Pacific Northwest NATIONAL LABORATORY

PNNL-33524

Plan for Development and Application of Risk Assessment Approach for Transportation Package Approval of an MNPP for Domestic Highway Shipment

December 2021

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U.S. DEPARTMENT OF ENERGY

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Acronyms and Abbreviations

ARF	airborne release fraction
CDF	Core Damage Frequency
CFR	*Code of Federal Regulations*
CRSS	Crash Report Sampling System
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DR	damage ratio
EPA	U.S. Environmental Protection Agency
FARS	Fatality Analysis Reporting System
FGR	Federal Guidance Report
GAO	U.S. Government Accountability Office
GES	General Estimates System
GIS	geographic information system
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
LERF	Large Early Release Fraction
LPF	leak path factor
MAR	material at risk
MCMIS	Motor Carrier Management Information System
MNPP	mobile nuclear power plant
NHTSA	National Highway Traffic Safety Administration
NRC	U.S. Nuclear Regulatory Commission
PAR	police accident report
PNNL	Pacific Northwest National Laboratory
PRA	Probabilistic Risk Assessment
QHG	quantitative health guidelines
RF	respirable fraction
RG	regulatory guide
SAR	safety analysis report
SSURGO	Soil Survey Geographic (database)
STATSGO	State Soil Geographic (database)
TRISO	Tristructural Isotropic (particle)
WSMR	White Sands Missile Range

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1.0 Introduction

For nuclear reactors, Probabilistic Risk Assessment (PRA) has been conducted since the 1970s [e.g., see WASH-1400 (NRC 1975), NUREG-1150 (NRC 1990), and NUREG-1935 (Chang et al. 2012)]. PRA has also been used to assess a dry cask storage system at a nuclear power plant [see NUREG-1864 (NRC 2007)]. PRA techniques have also been applied to the transportation of spent nuclear fuel, most notably in NUREG/CR-4829 (Fischer et al. 1987), NUREG/CR-6672 (Sprung et al. 2000), and NUREG-2125 (NRC 2014). Additional guidance is provided in International Atomic Energy Agency (IAEA) IAEA-TECDOC-1346 (2003). Transportation PRA was also used in the evaluations of transportation impacts in reports such as the Repository Final Environmental Impact Statement (DOE 2002) and the Repository Final Supplemental Environmental Impact Statement (DOE 2008).

The purpose of this plan is to provide the planning bases for the development and application of a PRA methodology for the highway transport of the Project Pele prototype mobile nuclear power plant (MNPP) that would support a risk-informed pathway for regulatory approval. In addition to a MNPP Transportation PRA, the methodology, technical information, data, and example analyses will be provided to the two Project Pele vendors, BWXT and X-Energy, with the expectation that the PRA methodology, technical information, data, and analysis approaches will be used to support a request for a 10 CFR 71.12 exemption that will be submitted by BWXT or X-Energy to the U.S. Nuclear Regulatory Commission (NRC) for approval of the Project Pele transportation package. Additionally, this information will also be provided to the NRC for review, contribution, and endorsement of the process at the same time it is provided to the Project Pele vendors. BWXT or X-Energy will bear the ultimate responsibility for the submittal of the transportation safety analysis report (SAR) and the request for exemption to the NRC.

The structure of this plan is based on the transportation PRA methodology, technical information, data, and example analyses that will be provided to the vendors. In order to develop the MNPP plan, several assumptions must be made (e.g., selection of White Sands Missile Range [WSMR] as a destination). In addition, the proceeding products from this plan are meant to be adaptive and will be updated and revised based on vendor and Project Pele prototype MNPP design information and refinement.

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2.0 Content of the Transportation PRA Methodology, Information, and Data

The MNPP transportation PRA methodology, technical information, data, and example analyses that will be provided to BWXT and X-Energy will be organized into seven sections and appendices as needed.

1. Definition of Regulatory Approach

   This section will discuss the 10 CFR Part 71 exemption process, other potential regulatory approaches, and identify the requirements for which an exemption is being requested. Based on the amount of vendor design information available from Project Pele Phase 1B, evaluation of which 10 CFR Part 71 requirements will require an exemption may be qualitative or semi-quantitative. However, given the technical uncertainties and potential risk to the public and the fact that transport of a MNPP will be a first-of-a-kind endeavor, it is expected that the exemption process will need to be supported by a more quantitative assessment than has been used in the past.

2. Definition of Safety Goals and Risk Evaluation Guidelines

   This section will discuss potential risk evaluation guidelines, propose risk evaluation guidelines, and justify that the proposed risk evaluation guidelines are consistent with NRC's safety goals, current NRC guidance, and historical practice. Though regulatory risk evaluation guidelines do not exist for transportation of nuclear material as they do for nuclear power plants, NRC has suggested guidance in a report titled "Risk-Informed Decisionmaking for Nuclear Material and Waste Applications" (NRC 2008). However, there are significant challenges to applying this approach as it involves use of quantitative health guidelines (QHGs) that have not been endorsed by NRC or used in a significant way. Moreover, the details of applying it to nuclear material transport has not been completely worked out. Even nuclear power plant risk-informed applications, in which the use the PRA technology is mature and well-accepted by the NRC, do not use risk estimates calculated in terms of health impacts. Rather, measures of Core Damage Frequency (CDF) and Large Early Release Fraction (LERF) are used as surrogates because they are much more attainable and practical to use than QHGs. NRC has issued guidance in Regulatory Guide (RG) 1.174, Revision 3 (NRC 2018) that provides risk acceptance thresholds for risk-informed licensing applications in terms of CDF and LERF and increases in CDF or LERF. Therefore, the use of QHGs as risk evaluation guidelines need to be (1) developed in more detail and vetted with the applicable regulatory agencies such as NRC, or (2) risk evaluation guidelines need to be developed or adapted from another source and vetted with the applicable regulatory agencies.

   The U.S. Department of Energy (DOE) provides guidance for non-reactor nuclear facilities that might be considered and used in the development of risk evaluation guidelines. Rather than requiring the calculation of population dose in terms of latent cancer and facilities, the maximum radiological (or toxic) dose to the nearest member of the public and onsite worker are calculated and then judged to be acceptable or not. This kind of approach can be readily applied to risk assessment results based on determination of bounding accidents.

Technically, use of QHGs would require that the dose contribution from high-likelihood low-consequence events as well as low-likelihood high-consequence events be determined.

In any event, it is important to consider approaches to risk acceptance and engage with applicable regulators at this early phase of MNPP transportation because it takes significant time to effect any needed regulatory change. Even though a risk-informed approach may be achievable under an exemption process, it is likely that regulatory change will be needed in the future when more frequent and multiple MNPP transports will be needed.

3. MNPP Transportation PRA Methodology, Information, and Data

This section will describe the transportation PRA methodology, information, and data. Within this section the following areas will be addressed:

3.1 Definition of Risk Assessment Approach

This section will define the risk assessment approach. This approach will involve the use of a limited scope transportation PRA augmented with bounding analyses where feasible. Because the Project Pele prototype MNPP will likely meet some, but not all, of the 10 CFR Part 71 requirements, a full scope transportation PRA will likely not be required.

3.2 Characterization of the Transportation Package Inventory

The section will present the Project Pele prototype MNPP radionuclide inventory, including fuel, circulating radioactivity, and radioactivity that may be in other locations.

3.3 Identification and Definition of Transportation Package Safety Functions

This section will discuss the identification and definition of transportation package safety functions, including removal of heat, prevention of criticality while configured for transport, minimization or prevention of release, and minimization or prevention of direct radiation exposure.

3.4 Definition of Accident Scenarios

This section will define potential transportation accident scenarios, including identification of accident scenarios that could lead to a release of radioactive material, loss of shielding, or criticality.

Previous transportation PRAs have defined scenarios in terms of impact speeds and fire temperatures. An example of how truck transportation accidents involving releases radioactive material have been defined is shown in Figure 1.

Impact Speed

Impact speed exceeds 120 mph	1[a] Seal Failure: Impact (Part) 6.0×10^{-7}[(b)] (Ru) 6.0×10^{-7} (Cs) 2.4×10^{-8} (Kr) 8.0×10^{-1} (Crud) 2.0×10^{-3} Prob 1.53×10^{-8}[(c)]	11 Seal Failure: Impact (Part) 6.1×10^{-7} (Ru) 6.1×10^{-7} (Cs) 2.4×10^{-8} (Kr) 8.2×10^{-1} (Crud) 2.0×10^{-3} Prob 1.44×10^{-10}	12 Seal Failure: Impact (Part) 6.7×10^{-7} (Ru) 6.7×10^{-7} (Cs) 2.7×10^{-8} (Kr) 8.9×10^{-1} (Crud) 2.2×10^{-3} Prob 1.02×10^{-12}	13 Seal Failure: Impact (Part) 6.8×10^{-7} (Ru) 6.8×10^{-7} (Cs) 5.9×10^{-6} (Kr) 9.1×10^{-1} (Crud) 2.5×10^{-3} Prob 0	17 Shear/Puncture; Seal Failure by Fire (Part) 6.8×10^{-7} (Ru) 6.4×10^{-6} (Cs) 5.9×10^{-6} (Kr) 9.1×10^{-1} (Crud) 3.3×10^{-3} Prob 0
Impact speed from 90 to 120 mph		8 Seal Failure by Fire (Part) 6.1×10^{-7} (Ru) 6.1×10^{-7} (Cs) 2.4×10^{-8} (Kr) 8.2×10^{-1} (Crud) 2.0×10^{-3} Prob 1.13×10^{-8}	9 Seal Failure by Fire (Part) 6.7×10^{-7} (Ru) 6.7×10^{-7} (Cs) 2.7×10^{-8} (Kr) 8.9×10^{-1} (Crud) 2.2×10^{-3} Prob 8.03×10^{-11}	10 Seal Failure by Fire (Part) 6.8×10^{-7} (Ru) 6.8×10^{-7} (Cs) 5.9×10^{-6} (Kr) 9.1×10^{-1} (Crud) 2.5×10^{-3} Prob 0	16 Shear/Puncture; Seal Failure by Fire (Part) 6.8×10^{-7} (Ru) 6.4×10^{-6} (Cs) 5.9×10^{-6} (Kr) 9.1×10^{-1} (Crud) 3.3×10^{-3} Prob 0
Impact speed from 60 to 90 mph		5 Seal Failure by Fire (Part) 3.2×10^{-7} (Ru) 3.2×10^{-7} (Cs) 1.3×10^{-8} (Kr) 4.3×10^{-1} (Crud) 1.8×10^{-3} Prob 4.65×10^{-7}	6 Seal Failure by Fire (Part) 3.7×10^{-7} (Ru) 3.7×10^{-7} (Cs) 1.5×10^{-8} (Kr) 4.9×10^{-1} (Crud) 2.1×10^{-3} Prob 3.31×10^{-9}	7 Seal Failure by Fire (Part) 2.1×10^{-6} (Ru) 2.1×10^{-6} (Cs) 2.7×10^{-5} (Kr) 8.5×10^{-1} (Crud) 3.1×10^{-3} Prob 0	15 Shear/Puncture; Seal Failure by Fire (Part) 9.0×10^{-6} (Ru) 5.0×10^{-5} (Cs) 5.5×10^{-5} (Kr) 8.5×10^{-1} (Crud) 5.9×10^{-3} Prob 0
Impact speed from 30 to 60 mph		2 Seal Failure by Fire (Part) 1.0×10^{-7} (Ru) 1.0×10^{-7} (Cs) 4.1×10^{-9} (Kr) 1.4×10^{-1} (Crud) 1.4×10^{-3} Prob 5.88×10^{-5}	3 Seal Failure by Fire (Part) 1.3×10^{-7} (Ru) 1.3×10^{-7} (Cs) 5.4×10^{-9} (Kr) 1.8×10^{-1} (Crud) 1.8×10^{-3} Prob 1.81×10^{-6}	4 Seal Failure by Fire (Part) 3.8×10^{-6} (Ru) 3.8×10^{-6} (Cs) 3.6×10^{-5} (Kr) 8.4×10^{-1} (Crud) 3.2×10^{-3} Prob 7.49×10^{-8}	14 Shear/Puncture; Seal Failure by Fire (Part) 1.8×10^{-5} (Ru) 8.4×10^{-5} (Cs) 9.6×10^{-5} (Kr) 8.4×10^{-1} (Crud) 6.4×10^{-3} Prob 7.49×10^{-11}
No Impact	19 No Releases Prob 0.99993			18 Seal Failure by Fire (Part) 6.7×10^{-8} (Ru) 6.7×10^{-8} (Cs) 1.7×10^{-5} (Kr) 8.4×10^{-1} (Crud) 2.5×10^{-3} Prob 5.86×10^{-6}	
	No Fire	*End temperature: ambient to 350°C (662°F)*	*End temperature: 350°C to 750°C (662°F to 1,382°F)*	*End temperature: 750°C to 1,000°C (1,382°F to 1,832°F)*	*End temperature: 750°C to 1,000°C (1,382°F to 1,832°F)*

Cask Temperature in Fire

a. The numbers at the top of each cell refer to an accident scenario (called a case) in DIRS 152476-Sprung et al. (2000, p. 7-74).

b. (Part) is the release fraction for particulates; (Ru) is the release fraction for ruthenium; (Cs) is the release fraction for volatiles; (Kr) is the release fraction for gas; (Crud) is the release fraction for crud. The numbers next to them are the fraction that would be released in the accident.

c. The conditional probability that, if there was an accident, the particular cell would describe the accident scenario.

Figure 1. Impact Speed and Temperature Matrix for Truck Transportation Accidents Involving Spent Nuclear Fuel (DOE 2002)

3.5 Collection and Analysis of Route-Specific Data on Potential Transportation Hazards

This section will discuss the collection and analysis of route-specific data on potential transportation hazards, including frequency of hard targets, bridges and associated heights, etc.

This section will focus on the occurrence frequencies for route wayside surfaces such as “Hard Rock,” “Soft Rock,” “Rocky Soil,” etc. As discussed in Mills et al. (2006), it is envisioned that the occurrence frequencies of “Hard Rock”, “Soft Rock”, and “Rocky Soil” will be developed using the State Soil Geographic (STATSGO) database or similar database such as the Soil Survey Geographic (SSURGO) database, which is a finer resolution version of the STATSGO database. The STATSGO database divides the continental United States into a very large number of small geographic areas called Map Units. Each Map Unit has a unique identification number called a “muid” and the location of each Map Unit is specified using a digitized map of the continental United States.

Map Units are subdivided into a number of smaller areas: Each of these subcomponent areas also has a unique identification number. For each Map Unit subcomponent, the STATSGO database tabulates:

- the fractional area of the subcomponent relative to the total area of the Map Unit that contains the subcomponent
- the minimum and maximum depth to coherent, monolithic bedrock formations that must be removed by blasting (i.e., “Hard Rock”) and to bedrock that can be removed by a backhoe because it fragments relatively easily (i.e., “Soft Rock”)
- the depths of the top and bottom of any layers of “Rocky Soil” that lie above the bedrock the percentage by mass of the rocks in each “Rocky Soil” layer that have average diameters (d_{rock}) that fall within a given size range (e.g., $d_{rock} \geq 10$ inches, 10 inches $> d_{rock} \geq 3$ inches)

It is envisioned that the following definitions will be used for the identification of Map Unit subcomponents that will behave like “Hard Rock”, “Soft Rock”, “Rocky Soil”, or “Other Soils, Clay, Silt”.

- A Map Unit subcomponent would be defined to be “Hard Rock”, whenever the average depth to the bedrock that lies below the subcomponent surface was on average ≤ 2 feet and the bedrock could only be removed by blasting.
- If the Map Unit subcomponent is not defined to be “Hard Rock”, then it would be defined to be “Soft Rock”, whenever the average depth to the bedrock that lies below the subcomponent surface is on average ≤ 2 feet and the bedrock could be removed by a backhoe.
- If the Map Unit subcomponent is not “Hard Rock” or “Soft Rock”, then it would be defined to be “Rocky Soil”, whenever the mass percent of rocks in the rocky soil layers in the top 3 feet of the soil below the subcomponent surface is ≥ 25 percent, the average diameter of these rocks is ≥ 3 inches, and the sum of the thicknesses of these layers is ≥ 2 feet.

- If the Map Unit subcomponent wasn't "Hard Rock", "Soft Rock", or "Rocky Soil", then it would be defined to be "Other Soils, Clay, or Silt".

GIS methods of analysis such as ARCVIEW will be used to overlay transportation routes from Idaho National Laboratory (INL) to WSMR onto the STATSGO digitized map of the continental United States and then to determine the wayside-surface occurrence frequencies.

The assumed highway transport route for the Project Pele Prototype MNPP will be from the INL to WSMR in New Mexico. More than one route may be evaluated. It is envisioned that the highway transport route will be estimated using the WebTRAGIS computer code (Peterson 2018). Figure 2 illustrates a potential highway route from INL to WSMR generated using WebTRAGIS based on the highway route controlled quantity routing requirements in 49 CFR 397.101. Figure 3 illustrates a potential sensitivity case where the E-470 beltway is used to bypass the center of Denver, Colorado.

The assumed destination of WSMR has been made for the purposes of analysis in the transportation PRA as well as demonstration of process and can be later altered if necessary by the Project Pele vendors to reflect program refinements prior to submittal of the transportation safety analysis report and the request for exemption to the NRC.

3.6 Collection and Analysis of Transportation Accident Rate Data for Large Trucks

This section will discuss transportation accident rate data for large trucks. Ideally this data would be specific to trucks with a gross vehicle weight of about 150,000 lbs. In developing this data, it will be assumed that the MNPP shipment will be of sufficient weight that it will be subject to heavy haul permitting in each state through which it passes, and may be subject to superload permitting in some states. Specific permitting requirements vary by state. Table 1 lists the State superload width, height, length, and weight requirements for the 50 States and District of Columbia.

As discussed in Mills et al. (2006), three primary highway accident databases maintained by the U.S. Department of Transportation (DOT) will be considered for development of the heavy-haul truck accident statistics:

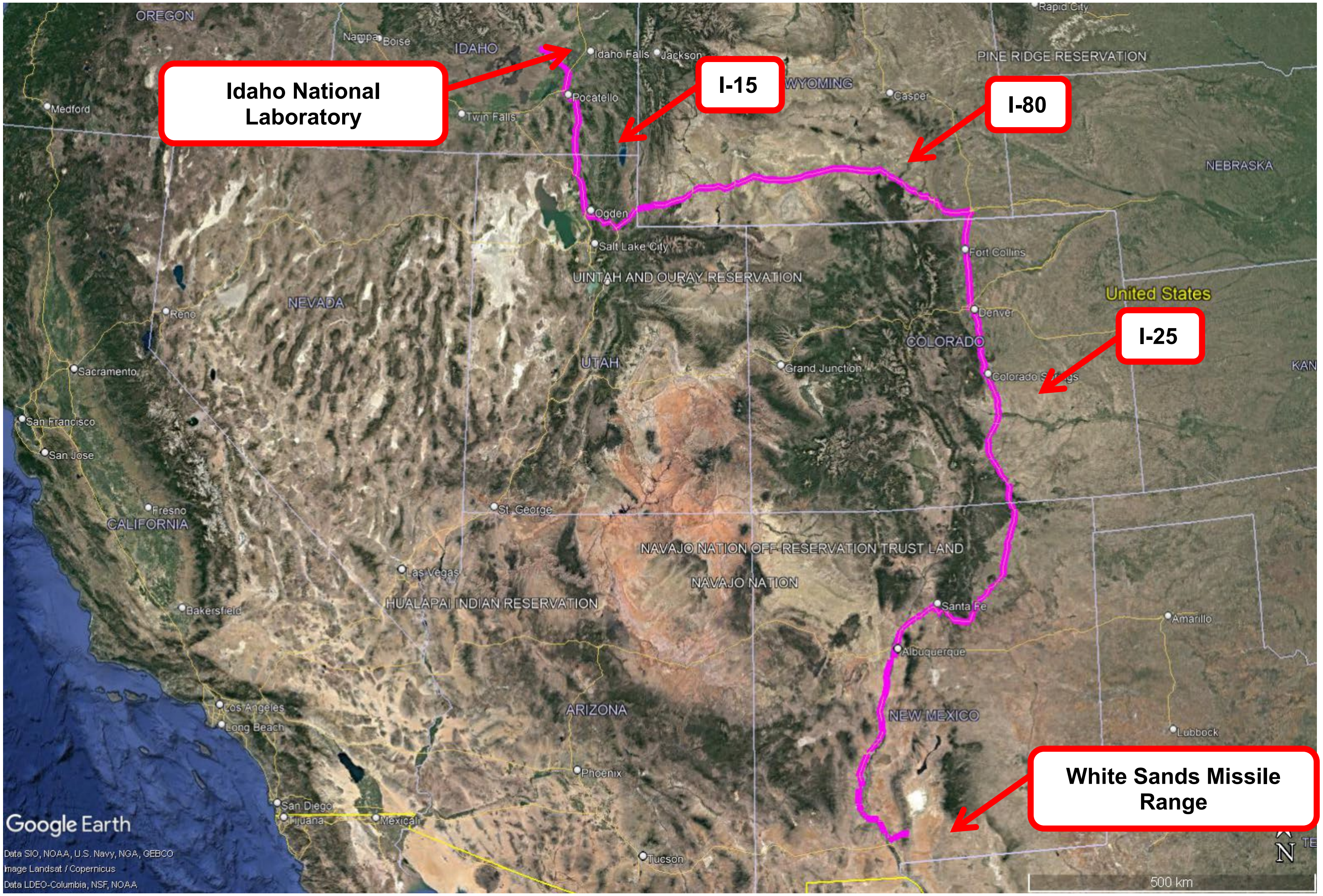

Figure 2. Potential Highway Route Controlled Quantity Route from Idaho National Laboratory to White Sands Missile Range

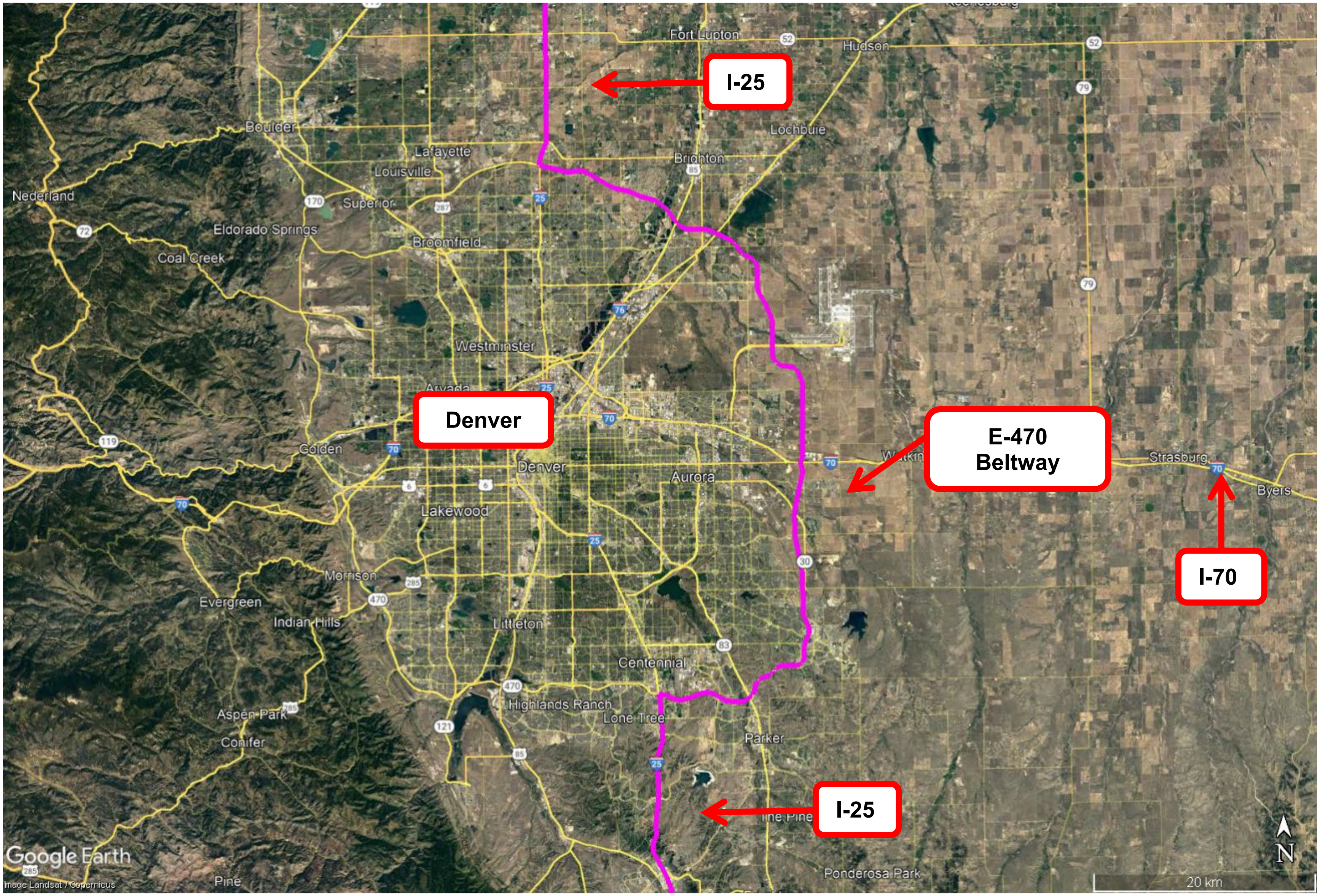

Figure 3. Potential Highway Routing Sensitivity Case to Bypass Denver, Colorado

Table 1. State Superload Width, Height, Length, and Weight Requirements for the 50 States and District of Columbia

State	Superload Width Requirement	Superload Height Requirement	Superload Length Requirement	Superload Weight Requirement (lb.)
Alabama	16 feet 0 inches	16 feet 0 inches	150 feet 0 inches	250,000
Alaska	18 feet 0 inches	18 feet 0 inches	150 feet 0 inches	250,000
Arizona	14 feet 0 inches	16 feet 0 inches	120 feet 0 inches	250,000
Arkansas	18 feet 0 inches	17 feet 0 inches	100 feet 0 inches	180,000
California	15 feet 0 inches	17 feet 0 inches	135 feet 0 inches	None specified
Colorado	17 feet 0 inches	16 feet 0 inches	130 feet 0 inches	500,000
Connecticut	16 feet 0 inches	15 feet 4 inches	150 feet 0 inches	200,000
Delaware	15 feet 0 inches	15 feet 0 inches	120 feet 0 inches	120,000
District of Columbia	Varies	Varies	Varies	Varies
Florida	16 feet 0 inches	16 feet 0 inches	150 feet 0 inches	199,000
Georgia	16 feet 0 inches	18 feet 0 inches	None specified	150,000
Hawaii	None specified	None specified	None specified	None specified
Idaho	16 feet 0 inches	16 feet 0 inches	120 feet 0 inches	Varies
Illinois	14 feet 6 inches	14 feet 6 inches	145 feet 0 inches	120,000
Indiana	16 feet 0 inches	15 feet 0 inches	110 feet 0 inches	120,000
Iowa	18 feet 0 inches	18 feet 0 inches	120 feet 0 inches	156,000
Kansas	None specified	None specified	None specified	150,000
Kentucky	16 feet 0 inches	15 feet 6 inches	125 feet 0 inches	250,000
Louisiana	Varies	Varies	Varies	232,000
Maine	16 feet 0 inches	16 feet 0 inches	125 feet 0 inches	130,000
Maryland	16 feet 0 inches	16 feet 0 inches	100 feet 0 inches	120,000
Massachusetts	14 feet 0 inches	Varies	120 feet 0 inches	130,000
Michigan	16 feet 0 inches	15 feet 0 inches	150 feet 0 inches	None specified
Minnesota	16 feet 0 inches	15 feet 6 inches	150 feet 0 inches	155,000
Mississippi	20 feet 0 inches	17 feet 0 inches	120 feet 0 inches	190,000
Missouri	16 feet 0 inches	16 feet 0 inches	150 feet 0 inches	160,000
Montana	18 feet 0 inches	17 feet 0 inches	150 feet 0 inches	None specified
Nebraska	16 feet 0 inches	16 feet 0 inches	100 feet 0 inches	160,000
Nevada	17 feet 0 inches	18 feet 0 inches	200 feet 0 inches	500,000
New Hampshire	15 feet 0 inches	13 feet 6 inches	110 feet 0 inches	149,999

State	Superload Width Requirement	Superload Height Requirement	Superload Length Requirement	Superload Weight Requirement (lb.)
New Jersey	None specified	None specified	None specified	None specified
New Mexico	None specified	None specified	None specified	None specified
New York	16 feet 0 inches	16 feet 0 inches	160 feet 0 inches	199,999
North Carolina	15 feet 0 inches	None specified	None specified	132,000
North Dakota	18 feet 0 inches	18 feet 0 inches	120 feet 0 inches	150,000
Ohio	14 feet 0 inches	14 feet 6 inches	None specified	120,000
Oklahoma	16 feet 0 inches	15 feet 0 inches	110 feet 0 inches	202,000
Oregon	16 feet 0 inches	17 feet 0 inches	150 feet 0 inches	None specified
Pennsylvania	16 feet 0 inches	None specified	160 feet 0 inches	201,000
Rhode Island	14 feet 0 inches	13 feet 6 inches	90 feet 0 inches	120,000
South Carolina	16 feet 0 inches	16 feet 0 inches	None specified	130,000
South Dakota	None specified	None specified	None specified	None specified
Tennessee	16 feet 0 inches	15 feet 0 inches	120 feet 0 inches	100,000
Texas	None specified	None specified	None specified	254,300
Utah	17 feet 0 inches	17 feet 6 inches	175 feet 0 inches	125,000
Vermont	15 feet 0 inches	14 feet 0 inches	100 feet 0 inches	150,000
Virginia	15 feet 0 inches	15 feet 0 inches	150 feet 0 inches	115,000
Washington	16 feet 0 inches	16 feet 0 inches	125 feet 0 inches	200,000
West Virginia	16 feet 0 inches	None specified	None specified	120,000
Wisconsin	16 feet 0 inches	None specified	160 feet 0 inches	100,000
Wyoming	18 feet 0 inches	17 feet 0 inches	120 feet 0 inches	160,000

Source: U.S. Government Accountability Office (GAO) (2015)

- Fatality Analysis Reporting System (FARS), maintained by the National Highway Traffic Safety Administration (NHTSA)
- General Estimates System (GES) databases, maintained by NHTSA
- Motor Carrier Management Information System (MCMIS) crash file, that is compiled by the Federal Motor Carrier Safety Administration

In addition, the NHTSA Crash Report Sampling System (CRSS) will also be considered for development of the heavy-haul truck accident statistics. CRSS was developed in 2016 and was not available for use by Mills et al. (2006).

The MCMIS crash file is often used to support truck safety analysis because it contains only truck accident data and allows accidents to be sorted by truck type (e.g., tractor/trailers) and by accident consequences (e.g., injuries, fatalities, property damage above a reporting threshold). For accidents resulting in a fatality, the FARS database, which is constructed by state analysts, provides more detail about vehicle configuration and significantly more information about crash circumstances and consequences than the MCMIS crash file.

The data in the GES database is extracted from a representative national sample of accidents selected from all of the accidents described in police accident reports (PARs). The selected PARs all describe accidents involving at least one vehicle traveling on a traffic-way that lead to injury, death, or property damage above a reporting threshold.

Other DOT traffic safety statistics tabulations, crash profiles and reports such as Large Truck and Bus Crash Facts (DOT 2021) will also be reviewed for use in the transportation PRA.

3.7 Identification of Potential Compensatory Measures

This section will discuss potential compensatory measures that could be credited in the MNPP transportation PRA or as a defense-in-depth measure. As with the transportation accident rate data, it will be assumed that the MNPP shipment will be of sufficient weight that it will be subject to heavy haul permitting in each state through which it passes, and may be subject to superload permitting in some states. Specific permitting requirements vary by state and in some cases may require specific measures that could be considered compensatory measures.

A list of possible compensatory measures is provided below; this list will be modified based on the results of the transportation PRA.

- Escort the reactor forward and aft for the entire route. Army to provide escorts.
- Choose a route that avoids bodies of water.
  - This will need to be balanced by the need to use the best quality of road, i.e., interstate highways.
- For bridges over bodies of water:
  - Conduct additional inspections as necessary of the bridges prior to shipping to verify condition.
  - Close bridge to other traffic while the reactor is on the bridge.
  - Reduce speed while crossing the bridge (e.g., 5 mph)
  - Schedule shipment to avoid high winds while on the bridge.
  - For bridges over navigable waterways, close waterway to traffic while reactor is on the bridge.
- Choose a route and schedule the shipment to avoid the potential for flash flooding.
- Ship at night to avoid other traffic.
- Avoid shipping during known times of high traffic volume.
- Conduct training for emergency responders along the route.

3.8 Development of a Transportation Accident Event Tree

This section will discuss the development of a truck transport accident event tree. These event trees include accidents involving collisions and accidents that do not involve collisions. Collision accidents include accidents with non-fixed object (trains, trucks, other vehicles, etc.) and fixed objects (bridges, buildings, walls, etc.). Non-collision accidents include fires and explosions, jackknifes, rollovers, etc. Event trees are typically constructed using transportation accident data and geographic information system (GIS) data. As such, event trees can be modified to include additional branches or exclude branches that are not applicable or of no interest.

The event trees developed for the MNPP transportation PRA will likely be similar to the event trees from Mills et al. (2006) which were developed for spent nuclear fuel and radioactive material transportation casks, shown in Figures 4 and 5. Using these as an example, these figures present event trees for truck accidents in the U.S. and for truck accidents specifically on interstate highways. However, the Mills event trees were not developed for transportation of a MNPP, so it is conceivable that new accident scenarios are possible particularly in consideration of any safety functions beyond containment, shielding, or criticality such as reactor cooling. In such a case, events trees would be adjusted accordingly.

The event tree portrayed in Figure 4 first divides truck accident initiating events into two groups:

- Fires, mechanical failures, accidents where the truck overturns, or jackknife accidents where the truck leaves the road and then runs into or hits something.
- Collisions where the truck runs into another vehicle or impacts an on-road structure.

So that an appropriate accident speed distribution can be selected to use in the estimation of truck accident risks, the event tree in Figure 4 indicates whether the accident occurred: (1) at a highway/railway grade crossing, (2) on level ground (i.e., not on a steep grade), (3) involved in a fall from a bridge, or (4) a plunge down an embankment. The event tree in Figure 4 specifies the type of object or surface that the truck runs into or hits but does not indicate whether this impact initiates fire.

The event tree in Figure 5 from Mills et al. (2006) restructures collisions with non-fixed objects from six branches into four branches:

- Trains (the only non-fixed object large enough to threaten the containment integrity of a transportation cask during a collision).
- Gasoline tank-trucks (not important for collisions but important for fire scenarios initiated by a collision).
- Other vehicles (motorcycles, cars, other trucks).
- Other small non-fixed objects (e.g., traffic cones, animals, pedestrians).

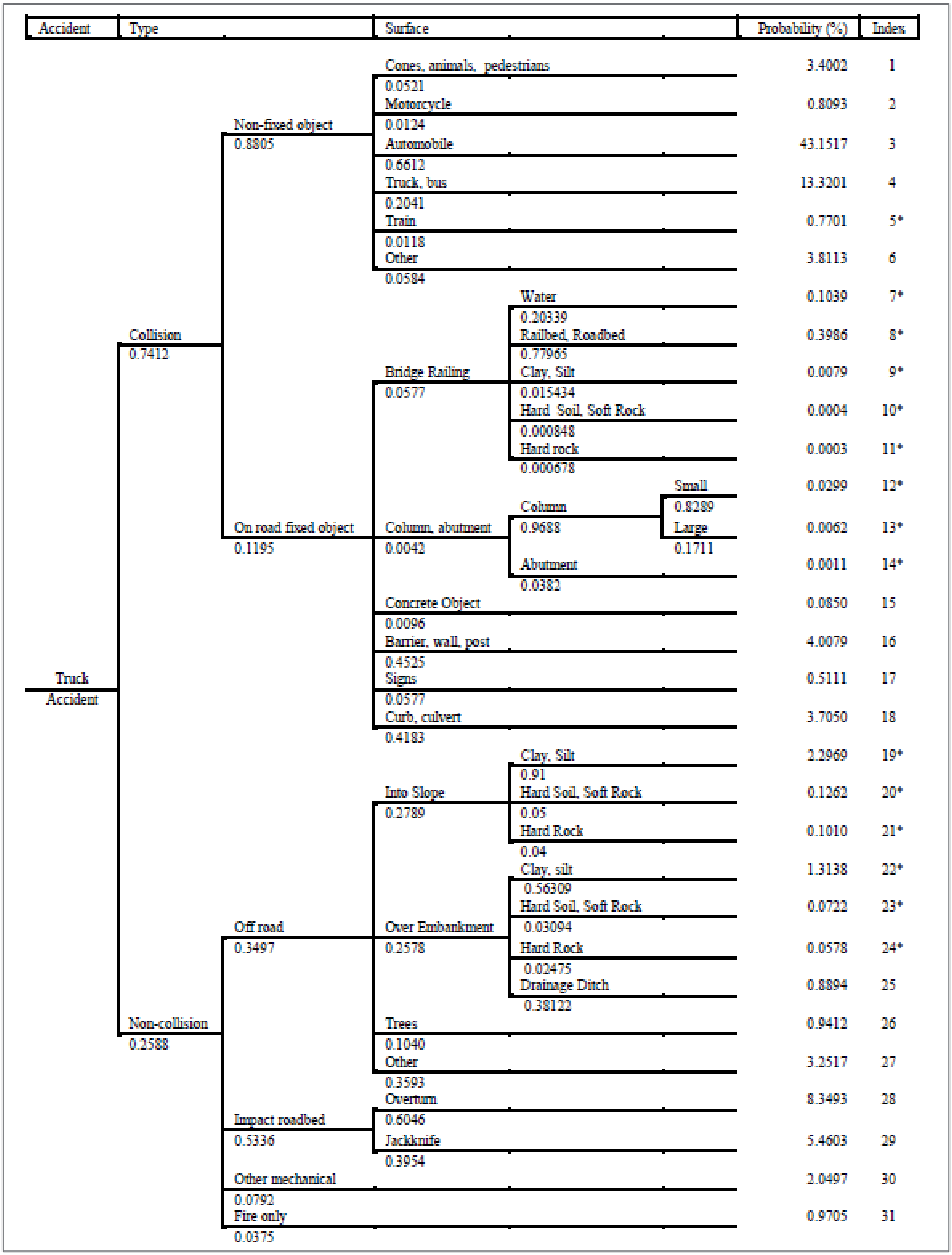

Figure 4. Truck Transport Accident Event Tree (Mills et al. 2006)

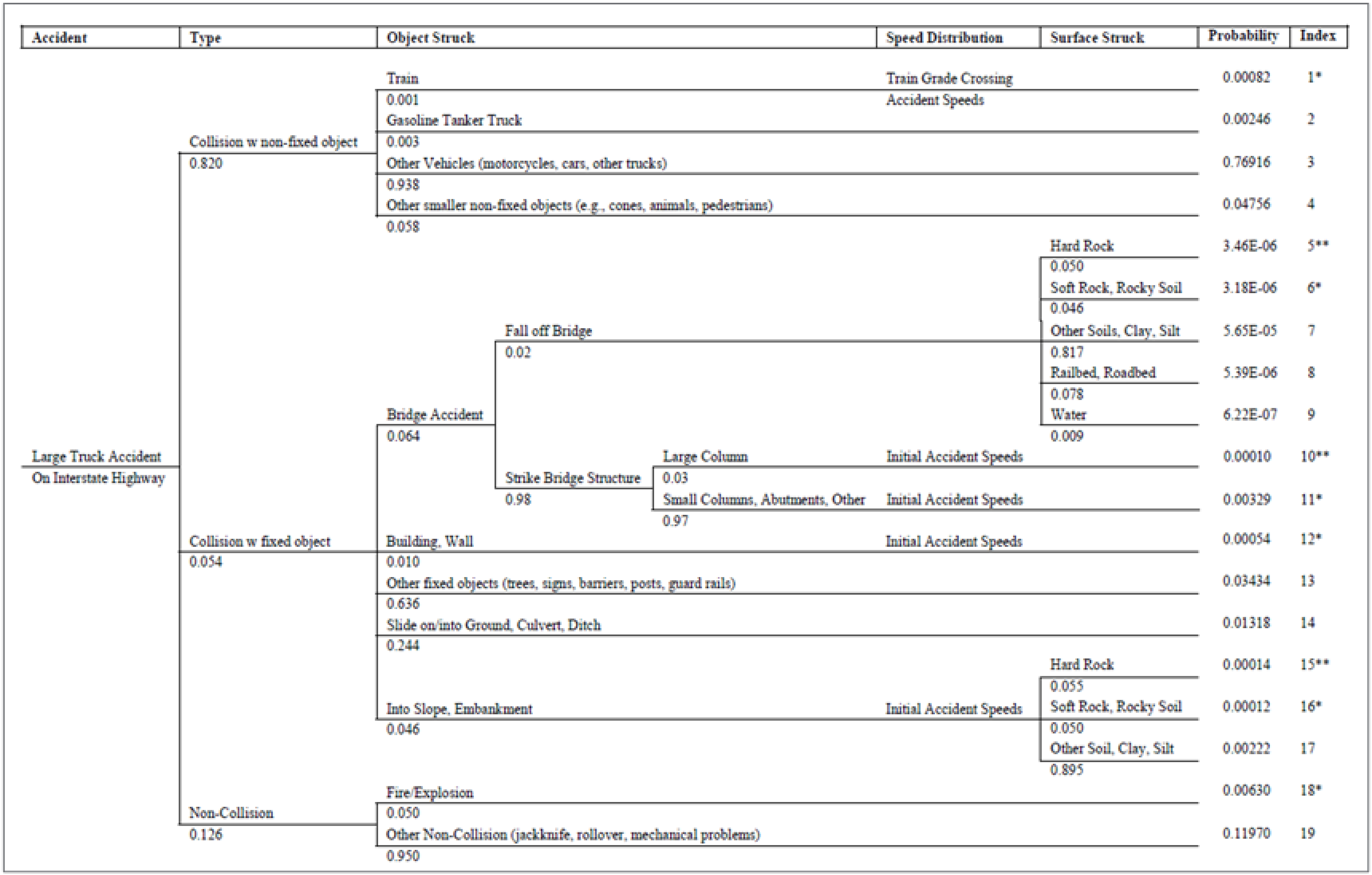

Figure 5. Interstate Highway Truck Accident Event Tree (Mills et al. 2006)

In Figure 5, collisions with fixed objects now appear as sub-branches of a single branch, “Collision with a fixed object.” The sub-branches of the “Collision with a fixed object” branch of the event tree in Figure 4 (paths 7 through 18 in Figure 4) have been restructured. The bridge railing and column and abutment branches are now treated as possible outcomes of bridge accidents, which are now divided into accidents that lead to falls from the bridge and accidents that lead to collisions with bridge components (columns, abutments), but not a fall from the bridge. Structures less massive than columns and abutments (e.g., buildings, walls) have been combined into a single path (path 12 in Figure 5), and all collisions with small, fixed objects (trees, signs, barriers, posts, guard rails) have been combined into a single path (path 13 in Figure 5).

In Figure 5, accidents in which the truck slides along the ground, perhaps into a culvert or a ditch, have been combined into a single path (path 14 in Figure 5). All non-collision paths that do not involve fires (e.g., mechanical problems, truck jackknifes or overturns) have been combined into a single pathway (path 19 in Figure 5).

The “Over Embankment” branch in Figure 4 (paths 22 through 25 in Figure 4) has been eliminated because the cask impact speed for these accidents should be bounded by the initial speed of the accident. The initial accident speed should bound the sliding speed because sliding friction should cause the transportation cask (or the truck that is carrying the cask) to slow down, rather than accelerate as it slides along the ground or down a slope. Therefore, since there is no good way to estimate the actual sliding speed of a truck or a cask, elimination of this event tree branch causes this set of accidents to be apportioned into branches 14 through 17 in Figure 5. For these branches in Figure 5, use of the initial accident speed to characterize the severity of the cask impact leads to an overestimate of cask damage.

Velocity distributions corresponding to event tree branches would also be required. Figure 6 and Figure 7 contain velocity distributions for hard rock from NUREG/CR-6672 (Sprung et al. 2000). In Figure 6 and Figure 7, velocity distributions V1 through V4 correspond to the velocity distributions for level ground, bridges, slopes, and highway-rail crossings, respectively.

Surface	Hard Rock		
Orientation	End	Corner	Side
P(orientation)	0.056	0.722	0.222

Velocity Distribution V1, Scenarios 12-14,19-21						
End	v	vL	vH	PL	PH	P
v30	30	0	30	0	0.74353	7.435300E-01
v60	60	58	62	0.97634	0.98383	9.800850E-01
v90	90	0	90	0	0.99956	9.995600E-01
v120=vseal	120	110	150	0.99999	1.0	9.999925E-01
Corner	v	vL	vH	PL	PH	P
v30	30	0	30	0	0.74353	7.435300E-01
v60	60	58	62	0.97634	0.98383	9.800850E-01
v90	90	0	90	0	0.99956	9.995600E-01
v120=vseal	120	110	150	0.99999	1.0	9.999925E-01
Side	v	vL	vH	PL	PH	P
v30	30	0	30	0	0.74353	7.435300E-01
v60	60	58	62	0.97634	0.98383	9.800850E-01
v90	90	0	90	0	0.99956	9.995600E-01
v120=vseal	120	110	150	0.99999	1.0	9.999925E-01
	End	Corner	Side	Wt Sum		
P(v60)-P(v30)	2.3656E-01	2.3656E-01	2.3656E-01	2.3656E-01		
P(v90)-P(v60)	1.9475E-02	1.9475E-02	1.9475E-02	1.9475E-02		
P(vseal)-P(v90)	4.3250E-04	4.3250E-04	4.3250E-04	4.3250E-04		
1.0-P(vseal)	7.5000E-06	7.5000E-06	7.5000E-06	7.5000E-06		

Velocity Distribution V2, Scenarios 7-11						
End	v	vL	vH	PL	PH	P
v30	30	28.95	30.95	0.6124	0.7464	6.827500E-01
v60	60	0	60	0	1	1.000000E+00
v90	90	0	90	0	1	1.000000E+00
v120=vseal	120	0	120	0	1	1.000000E+00
Corner	v	vL	vH	PL	PH	P
v30	30	28.95	30.95	0.6124	0.7464	6.827500E-01
v60	60	0	60	0	1	1.000000E+00
v90	90	0	90	0	1	1.000000E+00
v120=vseal	120	0	120	0	1	1.000000E+00
Side	v	vL	vH	PL	PH	P
v30	30	28.95	30.95	0.6124	0.7464	6.827500E-01
v60	60	0	60	0	1	1.000000E+00
v90	90	0	90	0	1	1.000000E+00
v120=vseal	120	0	120	0	1	1.000000E+00
	End	Corner	Side	Wt Sum		
P(v60)-P(v30)	3.1725E-01	3.1725E-01	3.1725E-01	3.1725E-01		
P(v90)-P(v60)	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00		
P(vseal)-P(v90)	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00		
1.0-P(vseal)	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00		

Figure 6. Example Velocity Distributions V1 and V2 for Hard Rock (Mills et al. 2006)

Velocity Distribution V3, Scenarios 22-24						
End	v	vL	vH	PL	PH	P
v30	30	0	30	0	0.28292	2.829200E-01
v60	60	0	60	0	0.96178	9.617800E-01
v90	90	0	90	0	0.99901	9.990100E-01
v120=vseal	120	115	150	0.99999	1.0	9.999914E-01
Corner	v	vL	vH	PL	PH	P
v30	30	0	30	0	0.28292	2.829200E-01
v60	60	0	60	0	0.96178	9.617800E-01
v90	90	0	90	0	0.99901	9.990100E-01
v120=vseal	120	115	150	0.99999	1.0	9.999914E-01
Side	v	vL	vH	PL	PH	P
v30	30	0	30	0	0.28292	2.829200E-01
v60	60	0	60	0	0.96178	9.617800E-01
v90	90	0	90	0	0.99901	9.990100E-01
v120=vseal	120	115	150	0.99999	1.0	9.999914E-01

	End	Corner	Side	Wt Sum
P(v60)-P(v30)	6.7886E-01	6.7886E-01	6.7886E-01	6.7886E-01
P(v90)-P(v60)	3.7230E-02	3.7230E-02	3.7230E-02	3.7230E-02
P(vseal)-P(v90)	9.8143E-04	9.8143E-04	9.8143E-04	9.8143E-04
1.0-P(vseal)	8.5714E-06	8.5714E-06	8.5714E-06	8.5714E-06

Velocity Distribution V4, Scenario 5						
End	v	vL	vH	PL	PH	P
v30	30	0	30	0	0.7421	7.421000E-01
v60	60	58	62	0.97125	0.9806	9.759250E-01
v90	90	0	90	0	0.9993	9.993000E-01
v120=vseal	120	118	150	0.99999	1.0	9.999906E-01
Corner	v	vL	vH	PL	PH	P
v30	30	0	30	0	0.7421	7.421000E-01
v60	60	58	62	0.97125	0.9806	9.759250E-01
v90	90	0	90	0	0.9993	9.993000E-01
v120=vseal	120	118	150	0.99999	1.0	9.999906E-01
Side	v	vL	vH	PL	PH	P
v30	30	0	30	0	0.7421	7.421000E-01
v60	60	58	62	0.97125	0.9806	9.759250E-01
v90	90	0	90	0	0.9993	9.993000E-01
v120=vseal	120	118	150	0.99999	1.0	9.999906E-01

	End	Corner	Side	Wt Sum
P(v60)-P(v30)	2.3383E-01	2.3383E-01	2.3383E-01	2.3383E-01
P(v90)-P(v60)	2.3375E-02	2.3375E-02	2.3375E-02	2.3375E-02
P(vseal)-P(v90)	6.9063E-04	6.9063E-04	6.9063E-04	6.9063E-04
1.0-P(vseal)	9.3750E-06	9.3750E-06	9.3750E-06	9.3750E-06

Figure 7. Example Velocity Distributions V3 and V4 for Hard Rock (Mills et al. 2006)

3.9 Development of Branch Probabilities

This section will discuss the development of probabilities for the branches of the transportation accident event tree. As discussed in Mills et al. (2006), the probability of a particular accident scenario is the product of all of the branch point fractions that lie on the scenario path. An example of this would be the following for a given accident:

The probability of a collision with a fixed object = 0.054
The probability the collision is into a slope or embankment = 0.046
The probability the slope or embankment is hard rock (assume initial accident speed) = 0.055

$P_{accident} = 0.054 \times 0.046 \times 0.055 = 0.000137$

where:

$P_{accident}$ = the probability of a particular accident scenario

Thus, before a particular accident scenario probability can be calculated, the branch point fractions must be determined. Since all of the fractions that comprise a single set of branches must sum to one, fraction values need only to be calculated for all but one of these branches. An example of branch point probability summing would be the following for the branch column titled “Type”:

The probability of a collision with a non-fixed object = 0.820
The probability of a collision with a fixed object = 0.054
The probability of a non-collision = 0.126

$P_{total} = 0.820 + 0.054 + 0.126 = 1.000$

where:

P_{total} = the sum of the branch point fractions

It is envisioned that the branch point fractions would be calculated using the methods discussed in Section 6 of Mills et al. (2006). Again, however, as stated in the section above, previously created transportation event trees were not developed for transportation of a MNPP, so it is conceivable that new accident scenarios are possible. In such a case, events tree branch point probabilities that are used to determine the likelihood of accident scenarios would need to be developed.

3.10 Transportation Accident Consequence Analysis

This section will discuss transportation accident consequences, including definition of source terms (e.g., leak path factors or attenuation factors, damage probabilities, release fractions). In this section bounding analyses will be performed. Additionally, bounding engineering analyses will likely need to be performed to inform the consequence analysis (e.g., for thermal and impact cases).

Consequence analysis will be based on determining the source term for the release, the mobility of that source term (i.e., particle size and behavior), and the corresponding risk/dose to a human receptor. It is envisioned that source terms will be estimated using the following five-component linear equation (DOE 1994):

Source Term = MAR x DR x ARF x RF x LPF

where:

MAR = Material at risk
DR = Damage ratio
ARF = Airborne release fraction
RF = Respirable fraction
LPF = Leak path factor

The five-component equation, while traditionally developed for non-reactor nuclear facilities, can be applied to an MNPP transportation accident analysis. The source term analysis will require information such as leak path factor or attenuation factors, damage probabilities, and release fractions for tristructural isotropic (TRISO) particles, compacts, or the MNPP depending on the transportation accident scenario for bounding consequence analyses. The consequence analysis will require understanding of the dose consequences that span scenarios with releases of radionuclides, ruptured TRISO particles, unruptured TRISO particle releases, or full containment within the reactor vessel.

For releases of radionuclides originating from ruptured TRISO fuel particles, it is envisioned that the consequence analysis would be based on traditional methodologies for estimating dispersion and dose calculations for radionuclides utilizing information such Federal Guidance Report (FGR) 13 (EPA 1999) and FGR 15 (EPA 2019). For transportation accident scenarios that have full containment of radionuclides within the reactor vessel, it is envisioned that the dose consequence analysis would be limited to an external dose evaluation for the reactor vessel.

For release scenarios for unruptured TRISO fuel particles, it is envisioned that the consequence analysis would be based on the environmental transport and internal dose evaluation in Condon et al. (2020) and Condon et al. (2021) because traditional accident analysis dispersion, internal exposure pathways, and dose coefficients would not apply. Unruptured TRISO particles size dictates their interaction with the environment and human receptors preventing the use of traditional methodologies based on radionuclide movement within the environment and the body.

For accident scenarios that include release of ruptured TRISO particles it is envisioned that a combination of the previous two approaches must be applied to estimate bounding dose consequences. However, the airborne release and respirable fractions that should be used in the consequence analysis for ruptured TRISO fuel involved in high energy events such as impact and/or high temperature events are uncertain based on current research. Bases need to be established for the release fractions and respirable fractions that are used in a bounding analysis to provide defensible insights from the risk estimates. Likewise, there will also be a level of uncertainty associated with the estimated damage ratios and leak path factors needed to estimate the radiological dose to the public. These factors are contingent on the response of the engineered containment and shielding to high energy events such as violent impacts and high temperature events. Therefore, bases need to be established for estimated damage ratio and leak path factors used in bounding analysis.

4. Discussions of Modeling Uncertainties

This section will discuss modeling uncertainties, including key assumptions and sources of uncertainty. Sensitivity analyses may also be performed to address these uncertainties. One of the advantages of a risk-informed approach is that it provides a means of testing the sensitivity of the results relative to key assumptions, thereby further enhancing decisionmaking. Therefore, uncertainty and sensitivity analyses should be performed in conjunction with a baseline risk assessment to gain confidence in, and understanding of, the results. In addition to uncertainty analysis and sensitivity analysis, analysis can also play an important role in enhancing the risk information being used for decisionmaking.

5. Defense-in-Depth and Safety Margin Considerations

NRC regulations for nuclear power plants require that important risk informed decisions based on comparison of bounding risk estimates to risk acceptance guidelines to also be supported by a philosophy of defense in depth and safety margin. The same should be expected for transportation of microreactors. This section will define the defense-in-depth philosophy and will include discussion of safety features/controls that are credited and not credited in the risk assessment. The section will also discuss safety margins to the extent design information is available). This is typically done by demonstrating that sufficient conservatism is preserved in the design parameters, such that reliability and effectiveness are reasonably ensured against the most demanding challenge. For the risk assessment, it also applies to ensuring that there is a sufficient safety margin to account for modeling and data uncertainties.

6. Technical Adequacy of the Transportation Risk Assessment

This section will discuss the technical adequacy of the transportation risk assessment, including definition of the independent peer review process and results, and identification of applicable national standards. The regulating authorities need to have confidence that the information developed from a risk assessment is sound and reliable. Accordingly, the technical content needs to be complete, correct, and accurate, and produce insights with appropriate fidelity to support any decision contemplated.

7. Conclusions

This section will discuss the conclusions from the MNPP transportation risk assessment, including comparison of risk assessment results to risk evaluation guidelines and identification of additional research, analysis needs, and supporting testing to be performed or finalized during Project Pele Phase 2.

8. Appendices

This section will contain any appendices that are required.

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