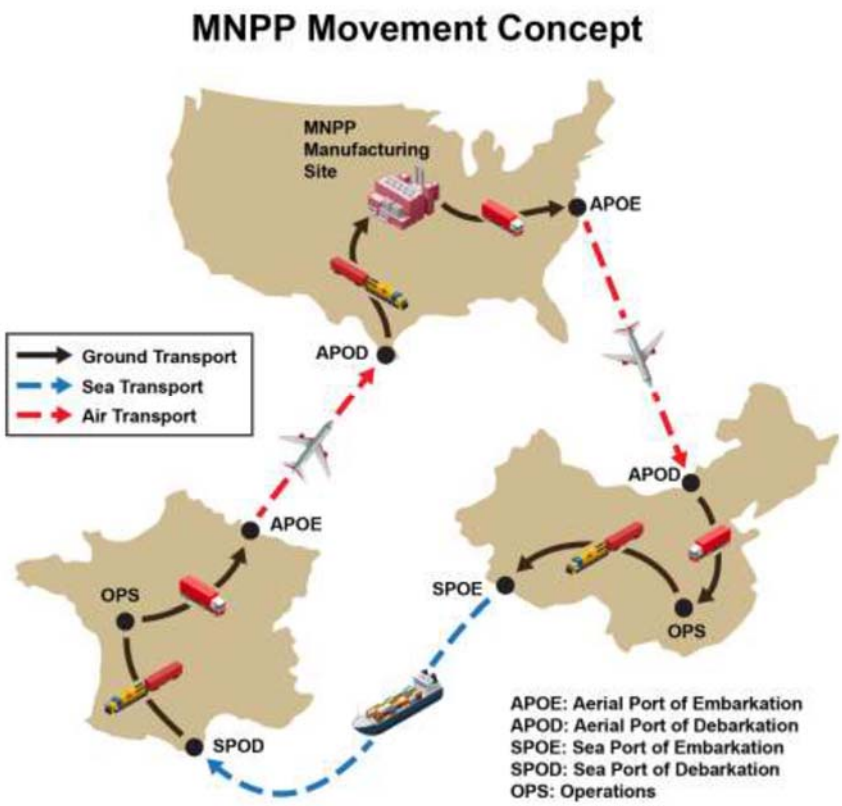

Figure 2. Mobile Nuclear Power Plant Concept of Transportation [10, p. 3.1]

Figure 3. Potential layout of mobile microreactor site at INL [11]

1.3 Scope

I studied current safety regulations of the NRC, DOT and EPA and their applicability to spent nuclear fuel transportation as a data framework for my overall analysis. I then used the analysis to develop a probabilistic risk assessment (PRA) as an evaluation tool for analyzing the watershed risk of transporting microreactors. Each PRA provided effect information on three different types of watersheds with recommendations to governing environmental agencies about dilution of released radioactive material. I then conducted a complete movement cycle analysis using three types of DoD transportation as a case study discussing the risks of the military microreactor transportation. This study does not include microreactor security during transportation.

CHAPTER 2. Regulations and Regulatory Guides Applicable to Micro Reactors

The Nuclear Regulatory Commission (NRC) publishes several spent nuclear fuel (SNF) regulatory and supporting documents and maintains regulatory frameworks within the NRC Regulations Title 10 Code of Federal Regulations. 10 CFR provides a regulatory framework for all non-exempted organizations who use nuclear materials. The United States Department of Defense is exempted as stated in 10 CFR 70.13, "to the extent that the Department receives, possesses and uses special nuclear material," for domestic licensing [12]. Although the DoD is exempted from licensing and material requirements, packaging and transportation must adhere to NRC guidelines for movements within public spaces. The packaging and transportation of licensed radioactive material is described in NRC 10 CFR 71, with special attention to subpart's E, F and G.

2.1 10 CFR 71

10 CFR 71 establishes the requirements for the packaging and transportation of licensed radioactive material. Subpart E refers to package approval standards and outlines tests to ensure adequate shipping. Type B packages are used to transport radioactive materials that present a potential hazard to the public (people and environment). Subpart F refers to package conditions during transportation and the tests required to meet approval standards. 10 CFR 71.73 covers hypothetical accident conditions and the tests to mitigate a hazardous leak to the public. There are six tests that act as minimum requirements for packages: free drop, crush, puncture, thermal immersion-fissile material, and immersion all packages. The free drop test involves the packages falling 9 meters (30 feet) at an angle that produce the maximum damage onto an unyielding, flat surface. The crush test differs from the free drop in the sense that in the crush test another object is falling while the package remains on its unyielding horizontal plane. The next test is the puncture

test where the package is dropped from a height of 1 meter (40 inches) onto a, “solid, vertical, cylindrical, mild steel bar” where the long axis of the bar is vertical. The thermal test engulfs the package in a hydrocarbon-fueled air fire with an average temperature of 800 °C (1,475 °F) sustained for 30 minutes. Finally, immersion for a package containing fissile material has two requirements. The first test states that, “where water inleakage has not been assumed for criticality analysis, immersion under a head of water of at least 0.9 (3 ft) in the altitude for which maximum leakage is expected [13].” For all packages, the package must withhold a water pressure equivalent to the pressure at a depth of at least 15 m (50 ft) [13].

2.2 NUREG 2125

NUREG 2125 provides a technical analysis in support of 10 CFR 71. The report is a risk assessment on the transportation of spent nuclear fuel that analyzes the potential of radioactive material release during a severe accident. Two accident scenarios are assessed; accidents where the spent fuel cask is not damaged or affected, and accidents where the spent fuel cask is affected. From 10 CFR 71.73, the test requirements that cover SNF transportation are the free drop, puncture, thermal, both immersion tests as well as requiring withstanding an external pressure of 2 million Pascals for at least one hour. Figure 4 shows the different package tests.

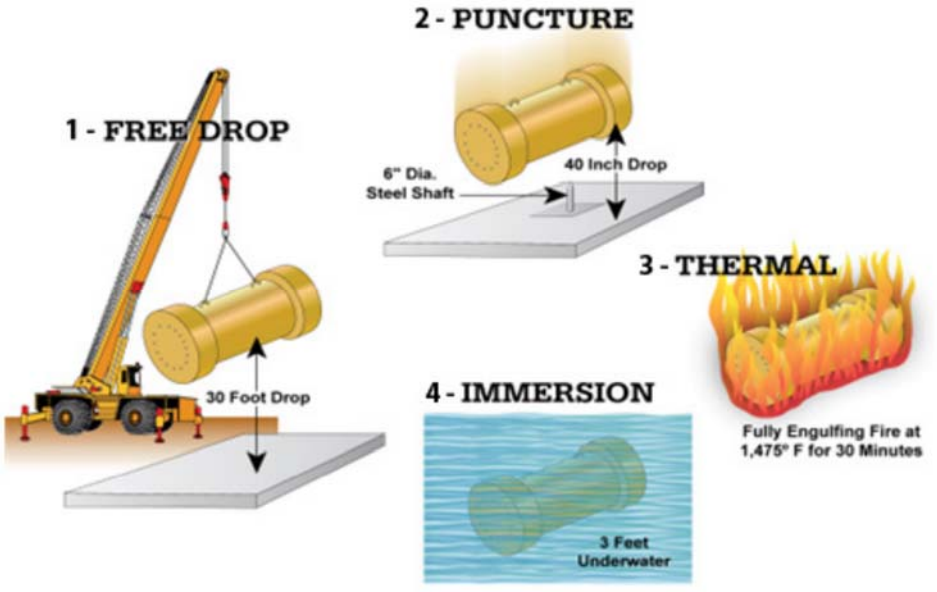

Figure 4. The four tests for SNF transportation [14, p. 9]

2.3 Environmental Regulations

The United States Environmental Protection Agency (EPA) is responsible for the Clean Water Act (CWA) of 1972. The CWA regulates discharges of pollutants into navigable surface waters. While the CWA does not regulate transportation pollutant discharge, pollutant guidelines are described for quantity levels, temperature, and material factors. Shortly after the establishment of the CWA, the Safe Water Drinking Act (SWDA) of 1974, was established to protect consumable or potentially consumable waters, including ground and surface waters. The act authorizes the EPA to establish minimum standards but allows each State to create more stringent standards. The Resource Conservation and Recovery Act (RCRA) authorizes the EPA to control hazardous waste during all aspects of the lifecycle, including transportation. Although the EPA publishes regulations, guidance and policies, the implementation and any additional guidelines are still authorized by the individual states.

Table 1. EPA and state guidelines for states along the route.

State	Routing Requirements	Inspection
Idaho [15, p. 10]	- Only use U.S and interstate highways - Must Avoid municipalities and population centers	As necessary
Wyoming [16, p. 12]	Follows EPA guidance only	Follows EPA guidance
Nebraska [17, pp. 17–2]	Make arrangements with authorities	Follows EPA guidance
Kansas [18, p. 49]	- Make arrangements with authorities - Avoid population density and activities - Must use bypass or beltway system around populated areas	Follows EPA guidance
Missouri	- Follows EPA guidance	Follows EPA guidance
Tennessee	- Follows EPA guidance	Follows EPA guidance
Georgia [19]	- Make arrangements with authorities	Follows EPA guidance

CHAPTER 3. Methodology

3.1 Overall Methodology

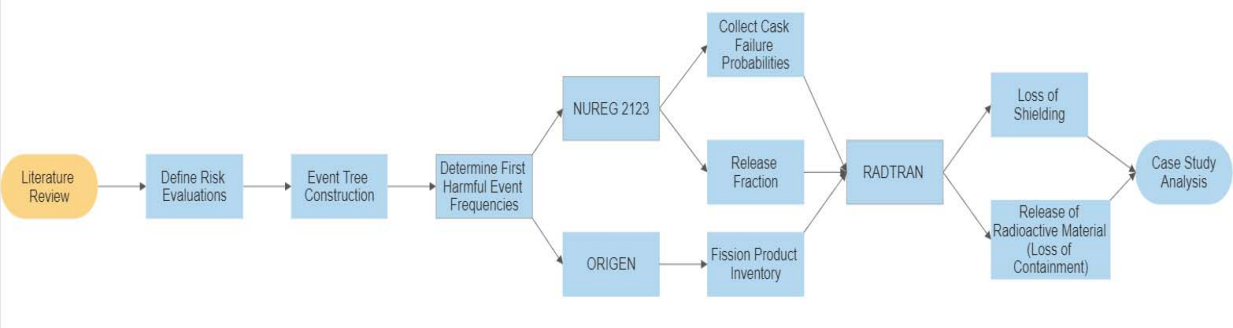

Figure 5. Overall Thesis Methodology

The probabilistic risk assessment and consequence analysis present a snapshot in time of the overall microreactor lifecycle, however the transportation phase is arguably riskiest due to the fluidity and uncontrollable events. The methodology of the risk assessment used along with the literature review are presented in the current chapter. Chapter 3 includes a literature review, brief description of PRA, the definition of safety used for this thesis, the data and software used, and the developed event trees per mode of transportation. Chapter 3 describes the methodologies used in this study; an event sequence diagram followed by an event tree. The event sequence diagram is broken down into specifics while the event tree is based upon data collected. The event sequence diagram helps to determine the risk used in the study of radiation leakage in watersheds. Since the study looks at the four types of transportation, ‘Types of Risk’ are the common ending sequence titles. The ‘End States’ along with their examples and applicable transportation method are shown in Table 2.

3.2 Literature Review

3.2.1 Historical Studies

The nuclear community is not new to the idea of transporting spent radioactive materials but typically, spent radioactive material is shipped separate from the reactor. Project Pele pushes these boundaries by shipping the fuel within the microreactor and associated contents. In 1978 Pacific Northwest National Lab (PNNL) developed a report on the risk of transporting spent nuclear fuel by truck. The report was written in anticipation of an increase in nuclear power plants within the United States and the eventual need to transport spent fuel to a disposal facility. The PNNL report defined risk as, "the product of the probability of a release of material to the environment and the consequences resulting from the release [20, p. 15]." In the study, four factors were used as input information: system description, release sequence identification, release sequence evaluation, and risk calculation and assessment. System description included what, where, when and how of the material shipped, the transportation system, including the spent fuel container, and the shipping route. At the time of the study, only pressurized water reactor (PWR) and boiling water reactor (BWR) fuel assemblies were considered, with spent fuel assumed to be in a cask surrounded by penetration barriers, a water-antifreeze solutions, an expansion chamber, and a singular lid attached with high-strength bolts.

The PNNL study researched five different accident environments: fire, impact, crush, immersion, and puncture. All five accident results were inflicted onto the cargo as well as the truck, however the immersion environment ended up null since the cask handled a water pressure of up to 40 ft below water surface. The study also looked at four mechanisms leading to significant release, gap release, vaporization release, leaching and oxidation. The risk of shipping spent fuel

came out to be 1.5 x 10^{-6} per shipment kilometer or once in 645,000 shipment kilometers [20, pp. 11–4].

3.2.2 Current Studies

In 2021, engineers at PNNL prepared a report on the challenges of microreactor transportability. The report, *Microreactor Transportability Challenges* written by Harold Adkins and Steven Maheras, discussed two options for transporting the spent fuel, shipping the reactor separately from its fuel and shipping the reactor with its fuel. Shipping the reactor separately from its fuel requires a Type B package for just the irradiated fuel and a fissile material package for the unirradiated fuel. Shipping the MNPP with its unirradiated and irradiated fuel, a challenge arises as the container meeting the fissile material package and Type B package requirements [21, p. 6].

Adkins and Maheras analyzed highway, rail and air transport challenges. Their findings indicate that the biggest challenge for highway transportation was obtaining multiple state permits to move the reactor container with irradiated fuel. Air transportation faces similar challenges. Due to enhanced testing requirements, moving a microreactor by air will face significant challenges meeting CFR 71.55(f) and IAEA requirements for Type C, when applicable. Transportation by rail faces a different type of requirement challenge. According to Adkins and Maheras "additional testing would be required to ship a microreactor and its components in compliance with AAR Standard S-2043 or if additional ballast weights could be added to the railcar to satisfy." Another challenge to all modes of transportation is the ability to verify defense-in-depth. The concept of defense-in-depth is heavily used in safety analyses and within PRA, an issue with verifying this concept could lead to denial of safety requirements.

The paper recommends options to address transportation challenges. The first option is to ship the fuel and microreactor separately. Shipping the fuel separately would simplify the

requirements for the reactor container design to meet transportation regulations with spent fuel. Of course, the packages containing the spent fuel will still have to be Type B or C depending on the mode of transportation. A second option proposed is to move the spent fuel within the reactor container, although issues might arise to successfully deploy a container that is also a Type B or C package due to weight and size.

The two authors, with the help of colleagues at PNNL have also conducted a PRA on truck transportation of a microreactor to determine the frequency of a specific accident sequence. For the analysis, the group used an already completed event tree from Mills et al. Figure 6 uses the type of collision, the object struck to cause the accident, the speed distribution as well as the surface struck if the truck were to flip. The event tree has 19 indexes with the most likely accidents occurring from a collision with another vehicle (motorcycles, cars etc.,) with a frequency of 0.76916 and a non-collision accident due to a cause other than a fire/explosion (jackknife, rollover etc.,) with a frequency of 0.11970 [22, p. 13].

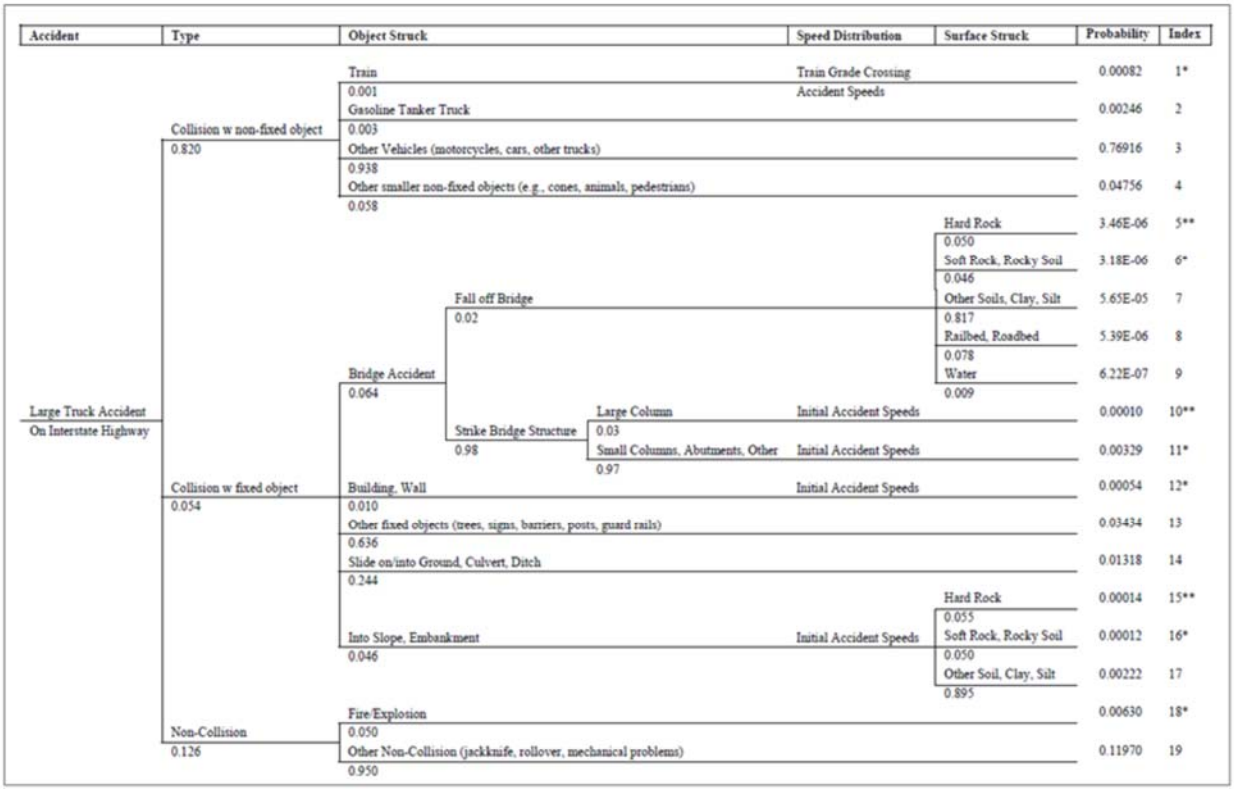

Figure 6. Current Developed Event Tree

Since the study conducted by the group at PNNL is intended for adaptability based on design refinements, no quantitative results exist within the consequence analysis. The consequence analysis is based on source term release estimated by Equation 1. [22, p. 17]

$$\text{Source Term} = \text{MAR} \times \text{DR} \times \text{ARF} \times \text{RF} \times \text{LPF} \quad (1)$$

where:
MAR = Material at risk

DR = Damage ratio

ARF = Airborne release fraction

RF = Respirable fraction

LPF = Leak path factor

With regards to the release of radionuclides from TRISO fuel depends on the particle being ruptured, unruptured or a full containment within the reactor vessel. For a ruptured TRISO fuel

particle, the dispersion and dose calculations use traditional methodologies. The airborne release has not been established for ruptured TRISO fuel, creating an uncertainty within the estimated damage ratios and leak path factors used in bounding analysis. For an unruptured TRISO fuel particle, the size of the particle affects the interaction within the environment. Therefore, the study recommends basing the consequence analysis on the environmental transport for environmental only research.

3.3 Probabilistic Risk Assessment and Safety Goals

Understanding the risk involved with transporting microreactors through and around the civilian population is extremely important. Not only can an accident involving a microreactor have immediate effects, but it can also have long lasting effects on the environment furthering the effect on the human population. In general mathematical terms, risk is defined as the product of the frequency of an event with the corresponding damage [23, p. 9]. In Equation 1, R_i represents risk in a particular sequence F_i, is the frequency of an event in that sequence (events per unit time), and D_i the corresponding damage.

$$R_i = F_i \times D_i \tag{2}$$

Risk is determined in this study using the "set of triplets" definition. In the "set of triplets" definition, risk is determined from the answers of three questions:

1. What can go wrong?
2. How likely is that to happen?
3. What are the consequences if it does happen?

The triplet definition is used rather than other definitions of risk due to its broader approach. By using a broader definition, the study is able to look at each stage of an accident logically. The answers to the first question within the triplet definition establish the questions asked for each

following event after the initiating event (accident). The probabilities and frequencies of the following events help to analyze the end state of consequence(s). The answers to each question become aspects of an event tree.

An event tree is a logical depiction of a series of events over a period of time. [23, p. 17] An event tree has three main aspects: the initiating event, the failure or success headings, and the end state. The initiating event can either be the failure of a system or it can occur externally of the system.[23, p. 17] In the case of the event trees in Ch.3.6, the initiating event is the accident of the mode of transportation. Subsequent events in a traditional event tree are either failure or success states of safety systems that are utilized to prevent the worst consequence. The safety systems are used as headings and "tree" branches depending on the success or failure of that system. Each continual branch leads to an accident sequence at the end state or consequence. In the transportation event trees, the headings are not safety systems but rather accident-related questions with yes or no answers. The accident sequences lead to a final end state of the initial consequence of the accident.

Prior to any analysis or event tree construction for the transportation of mobile microreactors, the success scenario is defined. The success scenario for each transportation type is the same; no loss of containment during an accident. The Table 2 end states were adapted from a report done on the decommissioning of the Diablo Canyon Power Plant [24]. The report identified five types of risks: non-radiological, non-incident radiological, degradation of shielding, airborne dispersion risks and loss of containment. Of the five risks, the three chosen for this study captured the four types of transportation: non-radiological, degradation of shielding, and loss of containment. In this study, the end state that represents the success scenario is "No Release Accident." Although two end states are only the potential of a loss of containment, they are

considered a failure for conservative reasons. There are two failed states that have the same initial failure, “loss of containment” but are categorized separately due to their proximity to surface water.

Table 2. End State Definitions and Damage Examples

End States	Definition	Example of Damage
Loss of Containment (LOC)	The container is damaged to the point of creating a pathway of radionuclide release.	Container is punctured and internal structures are damaged
Loss of Containment – Water (LOC-Water)	The container is damaged with a release of radionuclide within 20 ft of surface level water source.	Container is punctured and internal structures are damaged
Potential Loss of Containment	The container is damaged, but no hole exists.	The container has a bend within the material but no puncture exists
Potential Loss of Containment – Water	The container is damaged without puncture within 20 ft of surface level water source.	The container has a bend within the material but no puncture exists
No Release Accident	The container nor equipment inside is damaged.	The mode of transportation was in an accident but no damage occurred to the container

3.4 Data Sources

I used the U.S Department of Transportation (DOT) was used as a starting point for the event tree frequency development. For each mode of transportation, the DOT has a specific administration that collects and monitors data as well as implements queries to sift through the data. Highway data is monitored by the National Highway Traffic Safety Administration (NHTSA) using the Fatality and Injury Reporting System Tool (FIRST). FIRST customizes queries from the Fatality Analysis Reporting System (FARS) and the Crash Report Sampling System (CRSS). Users select sample queries or build their report via different options starting with the selection of categories of importance. I used a vehicle importance category so that the accidents include semi-trucks.

Query results yield the number of accidents per first harmful event by year categorized by fatal, injury-only, and property damage-only accidents. Since the CRSS database classifies the first

harmful events very specifically, each first harmful event was classified into the type of accident then the first harmful event that matched with the event tree. The first harmful events across the three categories were summed by year. Table 3 shows the total of the three types of accidents with their corresponding first harmful events while Table 4 shows the frequencies involved with each accident type and first harmful event.

Table 3. Total Accident Types and First Harmful Events across 2015 – 2020 - Highway

Type of Accident	Sum of 2015	Sum of 2016	Sum of 2017	Sum of 2018	Sum of 2019	Sum of 2020
Collision with Fixed Object	**13599**	**14193**	**14812**	**15162**	**13809**	**16115**
Bridge Component	1618	554	270	679	800	471
Other Fixed Collision	2876	5802	4704	3614	4980	2986
Road Component	9105	7837	9838	10869	8029	12658
Collision with Non-Fixed Object	**166857**	**161154**	**196438**	**216215**	**216500**	**180175**
Non-vic	2050	4073	3746	3687	2743	3393
Other Non-Fixed Collision	398	1358	1299	2879	1451	4077
Vic outside of convoy	164409	155723	191393	209649	212306	172705
Non-Collision	**2886**	**3958**	**5818**	**5528**	**4338**	**4312**
Fire	1	542	515	394	381	502
Other Non-Collision	58	1077	501	130	265	3
Jackknife/rollover	2827	2339	4802	5004	3692	3807
Grand Total	**183342**	**179305**	**217068**	**236905**	**234647**	**200602**

Table 4. Calculated Frequencies per Accident Type and First Harmful Event - Highway

Type of Accident	2015	2016	2017	2018	2019	2020	Average	Standard Deviation
Collision with Fixed Object	0.074172857	0.079155629	0.068236682	0.064000338	0.058850102	0.080333197	0.0708	0.00858
Bridge Component	0.008825037	0.003089707	0.00124385	0.002866128	0.003409377	0.002347933	0.00363	0.00266
Other Fixed Collision	0.015686531	0.032358272	0.021670629	0.01525506	0.021202337	0.014885196	0.0202	0.00669
Road Component	0.049661289	0.043707649	0.045322203	0.04587915	0.034217356	0.063100069	0.0470	0.00943
Collision with Non-Fixed Object	0.910086069	0.898770252	0.904960657	0.912665414	0.922662553	0.898171504	0.9079	0.00930
Non-vic	0.011178129	0.022715485	0.017257265	0.0155632	0.011699	0.016914089	0.0159	0.00423
Other Non-Fixed Collision	0.002170806	0.007573687	0.0059843	0.012152551	0.006183757	0.020323825	0.00906	0.00638
Vic outside of convoy	0.896733973	0.86848108	0.881719093	0.884949663	0.904788896	0.860923359	0.883	0.0165
Non-Collision	0.015741074	0.02207412	0.026802661	0.02334248	0.018487345	0.021495299	0.0213	0.00384
Fire	5.45429E-06	0.003022782	0.002372528	0.001663114	0.001623716	0.002502468	0.00187	0.00105
Other Non-Collision	0.000316349	0.006006525	0.002308033	0.000548743	0.001129356	1.49555E-05	0.00172	0.00225
Jackknife/rollover	0.015419271	0.013044812	0.0221221	0.021122391	0.015734273	0.018977877	0.0177	0.00357

A similar process was performed for rail accidents using Federal Railroad Administration and the Office of Safety Analysis data. Queries were used to collect data for categorization by type of accident and first harmful event that corresponds with the event tree. Table 5 depicts the total of the three types of accidents with their corresponding first harmful events while Table 6 shows the frequencies involved with each accident type and first harmful event.

Table 5. Total Accident Types and First Harmful Events across 2015 – 2020 – Rail

Type of Accident	Sum of 2015	Sum of 2016	Sum of 2017	Sum of 2018	Sum of 2019	Sum of 2020
Accident Train Remained on Track	**125**	**151**	**111**	**134**	**134**	**88**
Fire/Other Extreme Environmental Condition	125	151	111	134	134	88
Collision	**23**	**11**	**18**	**26**	**20**	**19**
Fixed Object On Track	2	4	1	2	2	6
Non-Fixed Object on Track	21	7	17	24	18	13
Derailment	**324**	**272**	**335**	**320**	**341**	**312**
Human Error	75	64	76	60	76	75
Mechanical Error	94	68	96	101	121	90
Object on Track	11	9	15	10	8	13
Track Maintenance	115	120	129	124	122	113
Weather Encounter	29	11	19	25	14	21
Grand Total	**472**	**434**	**464**	**480**	**495**	**419**

Table 6. Calculated Frequencies per Accident Type and First Harmful Event - Rail

Type of Accident	2015	2016	2017	2018	2019	2020	AVG	STD DEV
Accident Train Remained on Track	0.2648 3051	0.3479 2627	0.2392 2414	0.2791 6667	0.2707 0707	0.2100 2387	0.26864 642	0.046 3
Collision	0.0487 2881	0.0253 4562	0.0387 931	0.0541 6667	0.0404 0404	0.0453 4606	0.04213 0718	0.009 9
Fixed Object On Track	0.0869 5652	0.3636 3636	0.0555 5556	0.0769 2308	0.1	0.3157 8947	0.16647 6832	0.135 8
Non-Fixed Object on Track	0.9130 4348	0.6363 6364	0.9444 4444	0.9230 7692	0.9	0.6842 1053	0.83352 3168	0.135 8
Derailment	0.6864 4068	0.6267 2811	0.7219 8276	0.6666 6667	0.6888 8889	0.7446 3007	0.68922 2862	0.041 4
Human Error	0.2314 8148	0.1474 6544	0.1637 931	0.125	0.1535 3535	0.1789 9761	0.16671 2165	0.036 4
Mechanical Error	0.2901 2346	0.1566 8203	0.2068 9655	0.2104 1667	0.2444 4444	0.2147 9714	0.22056 0047	0.044 3
Object on Track	0.0233 0508	0.0207 3733	0.0323 2759	0.0208 3333	0.0161 6162	0.0310 2625	0.02406 52	0.006 3
Track Maintenance	0.2436 4407	0.2764 977	0.2780 1724	0.2583 3333	0.2464 6465	0.2696 8974	0.26210 7787	0.015
Weather Encounter	0.0614 4068	0.0253 4562	0.0409 4828	0.0520 8333	0.0282 8283	0.0501 1933	0.04303 6678	0.014 2

While the Maritime Administration (MARAD) collects all maritime accident reports, the best query tool to pull associated data is the Case Analysis and Reporting Online (CAROL) monitored by the National Transportation Safety Board (NTSB). CAROL was originally created as a comprehensive aviation accident database but now includes investigations into all modes of transportation. Using the advanced search, marine accidents that included a barge or a cargo vessel were queried. Table 7 depicts the total of the three types of accidents with their corresponding first harmful events while Table 8 shows the frequencies involved with each accident type and first harmful event.

Table 7. Total Accident Types and First Harmful Events across 2015 – 2020 - Maritime

Type of Accident	Sum of 2015	Sum of 2016	Sum of 2017	Sum of 2018	Sum of 2019	Sum of 2020
Post Launch	**2**	**2**	**1**	**1**	**4**	**2**
Collision with Object	0	0	0	0	1	1
Grounded	0	0	0	0	1	0
Human Error	2	0	0	0	1	0
Mechanical Error	0	1	1	0	0	0
Ship on Ship Collision	0	0	0	1	1	1
Weather Encounter	0	1	0	0	0	0
Prior to Launch	**0**	**0**	**0**	**0**	**1**	**0**
Fire on Board	0	0	0	0	1	0
Forklift Accident	0	0	0	0	0	0
Weather Encounter	0	0	0	0	0	0
Grand Total	**2**	**2**	**1**	**1**	**5**	**2**

Table 8. Calculated Frequencies per Accident Type and First Harmful Event - Maritime

Type of Accident	Sum of 2015	Sum of 2016	Sum of 2017	Sum of 2018	Sum of 2019	Sum of 2020	AVG	STDev
Post Launch	1	1	1	1	0.8	1	0.966667	0.08165
Collision with Object	0	0	0	0	0.2	0.5	0.116667	0.204124
Grounded	0	0	0	0	0.2	0	0.033333	0.08165
Human Error	1	0	0	0	0.2	0	0.2	0.4
Mechanical Error	0	0.5	1	0	0	0	0.25	0.41833
Ship on Ship Collision	0	0	0	1	0.2	0.5	0.283333	0.402078
Weather Encounter	0	0.5	0	0	0	0	0.083333	0.204124
Prior to Launch	0	0	0	0	0.2	0	0.033333	0.08165
Fire on Board	0	0	0	0	0.2	0	0.031333	0.08165
Forklift Accident	0	0	0	0	0	0	0.001	0
Weather Encounter	0	0	0	0	0	0	0.001	0

3.5 Analysis Tools

Three computer programs were used to build the event trees, gather the decay constant and conduct the consequence analysis: SAPHIRE, ORIGEN2 and RADTRAN. SAPHIRE, developed by the NRC in 1987, is used to "create and analyze probabilistic risk assessments [25]." SAPHIRE 8 is the current version released for domestic use and is accessible through Oak Ridge National Lab (ORNL). The program produces fault and event trees with uncertainties. In this study, the event trees are built in SAPHIRE 8 then transferred to Microsoft Excel for visualization. ORIGEN2 code calculates radioactive decay constants. ORIGEN will "calculate buildup, decay, and processing of radioactive materials" by using a matrix exponential method to solve differential equations with constant coefficients [26]. Finally, RADTRAN assesses potential radioactive

material exposure within the waters of the Mississippi River. Originally developed in 1977 by Sandia National Laboratory, RADTRAN is used to, “evaluate radiological consequences of incident-free…as well as the radiological risks from vehicular accidents occurring during transportation [27, p. 1].”

3.6 Transportation Accident Event Tree Descriptions

The transportation accident event trees quantify the frequency of containment releases. Accident-causing phenomena are listed in the sections below by type of transportation. The last sequence question in each event tree addresses the distance of the accident to water. Since the study is researching the impact on surface water, the distance to flowing water is important for the radionuclide release.

3.6.1 Truck

Figures 7, 8 and 9 are new accident event trees for tuck trailer accidents along a highway or interstate. When compared to the accident event tree developed in NUREG 2125, the speed distribution and surface struck top events are removed yet container damage, container puncture and proximity to key terrain have been added.

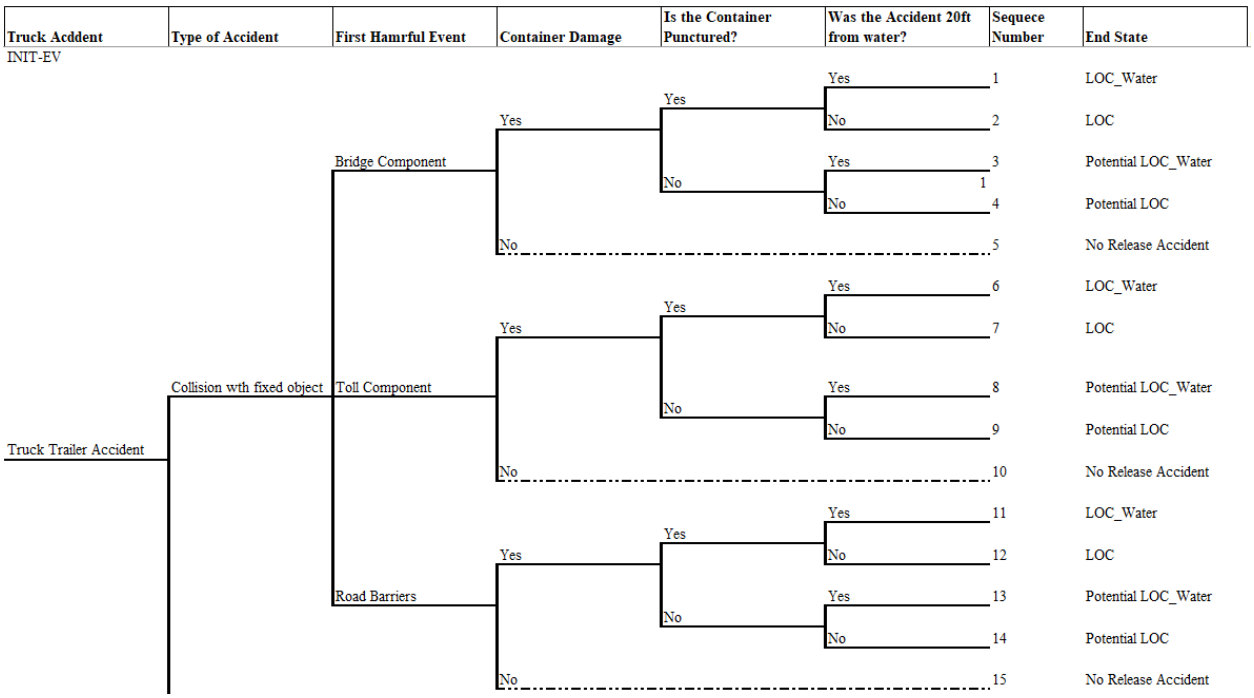

Figure 7. Truck Accident Containment Event Tree (Collision with a fixed object)

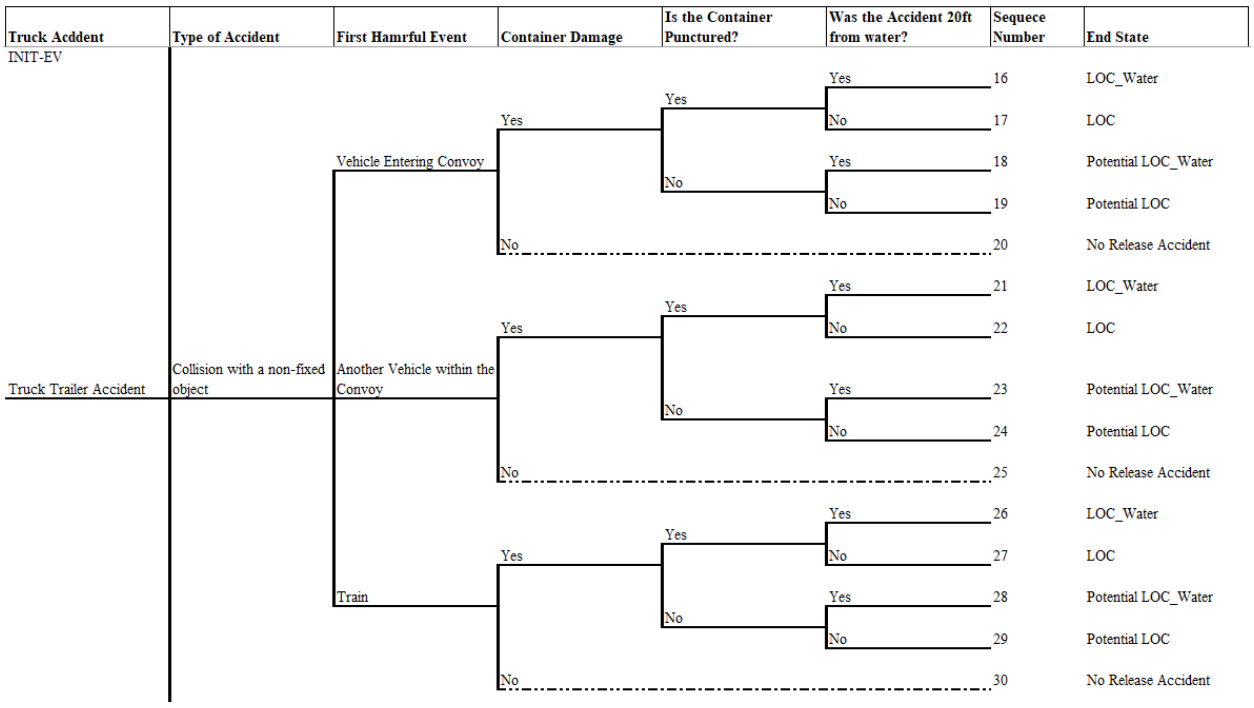

Figure 8. Truck Accident Containment Event Tree (Collision with a non-fixed object)

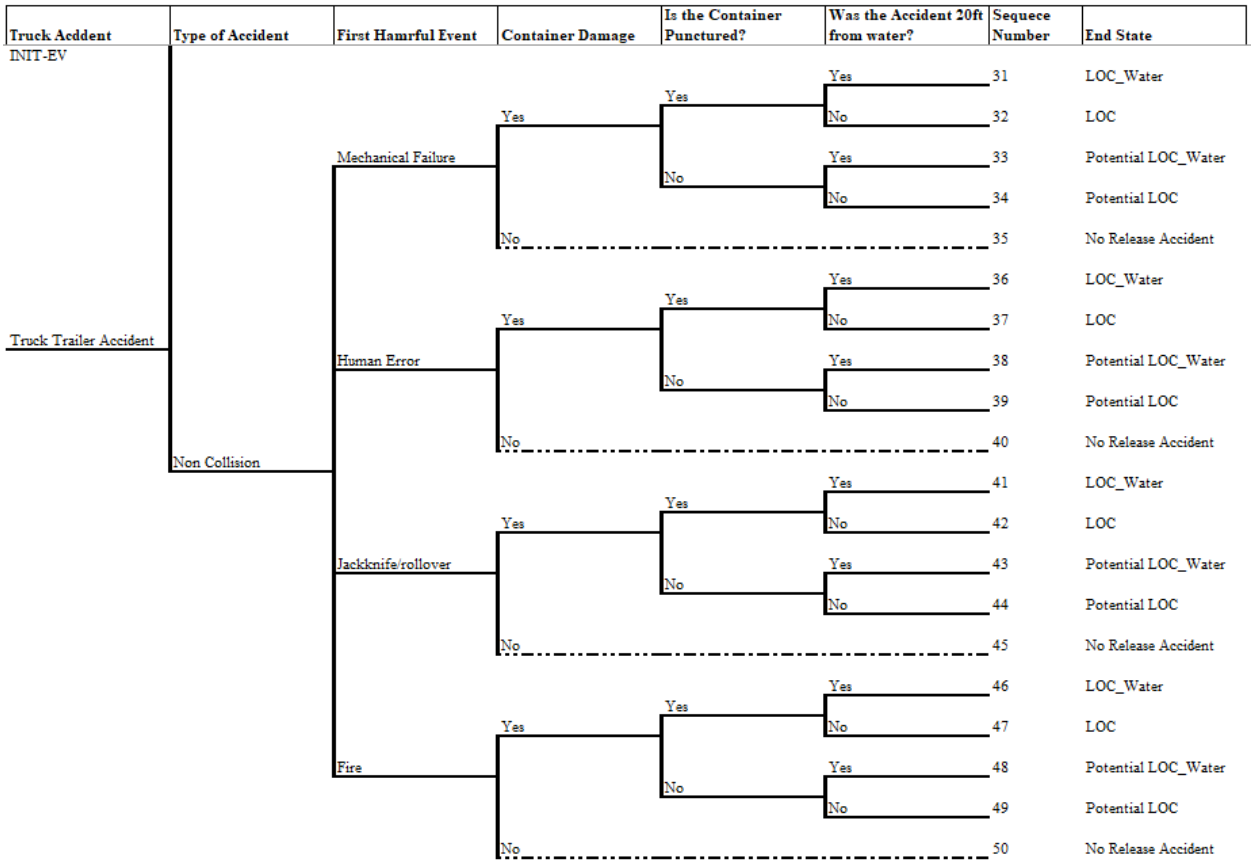

Figure 9. Truck Accident Containment Event Tree (Non-Collision)

(1) Definition of Accident Scenarios

Truck accident scenarios were created using the "set of triplets" process, categorizing accident data from the U.S Department of Transportation's (DOT) Bureau of Transportation Statistics and the U.S Army's Risk Management Information System (RMIS) while also reviewing NUREG-2125. Unlike NUREG-2125 the only accident scenarios discussed are accidents in which the fuel cask is affected.

(2) Development of Event Tree Branches

In this section the branches within the Truck Accident Event Tree are defined and described.

A: Type of Accident: What category of the accident caused the accident?

There are three classifications of truck accident categories, collision with a fixed object, collision with a non-fixed object, and a non-collision. Since an accident has already occurred there is no success or failure however to determine the likelihood of radionuclide release.

B: Cause of Accident: What phenomena caused the accident?

A fixed object is defined as an object along a route that cannot be moved under its own volition. If a truck has a collision with a fixed object, there are three initiators of the accident; the truck hit a bridge component, a toll component or a road barrier. A truck can hit a bridge component by either going under an overpass that has a low clearance or any railing on a bridge. Like a truck colliding with a bridge component, an impact with a toll can also occur due to low clearance. A toll collision can also damage the side of a vehicle due to the width of the vehicle and the narrowness of the toll. A truck can impact with road barriers, either concrete or fillable traffic barriers. A collision with a bridge component, specifically the stringers under an overpass, is the worst scenario as the impact will most likely be on the reactor container and the speed of the vehicle is much higher than colliding with a toll, causing a larger effect.

A non-fixed object is another entity of the road with the ability to move itself. Although a collision between a person or animal and a truck is an accident, it is not considered for this research since a human cannot create a large enough impact to affect the reactor container. There are two types of non-fixed object phenomena that can cause an accident, a vehicle entering the convoy or another vehicle within the convoy. A vehicle entering the convoy can collide with a truck from any direction creating the potential for damage to the reactor container. Additionally, an accident initially caused by a jackknifed truck is considered in this branch due to the impact coming from a non-fixed object entering the accident. A collision with a vehicle within the convoy can occur

due to rear-ending either in the front or behind. A rear-end collision to the truck transporting the reactor container is assessed to be the most problematic inducing scenario out of collisions within a non-fixed object due to the impact occurring directly to the container.

An accident that is not categorized by a type of collision has four phenomena: mechanical failure, rollover, slide off road, and fire. A mechanical failure is a failure of the vehicle itself or component of the trailer that causes the truck unit non-mission capable and an accident. An example of an accident inducing mechanical failure is a sudden brake failure. A rollover accident is a non-collision accident where the vehicle is turned completely upside down. Although very problematic to the reactor container, the likelihood is very low due to the attached trailer. In an accident where the vehicle slid off the road, the most severe result is the trailer and reactor container being turned on the side against the ground. The impact between the ground and reactor trailer is similar to a rollover accident in that it can result in a compressed container however the amount of force used to create a rollover is much less than turning a vehicle on its side, lessening the blow to the container. A truck sliding off the road and turning on the side is more likely than a rollover. Finally, a fire is considered its own non-collision accident instead of being included in another cause because the effect the fire has on the reactor container is enough to make it its own accident phenomena.

Human error is considered in each accident cause and is not given its own branch. The intent of not making human error separate is that human error although might be the reason for the accident it is not the cause of the accident. For example, a non-fixed collision accident caused by another vehicle within the convoy might be a rear-ending due to human error but the impact to the reactor container is from the hit from the other vehicle.

C: Container Damage: Is the container damaged?

Success for this event means that the container is not damaged and continues to act as a barrier to fission product release whereas failure means the container is damaged. Damage to the container does not specifically mean that fission products are released but the potential is present. All accident causes can result in container damage. The determining factor for success or failure is the impact force.

D: Damage Penetration: Was the damaged container penetrated i.e., is there a crack or hole in the walls of the container?

Success for this event is that there is no puncture to the barrier walls while any opening in the container's barrier is a failure. An event where there is damage to the container but not a puncture of the barrier walls is a collision with the abutments of a toll and causes a scratch on the outside of the walls. A success does not immediately mean that there is no radionuclide release due to still being a local failure, such as a shear in the material makeup of the container walls.

E: Proximity to Water: Is the accident within 20ft of a surface water source?

Success for this event is an accident occurs over 20ft from a surface water source and a failure is within the 20ft radius of a surface water source. A failure event example is a rollover that occurs where the container is damaged and punctured on the embankment of a bridge crossing a river, failing to "loss of container next to water" end state. A failure event also occurs even if the container is not punctured but still damaged due to the potential of shear, leading to the "potential of loss of containment next to water" end state.

Table 9. Truck Containment Event Tree Top Events.

Event Node/State	Description
A	Type of Accident
Collision with a fixed Object	The vehicle hauling the container or the trailer the container is on, collided with an object that is immovable by its own will
Collision with a non-fixed Object	The vehicle hauling the container or the trailer the container is on, collided with an object that was either moving or is easily moved
Non-Collision	The vehicle hauling the container or the trailer the container is on, did not collide with any object
B	First Harmful Event
Bridge Component	The vehicle or the container collided with a bridge component (abutment, railing, stringer)
Toll Component	The vehicle or the container collided with a toll component (abutment, deck, wingwall)
Road Barriers	The vehicle or the trailer the vehicle is on, collided with a road fixture (barriers, guardrails)
Vehicle Entering Convoy	The vehicle or trailer hauling the container is impacted or impacts an outside vehicle entering the convoy
Vehicle within Convoy	The vehicle or trailer hauling the container is impacted or impacts a vehicle from within the convoy
Train	The vehicle or the container is impacted by a train at a rail crossing
Mechanical Failure	The vehicle or the trailer hauling the container has a mechanical failure (fifth wheel malfunction, engine failure)
Human Error	The driver of the vehicle makes an error or an error was made prior and caused an error while driving
Jackknife/Rollover	The trailer pushes the hauling vehicle to one side folding itself or the vehicle and trailer are on a non-wheel plane
Fire	The hauling vehicle, trailer or container catch on fire
C	Container Damage
Success	Container is not damaged
Failure	Container is damaged and is not available as a barrier to fission product release
D	Container Puncture
Success	Container is damaged but there is no opening through the container
Failure	Container has failed and there is a direct opening for fission product release
E	Distance from Water
Success	The accident is not within affecting distance to surface water
Failure	The accident is within affecting distance to surface water

3.6.2 Rail

Figures 10, 11 and 12 are new accident event trees for train accidents along a rail. The three figures depict a collision, a non-collision or an other accident which is classified as an accident where the train remains on the track.

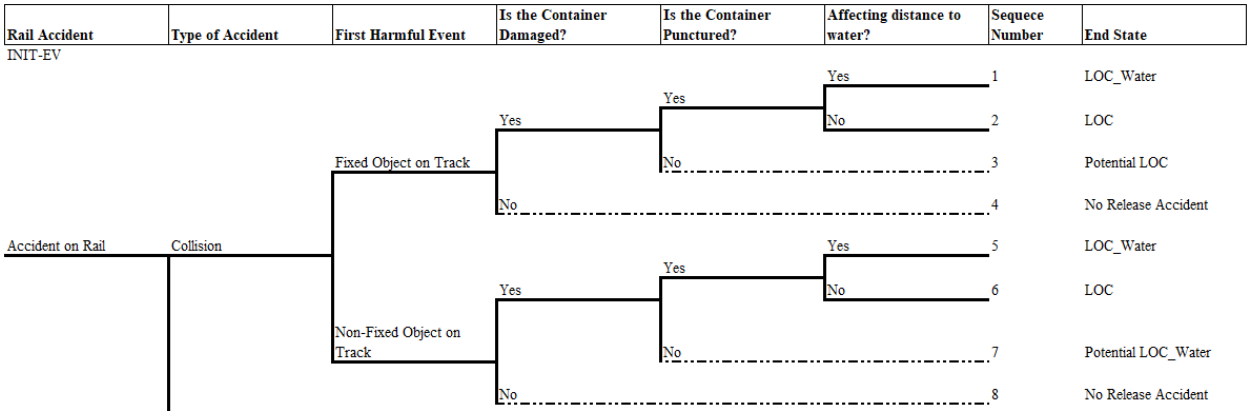

Figure 10. Rail Containment Event Tree (Collision)

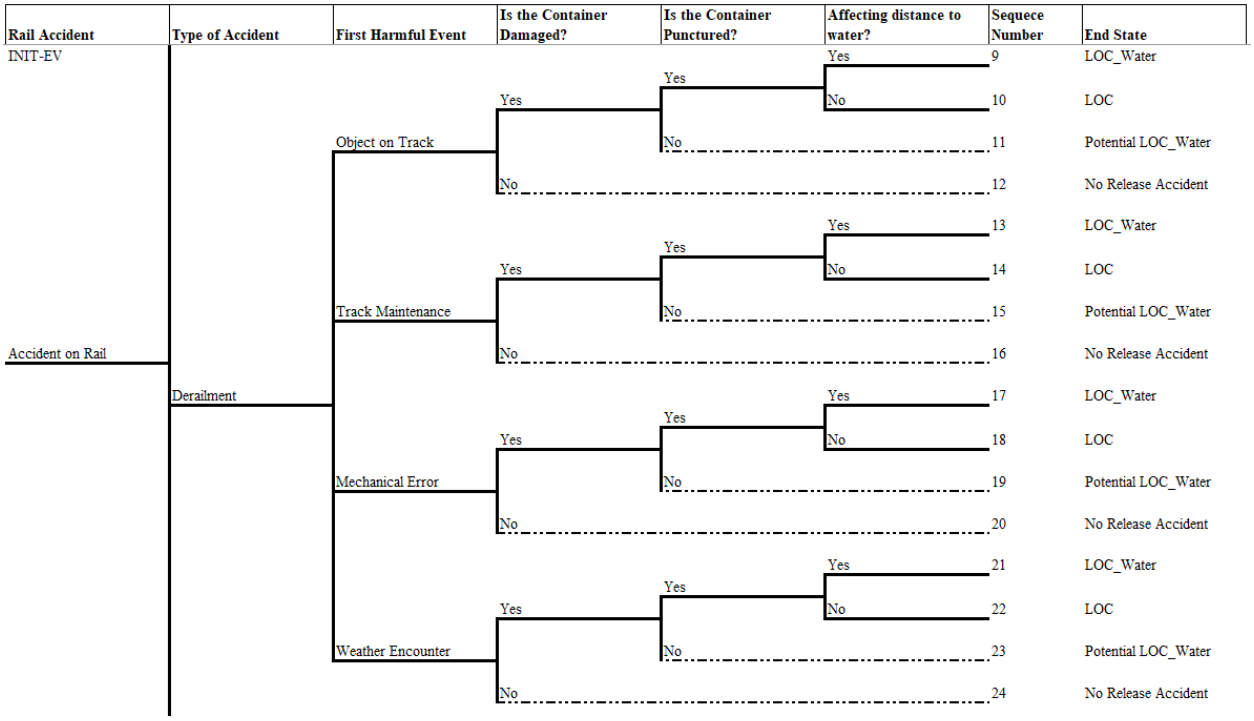

Figure 11. Rail Containment Event Tree (Derailment)

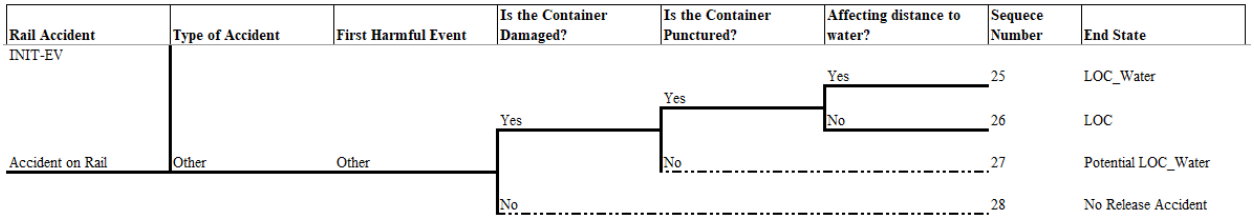

Figure 12. Rail Containment Event Tree (Other)

(1) Definition of Accident Scenarios

Rail transportation accident event trees are accidents with affected containers. An affected container results in either a loss of shielding without a release of radioactive materials or causes a loss of shielding where radioactive material is released.

(2) Development of Event Tree Branches

In this section the event tree branches for rail transportation are defined and described.

A: Type of Accident: What category does this accident classify as?

The accident event sequence is important to determine the type of accident for rail transportation because a collision may cause a follow-on derailment, but the accident is due to the collision. There are three types of accident for rail transportation: collision, derailment and other. An initial collision in the event sequence means that the train hit an object large enough to change speed. A train derailment results in a change of direction.

B: First Harmful Event: What was the first harmful event in the accident event sequence?

A freight train's momentum can continue for more than a mile after the conductor applies the emergency brakes. A train's collision is generally one of two harmful events; the train collided with fixed or non-fixed object on the tracks. In the event of a collision a 'Fixed Object on Track' is defined as an inanimate immobile object. For example, if the train's conductor does not see a tree within enough time to stop, a collision will occur due to the train's momentum following the application of brakes. A train can also collide with a non-fixed object such as a car at a railroad

crossing. Since a freight train can take over a mile to come to a complete stop, a car driving across the tracks or getting stuck on tracks will often result in a collision.

Train derailments frequently occur due to a variety of different reasons. Objects on train tracks either fixed or non-fixed can cause a derailment depending on the size of the object. The reason a train colliding with an object on the track is not considered a collision but rather a derailment is because the directional change in the train's acceleration. Track maintenance can also result in a harmful event due to incomplete track construction or ongoing maintenance causing the train to derail. A mechanical error refers to part of the train's internal system having a malfunction. A mechanical error can be an electronic system error, like a control panel malfunction, or a non-electrical system like a brake. Finally, a weather encounter can be caused by ice on the tracks resulting in the beginning of an accident sequence.

C: Container Damage: Is the container damaged?

Success for this event means that the container is not damaged and continues to act as a barrier to fission product release whereas failure means the container is damaged. Damage to the container does not specifically mean that fission products are released but the potential is present. All accident causes can result in container damage. The determining factor for success or failure is the impact force.

D: Damage Penetration: Is the container punctured?

Success for this event is that there is no puncture to the barrier walls while any opening in the container's barrier is a failure. An event where there is damage to the container but not a puncture of the barrier walls is a collision with the abutments of a tunnel and causes a scratch on the outside of the walls. A success does not immediately mean that there is no radionuclide release due but may be a local failure such as a shear in the material makeup of the container walls.

E: Distance from water: Is it within an affecting distance to water?

Success for this event is an accident occurring more than 20ft from a surface water source and a failure is defined as an accident closer than 20ft from a surface water source. A failure event example is a rollover that occurs where the container is damaged and punctured on the embankment of a bridge crossing a river, failing to “loss of container next to water” end state. A failure event also occurs even if the container is not punctured but still damaged due to the potential of shear, leading to the “potential of loss of containment next to water” end state.

Table 10. Rail Containment Event Tree Top Events

Event Node/State	Description
A	Type of Accident
Collision	A rail car or the container impacts an object along the track route
Derailment	A rail car or the entire train comes off the track
Other	A human error or a fire
B	First Harmful Event
Fixed Object on Track	A rail car or the container collided with an immovable object along the track (boulder, fallen tree)
Non-Fixed Object on Track	A rail car or the container collided with an movable object along the track (car, another train)
Object on Track	The rail car or container is forced off the track due to any object on the track (car, animal, person)
Track Maintenance	The train is pushed off the track due to an issue within the track maintenance
Mechanical Error	The train comes off the track due to an internal system error (loss of a connecting pin, control system error)
Weather Encounter	The train is derailed due to a weather phenomenon (ice on track, flood)
Other	
C	Container Damage
Success	Container is not damaged
Failure	Container is damaged and is not available as a barrier to fission product release
D	Container Puncture
Success	Container is damaged but there is no opening through the container
Failure	Container has failed and there is a direct opening for fission product release
E	Distance from Water
Success	The accident is not within affecting distance to surface water
Failure	The accident is within affecting distance to surface water

3.6.3 Maritime

Finally, Figures 13 through 16 are the accident event trees for a ship or barge accident. There are two phases of the operation, prior to launch and post launch. Breaking up the event tree into phases was important due to the ship or barge being on water so any accident involves key terrain immediately.

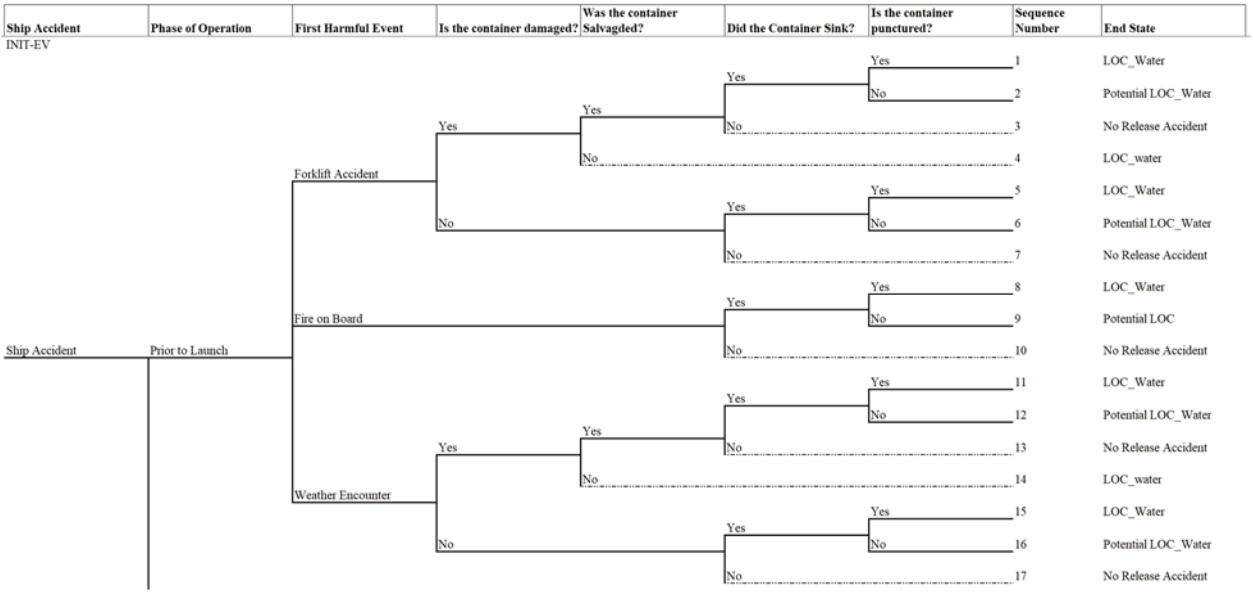

Figure 13. Barge Containment Event Tree (Prior to Launch)

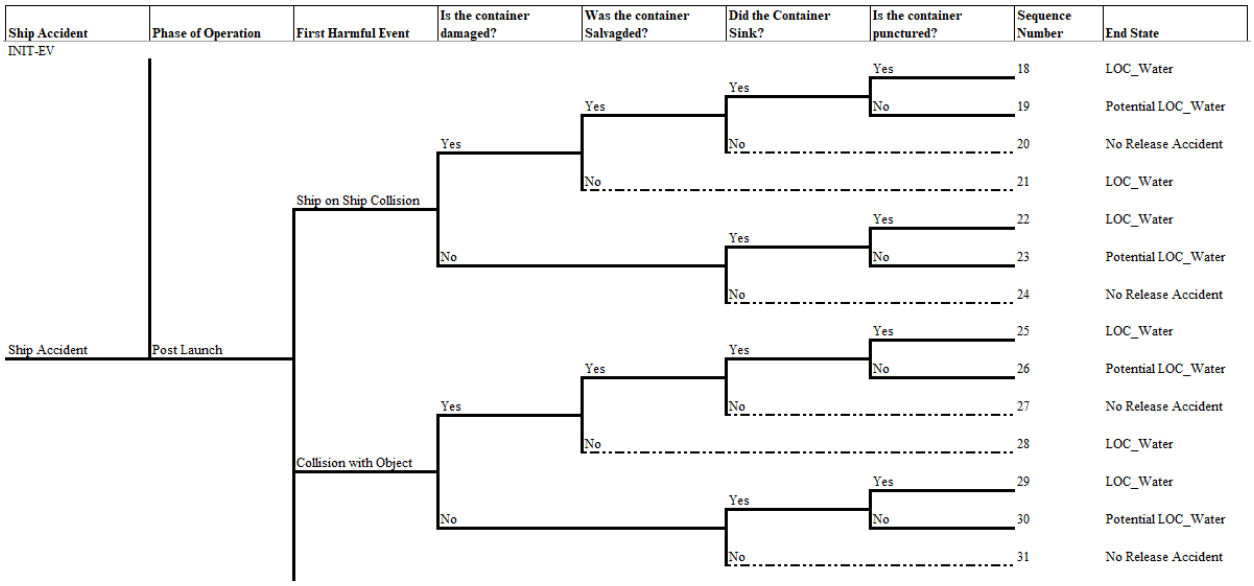

Figure 14. Barge Containment Event Tree (Post Launch – Collision)

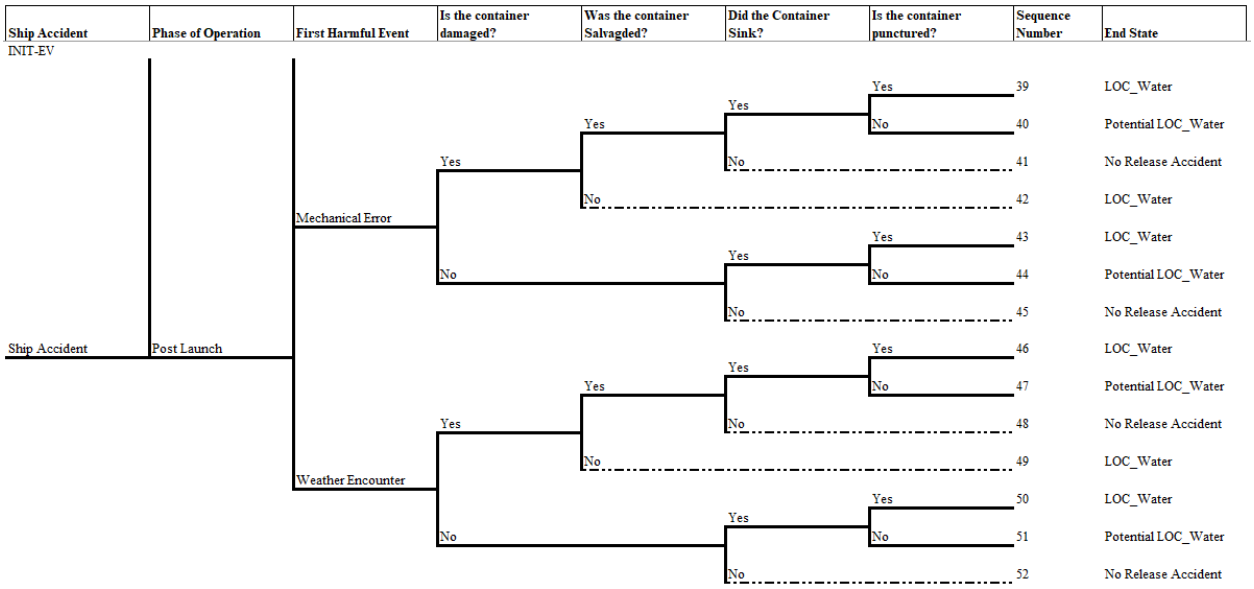

Figure 15. Barge Containment Event Tree (Post Launch – Non-collision)

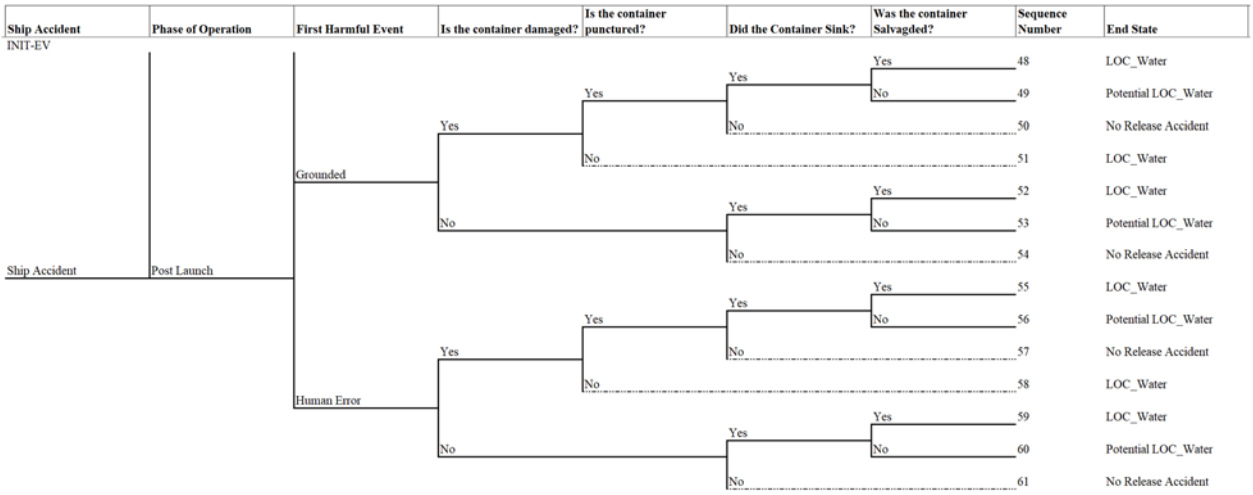

Figure 16. Barge Containment Event Tree (Post Launch – Non-collision continued)

(1) Definition of Accident Scenarios

Finally, maritime accident scenarios are defined in a similar manner as truck and rail transportation methods. The difference between maritime transportation accident scenarios and the other two modes, is any accident that causes a loss of shielding immediately impacts the water.

(2) Development of Event Tree Branches

In this section the event tree branches for maritime transportation are defined and described.

A: Phase of Operation: When did the accident occur?

The accident event sequence is important to determine the level of consequence and emergency response. An accident that occurs prior to the launch of the ship or barge has the ability to access on land recovery assets much quicker than a ship already moving. Although it is not a "yes" or "no" result, success for this event is the accident occurring prior to the launch of the ship or barge allowing for a rapid recovery. There is not a particular failure during this part of the event tree, however emergency and safety operations become more difficult after a ship has embarked.

B: First Harmful Event: What was the first harmful event in the accident event sequence?

Still a part of establishing the event sequence, determining the first harmful event starts the accident. Within the operation's pre-launch phase, there are three first harmful events that can have a negative effect on a container; a forklift accident, a fire on board and a weather encounter. A forklift accident can be a myriad of accidents to include, dropping the container, puncturing the container with the forks, or pushing the container overboard. An onboard fire does not always result with the container in the water however if the fire not contained then container damage can occur. Finally, a weather encounter prior to the launch can also cause the container or other containers to move and either force it overboard or damage it from impacting other containers.

After the launch there are four first harmful events that can affect the ship and microreactor container; ship-on-ship collision, collision with an object, mechanical errors, and a weather encounter. A ship-on-ship collision is more common in enclosed water spaces such as rivers or ports and can damage a microreactor by either impact with other containers onboard or even being

pushed overboard. A collision with an inanimate object will result in an accident. For example, an accident may occur when a ship collides with a levee or lock component. An accident involving a collision between a ship and an inanimate object can damage containers result in containers going overboard. A mechanical error can occur at any point and is due to internal systems failing. An example of a mechanical error on a ship is a failed clutch either due to unexpected wear-out or loss of air controlled to the clutch, resulting in speed related accidents [28]. A weather encounter such as high winds can also cause an accident, causing the potential for impacts between containers.

C: Container Damage: Is the container damaged?

Success for this event means that the container is not damaged and continues to act as a barrier to fission product release whereas failure means the container is damaged. Damage to the container does not specifically mean that fission products are released but the potential is present. All accident causes can result in container damage. The determining factor for success or failure is the impact force.

D: Damage Penetration: Is the container punctured?

Success for this event is that there is no puncture to the barrier walls while any opening in a container's barrier is a failure. An event where there is damage to the container but not a puncture of the barrier walls is a collision with another container or a loading vehicle while on board. The collision can cause a scratch on the outside of the walls but not puncture the container. A success does not immediately mean that there is no radionuclide release due to still being a local failure, such as a shear in the material makeup of the container walls.

E: Container Sinkage: Did the container sink?

Success for this event is the container not sinking while the failure is a container sinking. The container sinking is after the damage to the container top event because the impact of the

container into water cannot cause a seal failure, “due to the lack of shear strength of the water” [14, p. 129]. When a container is already damaged, water depth becomes the primary characteristic. Submerging a container results in damage to the container’s package[14, p. 129]. Therefore, the failure for this event, the container sinking is fully underwater.

F: Container Salvaged: Was the container Salvaged?

Success and failure for this event is based off the Type B packaging testing requirements. Since a Type B package must withstand an immersion under 15 feet for at least eight hours, success for a rescue of the container is within the eight hours [23, p. 2]. Failure for container salvage is a rescue attempt over eight hours.

Table 11. Ship Containment Event Tree Top Events

Event Node/State	Description
A	Phase of Operation
Prior to Launch	An accident occurs while the ship is docked at port
Post Launch	An accident occurs while the ship is in consistent, cruising movement
B	First Harmful Event
Forklift Accident	A forklift is the cause of the accident while on the ship (drop, push overboard, puncture)
Fire on Board	A fire occurs on board the ship and the container is exposed for longer than 30 minutes
Weather Encounter	An accident occurs due to weather impairing normal operations (high winds, heavy rainfall)
Ship on Ship Collision	The ship collides with another ship
Collision with Object	The ship collides with an object that is not another ship (levee, lock, dam)
Mechanical Error	A system (electronic or physical) on the ship ceases to work
C	Container Damage
Success	Container is not damaged
Failure	Container is damaged and is not available as a barrier to fission product release
D	Container Puncture
Success	Container is damaged but there is no opening through the container
Failure	Container has failed and there is a direct opening for fission product release
E	Container Sinkage
Success	The container is not submerged underwater
Failure	The container is submerged at least 15 feet of water
F	Container Salvaged
Success	The container is salvaged within 8 hours of the accident
Failure	The container is not salvaged within 8 hours of the accident

CHAPTER 4. Developed Transportation Event Trees

4.1 Accident Frequency Determination

Each sequence number in the created event trees in Chapter 3 corresponds with a particular accident scenario. Based on the product of each branch point frequency, the overall frequency of the particular accident scenario is determined. However, the event trees created in Chapter 3 do not provide any frequencies on the branch trees. The data collected from the DoT provides a necessary start to determining branch frequencies. To determine the frequencies, the relative frequency approach is used such that, the frequency of an event E, is equal to the amount of X number of times out a number n fixed amount of experiments (Equation 3) [23, p. 19]. For transportation frequencies, the number of accidents involving hazardous materials out of total distance traveled.

$$P(E) = \frac{X}{n} \tag{3}$$

where:

$P(E)$ = The frequency of an event

X = the number of times an accident occurs

n = the total number of experiments

Finally, an accident involving the container carrying spent nuclear fuel does not mean that there is a release of radioactive nuclides into the environment. To determine a frequency that the accident is severe enough to cause damage, the fraction of accidents that might cause a release of radioactive material is involved. With the severity fraction, the final frequency is determined with Equation 4 [30, p. 38].

$$P_{end\ state} = P(E)_{total} \times F_{severity} \quad (4)$$

where:

$P_{end\ state}$ = The frequency of an end state

$P(E)_{total}$ = The total frequencies of an event

$F_{severity}$ = The severity fraction

Using NUREG 2125, analysis from the pulled DoT accident data and accident analysis reports, the conditional frequencies for each accident sequence in the developed event trees. Despite the different modes, all initiating event frequencies were determined the same. The total ton-miles of freight was determined per year for each transportation method from the DoT's Bureau of Transportation Statistics [31]. An average of the total ton-miles of freight was then divided by the average number of accidents resulting in the initiating event's frequency, with a unit of accidents/ton-miles of freight (Table 12). The total ton-miles of freight was used as the *n* variable from Equation 3, while total accidents represented the *X* value.

Table 12. Event Tree Inputs per Mode of Transportation

Mode of Transportation	**Average Ton-Miles of Freight**	**Average Number of Accidents**	**Frequency of Initiating Event [average accident/average ton-miles of freight]**
Highway	2,258,224	208,644.8	0.092393316
Railway	1,630,410	460.7	0.000282547
Internal Maritime	25,384.3	2.2	8.38544E-06

4.2 Truck

All branch frequencies in the "Type of Accident" and "First Harmful Event" columns were determined using the FARS data query. The total number of accidents per year were then divided by the "Type of Accident" and the "First Harmful Event" number of accidents. After the individual

year accident type and FHE frequencise were determined, the average of each event and standard deviation was determined (Table 13).

Table 13. Highway Accident Event Frequencies

Accident Event	Average ± Std. Dev.
Collision with Fixed Object	0.0708 ± 0.00858
Bridge Component	0.00363 ± 0.00266
Road Component	0.0470 ± 0.00943
Toll Component	0.0202 ± 0.00669
Collision with Non-Fixed Object	0.908 ± 0.00930
Non-vehicle	0.0159 ± 0.00423
Train	0.00906 ± 0.00638
Vehicle outside of the Convoy	0.883 ± 0.0165
Non-Collision	0.0213 ± 0.00384
Fire	0.00187 ± 0.00105
Mechanical Error	0.000860 ± 0.00113
Jackknife/rollover	0.0177 ± 0.00357
Human Error	0.000860 ± 0.00113

Overall damage to the container as well as if the container is punctured is based off the yield strength of the material struck. For a collision with a fixed object, the only collision type that has a yield strength enough to damage the container is a collision with a bridge component. According to Mills et al., manmade structures that are similar to bridge abutments and reinforced concrete columns, “will act like yielding objects if they are struck by a truck cask [30, p. 24].” Therefore, all branch frequencies for “Container Damage” and “Container Puncture” for ‘yes’ branches are arbitrarily set to 0.001 as the smallest value. For non-fixed collisions and non-collisions, the surface of the surrounding ground is used as a conservative baseline. Only a high-speed collision into a highly compacted soil layer will act as an unyielding surface that can cause damage to the container. Soils that are considered highly compacted are hard rock, soft rock and rocky soil. From Mills et al., the frequencies of occurrence of highly compacted soils are taken for

the damage and puncture branches [30, p. 24]. Finally, the frequency of occurrence that the SNF container is near water is 0.0023, no matter the type of accident.

With the determined and researched branch frequencies, the new highway event tree is completed with all conditional frequencies. In Figures 17, 18, and 19 the scenario frequencies are the products of all branches leading to that scenario.

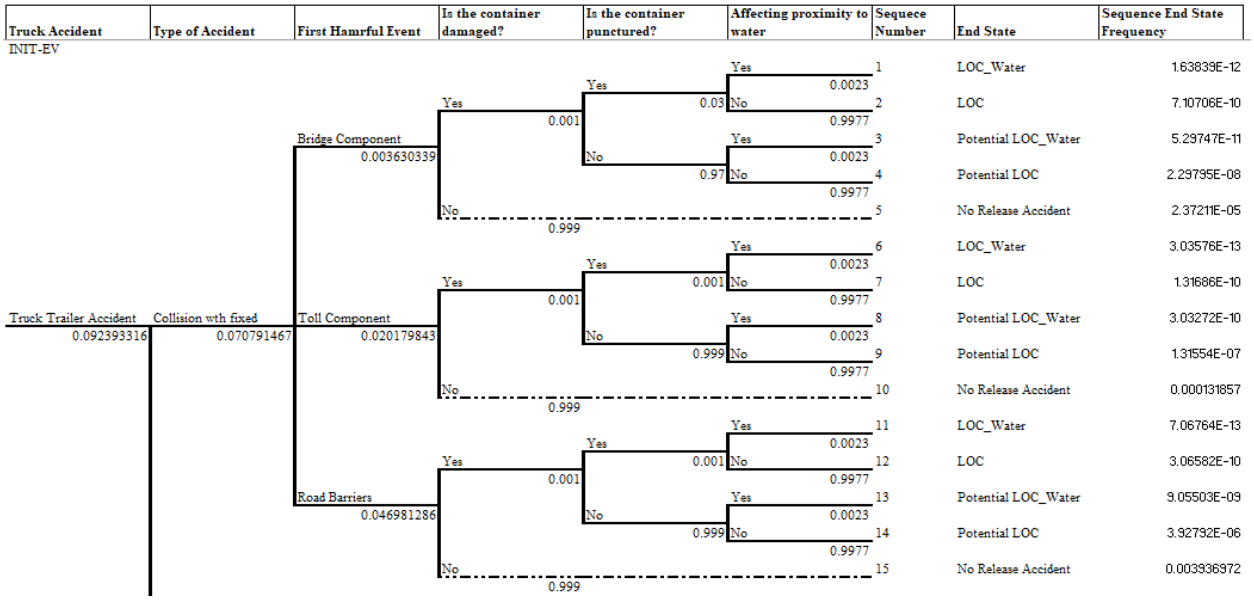

Figure 17. Completed Truck Accident Containment Event Tree (Collision with a fixed object)

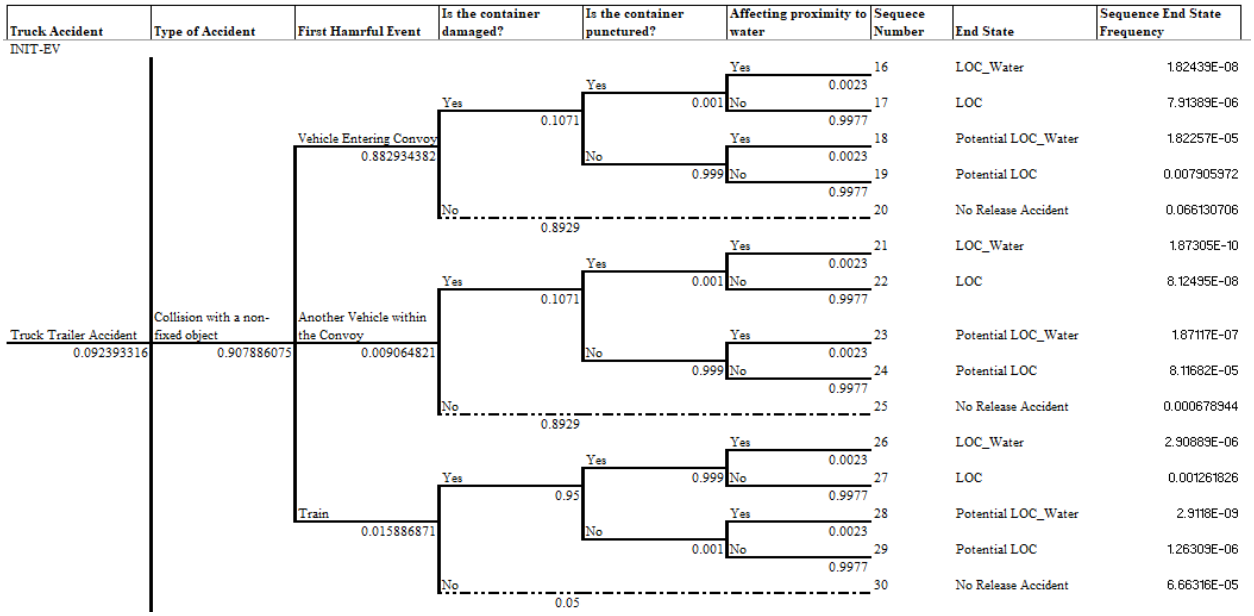

Figure 18. Completed Truck Accident Containment Event Tree (Collision with a non-fixed object)

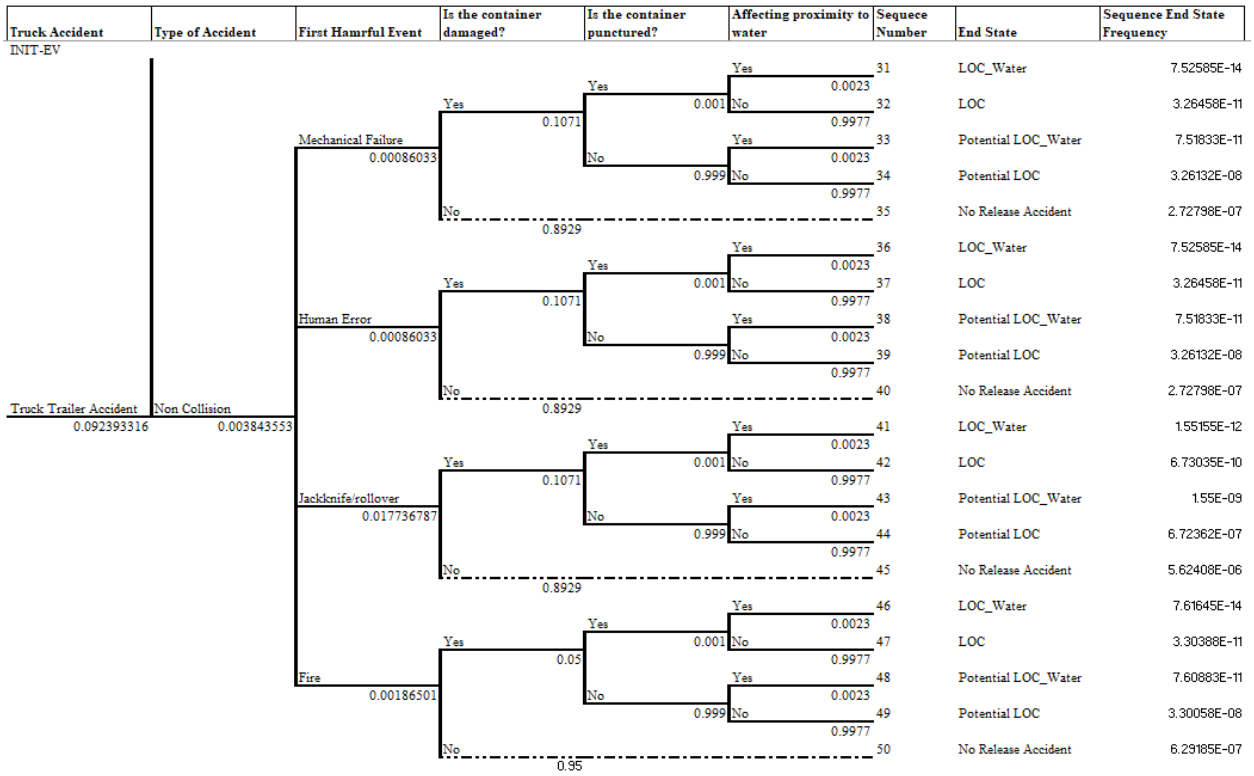

Figure 19. Completed Truck Accident Containment Event Tree (Non-Collision)

4.3 Rail

The railway accident sequence event frequencies were determined very similar to the highway frequencies (Table 14). The main difference between the two was the container damage likelihood upon a collision. The collision "Container Damage" and "Container Puncture" differ based on NUREG 2125's conditional frequencies based off speed. For an impact speed between 48 to 80 kph, the frequencies of damage are 6.34E-6 [14, p. 482]. For the derailment, the "Container Damage" and "Container Puncture" frequencies stayed the same as the highway frequencies based on the average soil composition across the United States. Finally, the "Other" accident type refers to accidents where FHE was not a collision, and a derailment did not occur. Accidents that can fit into the "Other" category are human error, weather encounter, mechanical errors and fires. Fires pose the strongest damages to a container of the group since impact is required to cause damage otherwise. The damage and puncture frequencies are from NUREG's Fire Event Tree, where the "Flammable HM in Consist" branch is used as the "Container Damage" branch and the "Release" branch is used as the "Container Puncture" branch [14, p. 489]. The resulting sequence event conditional frequencies are then found using the product of each branch frequency in Figures 20, 21 and 22.

Table 14. Rail Accident Event Frequencies

Accident Event	**Average ± Std. Dev.**
Collision	0.0421 ± 0.00996
Fixed Object on Track	0.00636 ± 0.00456
Non-Fixed Object on Track	0.0223 ± 0.0257
Derailment	0.689 ± 0.0414
Object on Track	0.0241 ± 0.00634
Track Maintenance	0.262 ± 0.0150
Mechanical Error	0.205 ± 0.0285
Weather Encounter	0.0430 ± 0.0142
Other	0.269 ± 0.0463

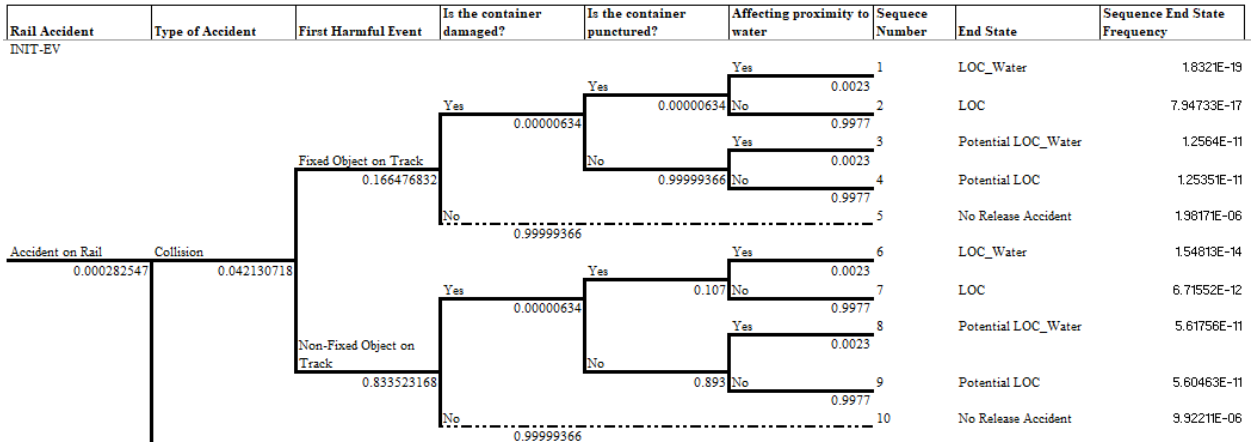

Figure 20. Completed Rail Containment Event Tree (Collision)

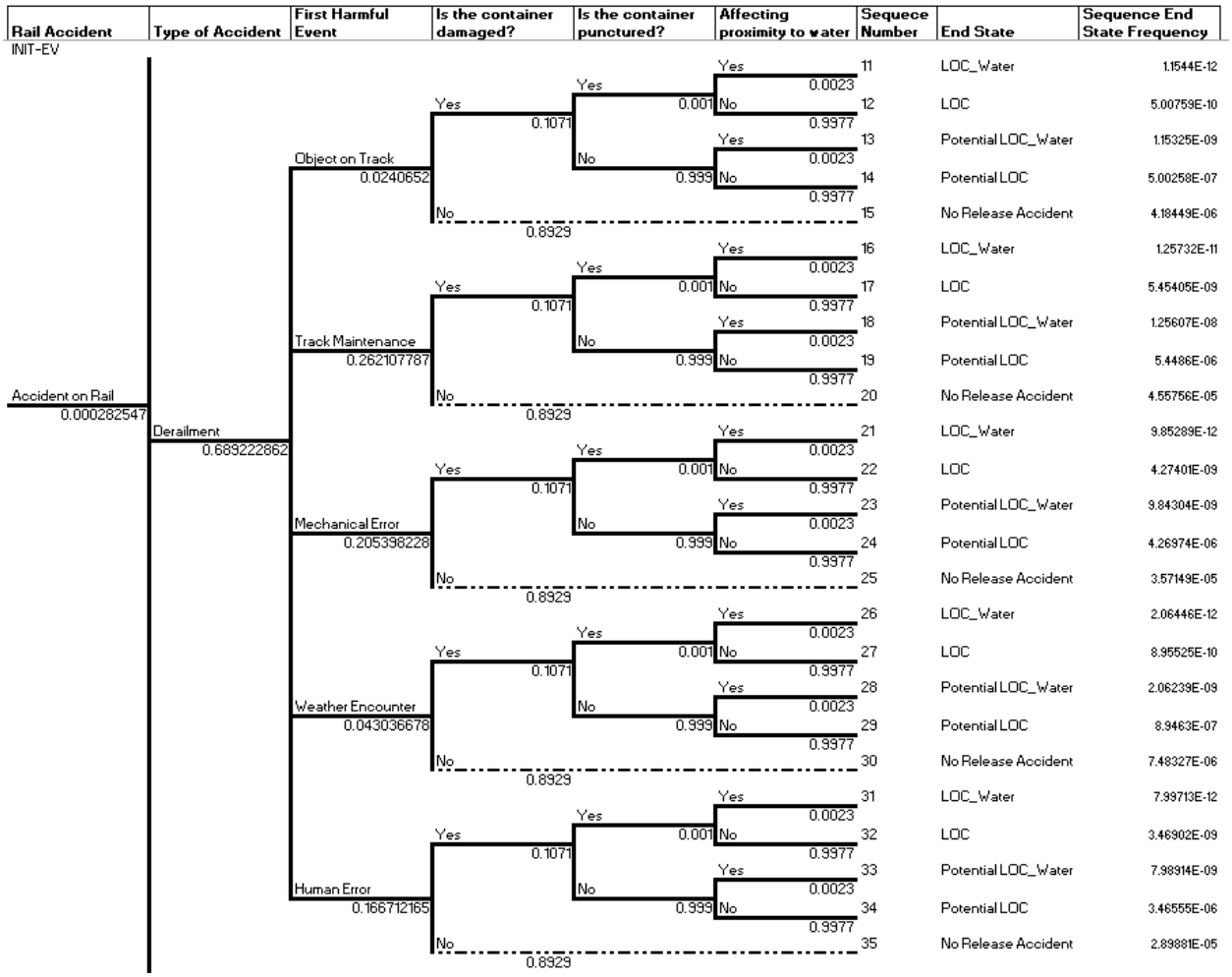

Figure 21. Completed Rail Containment Event Tree (Derailment)

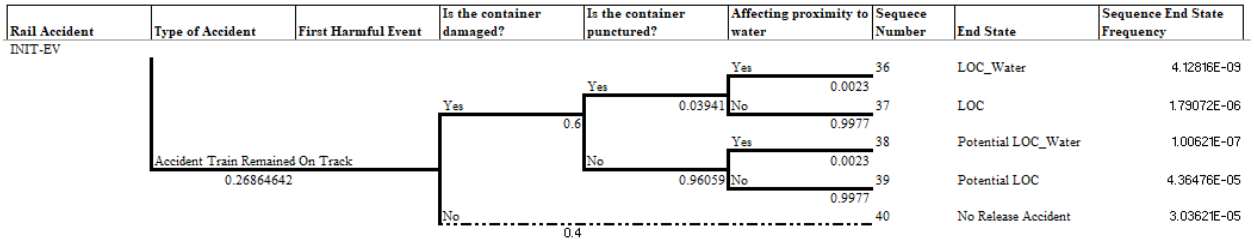

Figure 22. Completed Rail Containment Event Tree (Accident Train Remained On Track)

4.4 Maritime

The "Phase of Operation" and "First Harmful Event" branch frequencies were determined with the same process as the highway and railway accident branch frequencies. Since intermodal maritime accidents are five times less likely to occur than highway and three times less likely to occur than rail modes of transportation, not all first harmful event branches occurred from 2015 to 2020. Although there were no "weather encounter" accidents or "forklift accidents" during the set time period, the values were set to 0.001, the smallest value while keeping consistency in orders of magnitude and continuing to sum to one. The first two branch frequencies are shown in Table 15.

Table 15. Maritime Accident Event Frequency

Accident Event	Average ± Std. Dev.
Prior to Launch	0.0333 ± 0.0817
Fire on Board	0.0313 ± 0.0817
Forklift Accident	0.001 ± 0
Weather Encounter	0.001 ± 0
Post Launch	0.967 ± 0.0817
Ship on Ship Collision	0.283 ± 0.402
Collision with Object	0.117 ± 0.204
Mechanical Error	0.25 ± 0.418
Weather Encounter	0.083 ± 0.204
Grounded	0.0333 ± 0.0817
Human Error	0.2 ± 0.4

Overall damage to the container was based on the Type B package requirements and configurations of freight onto a ship. Since there is little to no impact, 0.001 was the "yes" branch frequency for all container damages except for the forklift. The reason the forklift has a damaging frequency of 0.95 is due to the height of which the container can drop onto the ship's unyielding surface. Additionally, the forklift's forks have the ability to penetrate the container within the Type B requirements of a, "1-meter drop onto a fixed 15-centimeter (cm) diameter steel cylinder [14, p. 8]." Since forks are longer than one meter and have a diameter larger than 15-cm the likelihood of puncture is almost guaranteed, therefore the "yes" branch frequency is set at 0.999. From the intermodal accident reports pulled from 2015 to 2020 none of the freight carrying barges sank nor had any freight sink. The same assumption made for the first harmful events was used to make the "yes" branches all 0.001. Finally, the frequency that the container is salvaged is set to 0.999 due to the ease and proximity of emergency equipment to intermodal maritime routes. The final sequence event frequencies are shown in Figures 23 through 26.

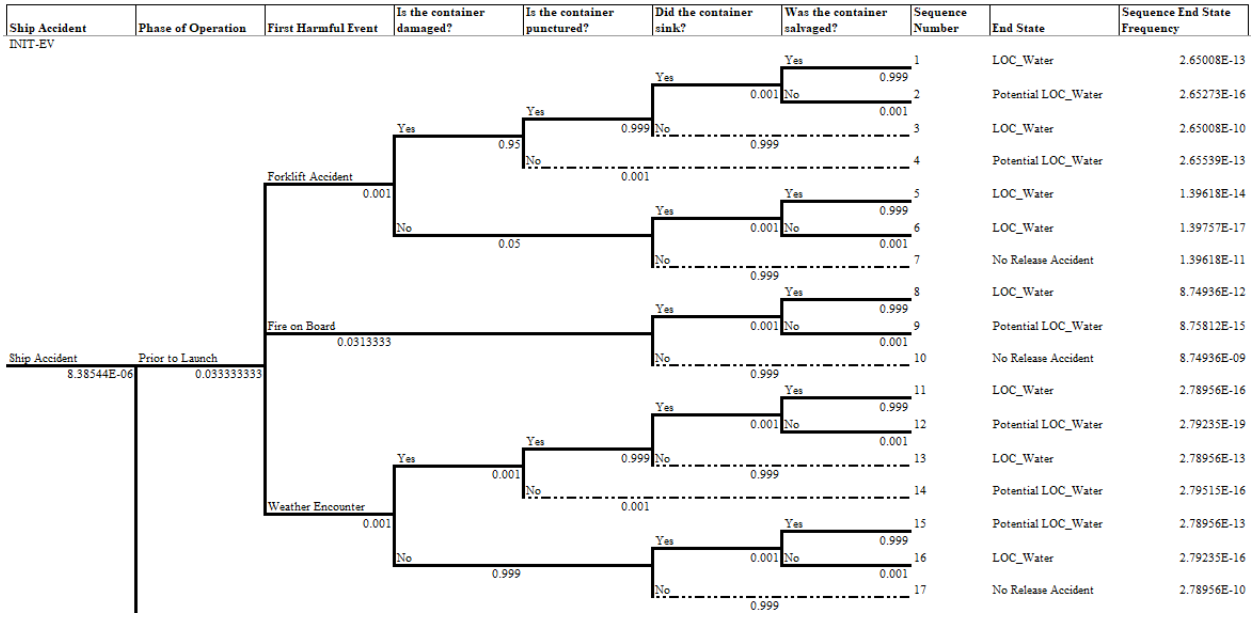

Figure 23. Completed Maritime Accident (Prior to Launch)

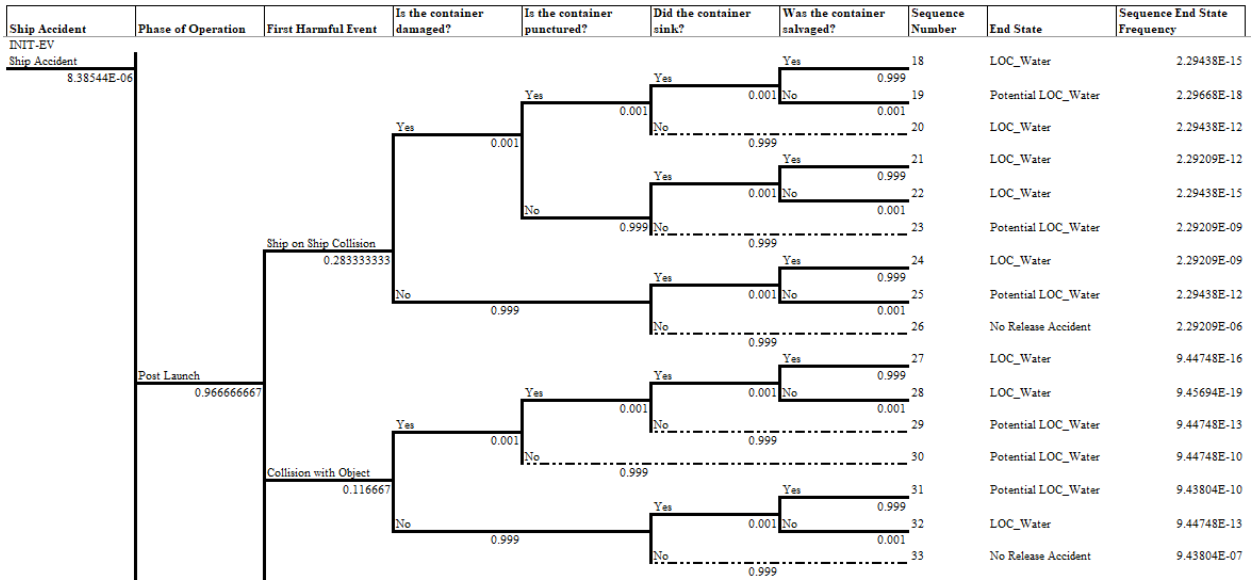

Figure 24. Completed Maritime Accident (Post Launch – Collision)

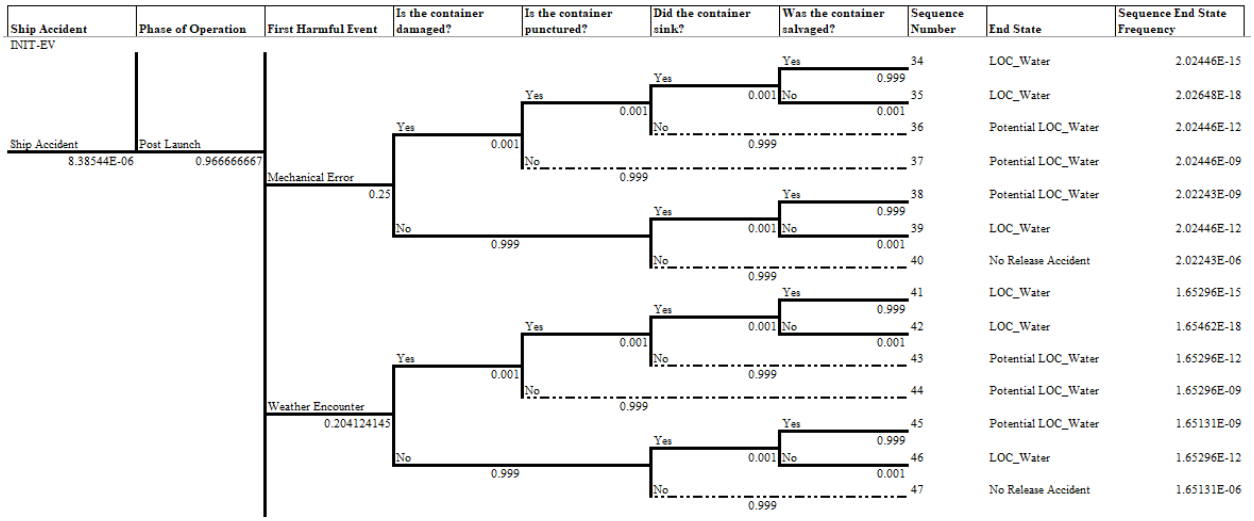

Figure 25. Completed Maritime Accident (Post Launch – Non-Collision)

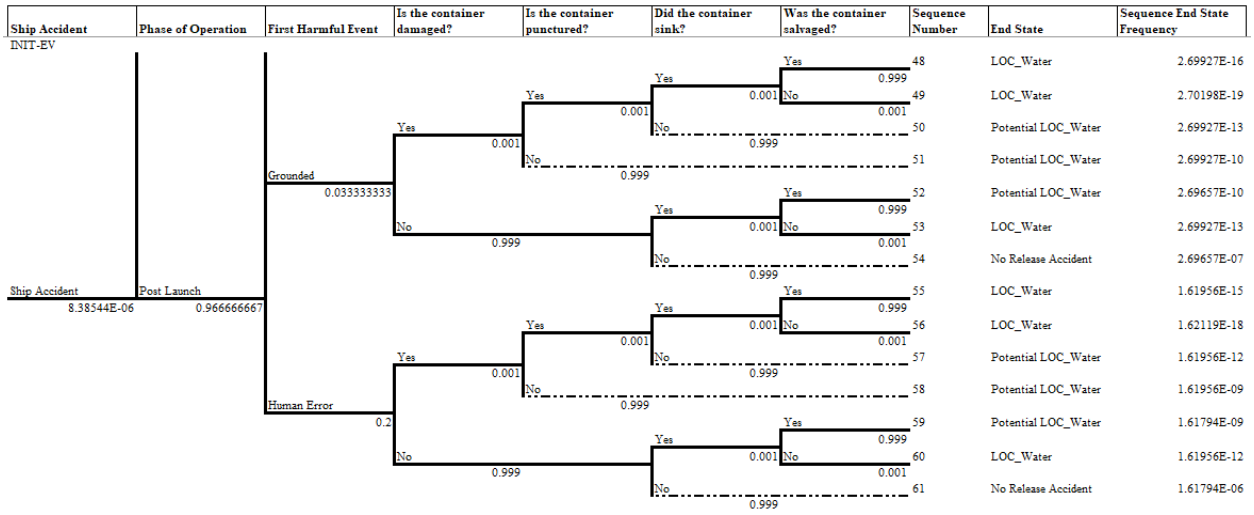

Figure 26. Completed Maritime Accident (Post Launch – Non-Collision continued)

CHAPTER 5. Consequence Analysis

Transportation of hazardous material and the potential consequences an accident can cause to the surrounding environment and population has resulted in an increased concern to the public. With an increase in radioactive materials that the Pele Program can bring, consequence analysis of a spent nuclear fuel transportation accident is necessary. The Mississippi River is a major transportation feature. Due to its physical properties, there are no coast-to-coast routes that do not involve crossing or using the Mississippi River.

5.1 Key Terrain

Transporting a MNPP across the United States is bound to go through major key terrain not only population centers. The Mississippi River Watershed is a major part of any route traveling across the United States due to the size and location in the middle of the country. The Mississippi River is a north-south flowing river that divides the United States in approximately half. Starting in Minnesota, the Mississippi River flows 2,350 miles to the Gulf of Mexico [32]. The Mississippi River Watershed is made up of a drain area of about 1.2 million square miles from 32 states and two Canadian provinces [32]. Figure 27 is a map of the Mississippi River Basin and the size of its watershed. According to the U.S National Park Service, “communities up and down the river use the Mississippi to obtain freshwater [32],” while the EPA claims that, “more than 50 cities rely on the Mississippi for daily water supply [32].”

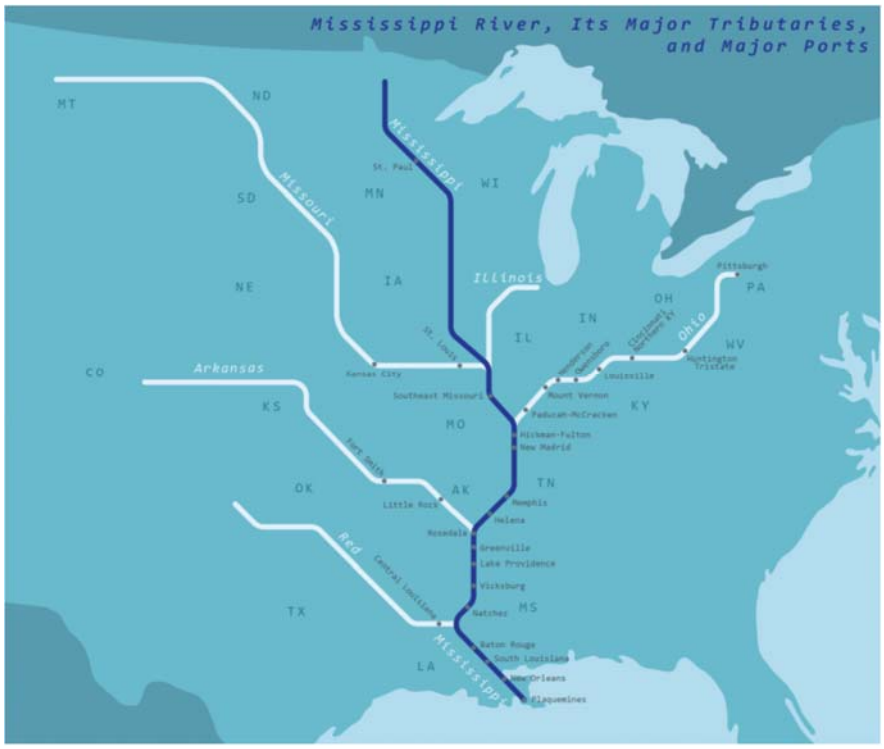

Figure 27. The Mississippi River Watershed [33]

The Mississippi River has a nine foot shipping channel until Baton Rouge, Louisiana, then turns into a 45 foot channel until the end at the Head of Passes, LA [32]. The United States Army Corps of Engineers (USACE) maintains the navigation channels through a series of locks, dams, levees and dredging. In 2019, more than 500 million tons of freight was carried along just the Mississippi River [33].

The Great Plains is another piece of key terrain along any route across the United States. The Great Plains consists of three of the seven state stopping points along the highway route from Idaho National Labs to the Port of Savannah. The region is especially known for its agricultural importance. Agriculture is so important within the plains that more than 80% of the region is dedicated to agriculture activities (crops, pastures, ranges) and has a market value of approximately $92 billion [34, p. 169]. Figure 28 shows the states are part of the Great Plains.

Figure 28. Map of the Great Plains

Due to the length of the Great Plains and the Mississippi River Watershed, any transportation route from west to east or vice versa must cross both. Two cities are analyzed during the highway analysis, the city with the highest risk or impact and St, Louis, Missouri. St. Louis, Missouri has a vast transportation network including a road and rail network crossing the Mississippi River as well as a major port along the river. The transportation network for the three modes is why routes studied in this analysis involve St. Louis. Figures 29 through 33 are maps of the three modes of transportation routes. Two important notes for the maps are the use of interstate highways with the avoidance of major city centers and the use of rail networks that allow freight

transportation. The avoidance of the major city centers is in accordance with two of the seven states environmental guidance (Table 1) and the intent of 49 CFR part 397 [35]. Transportation by rail across the country must occur with the use of two rail networks: Union Pacific Railway (Figure 30) and Norfolk Southern Railway (Figure 31).

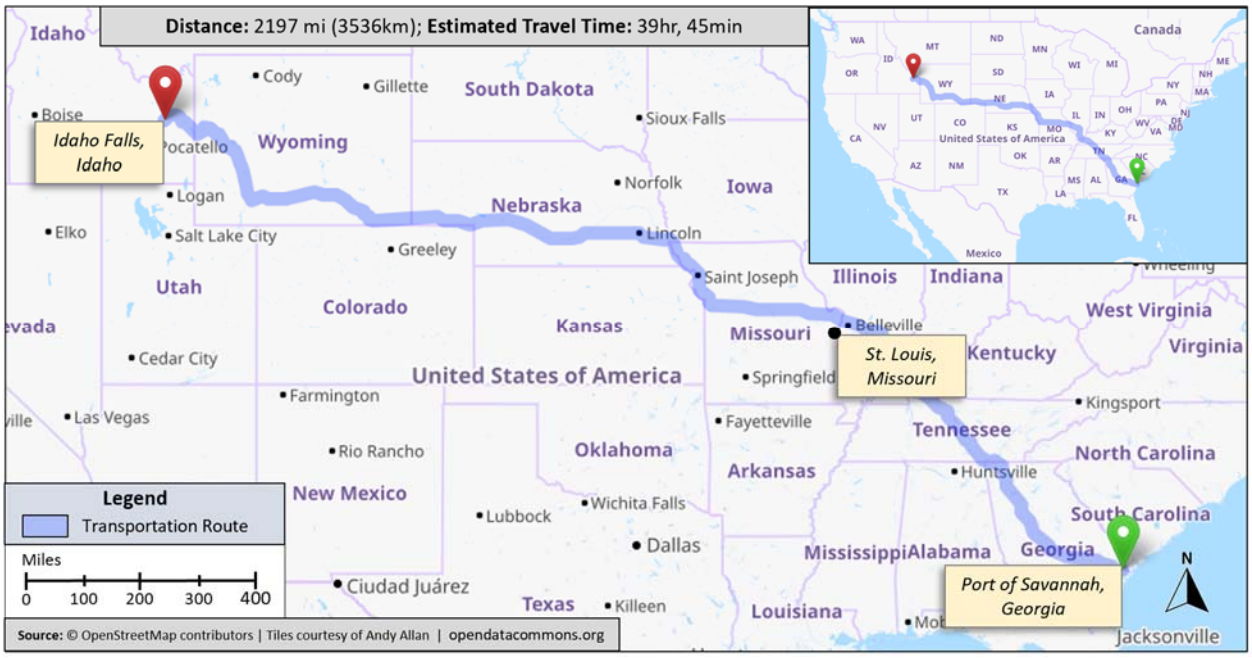

Figure 29. Highway Route from PoS to INL [36]

Figure 30. Rail Route from St Louis to INL (Union Pacific Railroad) [37]

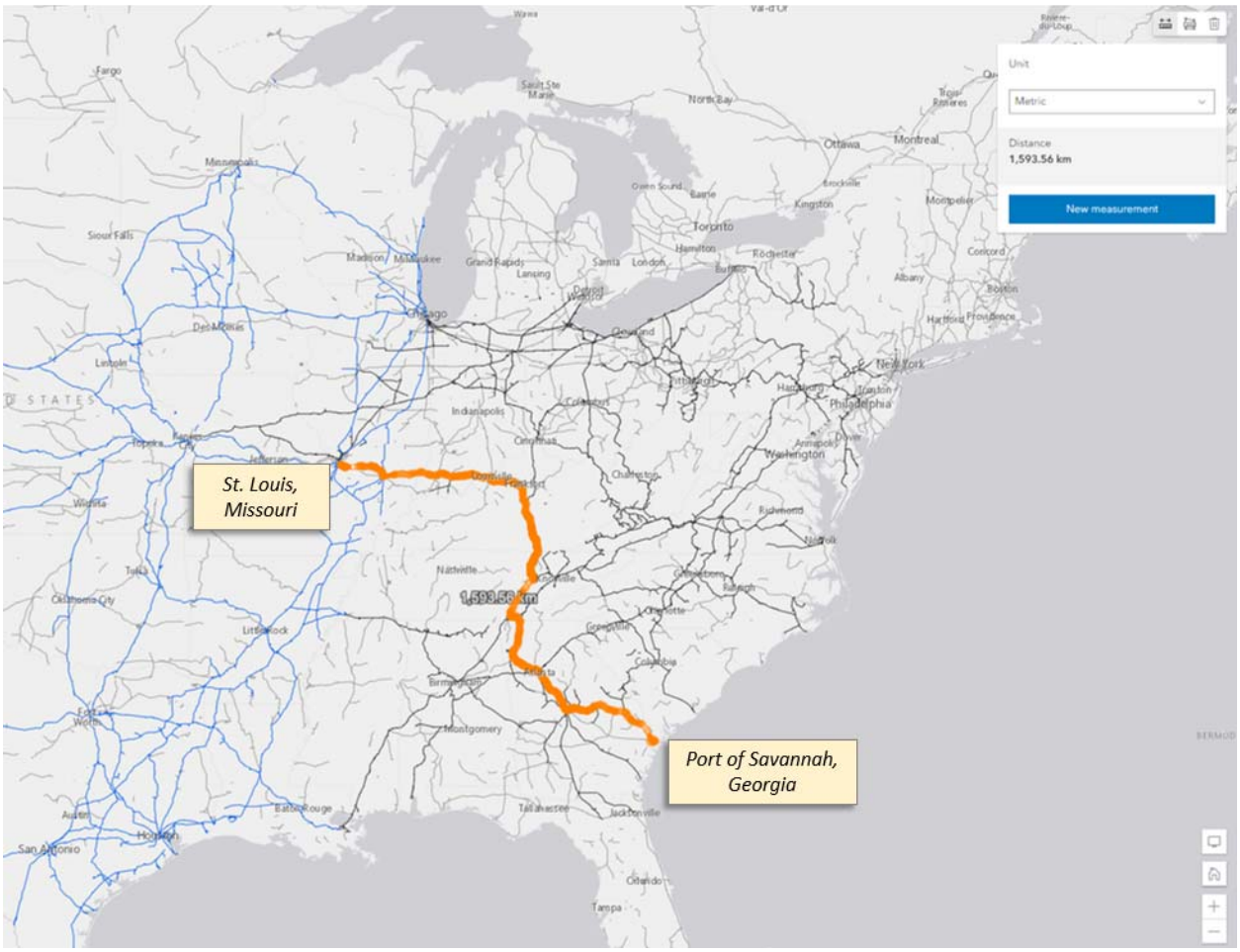

Figure 31. Rail Route from PoS to St. Louis (Norfolk Southern Railroad) [37]

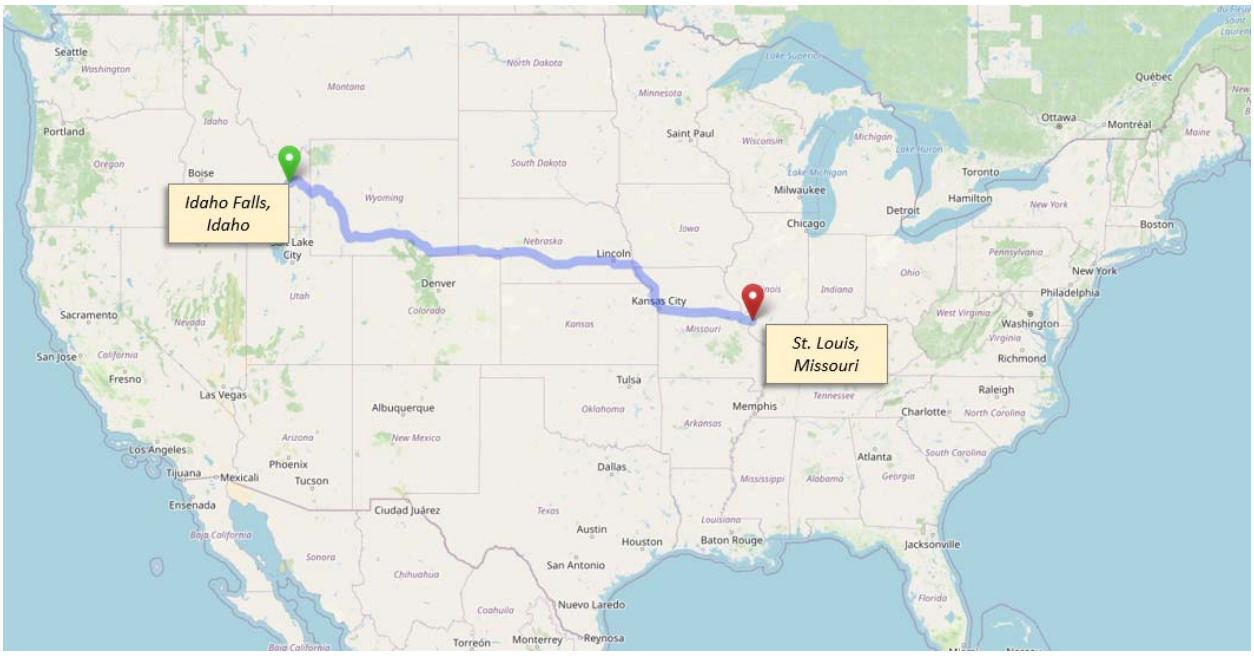

Figure 32. Highway Route from St. Louis to INL [36]

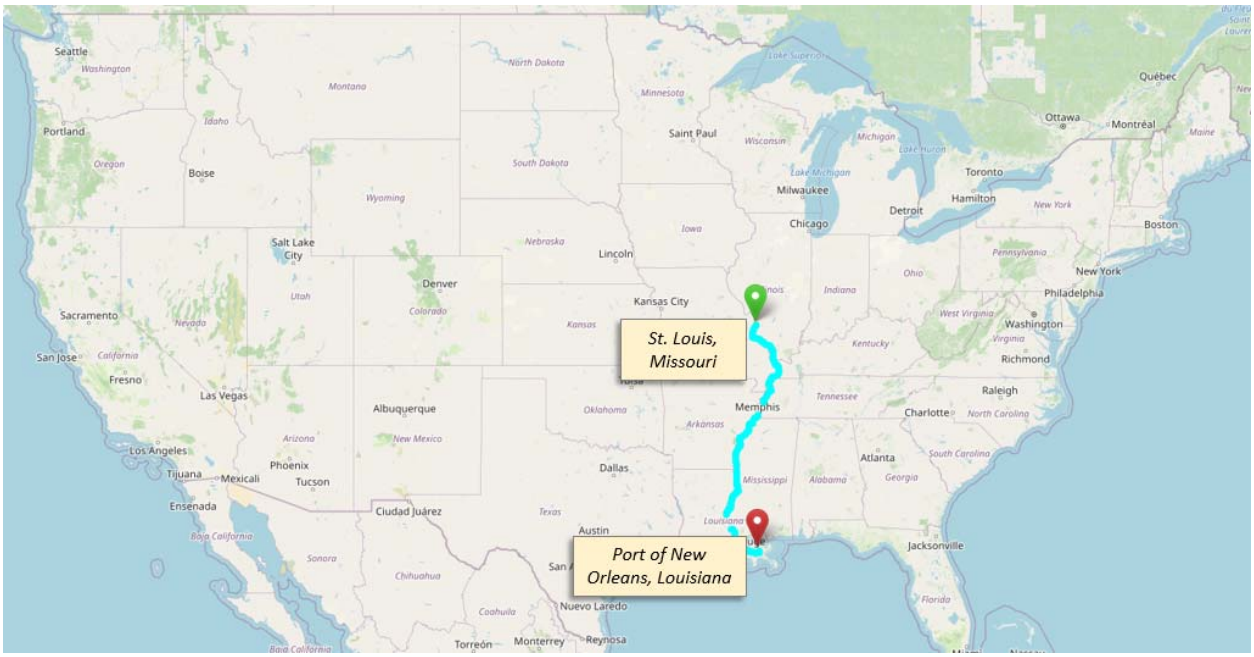

Figure 33. Ship Route from PoNOLA to St. Louis [36]

5.2 RADTRAN Inputs

Risk within spent nuclear fuel transportation is the product of frequency and consequence. According to NUREG 2125, there are two factors that contribute to the frequency a SNF cask is

in an accident; the frequency the vessel is in an accident, and that the accident will be a certain type of accident [14, p. 112]. Using the accident data collected from the DoT, the amount of accidents by accident scenario and type of transportation was collected in the methodology, see Chapter 3.4. Input data for RADTRAN was also collected for a series of parameters.

RADTRAN requires some data that is from actual conditions as well as some provided default values. Required inputs for RADTRAN depend on the type of transportation, incident free or accidents [38, p. 7]. For either, the route and type of transportation vessel is required. The selected route for all three modes of transportation starts at Idaho National Laboratory (INL), Idaho and crosses the Mississippi River. The end point for the truck and train is the Port of Savannah (PoS), Georgia, whereas the end point for the barge is the Port of New Orleans (PoNOLA), Louisiana. A discussion on the parameters and the collection of the corresponding data is provided below.

5.2.1 Radionuclide Inventory

Since the release is based on what radionuclides are inside the container, an inventory list is needed. The ORIGEN code was used to determine the radionuclides and their respective activities. The TRISO fuel inside the MNPP contains UO_2 fuel, similar to a Light Water Reactor (LWR) so the ORIGEN code computes the isotopic compositions for that. A MNPP can run 1 to 5 MWth for a minimum of three years, during which the reactor can be moved to different locations. Using a 33% efficiency, the fission products were assessed from one to five MWe at one, three and five years. The results of the fission products in Curies are in Tables 16 through 18.

Table 16. Fission Products at 1 MWe

Chemical Group	Element or Isotope	Radioactive Activity [Ci] – 1 year	Radioactive Activity [Ci] – 2 years	Radioactive Activity [Ci] – 3 years	Release Fraction
Noble Gas	Kr-85	3.62E-01	0.7009	1.019	1.00E+00
	Kr-87	7.63E-04	0.000761	0.000758	1.00E+00
	Kr-88	2.42E-03	0.002414	0.002406	1.00E+00
	Xe-133	3.02E-01	0.3013	0.3004	1.00E+00
	Xe-135	2.08E-02	0.02069	0.02062	1.00E+00
Halogens	I-131	1.90E-01	0.1898	0.1892	1.00E+00
	I-132	3.43E-03	0.003422	0.003411	2.00E-02
	I-133	4.99E-02	0.04977	0.04961	1.00E+00
	I-134	2.39E-03	0.00238	0.002373	1.00E+00
	I-135	1.51E-02	0.01501	0.01496	1.00E+00
Alkali Metals	Cs-134	1.83E-03	0.006576	0.01344	1.00E+00
	Cs-136	6.65E-04	0.000725	0.0007844	1.00E+00
	Cs-137	1.35E+01	26.61	39.45	1.00E+00
	Rb-86	8.22E-06	8.66E-06	9.114E-06	1.00E+00
Chalcogens	Te-127	4.06E-04	0.00041	0.00041	2.00E-02
	Te-129	2.50E-04	0.000249	0.0002485	2.00E-02
	Te-132	1.16E-01	0.1159	0.1155	2.00E-02
Alkali Earths	Sr-89	1.38E+00	1.383	1.379	2.00E-03
	Sr-90	8.33E+00	16.47	24.41	2.00E-03
	Se-91	1.36E-02	0.01353	0.01348	2.00E-03
	Ba-140	7.15E-01	0.7126	0.7103	2.00E-03
	Y-90	2.09E-03	0.004134	0.006126	2.00E-03
	Y-91	1.98E+00	2	1.993	1.00E-01
Transition Elements	Zr-95	2.45E+00	2.487	2.479	1.00E-02
	Zr-97	2.56E-02	0.02555	0.02547	1.00E-02
	Nb-95	1.35E+00	1.366	1.362	1.00E-02
Miscellaneous	Sb-127	4.09E-03	0.004074	0.004062	1.00E+00
	Sb-129	9.45E-04	0.000942	0.0009395	1.00E+00
	Mo-99	1.05E-01	0.1049	0.1045	1.00E-06
	Ru-103	8.11E-01	0.8092	0.8068	2.00E-05
	Ru-105	1.27E-03	0.001262	0.001259	2.00E-05
	Ru-106	4.86E-01	0.7297	0.852	2.00E-05
Lanthanides	La-140	9.38E-02	0.09348	0.09318	1.00E-06
	Ce-141	1.73E+00	1.719	1.714	1.00E-06
	Ce-143	7.48E-02	0.07454	0.0743	1.00E-06
	Ce-144	8.42E+00	11.86	13.25	1.00E-06
	Pr-143	7.38E-01	0.7353	0.7329	1.00E-06
	Nd-147	2.36E-01	0.2349	0.2342	1.00E-06
	Np-239	6.73E-02	0.06751	0.06772	1.00E-06

Table 16 (continued).

Transuranic	**Pu-238**	**8.19E-07**	**6.7E-06**	**2.283E-05**	**1.00E-06**
	Pu-239	7.13E+00	14.3	21.44	1.00E-06
	Pu-240	9.10E-03	0.0366	0.08261	1.00E-06
	Pu-241	8.21E-06	6.53E-05	0.0002185	1.00E-06
	Am-241	9.91E-08	1.58E-06	7.928E-06	1.00E-06

Table 17. Fission Products at 3 MWe

Chemical Group	Element or Isotope	Radioactive Activity [Ci] – 1 year	Radioactive Activity [Ci] – 2 years	Radioactive Activity [Ci] – 3 years	Release Fraction
Noble Gas	Kr-85	1.085	2.101	3.052	1.00E+00
	Kr-87	0.002274	0.002251	0.002228	1.00E+00
	Kr-88	0.007218	0.007145	0.007071	1.00E+00
	Xe-133	0.901	0.8921	0.8831	1.00E+00
	Xe-135	0.05768	0.05706	0.05643	1.00E+00
Halogens	I-131	0.5675	0.562	0.5563	1.00E+00
	I-132	0.01023	0.01013	0.01003	2.00E-02
	I-133	0.1488	0.1474	0.1459	1.00E+00
	I-134	0.007118	0.007047	0.006976	1.00E+00
	I-135	0.04489	0.04445	0.04399	1.00E+00
Alkali Metals	Cs-134	0.01617	0.05929	0.1225	1.00E+00
	Cs-136	0.002317	0.002824	0.003338	1.00E+00
	Cs-137	40.37	79.8	118.3	1.00E+00
	Rb-86	2.73E-05	3.14E-05	3.56E-05	1.00E+00
Chalcogens	Te-127	0.001212	0.001218	0.001208	2.00E-02
	Te-129	0.000745	0.000739	0.000731	2.00E-02
	Te-132	0.3465	0.3432	0.3397	2.00E-02
Alkali Earths	Sr-89	4.124	4.094	4.052	2.00E-03
	Sr-90	25	49.38	73.16	2.00E-03
	Se-91	0.04045	0.04005	0.03963	2.00E-03
	Ba-140	2.131	2.11	2.088	2.00E-03
	Y-90	0.006284	0.01241	0.01837	2.00E-03
	Y-91	5.916	5.92	5.858	1.00E-01
Transition Elements	Zr-95	7.325	7.362	7.286	1.00E-02
	Zr-97	0.07641	0.07566	0.07488	1.00E-02
	Nb-95	4.024	4.044	4.003	1.00E-02
Miscellaneous	Sb-127	0.01219	0.01208	0.01197	1.00E+00
	Sb-129	0.002818	0.002792	0.002765	1.00E+00
	Mo-99	0.3136	0.3105	0.3073	1.00E-06
	Ru-103	2.423	2.398	2.375	2.00E-05
	Ru-105	0.003776	0.003746	0.003714	2.00E-05
	Ru-106	1.458	2.189	2.552	2.00E-05

Table 17 (continued).

Lanthanides	**La-140**	**0.2796**	**0.2769**	**0.2741**	**1.00E-06**
	Ce-141	5.141	5.091	5.04	1.00E-06
	Ce-143	0.2229	0.2207	0.2184	1.00E-06
	Ce-144	25.23	35.44	39.41	1.00E-06
	Pr-143	2.199	2.177	2.154	1.00E-06
	Nd-147	0.7025	0.6956	0.6885	1.00E-06
	Np-239	0.2032	0.2051	0.207	1.00E-06
Transuranic	Pu-238	2.24E-05	0.000185	0.000639	1.00E-06
	Pu-239	21.31	42.6	63.66	1.00E-06
	Pu-240	0.08227	0.3322	0.7528	1.00E-06
	Pu-241	0.000223	0.001783	0.006006	1.00E-06
	Am-241	2.69E-06	4.3E-05	0.000218	1.00E-06

Table 18. Fission Products at 5 MWe

Chemical Group	**Element or Isotope**	**Radioactive Activity [Ci] – 1 year**	**Radioactive Activity [Ci] – 2 years**	**Radioactive Activity [Ci] – 3 years**	**Release Fraction**
Noble Gas	Kr-85	1.808	3.499	5.077	1.00E+00
	Kr-87	0.003765	0.003699	0.003631	1.00E+00
	Kr-88	0.01195	0.01174	0.01153	1.00E+00
	Xe-133	1.492	1.467	1.44	1.00E+00
	Xe-135	0.08937	0.08764	0.08586	1.00E+00
Halogens	I-131	0.9397	0.9241	0.9078	1.00E+00
	I-132	0.01695	0.01666	0.01637	2.00E-02
	I-133	0.2464	0.2423	0.2379	1.00E+00
	I-134	0.01179	0.01159	0.01138	1.00E+00
	I-135	0.07432	0.07307	0.07176	1.00E+00
Alkali Metals	Cs-134	0.045	0.1665	0.3464	1.00E+00
	Cs-136	0.004335	0.005669	0.007035	1.00E+00
	Cs-137	67.28	132.9	196.9	1.00E+00
	Rb-86	4.99E-05	6.14E-05	0.00007343	1.00E+00
Chalcogens	Te-127	0.002009	0.002006	0.001975	2.00E-02
	Te-129	0.001235	0.001215	0.001194	2.00E-02
	Te-132	0.5739	0.5642	0.5542	2.00E-02
Alkali Earths	Sr-89	6.844	6.728	6.605	2.00E-03
	Sr-90	41.65	82.24	121.7	2.00E-03
	Se-91	0.06697	0.06581	0.06461	2.00E-03
	Ba-140	3.528	3.468	3.406	2.00E-03
	Y-90	0.01048	0.02068	0.0306	2.00E-03
	Y-91	9.821	9.729	9.551	1.00E-01

Table 18 (continued).

Transition Elements	**Zr-95**	**12.17**	**12.1**	**11.88**	**1.00E-02**
	Zr-97	0.1265	0.1244	0.1221	1.00E-02
	Nb-95	6.683	6.648	6.528	1.00E-02
Miscellaneous	Sb-127	0.02019	0.01989	0.01957	1.00E+00
	Sb-129	0.004668	0.004593	0.004515	1.00E+00
	Mo-99	0.5192	0.5105	0.5013	1.00E-06
	Ru-103	4.021	3.945	3.878	2.00E-05
	Ru-105	0.00626	0.006173	0.006082	2.00E-05
	Ru-106	2.431	3.649	4.245	2.00E-05
Lanthanides	La-140	0.463	0.4553	0.4474	1.00E-06
	Ce-141	8.513	8.369	8.221	1.00E-06
	Ce-143	0.369	0.3627	0.3562	1.00E-06
	Ce-144	42.01	58.81	65.08	1.00E-06
	Pr-143	3.64	3.578	3.513	1.00E-06
	Nd-147	1.163	1.144	1.123	1.00E-06
	Np-239	0.3407	0.3461	0.3515	1.00E-06
Transuranic	Pu-238	0.000105	0.000878	0.003069	1.00E-06
	Pu-239	35.4	70.49	104.9	1.00E-06
	Pu-240	0.2295	0.9304	2.116	1.00E-06
	Pu-241	0.001039	0.008353	0.02828	1.00E-06
	Am-241	1.25E-05	0.000201	0.001022	1.00E-06

5.2.2 Accident Rate (Route Characteristic)

Transporting a MNPP across the U.S via highway or railway is a long journey. For a hazardous material movement within the U.S Army, the transporter is only allowed to stop for refueling; this restriction dictated the link lengths within the route planning. The total length of a trip from to PoS to INL is 3536 kilometers (2917 miles), roughly 40 hours. Due to the length of the route, there are seven linkage points, or stops, for refueling and driver changes with an average of 509 km (316 mi) and the longest leg of the route of 830 km (515 mi) from Chyenne, Wyoming to INL. By DoT mandate, a loaded semi-truck has a maximum speed of 80.5 kph (50mph) no matter if the local speed limit is higher. At each link, the population density was determined for the city as well as the accident rate. From the accident rate, the death per accident rate was determined. Finally, the farm fraction by state and the population type were determined.

Table 19. Highway Route Characteristics

Route Link	Length (km)	Speed (kmh)	Population Density (population/km^2)[39]	Accident Rate (accident/km)	Death rate (deaths/accident)	Population Type	Farm Fraction
INL - Cheyenne, WY	830	80.5	903.3	18.0[40]	0.0051[40]	Urban	0.46[41], [39]
Cheyenne - Lincoln, NE	711	80.5	1194	19.0[42]	0.0024[42]	Urban	0.90[43], [39]
Lincoln - Kansas City, MO	325	80.5	905.2	1.83[44]	0.0067[44]	Urban	0.62[45], [39]
Kansas City - St Louis, MO	400	80.5	914.5	6.69[46]	0.0036[46]	Urban	0.62[47], [39]
St Louis - Nashville, TN	498	80.5	764.8	10.2[48]	0.0077[48]	Urban	0.40[49], [39]
Nashville - Atlanta, GA	399	80.5	787.7	4.35[50]	0.0028[50]	Urban	0.27[51], [39]
Atlanta - PoS, GA	400	80.5	580.5	12.7[50]	0.0022[50]	Urban	0.27[51], [39]

Table 20. Rail Route Characteristics

Route Link	Length (km)	Speed (kph)	Population Density (population/km^2) [39]	Accident Rate (accident/km) [52]	Death rate (deaths/accident) [52]	Population Type	Farm Fraction
INL – St Louis, MO	2728.94	24	914.5	0.160	0.043	Urban	0.62 [47], [39]
St. Louis – PoS, GA	1593.56	24	580.5	0.301	0.13	Urban	0.27 [51], [39]

Table 21. Ship Route Characteristics

Route Link	Length (km)	Speed (kph)	Population Density (population/km^2)[39]	Accident Rate (accident/km)	Death rate (deaths/accident)	Population Type	Farm Fraction
INL - Cheyenne, WY	830	80.5	903.3	18.0[40]	0.0051[40]	Urban	0.46[41], [39]
Cheyenne - Lincoln, NE	711	80.5	1194	19.0[42]	0.0024[42]	Urban	0.90[43], [39]
Lincoln - Kansas City, MO	325	80.5	905.2	1.83[44]	0.0067[44]	Urban	0.62[45], [39]
Kansas City - St Louis, MO	400	80.5	914.5	6.69[46]	0.0036[46]	Urban	0.62[47], [39]
St Louis – PoNOLA, LA	2239.73 [53]	7	515.2	0.0175 [54]	0.11 [54]	Rural	0.62 [55], [39]

5.2.3 Conditional Frequency of Accident Severity

Each mode of transportation has a separate conditional frequency. The end state frequencies developed in Chapter 4 are used as conditional frequencies as an input for RADTRAN. The conditional frequencies help determine the risk at each linking point.

5.2.4 Release Fractions

The release fractions of fission products during the accident are assumed to be similar to the releases fraction used for the LWR spent nuclear fuel. The release fraction shown in Table 16-18 obtained from NUREG/CR-4982 and NUREG/CR 6451[56], [57].

5.3 Transportation Accident Analysis

This section describes the RADTRAN outputs and the potential impacts to the effected region. As expected, the highway transportation has the largest dose risk to the individual however

it is important to understand that the frequency of such an accident is still very small. The individual dose risk from the ground is also determined due to the importance of agriculture and surface water in the selected regions. According to 10 CFR 71.41, radioactive materials that are in a close transport vehicle, secured within the vehicle and do not have a loading or unloading operation during transportation, have a limit of 1000 mrem/h [58]. In the case of the highway and rail operations, there is no loading and unloading, however for the maritime, loading onto the barge occurs, making the limit 100 mrem/h [58]. For this report, the limit of 100 mrem/h is used as an additional safety measure.

5.3.1 Truck Accident Analysis

Highway transportation via truck poses the highest dose risk to the individual and individual ingesting via ground from an accident involving a vehicle entering the convoy. Lincoln, Nebraska is considered the city with the highest risk of an accident for both the ground and individuals. An accident involving a vehicle entering a convoy poses the greatest risk to the surrounding individuals. A collision with a vehicle entering the convoy is the highest probable accident, increasing the overall risk. That same event also reaches a dose risk higher than the maximum allowable limits across the investigated operating parameters. Obviously, the longer the MNPP is being in operation with higher power, the higher the dose risk to the individual expected. For example, in Lincoln, NE, collision incidents involving a vehicle entering a convoy were analyzed for operating power levels of 1 MWe, 3 MWe, and 5 MWe, over one-year cycle that can potentially cause a dose risk of a 2.32E-02 rem, 6.86E-02 rem, and 1.140E-01 rem, respectively. Conversely, under the same power conditions but over a three year cycle, the corresponding dose risks were found to be 6.69E-02 rem, 1.99E-01 rem, and 3.31E-01 rem, respectively.

The ingestion via ground is also highest with an accident involving a collision with a vehicle entering the convoy. Though not above the maximum allowable dose, if the accident involves multiple accident events, the dose risk could reach a concerning level. For the end state sequences initiated with accident with non-fix object that related to a collision with a train, the individuals of Lincoln, NE will highly face a maximum dose risk. The collision train investigated with an operating power level of 1 MWe at different interval of operating cycle length of a 1,2, and 3 year the does risk found to be 3.72E-03 rem, 7.23E-03 rem and 1.07E-02 rem respectively. However, with the same cycle length interval at 5 MWe operating power level the does risk found to be as 1.83E-02 rem, 7.23E-03 rem and 1.07E-02 rem respectively. The ground does risk for collision with a vehicle in the convoy is still lower than the risk induces by the accident involving a collision with a vehicle entering the convoy or collision with a train by a two order of magnitude at lower operating power and length cycle and by one order of magnitude at higher operating power with high cycle length.

Furthermore, it was previously discussed in Chapter 3 that a collision with a vehicle within the convoy is classified as a rear-end collision, which is less likely to cause damage to the container to the extent that the reactor vessel is compromised compared to a collision with a train. However, in the event of such an incident, it is expected that the annual limit of dose to individual members of the public will be violated. The results of the dose risk analysis for individuals and the ground, at three different operating power levels (1 MWe, 3 MWe, and 5 MWe) with a three year cycle, indicate that the doses are 6.69E-02 rem, 1.99E-01 rem, and 3.31E-01 rem, and 1.36E-04 rem, 3.63E-04 rem, and 6.0E-04 rem, respectively. Figures 34 and 35 depict the individual and ground risk at Lincoln, NE.

The Nuclear Regulatory Commission (NRC) stipulates in 10 CFR 20.1301 a limit to the total effective dose equivalent (TEDE) to which the general public should not exceed 0.1 rem [59]. However, this study reveals that collisions involving vehicles entering convoy at higher power and operation cycle length have resulted in exceeding the NRC's established limit for dose limit for individual members of the public. This attribute to the accumulative increase of the fission product for the higher cycle operation length with higher power and to the higher conditional frequency of the collisions involving vehicles entering a convoy compering to the other investigated accident as shown in Figures 23, 24, and 25 in section 4.2.

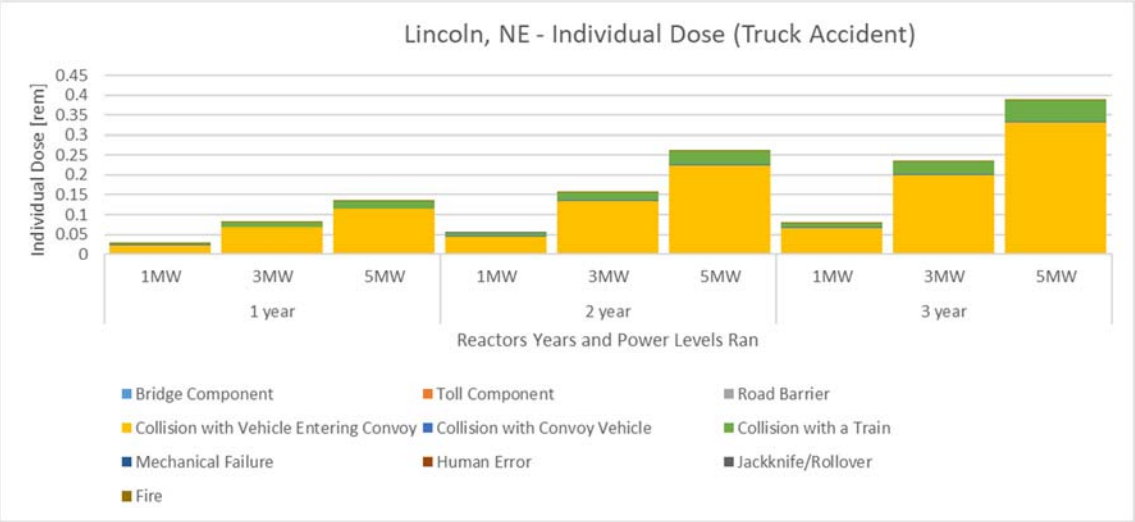

Figure 34. Comparison of highway accident events to the individual over interval length cycle and different operation power levels in Lincoln, NE

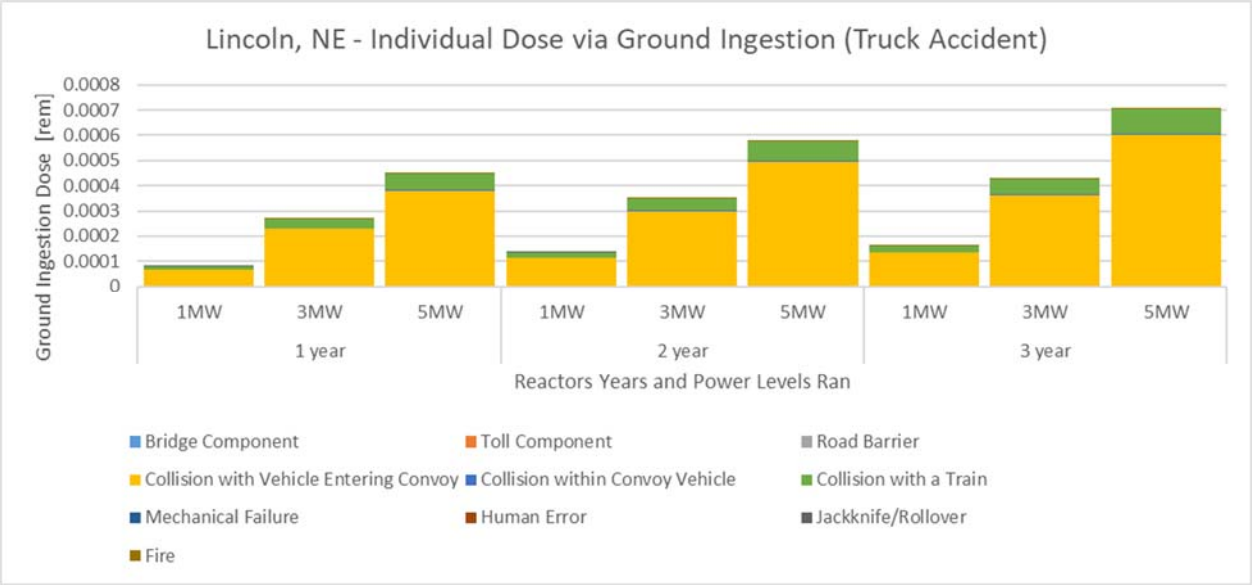

Figure 35. Comparison of highway accident events to the ground risk over interval length cycle and different operation power levels in Lincoln, NE

St. Louis, Missouri is an important city along the transportation route, given its location along the Mississippi River. A pattern similar to that of Lincoln city has been identified for St. Louis, where collisions with vehicles entering the convoy can result in an individual dose risk that exceeds the dose limit in 10 CFR 20.1301. The study investigated the potential dose risks resulting from a collision incident involving a vehicle entering a convoy near St. Louis link, considering different operating power levels of 1 MWe, 3 MWe, and 5 MWe over one-year cycle. The findings indicated that the collision incident could lead to dose risks of 4.61E-03 rem, 1.36E-02 rem, and 2.27E-02 rem, respectively. However, when the same power conditions were considered over a three year cycle, the corresponding dose risks were found to be higher as 1.33E-02 rem, 3.95E-02 rem, and 6.56E-01 rem, respectively. For the sequences analysis related to a collision with a train in the St. Louis were investigated with an operating power level of 1 MWe at different interval of operating cycle length of a 1,2, and 3 year the dose risk found to be 7.38E-04 rem, 1.43E-03 rem and 2.13E-03 rem respectively. However, with the same cycle length interval at 5 MWe operating

power level the dose risk found to be as 3.63E-03 rem, 7.08E-03 rem and 1.05E-02 rem respectively.

The ingestion via ground at St. Louis link were analyzed in this study and based on the power level of 5MWe with operational cycle of three years the ground dose risk for the following accidents: collisions with vehicles entering the convoy, Collision with vehicle within Convoy and collisions with train were found to be 9.12E-05 rem, 9.36E-07 rem and 1.46E-05 rem respectively. Where the highest induce risk accident is a collision with a vehicle entering the convoy. The conurbation of other investigated accidents carried out in this study at St. Louis for the individual and ground risk are depict in Figures 36 and 37.

The variance in dose risks between St. Louis and Lincoln is attributable to discrepancies in their population densities and corresponding accident rates. Despite having a larger population than Lincoln, St. Louis' residents are dispersed across neighboring municipalities and counties, while Lincoln's population is concentrated within the city limits. Since the population in Lincoln is denser, the accident rate is also more prevalent than in St. Louis where the accidents within the city and its highways surrounding the city.

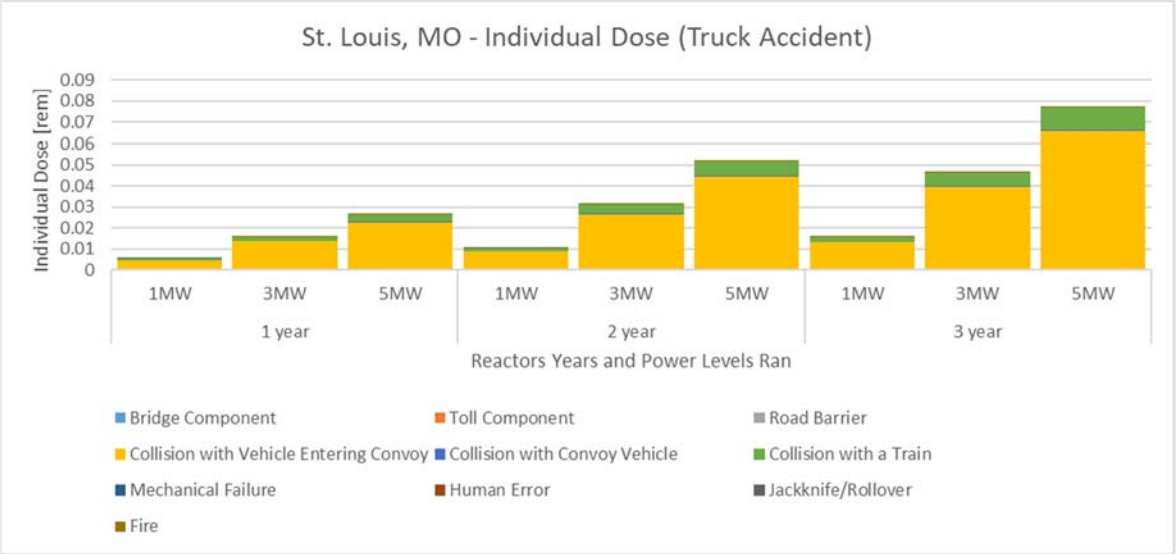

Figure 36. Comparison of highway accident events to the individual risk over interval length cycle and different operation power levels in St. Louis, MO

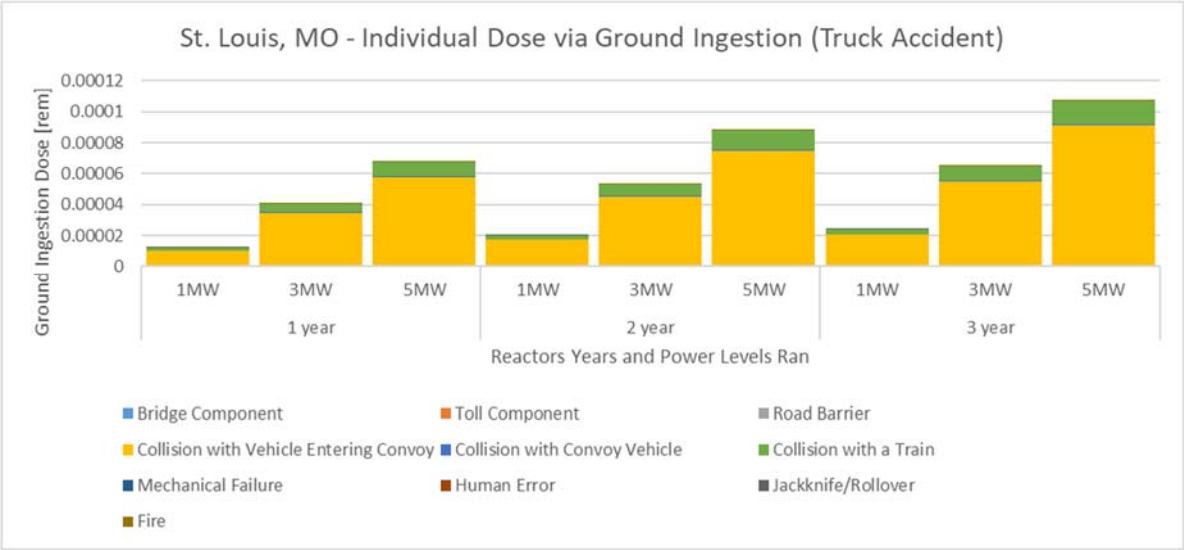

Figure 37. Comparison of highway accident events to the ground risk over interval length cycle and different operation power levels in St. Louis, MO

5.3.2 Rail Accident Analysis

The rail accident subsequent as the highest dose risk to individuals is classified as the 'other' in the rail event tree as shown in Figure 26 and Figure 27 and discussed in section 4.3 primarily includes accidents caused by human error or fires. Although such events are less probable than derailment accidents, the likelihood of container damage and reactor vessel breach is considerably high. As a result of the increase in the conductional frequency, the dose risk of the category ‘other' exceeds all the other types of rail accidents were included in this study. However, neither the individual dose risk nor the ground ingestion dose risk exceeds the dose limit for individual members of the public annual limit or raised a caution concern level. Figures 38 and 39 depict the dose risks to the individual and ground at St. Louis, MO due to a train accident.

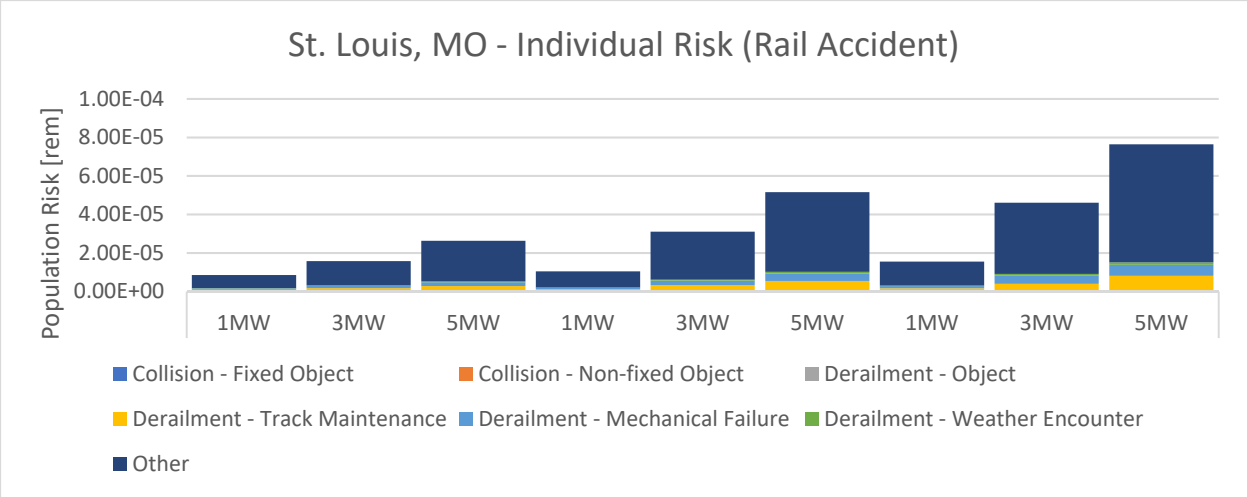

Figure 38. Comparison of Railway accident events to the individual risk over interval length cycle and different operation power levels in St. Louis, MO

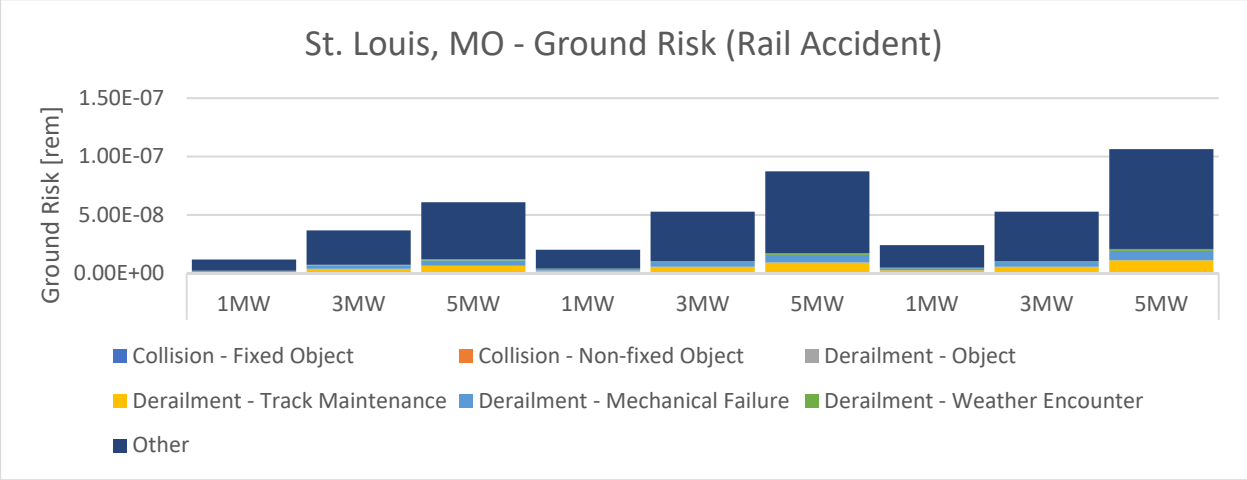

Figure 39. Comparison of Railway accident events to the ground risk over interval length cycle and different operation power levels in St. Louis, MO

5.3.3 Maritime Accident Analysis

The event tree model for maritime accident analysis incorporates two branch accidents as prior and post launch, which incorporates incidents such as mechanical and human errors, collisions with objects or other ship, among others (refer to section 4.4). The analysis of the New Orleans link showed that the post launch sequence exhibits a higher risk to the general public about one order of magnitude compared to prior launch accidents. The dose risk of the post launch

mechanical failure event at operating power level of 5MWe and one, two and three years of operating cycle length found to be as 1.69E-10 rem, 3.30E-10 rem and 4.89E-10 rem respectively. On another hand, the highest contributed branch of prior launch accident to the dose risk is related to the weather condition. The dose risk of weather incident at operating cycle of three years and power levels of 1 MWe, 3 MWe and 5 MWe found to be as 6.80E-15 rem 2.03E-14 rem and 4.89E-10 rem respectively.

Similarly, the dose risk to the ground indicated similar pattern to the dose risk to the general public where it's increased with increasing the operation parameters. The ground dose risk of accident involving a post launch mechanical error at operating power levels of 1 MWe, 3 MWe and 5 MWe and three years of operating power have been found to be 7.78E-14 rem , 1.90E-13 rem and 3.83E-13 rem respectively. The population and ground dose risks in New Orleans, LA shown in Figures 40 and 41.

The accident involving a mechanical error post launch poses the most dose risk to the population and ground due to the likelihood of a mechanical error as well as the likelihood of follow-on harmful events. For example, an accident where a ship-on-ship collision is the first harmful event, the collision is typically also the only harmful event; whereas for accidents that the first harmful event is a mechanical error, other harmful events can occur. Most importantly, the post launch phase of a maritime operation has a much higher dose risk due to the time it takes to rescue the vessel as opposed to when the vessel is next to land. No maritime accident in either phase of the operation gives an accident dose risk of higher than 0.1 rem.

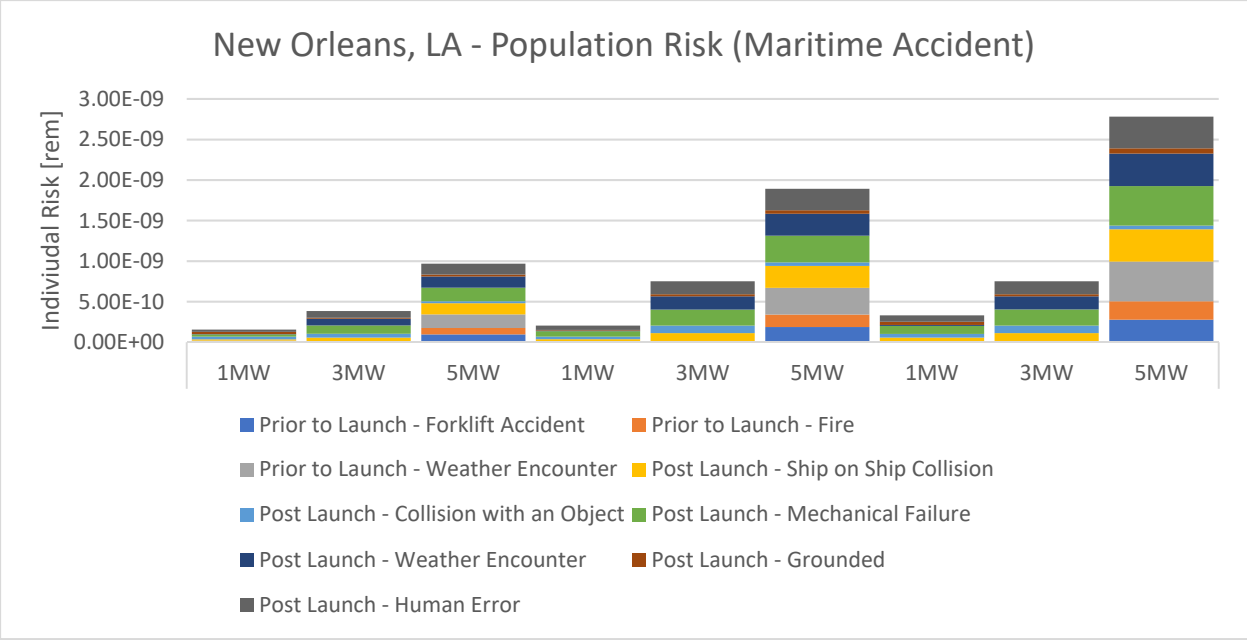

Figure 40. Comparison of Maritime accident events to the ground risk over interval length cycle and different operation power levels in New Orleans, LA

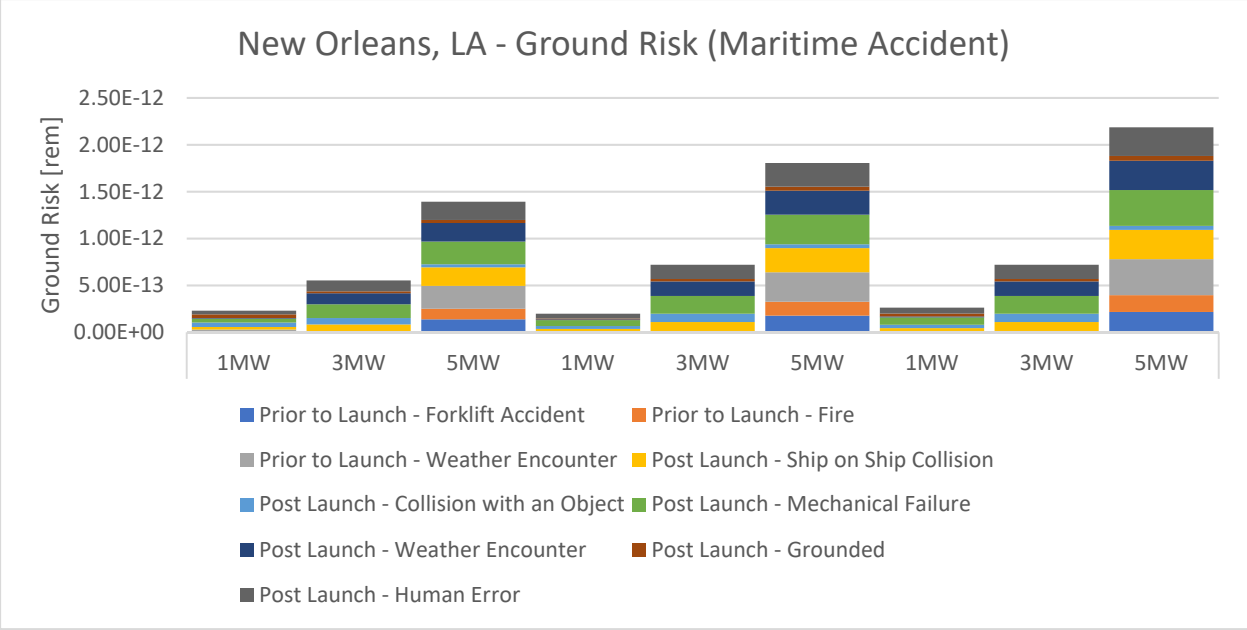

Figure 41. Comparison of Maritime accident events to the ground risk over interval length cycle and different operation power levels in New Orleans, LA

5.4 Discussion

This section describes major highlights from the RADTRAN outputs for both the individual and ground dose risk levels from the first harmful events, as well as the major highlights from the developed event trees. The section will first describe the dose levels to the individual from an accident involving a reactor that operated for three years at a power level of 5 MWe, then provide an analysis on the event trees to determine the largest end state frequency. During the event tree analysis, the type of accidents will be analyzed to determine the accident with the largest effect on the consequences. Finally, a prevention and mitigation strategy is discussed to provide a recommendation for the best mode of transportation.

5.4.1 Dose Risks to the Public

Based on the insights from the individual mode analysis, a review of the entire route is conducted. The review uses the individual dose risks per first harmful event and graphs over the stopping cities. The route consequence per first harmful event correlation is shown in Figure 42 and Table 22.

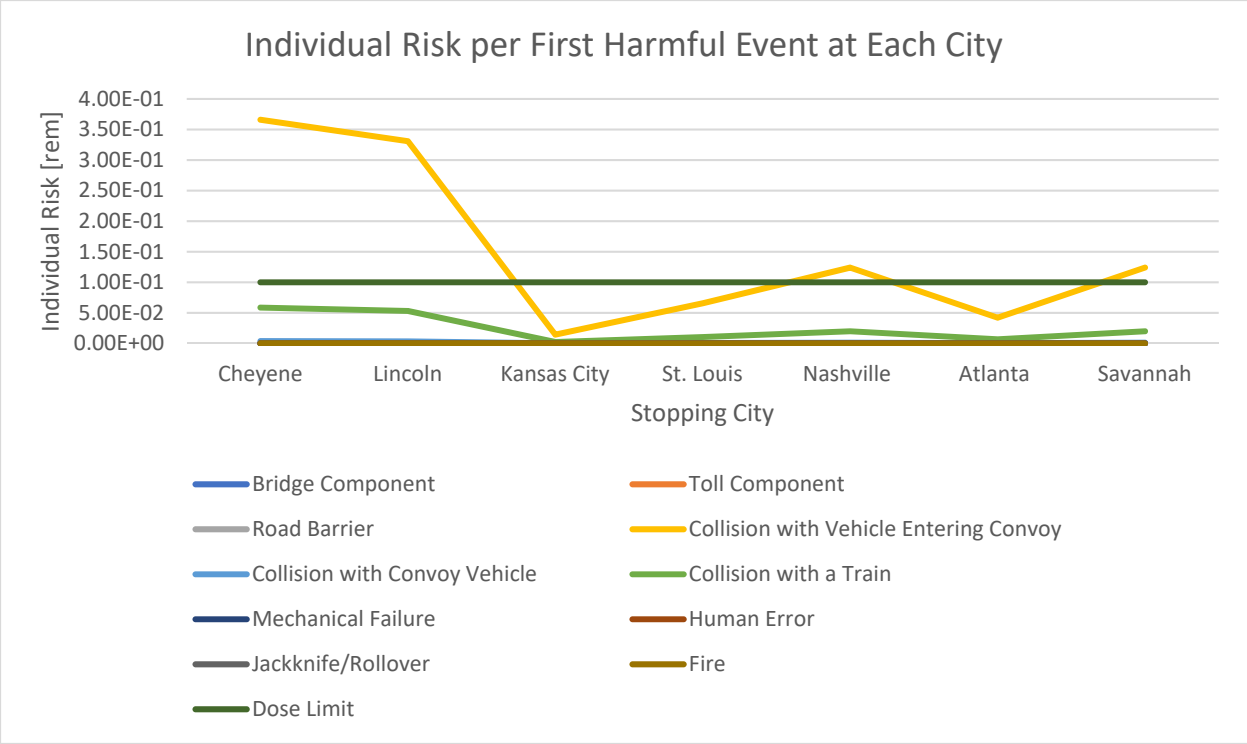

Figure 42. Individual Risk per First Harmful Event Accident at 5 MWe full power over 3 years along the route

Table 22. Individual Risk per First Harmful Event Accident at 5 MWe full power over 3 years along the route

Stopping City	Bridge Component	Toll Component	Road Barrier	Collision with Vehicle Entering Convoy	Collision with Convoy Vehicle	Collision with a Train	Mechanical Failure	Human Error	Jackknife/Rollover	Fire	Dose Limit
Cheyenne	1.09E-06	6.09E-06	1.82E-04	3.66E-01	3.76E-03	5.86E-02	1.51E-06	4.89E-04	3.11E-05	1.53E-06	1.00E-01
Lincoln	9.90E-07	5.50E-06	1.64E-04	3.31E-01	3.40E-03	5.30E-02	1.36E-06	4.42E-04	2.81E-05	1.38E-06	1.00E-01
Kansas City	4.29E-08	2.38E-07	7.11E-06	1.43E-02	1.47E-04	2.29E-03	5.91E-08	1.91E-05	1.22E-06	5.98E-08	1.00E-01
St. Louis	1.96E-07	1.09E-06	3.26E-05	6.56E-02	6.74E-04	1.05E-02	2.71E-07	8.77E-05	5.58E-06	2.74E-07	1.00E-01
Nashville	3.72E-07	2.07E-06	6.17E-05	1.24E-01	1.28E-03	1.99E-02	5.13E-07	1.66E-04	1.06E-05	5.19E-07	1.00E-01
Atlanta	1.26E-07	6.99E-07	2.09E-05	4.20E-02	4.31E-04	6.73E-03	1.73E-07	5.61E-05	3.57E-06	1.75E-07	1.00E-01
Savannah	3.72E-07	2.07E-06	6.17E-05	1.24E-01	1.28E-03	1.99E-02	5.13E-07	1.66E-04	1.06E-05	5.19E-07	1.00E-01

As seen in Figure 47 and Table 22, four cities along the route have a dose risk higher than the maximum allowable amount for a collision with a vehicle entering the convoy. Table 22 is a heat map that where all values that are yellow or orange are at or over the allowable maximum dose level. The two values that are red, a collision entering the convoy within Cheyenne and Lincoln, are well over the maximum dose level and the highest values in the accident scenarios.

5.4.2 Event Tree Analysis

Table 23 presents a summary of the end states for each initiating event. For each mode of transportation, the "No Release Accident" end state has the highest frequency, meaning that an accident is most likely not going to have any effect on the population either by ingestion via air or through the ground. The "Potential LOC" and "LOC" are the next highest frequencies for both highway and railway transport modes, respectively. The loss of containment accident end states are mainly first order effects to the immediate surrounding population however their distance to water or other key terrain does not create a second or third order effect.

Table 23. Summation of End State Frequencies [number of accidents per freight ton miles]

End State	Highway Accident	Railway Accident	Maritime Accident
LOC_Water	2.92733E-06	4.16182E-09	2.57751E-09
LOC	0.001269823	1.80532E-06	N/A
Potential LOC_Water	1.84269E-05	1.34298E-07	1.15395E-08
Potential LOC	0.007993256	5.82264E-05	N/A
No Release Accident	0.070975631	0.000164212	6.91867E-06

5.4.3 Recommended Mode of Transportation

This work is a tool for decision makers in the early stages of transportation and route planning due to assumptions made that cause limitations in the overall results. The largest assumption within the work is the container damage and container puncture frequencies. The values for the container damages are based off of previous work for Type B packages but not ISO certified containers. Another uncertainty in the report is the accident locations along the route. Within RADTRAN, the accident values are only at the link city, not between the cities along the route. Another aspect of the work that is a limitation is risks related to change in transportation modes, such as risk in loading or unloading from a truck onto a railcar or barge.

For decision makers in the initial phase of transportation operation analysis, this research can help develop courses of actions and comparing the courses. Within the United States, maritime transportation is the safest followed by rail and finally highway. A major issue with maritime transportation is the time required and location of navigable waters. Many remote locations where a MNPP might be needed do not have navigable waters nearby. Rail is a much quicker mode of transportation than maritime and still does not have an accident risk resulting in an individual dose risk higher than the maximum allowable dose. While rail is also more accessible than maritime, it still requires the transfer from a truck to a railcar, which can increase the frequency of an accident. Finally, highway transportation results in the highest risk to an individual with some accidents causing an individual dose risk higher than the maximum allowable amount. However, highway transportation limits the amount transfers between different transportation vessels. Highway transportation also allows for a more door-to-door pickup and delivery.

Due to the brief comparison discussed, highway is the best mode of transportation of a MNPP. The door-to-door transportation eliminates the risk of an accident occurring while

transferring to a different mode of transportation. The first harmful event that poses the greatest risk is a collision with a vehicle entering the convoy, by either cutting off or side swiping the truck. There are several ways to minimize a vehicle entering a convoy such as having a police escort. Another way to minimize risk is to avoid cities like in the case of Cheyenne and Lincoln, where a beltway highway around the city does not exist at a distance far from the city. A collision with a vehicle within a convoy is simple to minimize by adding distance between each convoy vehicle. Although adding space between the vehicles adds room for another vehicle to enter the convoy, the additional room also minimizes the collision of any vehicle. Finally, the minimization of a collision with a train is also simple, by ensuring the convoy stay along highways and interstates. Each vehicle within the convoy also needs a hazardous material body suit for immediate mitigation of dose effects. By communicating with each state's DOT, avoiding, and minimizing high dose causing risks is possible when route planning.

CHAPTER 6. Conclusion and Future Work

6.1 Conclusion

This research identified transportation regulations involving Micro Reactors and the accidents that can occur within three modes of transportation, developed an event tree to determine frequencies off the accidents. Finally, a case study was completed for the three modes of transportation across three routes to determine the individual and ground dose risk at major cities. A comparison of the three modes was discussed and a recommendation to minimize accident frequency was provided.

An important result of the research is that the frequency of a radionuclide release is very small. The largest risk for an individual and ground was with the highway mode of transportation and an accident with a vehicle outside of the convoy. The largest end state frequency within an accident involving a vehicle entering the convoy is the potential of a damage to the containment with 0.0079. Locations with a large population density had the highest risk to an individual with two cities along the route having an individual dose risk higher than the maximum allowable limit 0.1 rem.

Finally, the discussion for the decision maker was presented. The highway mode of transportation was recommended as the best mode of transportation for a MNPP due to the door-to-door pickup and delivery capability that neither rail nor maritime provide. Highway transportation was also recommended due to the less amount of time needed when compared to maritime or rail. Suggestions to minimize the frequency of an accident involving a vehicle outside of the convoy was provided to better improve the highway mode of transportation recommendation.

6.2 Future Work

This research handled a risk analysis on mobile microreactors during transportation. The study considered three of the four modes of transportation, excluding air. Further analysis for air transportation should be conducted since air is a major mode of transportation for the DoD. Additionally, the event tree framework completed in this study can be expanded to include fault trees linked to the top events. The road movements analyzed were only on US highways and interstates with an assumption of a high level of drivability. Not every nation that the U.S. military goes, potentially needing a microreactor, has the same road maintenance. Future work needs to be done to expand the event trees created to include infrastructure levels of confidence.

Another area of future work is determining the regulations and protocols of an accident during the transportation phase, specifically who reacts, what the personnel within the convoy do and the first actions required to minimize radionuclide contamination to the environment and population. The safety and security of the reactor container during transportation is an area of future work, addressing which entity has the jurisdiction to manage the security across state and international borders.

Finally, surface water was the only type of water used during the consequence analysis. With 33% of Americans relying on ground water, further analysis must be done on the damage to ground water to aid with response to an accident protocol.

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