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Plan for the Development and Application of a Risk Assessment Approach for Transportation Package Approval of a Transportable Nuclear Power Plant for Maritime Shipment

January 2024

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U.S. DEPARTMENT OF ENERGY

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Richland, Washington 99354

Executive Summary

This plan proposes a strategy for licensing a transportable nuclear power plant, containing its unirradiated and irradiated fuel, as a transportation package for maritime transport using a probabilistic risk assessment framework in order to meet the regulatory requirements of 10 CFR Part 71. It is anticipated that initially, the deterministic transportation package licensing approach will be challenging due to the functional requirements of the transportable nuclear power plant. As such, a partial exemption request from the U.S. Nuclear Regulatory Commission coupled with applied compensatory measures are anticipated in support of providing equivalent safety to the public, worker, and environment. A plan is outlined as to how this would be demonstrated and a pathway is primarily outlined using the accompanying low accident rates which in turn support very low probabilities of release for a maritime application. Wherever possible, the proposed plan is supported by actual accident (casualty) data. Additional supporting information regarding a highway transportation probabilistic risk assessment in support of the Project Pele demonstration reactor that is currently under development is also referenced and discussed.

This report is intended to be used as a living document, whereby new transport modes and supporting information can be inserted to update and refine the developing risk assessment. To date, several sources of data were used to demonstrate that over the road (highway) and maritime shipment of a transportable nuclear power plant is safe. To that end, an additional source of data (S&P Global) has been found and employed since the initial release of this report in September of 2023. This information further compliments this assessment. This current data supports what has been provided by Nuclear Transport Solutions, the basis of the maritime plan.

Acknowledgments

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Acronyms and Abbreviations

ARF	airborne release fraction
BWXT	BWX Technologies
CDF	Core Damage Frequency
CFR	*Code of Federal Regulations*
CONEX	an intermodal container for shipping and storage
CSI	Criticality Safety Index
DOE	U.S. Department of Energy
DR	damage ratio
DWT	dry weight tonnage
EPA	U.S. Environmental Protection Agency
FGR	Federal Guidance Report
GWT	gross weight tonnage
HEU	highly enriched uranium
IAEA	International Atomic Energy Agency
INF X	Class X INF vessel where X = 1, 2, 3
LERF	Large Early Release Fraction
LLIS	Lloyd's List Intelligence Service
LMIS	Lloyd's Maritime Information Service
LPF	leak path factor
LPG	liquefied petroleum gas
LNG	liquefied natural gas
MAR	material at risk
NNSA	National Nuclear Security Administration
NRC	U.S. Nuclear Regulatory Commission
NTS	Nuclear Transport Solutions
PNNL	Pacific Northwest National Laboratory
PNTL	Pacific Nuclear Transport Limited
PRA	probabilistic risk assessment
QHG	quantitative health guidelines
RAM	radioactive material
RF	respirable fraction
RG	regulatory guide
SAR	safety analysis report
SNF	spent nuclear fuel
TNPP	transportable nuclear power plant
TRISO	Tri-structural Isotropic (particle)

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1.0 Introduction

Shipments of commercial spent nuclear fuel (SNF) in the United States use transportation packages that have been certified by the U.S. Nuclear Regulatory Commission (NRC). Transportation packages must meet the regulations cited in the Title 10 of the Code of Federal Regulations (10 CFR) Part 71 which are deterministic in nature. Licensing a transportable nuclear power plant (TNPP) containing its unirradiated or irradiated fuel inventory and prepared for transport is expected to be more challenging than licensing a typical radioactive material (RAM) transportation package. This is due to a TNPP having different functional requirements than a transportation package which is primarily a thick-walled cylindrical pressure vessel made of steel. In an effort to define a pathway to obtain transportation package approval for a TNPP, a 10 CFR Part 71.12 exemption request based on a probabilistic risk assessment (PRA) framework is proposed here. The TNPP is assumed to be TRi-structural ISOtropic (TRISO) fueled and anticipated to have a thermal heat load of around 20 MW thermal or less, making it possible to be transported as cargo for this plan. The TNPP is also assumed to be factory preloaded with fresh fuel before deployment. Operation of the TNPP is assumed to transform any fresh fuel it once carried to one that now carries SNF (shifting the requirement from a Type AF package to that of a Type BF package). Additionally, no refueling of the TNPP is expected in the field.

For nuclear reactors, 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]). The PRA has also been used to assess a dry cask storage system at a nuclear power plant (see NUREG-1864 [NRC 2007]). The PRA techniques have also been applied to the transportation of SNF, 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 (IAEA 2003).

A 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). A maritime PRA was developed in report SAND98-1171 (SAND98-1171 1998).

The purpose of this plan is to provide the outline of a basis for the development and application of a PRA methodology for maritime transport of a TRISO fueled TNPP, containing its unirradiated or irradiated fuel inventory, and is configured like a RAM transportation package and considered for transport as possible cargo for shipment (CONEX as opposed to platform, floating, or assembled and fueled at site application).[1] Licensing of this type of package would initially require a risk-informed transportation licensing pathway for regulatory approval. The maritime transportation PRA methodology is based on the transportation PRA methodology for highway transport presented in Maheras et al. (2021) and more fully developed in Coles et al (2022).

This plan for the development and application of a risk assessment approach for transportation package approval of a TNPP could be provided to vendors like BWX Technologies (BWXT), X-energy, and Westinghouse as well as others who are currently interested in the licensing of their TNPP products for maritime transport. The expectation is that the maritime transportation PRA

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[1] This report does not address licensing of a TNPP being used to provide propulsion.

methodology, technical information, data, and possible analysis approaches will be used to support initial licensing initiatives through a request for a 10 CFR 71.12 exemption that will be submitted by a vendor to the NRC for approval. Additionally, as this information becomes more refined and developed, it will also be provided to the NRC for review, contribution, and endorsement of the process at the same time as it is provided to TNPP vendors. However, vendors will bear the ultimate responsibility for developing the substantiated safety basis, the submittal of the transportation safety analysis report (SAR) and the request for exemption to the NRC. The work presented here is expected to be applicable both domestically and internationally. The above plan can be tailored to any vendor and has been fully fleshed out to the maximum extent possible given that TNPP designs are still in their infancy.

As mentioned previously, the maritime transportation PRA methodology is based on the transportation PRA methodology developed for highway transport. The highway transportation methodology was first proposed in Maheras et al. (2021) and more fully developed in Coles et al. (2022) for the Project Pele demonstration reactor. Specific areas addressed in Coles et al. (2022) include:

- Definition of regulatory approach.
- Definition of safety goals and risk evaluation guidelines.
- TNPP transportation PRA methodology, data, and results.
- Defense-in-depth and safety margin concerns.
- Technical adequacy of the transportation risk assessment.

For many of these areas, a highway transportation PRA and a maritime transportation PRA would be very similar. In other areas, especially those that deal with accident scenarios, routes, event trees, and accident data, a highway transportation PRA and a maritime transportation PRA would be significantly different. It is in these areas that this plan concentrates.

The structure of this plan is based on the transportation PRA methodology, technical information, data, and example analyses that could be provided to vendors. The reader of this report should note that this plan is meant to be adaptive and will need to be updated, revised, and refined based on vendor input, TNPP design criteria, regulatory recommendations, and client direction as practicable.

2.0 Content of the Transportation Probabilistic Risk Assessment Methodology, Information, and Data

The TNPP maritime transportation PRA methodology, technical information, data, are organized into several sections covering the regulatory approach, safety goals and risk evaluation guidelines, and TNPP probabilistic risk assessment methodology, information, and data.

2.1 Definition of Regulatory Approach

The definition of a regulatory approach for a highway transportation PRA and a maritime transportation PRA would be very similar and is discussed in Coles et al. (2022). Based on the amount of vendor design information available from the TNPP, evaluation of which 10 CFR Part 71 requirements would require an exemption may be qualitative or semi-quantitative. This will also be true for any TNPP with respect to the maritime effort. However, given the technical uncertainties and potential risk to the public and the fact that transport of a TNPP 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.

2.2 Definition of Safety Goals and Risk Evaluation Guidelines

The definition of safety goals and risk evaluation guidelines for a highway transportation PRA and a maritime transportation PRA would be very similar and is discussed in Coles et al. (2022). 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 Decision making for Nuclear Material and Waste Applications” (NRC 2008). However, there are challenges to applying this approach as it involves use of quantitative health guidelines (QHGs). 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 of 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 feasible to use compared to QHGs. The 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 assessed 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 TNPP transportation because it takes significant time to affect any needed regulatory change. Even though a risk-informed licensing 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 TNPP transports will be needed.

2.3 Transportable Nuclear Power Plant Transportation Probabilistic Risk Assessment Methodology, Information, and Data

This section describes the definition of accident scenarios for maritime transport, collection and analysis of sailing route data for potential maritime hazards, collection and analysis of sailing route data for potential maritime hazards, development of a maritime scenario event tree, development of maritime branch scenario probabilities, and maritime accident consequence analysis. Because of the differences between the maritime environment and the highway environment, it is expected that a highway transportation PRA and a maritime transportation PRA would be significantly different in these areas.

2.3.1 Definition of Accident Scenarios

Previous transportation PRAs have defined scenarios in terms of impact speeds and fire temperatures for truck based transport. An example of truck transportation accidents involving releases of radioactive material has been defined as shown in Figure 1.

Maritime accident scenarios in this work build upon truck event trees but adapt them to the maritime environment, see SAND98-1171. These scenarios revolve primarily around ship to ship collisions (also referred to simply as ship collisions) and/or fire-based events since these events are typically the only ones that could challenge a transportation package according to SAND98-1171 and other research as indicated below. Accident scenarios in SAND98-1171 considered details such as whether the transportation package could be damaged (crushed, punctured, shear etc.), whether the ship carrying the transportation package could catch fire, how the transportation package was tied down, specific vessel characteristics, etc. Damage models, such as hull penetration, are based on work by Minorsky (1959), who corelated ship damage to collision speed, ship displacement, and collision angle, were used in the scenario probabilities. Table 1 reproduces Table 8-1 from SAND98-1171 which summarizes scenario events. Postulated scenario events allow the construction of event trees (and relevant probabilities) from which eventually consequence analyses can be performed. Table 2 reproduces Table 8-3 from SAND98-1171, an example scenario of a transportation package with associated events for a small (charter) and large (break-bulk) freighter that travels from Charleston, South Carolina to Cherbourg, France.

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)

Table 1. Scenario Events of Consideration for Maritime Transport Accidents (Reproduced from Table 8-1 of SAND1998-1171)

Event	Probability
A ship collision occurs	$P_{collision}$
The radioactive material (RAM) ship is the struck ship	$P_{RAM\ ship\ struck}$
The strike location is midship	$P_{strike/midship}$
The RAM cask location is midship	$P_{cask/midship}$
The RAM hold is struck	$P_{RAM\ hold\ struck}$
Cask crush occurs	P_{crush}
Cask puncture or shear occurs	$P_{puncture/shear}$
A fire starts on the RAM ship, spreads to the RAM hold, engulfs the cask, and then burns hot enough and long enough to increase radioactive release from the failed case	$P_{severe\ engulfing\ fire}$
The RAM ship sinks	P_{sink}

Table 2. Sample Scenario Event Probabilities for Maritime Transport Accidents for a Trip from Charleston, South Carolina to Cherbourg, France aboard Charter and Break-Bulk Freighters (Reproduced from Table 8-3 of SAND1998-1171)

Event	Probability	Value	
		Charter Freighter	Break-Bulk Freighter
A ship collision occurs while sailing from Charleston to Cherbourg	$P_{collision}$	9.5×10^{-5}	9.5×10^{-5}
The radioactive material (RAM) ship is the struck ship	$P_{RAM\ ship\ struck}$	0.5	0.5
The strike location is midship	$P_{strike/midship}$	0.33	0.38
The RAM cask location is midship	$P_{cask/midship}$	1.0	1.0
The RAM hold is struck	$P_{RAM\ hold\ struck}$	1.0	0.33
Cask crush occurs	P_{crush}	0.03	0.1
Cask puncture or shear occurs	$P_{puncture/shear}$	0.2	0.2
A fire starts on the RAM ship, spreads to the RAM hold, engulfs the cask, and then burns hot enough and long enough to increase radioactive release from the failed case	$P_{severe\ engulfing\ fire}$	6.0×10^{-5}	2.0×10^{-5}
The RAM ship sinks	P_{sink}	3.6×10^{-3}	3.6×10^{-3}

2.3.2 Collection and Analysis of Sailing Route Data for Potential Maritime Hazards

Data from Nuclear Transport Services (NTS) is the primary source of data used in this work and is the only shipping service the DOE uses to transport Category 1 radioactive material[2]. It is expected that only a Class 3 INF vessel or ship (INF 3) will be capable of transporting a TNPP, and NTS has its own fleet of INF 3 ships.

As described above, the overall maritime PRA approach is very similar to that found in SAND98-1171. Additionally, some of the data used to develop SAND98-1171 will be used for comparison purposes to NTS data. Casualty data in SAND98-1171 is based on Lloyd's Maritime Information Service (LMIS) which is now Lloyd's List Intelligence Service (LLIS) who track the entire merchant marine fleet. Given that SAND98-1171 was published 25 years ago, more recent casualty data was required and was obtained from S&P Global. This data supports the NTS data.

Comparing pertinent casualty rates per nautical mile from SAND98-1171 and more recent casualty data (S&P Global) to NTS data is conservative because NTS has reported no release in over 50+ years of operation. Updated figures/tables based on this more recent casualty data have been found to be similar in nature to those found in SAND98-1171. While data related to liquefied natural gas (LNG) tankers and liquefied petroleum[3] gas (LPG) tankers were focused on in older sources, less emphasis is placed on them with newer S&P Global data since nuclear fuel carriers are tracked specifically. Accident rates for these ships are exceedingly low and ultimately support low probability of release estimates for maritime transport.

Data calls and communication to the U.S. Coast Guard, and the Army Corps of Engineers were initiated during early stages of composing this report but formal input was not yet received at the time of report finalization, and hence, is not included.

2.3.2.1 Nuclear Transport Services Data

Sea-route and other related shipping data comes primarily from NTS (Pacific Nuclear Transport Limited [PNTL[4]]) which has over 50 years of maritime experience (in addition to rail) in shipping nuclear materials (e.g., industry, nuclear fuel cycle, research and medical purposes) to Europe and to the United States. NTS is a subsidiary of the UK Government's entity Nuclear Decommissioning Authority and as previously mentioned, is the only worldwide shipper of Category 1 material (including highly enriched uranium [HEU]) and has a fleet of INF 3 ships (see Table 3 and Figure 2 and Figure 3). In terms of capability, NTS' INF 3 class vessels are able to transport 20–30 flasks[5]/ISO containers[6] in 4 holds within upper and lower decks and has transported thousands of metric tons of spent fuel around the world with no release.

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[2] Categorization of materials as defined in IAEA's Safety Guide RS-G-1.9: "Categorization of Radioactive Sources."

[3] SAND98-1171 defined LPG as Liquefied Propane Gas. Here the term Liquefied Petroleum Gas is used, as most available information related to tankers do not isolate propane but a wide range of petroleum products. LNG and LPG tankers have certain design characteristics. See http://www.liquefiedgascarrier.com/general-arrangement.html

[4] PNTL is the "shipping" business of NTS.

[5] Flask is used interchangeably with cask internationally.

[6] Based on personal communication with Andrew Gray of NTS in August of 2023.

Table 3. General Nuclear Transport Solutions Shipping Facts

Class INF 3 ships[7]	Pacific Heron, Pacific Grebe, European Shearwater and Pacific Egret
Other ships used by Nuclear Transport Services (NTS) to transport radioactive materials	Pacific Swan, Pacific Pintail (Oceanic Pintail), Pacific Sandpiper, Pacific Teal, Pacific Crane, Atlantic Osprey (INF 2 ship), Mediterranean Shearwater, Leven Fisher, and Pacific Fisher
Number of casks of material moved by sea	2,000+
Miles sailed	5,000,000+[8]
Countries sailed to	Australia, Slovenia, Japan, Sweden, Germany, Netherlands, Belgium, France, Portugal, Italy, Greece, Switzerland, United States

This table includes both active ships and decommissioned ships.

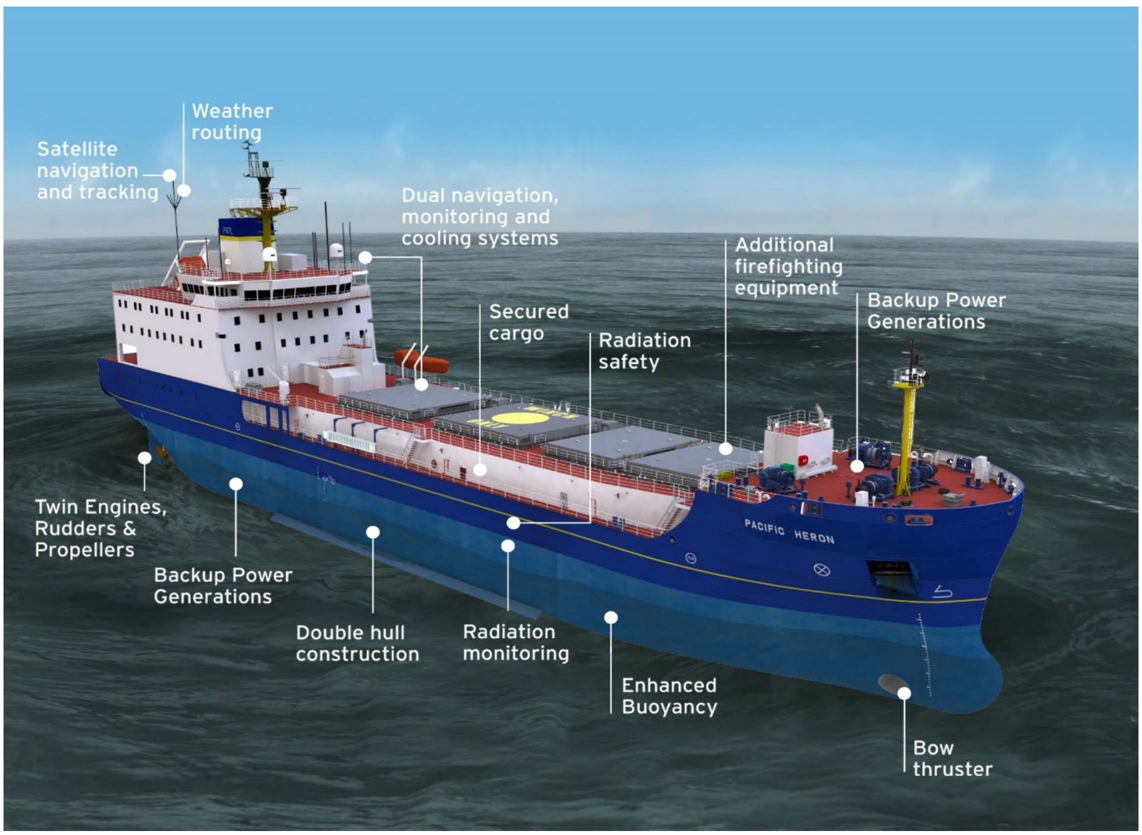

Figure 2. Class INF 3 Ship Features (Pacific Heron Displayed)

[7] Additional Ship details can be found in Table 5 and Table 8 of this plan.
[8] Value reported by NTS (2023) but also reported by World Nuclear News on the January 18, 2010 (https://world-nuclear-news.org/Articles/New-PNTL-ship-takes-to-the-water)

Figure 3. Nuclear Transport Solutions' Fleet of Class INF 3 Ships (Egret, Heron, and Grebe)

NTS has worked with the DOE and specifically with the National Nuclear Security Administration (NNSA), for over 40 years having shipped to U.S. ports (Charleston and Savannah) and has experience with the Foreign Research Reactor – Spent Fuel Program, disposition of gap material[9], and the Global Threat Reduction Initiative (GTRI). Radioactive materials shipped include MOX fuel, plutonium, HEU, SNF, vitrified high level waste, and sealed sources. Further package and contents details are described in Table 4. Vessel service dates used by NTS (past and current) are displayed in Table 5.

Table 4. Example Transportation Packages (Casks) and Material Shipped by Nuclear Transport Solutions

Contents Shipped	Transportation Package
High Level Waste (HLW)	Castor HAW28M, TN81, TN28
Mixed Oxide Fuels (MOX)	TN12/M4/12 MX6
Plutonium oxide (PuO_2)	9975, 9979, SAFKEG
Highly-enriched uranium	ES 3100, SAFKEG
Materials Testing Reactor (MTR)	GNS-16, NAC LWT, TN-MTR
Advanced Gas-Cooled Reactor (AGR)/M2	Magnox cask, Excellox 3B

[9] Gap material is high risk and/or vulnerable nuclear material not covered by other removal efforts. See https://www.energy.gov/sites/prod/files/em/GlobalThreatReductionInitiative.pdf for more information.

Table 5. Service Dates for Vessels Used by Nuclear Transport Solutions to Transport Radioactive Material.

Vessel
Leven Fisher 1969–1979
Mediterranean Shearwater 1982–1991
Pacific Swan 1979–2004
Pacific Teal 1982–2007
Pacific Crane 1980–2002
European Shearwater 1981–2010
Pacific Sandpiper 1985–2010/11
Atlantic Osprey[10] 2001–2014
Pacific/Oceanic Pintail 1987–2015
Pacific Heron 2008–present day
Pacific Grebe 2010–present day
Pacific Egret 2010–present day
Pacific Fisher 1978-1985

NTS has also shipped other radioactive materials not listed in Table 4, such as UO_3, UF_6, fresh uranium fuel, irradiated MOX, and spent fuel. While NTS vessels could carry more than 20 casks in practice, NTS has only shipped around 10 casks in one vessel due to Criticality Safety Index (CSI) restrictions. NTS identified that they had made at least 66 shipments with the Atlantic Osprey, an INF 2 vessel when it was still in operation. NTS has made more than 180 shipments[11] (with INF 3 ships) of spent (used) nuclear fuel, vitrified high-level waste, MOX fuel, and plutonium since 1975.

In terms of sea routes used by NTS, NTS has communicated to the authors of this report that all sea-routes assume their origin to start from their home port of Barrow-in-Furness in the United Kingdom whether their ship is empty or potentially laden. The sea routes themselves are relatively few in number and include:

- UK to Europe via the English Channel directly into mainland Europe (France, Portugal, Germany, Belgium, Netherlands);
- UK to Scandinavia direct travel from north of the British Isles when transiting to Sweden or Finland;
- UK to the Mediterranean Sea direct travel to Greece, Italy, and Slovenia;
- UK to the United States direct travel to the East Coast of the United States (Ports of Charleston South Carolina and Port of Savannah); and
- UK or Europe to Japan/South East Asia direct at times, or travel to France/Other European country first. Travel through the Panama Canal is permitted with Category 2

[10] Roll on, roll off (RoRo) vessel.
[11] Reported in 2013 per PNTL (2013).

material (depending on security posture) and Category 3 material[12]. If the cargo necessitates an onboard security force, then Panama canal transit is not permitted. Travel with Category 1 material which a TNPP is assumed to be classified as, necessitates travel around the Cape of Good Hope/Cape Horn as the Suez Canal is not currently being used for Category 1 radioactive shipments by NTS[13].

A sample of ports visited by NTS' fleet are described in Table 6.

Table 6. Example Ports Visited by Nuclear Transport Solutions Vessels Transporting Radioactive Material

United Kingdom: Barrow-in-Furness, Workington, Liverpool, and Scrabster
Belgium: Antwerp
France: Cherbourg
Germany: Bremerhaven, Nordenham
Netherlands: Walhamm, Rotterdam, Vlissingen
Spain: Bilbao, Santander
Sweden: Norrkoping, Studsvik
Australia: Port Kembla
Finland: Helsinki
Greece: Athens
Portugal: Setubal
Italy: Anzio, La Spezia
United States: Charleston, Savannah, Honolulu
South Korea: Busan
South Africa: Durban
Norway: Halden
Japan: Kobe, Mutsu-Ogawara Tokai, Hitachi-Naka, Omezaki, Genkai, Ikata, Yura, Takahama

Full electronic log registers by NTS were not available for the purposes of calculating trip distances, however, some basic trip distances can be calculated using shiptraffic.net for the five typical routes travelled by PNTL vessels mentioned above and are tabulated in Table 7 below. Figure 5 through Figure 6 illustrate these sample routes.

[12] Categorization of materials is defined in IAEA's Safety Guide RS-G-1.9: "Categorization of Radioactive Sources."
[13] Personal Communication between A. Rigato (PNNL) and A. Gray (NTS), September 2023

Table 7. Estimated Distances Travelled for Five Sample Routes Taken by Nuclear Transport Solutions Vessels

Sea Route	Nautical Miles Travelled
Port of Barrow to Port of Tokyo	17,587
Port of Barrow to Port of Cherbourg	497
Port of Barrow to Port of Helsinki	1,867
Port of Barrow to Port of Anzio	2,581
Port of Barrow to Port of Charleston	4,169

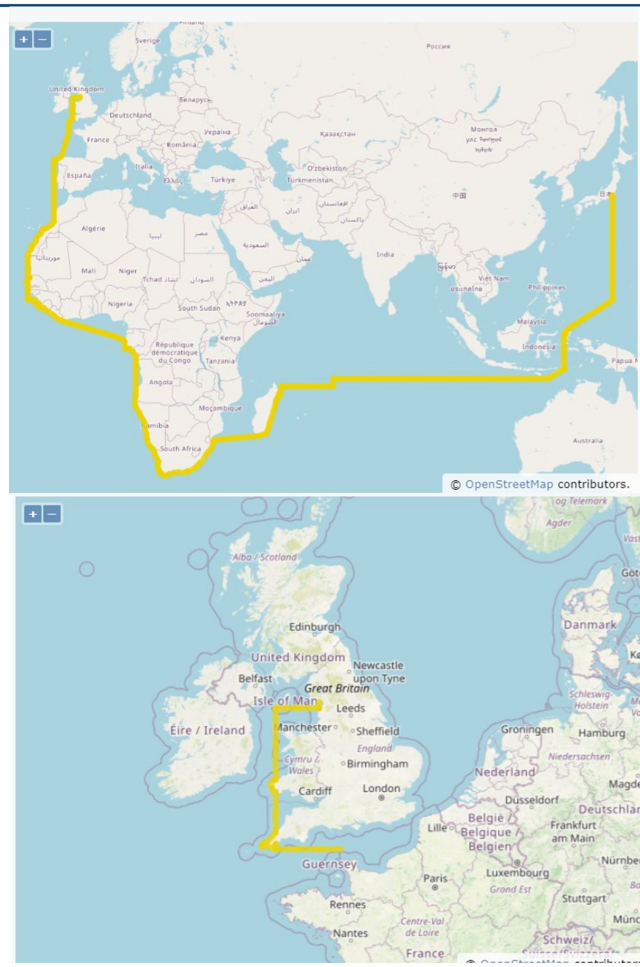

Figure 4. Assumed Sea Route from Port of Barrow to Port of Tokyo (Above), Assumed Sea-Route from Port of Barrow to Port of Cherbourg (Below)

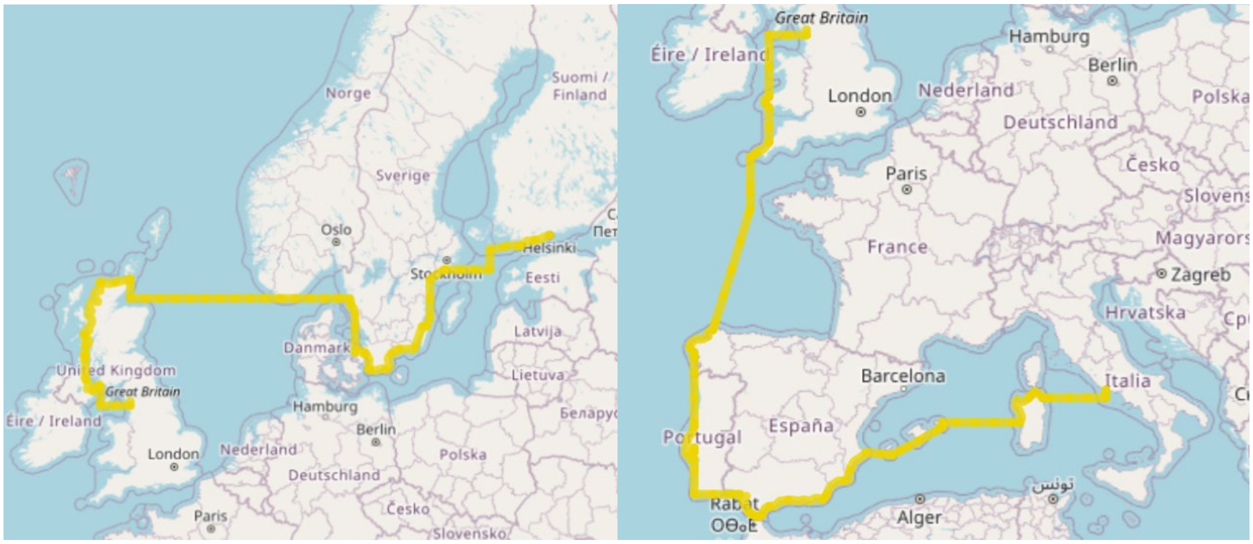

Figure 5. Assumed Sea Route from Port of Barrow to Port of Helsinki (Left), Assumed Sea-Route from Port of Barrow to Port of Anzio (Right)

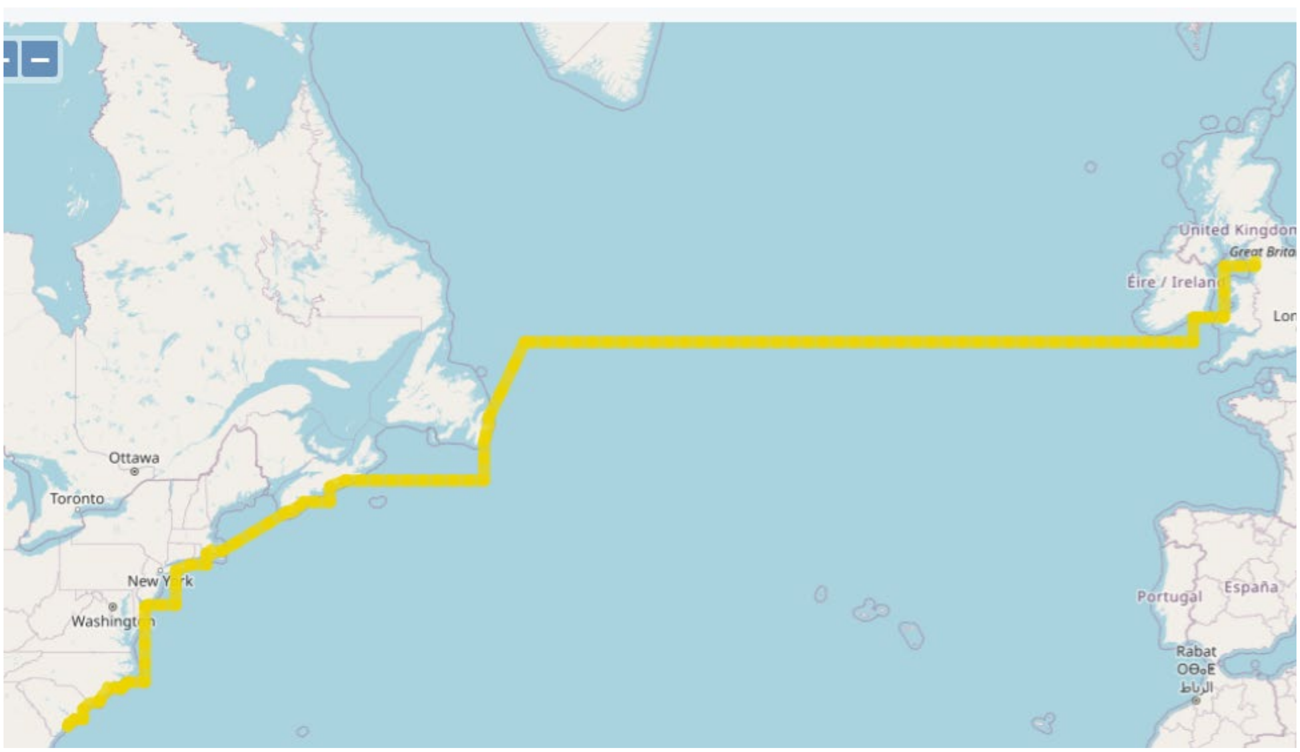

Figure 6. Assumed Sea Route from Port of Barrow to Port of Charleston

While more precise port call data from NTS was not available, an overall sense of nautical miles travelled by their INF 3 ships could be calculated crudely using an average of the 5 main sea routes described in Table 7:

Average distance of 5 routes = (17,587 + 497 + 1,867 + 2,581 +4,169)/5 = 5,340 NM

Assuming 180 shipments, this represents nearly a million nautical miles with just INF 3 ships.

Table 8 provides a list of known nuclear fuel carriers including NTS vessels (some have since been decommissioned or re-purposed).

Table 8. List of Nuclear Fuel Carriers (Other Dry Cargo)

No.	Name	International Maritime Organization No.	Flag	Gross Ton.	Dead Wt. Ton.	Length (m)	Beam (m)	Year of Build	Decom. Date/No Longer in Service	Registered Owner
1	XIN AN JI XIANG	9928530	China	5,656	1,931	96	18	2020		SHANGHAI XINAN SHIPPING CO
2	SEIEI MARU	9012202	Japan	4,053	3,206	100	16	1991	2019	NUCLEAR FUEL TRANSPORT CO LTD
3	ROKUEI MARU	9137935	Japan	4,913	2,810	100	17	1996		NUCLEAR FUEL TRANSPORT CO LTD
4	KAIEI MARU	9364095	Japan	4,924	2,795	100	17	2006		NUCLEAR FUEL TRANSPORT CO LTD
5	SEIEI MARU	9810848	Japan	4,568	3,018	100	17	2019		NUCLEAR FUEL TRANSPORT CO LTD
6	HJ CHEONGJEONGNURI	9488449	Rep. of Korea	2,959	1,221	79	16	2009		HANJIN TRANSPORTATION CO LTD
7	LEPSE	8884751	Russian Fed.	4,177	1,420	88	17	1961	2014	MURMANSK SHIPPING CO
8	SEREBRYANKA	8929513	Russian Fed.	2,925	1,625	102	15	1974		RUSSIA GOVT
9	IMANDRA	8953409	Russian Fed.	5,806	2,186	131	17	1980		RUSSIA GOVT
10	ROSSITA	9531894	Russian Fed.	2,557	1,620	84	14	2011		RUSSIA GOVT
11	SIGYN	8025941	Sweden	4,166	2,044	90	18	1982	2015	SVENSK KARNBRANSLEHANTERING AB

No.	Name	International Maritime Organization No.	Flag	Gross Ton.	Dead Wt. Ton.	Length (m)	Beam (m)	Year of Build	Decom. Date/No Longer in Service	Registered Owner
12	SIGRID	9631840	Sweden	6,694	1,600	100	19	2013		SVENSK KARNBRANSLEHANTERING AB
13	TIEN KUANG NO. 1	9015917	Taiwan	834	738	53	11	1991		TAIWAN POWER CO
14	PACIFIC FISHER[14]	7030949	United Kingdom	3,619	3,237	103	15	1970	1985	JAMES FISHER & SONS PLC
15	PACIFIC SWAN[15]	7621516	United Kingdom	4,473	3,792	103	16	1979	2005	Pacific Nuclear Transport Ltd (James Fisher & Sons Ltd)
16	PACIFIC CRANE[16]	7902362	United Kingdom	4,510	3,804	103	16	1980	2004	Pacific Nuclear Transport Ltd (James Fisher & Sons Ltd)
17	EUROPEAN[17] SHEARWATER	8010788	United Kingdom	2,493	1,583	80	13	1981	2009	JAMES FISHER & SONS PLC
18	PACIFIC TEAL[18]	8110631	United Kingdom	4,863	3,702	104	17	1982	2008	British Nuclear Transport Ltd, (James Fisher & Sons Plc, managers)
19	PACIFIC SANDPIPER[19]	8310695	United Kingdom	5,050	3,775	104	17	1985	2011	BRITISH NUCLEAR FUELS LIMITED
20	OCEANIC PINTAIL[20]	8601408	United Kingdom	5,271	3,865	104	17	1987	2020	NUCLEAR DECOMMISSIONING
21	PACIFIC HERON	9372913	United Kingdom	6,776	4,916	104	17	2008		PACIFIC NUCLEAR TRANSPORT LTD

[14] Operated by PNTL (NTS) from 1978–1985.
[15] Operated by PNTL (NTS) from 1979–2004.
[16] Operated by PNTL (NTS) from 1980–2002.
[17] Operated by PNTL (NTS) from 1978–1985.
[18] Operated by PNTL (NTS) from 1982–2007.
[19] Operated by PNTL (NTS) from 1985–2010/11.
[20] Went by Pacific Pintail. Operated by PNTL (NTS) from 1987–2015.

No.	Name	International Maritime Organization No.	Flag	Gross Ton.	Dead Wt. Ton.	Length (m)	Beam (m)	Year of Build	Decom. Date/No Longer in Service	Registered Owner
22	PACIFIC EGRET	9464871	United Kingdom	6,776	4,408	104	17	2010		PACIFIC NUCLEAR TRANSPORT LTD
23	PACIFIC GREBE	9464883	United Kingdom	6,840	4,902	104	17	2010		PACIFIC NUCLEAR TRANSPORT LTD
23	LEVEN FISHER[21]	5207225	United Kingdom	Unknown	3,000	79	12	1962	1979	PACIFIC NUCLEAR TRANSPORT LTD

Sources: www.vesseltracking.net, www.vesselfinder.com, marinetraffic.com, www.balticshipping.com, www.imo.org, www.shipvault.com, http://www.tynebuiltships.co.uk/ShipsE.html, S&P Global, and NTS

[21] Operated by PNTL (NTS) from 1969–1979.

2.3.2.2 SAND98-1171 Data

SAND98-1171 used the average of 2 years (1988 and 1993) of port call data from LMIS to determine the average number of nautical miles travelled by all ship types (general fleet) for a given year (Table 4-4 of SAND98-1171). The average distance calculated was assumed to hold steady for each year of the 15 years of incident data collected from LMIS from (1979–1993). Distances were calculated using great circle distances along with specific trip algorithms and the aid of an atlas during a time when online calculators were not available. Also, distances travelled were broken down by oceanic region to better understand collision rates (described later on). NTS data indicated that no collisions occurred over the past 50 years, and so this step was not undertaken for NTS data.

SAND98-1171 also looked specifically at LNG tankers and LPG tankers (Table 9) since they tend to have features[22] that radioactive material carriers typically have like double hulled construction and better trained crew. LPG and LNG tanker collision rates are lower when compared to the general fleet of ships and conservative when compared to NTS data.

Table 9. Distances Sailed, Ship Collisions, and Collision Frequencies for Liquefied Natural Gas Tankers, Liquefied Petroleum Gas Tankers, and All Ships (General Fleet). (Replicated Table 4-7 from SAND98-1171)

Tanker	Distance Sailed (Nautical Miles)			Collisions 1979–1993	Collision Frequency (per Nautical Mile Sailed)
	1998	1993	Total		
Liquefied Natural Gas (LNG)	4,080,851	5,439,253	9,520,104	1	1.4×10^{-8}
Liquefied Petroleum Gas (LPG)	23,367,726	29,189,792	52,557,518	16	4.1×10^{-8}
All Ships	1,030,266,200	1,144,634,277	2,174,900,488	1,237	7.6×10^{-8}

SAND98-1171 did not indicate how many LNG ships were part of the fleet in 1988 and 1993, but estimates using the following references in tandem, Maritime Page 2023, LMIS's Register Foundation (1988–2023), and Noble (2009) fleet size estimates[23] were made. Specifically, the number of vessels delivered, fleet size, fleet age, and vessels withdrawn from the fleet were tracked.

Summing the total number of miles travelled in 1988 and 1993 reported in SAND98-1171 and dividing by the sum of the fleet size in those years produces the values listed in Table 10, which represent the average distance a LNG or LPG tanker travelled in a given year. These values will be used in conjunction with more recent casualty data from S&P Global.

[22] More LNG and LPG features can be found here: http://www.liquefiedgascarrier.com/general-arrangement.html
[23] LMIS's register refers to both LNG and LPG ships collectively as "liquefied gas tankers" in their reports. Later years break out both LPG and LNG ships from this category.

Table 10. Liquefied Natural Gas and Liquefied Petroleum Gas Tanker Fleet Size and Average Distance in Nautical Miles Travelled by Year

Quantity	Year: 1988	Year: 1993	Weighted Average
Number of Liquefied Natural Gas (LNG) Tankers	49	54	NA
Number of Liquefied Petroleum Gas (LPG) Tankers	723	892	NA
Average Distance Travelled per LNG Tanker	83,283	100,727	92,428
Average Distance Travelled per LPG Tanker	32,321	32,946	32,664

2.3.2.3 S&P Global

For this work, casualty and movement data was obtained from S&P Global's (aka IHS Markit™) online platform Maritime Portal (Gold version) using AISLive (with Distance Tables module) and Sea-web® (with benchmark) platform features to examine various ship types including Class A AIS vessels[24]. A total of 159,995 ships were in their database in early December 2023. Maritime Portal distinguishes between ship types such as crude oil tankers, yachts, and nuclear fuel carriers and has movement data of these ships that goes as far back as 2008[25], and has casualty data that can go back as far as 1950.

Maritime Portal has ship specific data for all ships listed in Table 8 including dimensions, primary ship builder, engine maker, engine design, propulsion details, boiler information, compartment arrangement etc. as part of their full description as nuclear fuel carriers in their system. Maritime Portal does not have a set minimum or maximum on gross weight tonnage (GWT) or dry weight tonnage (DWT) of ships in its database. Given that nuclear fuel carriers are tracked specifically in Maritime Portal, these ships rather than any other were focused upon.

Using movement information, distances travelled between ports for a given nuclear fuel carrier were calculated using Maritime Portal's Veson Nautical tool. The user manually enters two or more ports in its interface and a distance is calculated between the ports and a route is charted (Figure 7). The user has the option to select routes that make use of Cape Horn, Cape of Good Hope, Gibralter, Suez Canal etc. The "direct" option (shortest distance) was used by default and the Suez Canal was avoided for ships that are in NTS's fleet when this route coincided with the direct option, since communication with NTS (Andrew Gray) indicated that this route is actively avoided by their ships. Instead, the next shortest distance was used in these cases which typically were thru the Panama Canal. More than 4,000 individual movement records with more than 300 unique port pairs were evaluated, resulting in more than 1,100,000 nautical miles of distance covered by the fleet of nuclear fuel carriers since 2008. This number is assumed to be low since routes taken are not always direct due to weather and logistical decisions. Maritime Portal also has a feature that plots the track of a given ship via AISLive (Figure 8) for up to a year, but does not calculate distances associated with it (the user can trace the route).

[24] The AIS Class A vessels are vessels with a gross tonnage of 300 or more engaged in international voyages or have a gross tonnage of 500 or more not engaged in international voyages as well as all passenger ships. Source: https://documentation.spire.com/ais-fundamentals/different-classes-of-ais/
[25] Some partial movement data was found for some nuclear fuel carriers prior to 2008 and was used in this report.

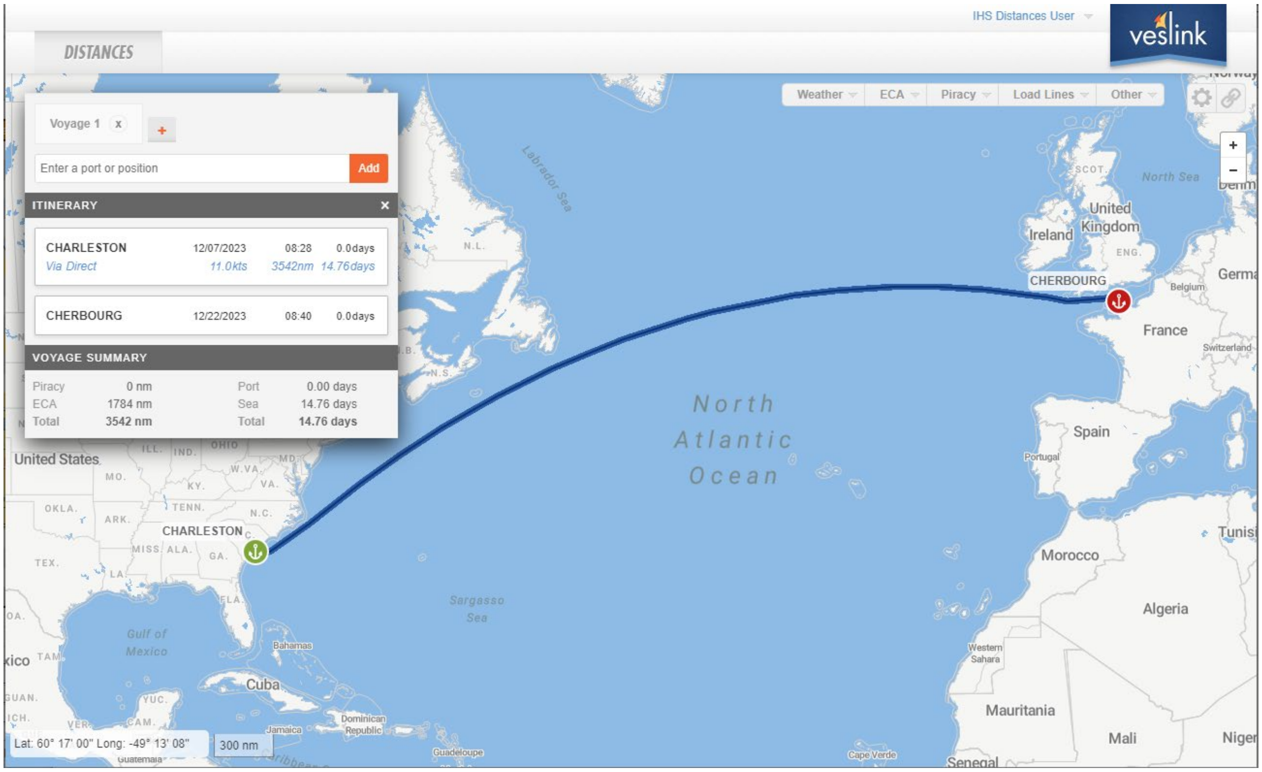

Figure 7 Sample Route taken by Maritime Portal's Veson Nautical Tool between Port of Charleston, South Carolina and Cherbourg, France with the "Direct" Option

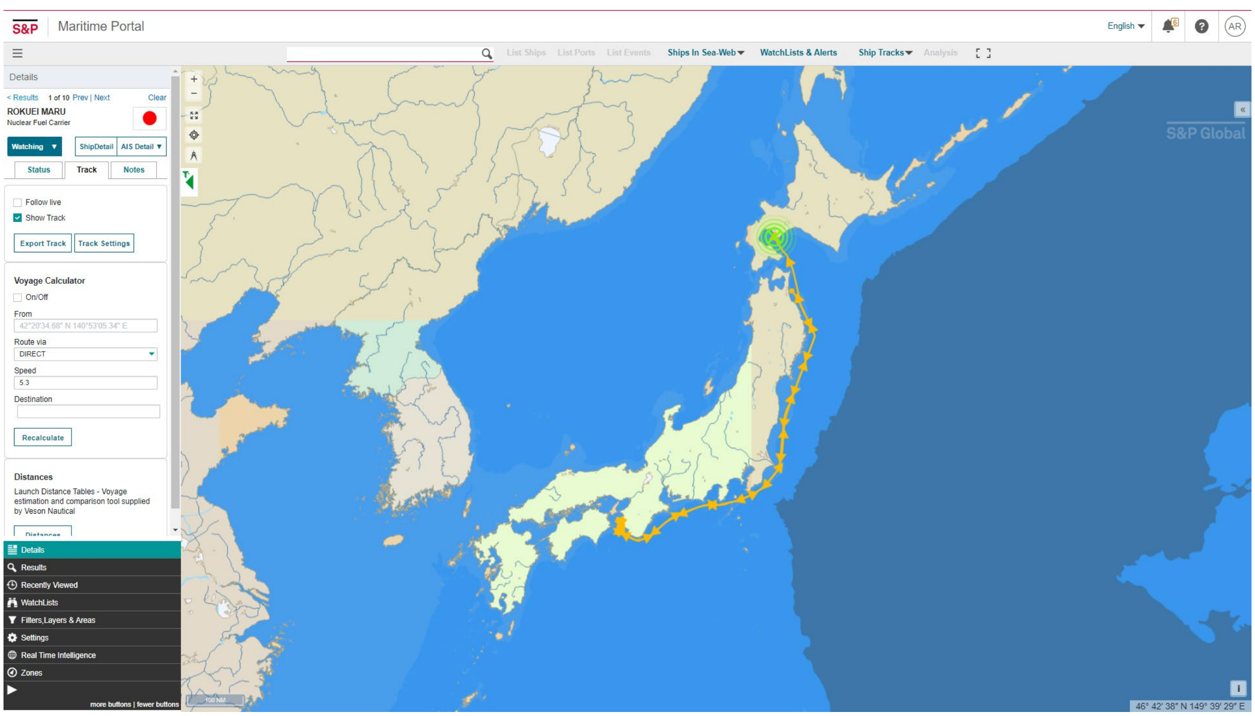

Figure 8. Track for the *Rokuei Maru* over the Past Calendar Year from Maritime Portal

Distance estimates for LNG and LPG tankers were not gathered using Maritime Portal given the ability to parse nuclear fuel carriers, however, an estimate was established using Table 10 above. Specifically, an estimate of the number of miles travelled by the LNG and LPG fleet for a given year can be estimated by using the average number of miles travelled in Table 10 and multiplying by the fleet size for a given year as displayed in Table 11. Several sources of data were used in developing this table. The number of LNG tankers was calculated from the difference in LNG tankers delivered, minus those that are no longer in service. After 1998, the number of LNG tankers no longer in service was interpolated using the number of LNG vessels delivered, and fleet size (685) confirmed by two sources in 2022. LPG tanker fleet size was also interpolated between 1999-2019, and from 2019 to 2022.

Table 11. Estimated Number of Liquefied Natural Gas and Liquefied Petroleum Gas Tankers and Their Estimated Distance Traveled by Year

Year	Number of Liquefied Natural Gas (LNG) Tankers Delivered	LNG Tankers No Longer in Service	Number of LNG Tankers	Number of LPG Tankers	LNG (nautical miles)	LPG (nautical miles)
1988	65*	16[#]	49	723[§]	4,279,680	23,616,585
1993	77*	17[#]	60	886[§]	5,240,424	28,940,933
1994	86*	19[#]	67	881[§]	5,851,807	28,777,609
1995	90*	19[#]	71	914§	6,201,169	29,855,545
1996	98*	19[#]	79	955[§]	6,899,892	31,194,798
1997	104*	20[#]	84	961[§]	7,336,594	31,390,786
1998	108[§]	20[#]	88	940[§]	7,685,956	30,704,827
1999	115*	22	113	978[§]	9,869,466	31,946,086
2000	128*	25	138	984	12,041,583	32,134,973
2001	129*	27	163	990	14,213,701	32,323,861
2002	138*	30	188	995	16,385,819	32,512,748
2003	153*	32	212	1,001	18,557,937	32,701,635
2004	175*	35	237	1,007	20,730,055	32,890,522
2005	194*	37	262	1,013	22,902,173	33,079,410
2006	220*	39	287	1,018	25,074,291	33,268,297
2007	253*	42	312	1,024	27,246,409	33,457,184
2008	303*	44	337	1,030	29,418,526	33,646,071
2009	343*	47	362	1,036	31,590,644	33,834,958
2010	370*	49	387	1,042	33,762,762	34,023,846
2011	388*	51	411	1,047	35,934,880	34,212,733
2012	390*	54	436	1,053	38,106,998	34,401,620
2013	407*	56	461	1,059	40,279,116	34,590,507
2014	441*	59	486	1,065	42,451,234	34,779,395
2015	468*	61	511	1,071	44,623,351	34,968,282
2016	499*	64	536	1,076	46,795,469	35,157,169

2017	531*	66	561	1,082	48,967,587	35,346,056
2018	588*	68	586	1,088	51,139,705	35,534,944
2019	632*	71	610	1,111¶	53,311,823	36,290,493
2021	731*	76	660	1,392	57,656,059	45,458,388
2022	763*	78	685[26]‡	1,532‡	59,828,177	50,042,335

LNG = Liquefied Natural Gas, LPG = Liquefied Petroleum Gas.
*Maritime Page (2023).
§Lloyd's Register (1987–1988, 1993–2000).
#Obtained from Noble PG. 2009. Lloyd's Registry used in calculating "LNG no longer in service" aka "disposal rate" from 1994–1998.
‡Atlas Magazine (2023).
¶Poten and Partners (2019).

2.3.3 Collection and Analysis of Maritime Accident Rate Data for Ships

Hazards that present the most credible chance of release for maritime shipping of RAM comes primarily from two sources: ship to ship collisions and fires resulting from ship collisions or other scenarios as stated in the SAND98-1171. Recent work by Christian and Kang (Christian and Kang 2017b) cite ship to ship collision as the most probable event of marine accidents when considering engine damage, grounding, sinking, and fire/explosion for Korean Maritime transport over the past three decades of SNF shipping experience. The same work (Christian and Kang 2017b) proposed a more sophisticated model when examining ship to ship collisions based on Monte Carlo simulation and examined the crossing of sea routes between ships and congested waterways. However, this methodology was not validated with actual casualty data.

Since LNG and LPG tankers share more in common with INF 3 ships compared to the general fleet, data based on those types of ships are focused upon and used as a conservative estimate of incidents (collisions/fire) per nautical mile relative to NTS data which reported no incidents. Work by Gucma and Mou (2022) is also presented below which discusses their work on LPG and LNG accident data. Newer collision/fire data is provided from S&P Global.

Historically, shipping accidents related to the transportation of radioactive material is exceedingly rare. In 1981, a collision took place between two merchant vessels: the Garnet which was carrying two Sr-90 sources and the Mola Venture outside Port-Said harbor in Egypt. The Garnet was sunk, and the two sources were salvaged in their original condition by the Atomic Energy Authority of Egypt (Sabek et. al. 1997). Additionally In 1984, the cargo ship Mont-Louis collided with the car ferry Olau Britannia off the Belgian coast and sank in the North Sea approximately 10.5 nautical miles north of Ostend, Belgium. The Mont-Louis's cargo included 350 metric tons of uranium hexafluoride in 30 48-Y cylinders. The Mont-Louis sank at a depth of 14 m. All 30 of 48-Y cylinders were recovered. Only one small leak in one 48-Y closure valve was found. As a note, the Mont-Louis was a roll-on roll-off cargo ship built in 1972 and most likely not a INF 3 vessel.

2.3.3.1 NTS Data

As mentioned above, NTS data indicates that they have never had an accident in 50+ years of experience and thus have never had a release of nuclear material over the course of

[26] Reported also by Rivieramm.com. Accessed September 2023 at https://www.rivieramm.com/opinion/opinion/five-years-of-transition-in-the-lng-sector-77091

5,000,000 nautical miles of travel reported back in 2010. Incidents/nautical mile in this case is zero for more than 180+ shipments of RAM.

2.3.3.2 SAND98-1171

Casualty data described in SAND98-1171 came from LMIS for a total of 15 consecutive years (1979–1993). SAND98-1171 looked at approach water ways near ports, the regions in which those ports are located, and oceanic regions and found that collisions occur more often near ports of departure and arrival than the general region in which the port is located. The port size did not affect collision rates near ports. Most of the work performed for SAND98-1171 looked at the whole fleet but found that lower collision rates per nautical mile of travel existed for LNG and LPG tankers. It found that tankers had collision rates around 2–5 times less than the entire fleet (see Table 9 above). Since LPG and LNG tankers have similar characteristics as purpose-built vessels designed to carry RAM (double hulled, and often well trained crew) they serve as a reasonable comparison to INF 3 vessels. Compared to NTS data, their rates of incidents are conservative.

In terms of fire, SAND98-1171 found the rates of fire to be insensitive to port or region and calculated the following values for the general fleet:

- 9.6×10^{-8} fires per nautical mile sailed
- 5.4×10^{-5} fires per port call

SAND98-1171 reported zero fires for LNG and LPG tankers while NTS reported zero incidents of any kind.

2.3.3.3 Gucma and Mou (2022)

Gucma and Mou (2022) obtained casualty data from the Maritime Portal of IHS Markit Database and looked at the accidents/incidents reported from 1963 to April 2022 for LNG and LPG tankers. The general casualty groups in which incidents/accidents were recorded were: collisions, contact, fire/explosion foundered, hull/machinery damage, stranded, war-loss/hostilities, and other. Some details related to weather, cargo condition, injury etc. were also available from Maritime Portal. They reported a total of 20 and 150 fire/explosions for LNG and LPG tankers respectively, and a total of 39 and 387 collisions for LNG and LPG tankers respectively, over the course of 59 years. Unfortunately, it was not clear if collisions incidents came from ship to ship collisions or not, nor were fire details available. Roughly 75% of any incidents recorded happened prior to 2000 for both LNG and LPG tankers despite their being fewer LNG and LPG tankers in the world fleet.

Dividing the number of collisions and fires incidents by the sum of all estimated nautical miles sailed by LNG (879,867,227 NM) and LPG (1,052,957,036 NM) tankers reported in Table 11 above (Section 2.3.2.3) produces the results reflected in Table 12. Note these values are very conservative, as the total number of nautical miles estimated to have been sailed by LNGs and LPGs was not calculated for each year over the past 59 years but rather 31 years. In addition, no filtering was done for collision incidents reported, as only ship to ship collisions are of interest in this plan. Thus, the collision rate is even lower than reported in Table 12. Nonetheless, the values reflected are comparable to those obtained in SAND98-1171 for LPG and LNG tankers.

Table 12. Estimated Incident/Accident Rates per Nautical Mile for Liquefied Natural Gas and Liquefied Petroleum Gas Tankers using Data by Gucma and Mou (2022)

Quantity	Accident/Nautical Mile
Liquefied Natural Gas (LNG) Fire Rate	2.3×10^{-8}
Liquefied Propane Gas (LPG) Fire Rate	1.4×10^{-7}
LNG Collision Rate	4.4×10^{-8}
LNG Collision Rate	3.7×10^{-7}

The incident rates reported in Table 12 are also much lower than SAND98-1171 for the general fleet.

2.3.3.4 S&P Global

As mentioned previously, S&P Global casualty data (described as “Events” in Maritime Portal) goes as far back as 1950. General events that are tracked include piracy, marine pollution, crew and passenger related events, security/legal events, and ship casualties. These events are further broken down into sub-events such as collisions, fire/explosions, robbery, war-loss, strandings incidents, crew illness, etc. Each event typically has a description associated with it (“Headline” in Maritime Portal).

Three events (besides 2 recorded strandings) for nuclear fuel carriers are recorded in Maritime Portal which are classified as “collision” based events. Two occurred in 1983 (one classified as “serious” the other “non serious”) and another “serious” event in 1998. The “serious” event occurred in France in 1983 when a cargo ship lost control due to a failed engine and struck the stern of a nuclear fuel carrier that was moored at port as well. The moorings of the nuclear fuel carrier were loosened as a result, and the nuclear fuel carrier went on to strike a moored ferry nearby. The nuclear fuel carrier’s door ramp was damaged. The “non serious” event occurred at port in Japan when a nuclear fuel carrier collided with a general cargo ship causing superficial damage to the nuclear fuel carrier (bent handrails, scored sheer strake by holds 1-4, and gouged gunwale above the deck along with side shield plates). The “serious” event in 1998 involved a moored nuclear fuel carrier being struck by a barge in 1998 in England while moored at port during adverse weather. The hull was damaged in three places and was repaired in 1999. For these 3 events, It is unclear if any of these occurred while the ships were actively carrying radioactive material. No other casualty information such as fire incidents were recorded.

As a broad casualty comparison, LPG/LNG and the remaining fleet were briefly examined. Specifically, casualty event data for both LNG and LPG tankers (up to early December 2023) indicated that there were:

485 collisions events (79 for LPGs, 19 for LNGs between 2008-2022) and,

183 fire/explosion events (36 for LPGs, 2 for LNGs between 2008-2022)

In Maritime Portal’s catalog that dates back to 1963. The current LNG and LPG fleet count is 2,821 ships while the remaining portion of the general fleet is recorded as being a total of 151,857 ships. The general fleet had 19,561 collisions events cataloged, and 9,086 fire/explosions events cataloged which date back to 1953.

In general, it is assumed that collisions do occur at ports and approach waterways more often than in open water and are independent of the port size like SAND98-1171 reported. Intuitively, this makes sense based on a funneling effect of traffic near a port (see Figure 7).

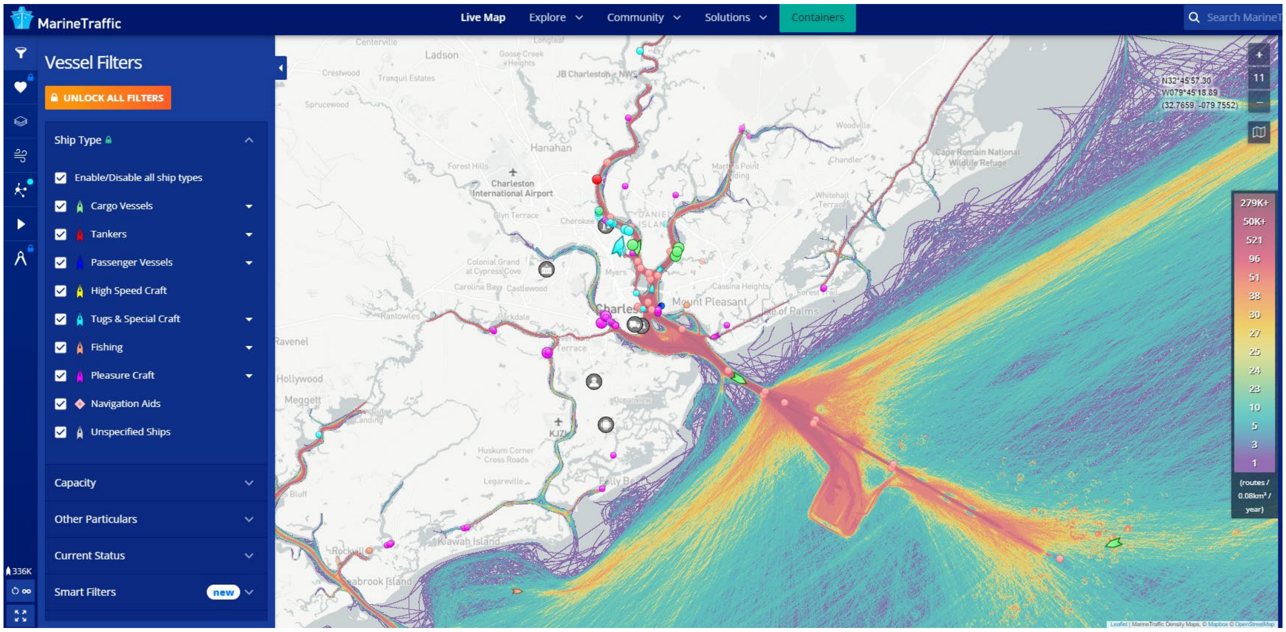

Figure 9. Ship Routes Taken in the Vicinity of the Port of Charleston, South Carolina over a 0.08 km^2 Area per Year (Accessed from https://www.marinetraffic.com/)

Since S&P Global data indicates very few events for nuclear fuel carriers, the need to investigate incidents at a regional level or port level is unnecessary. Ideally, all ports and their approach waters should be avoided in an effort to lower collision rates, but this is impractical. In summary, no collision or fire/explosion incidents were reported for nuclear fuel carriers during 2008-2023 with an estimated 850,000+ nautical miles of travel during this period.

For simple comparison sake, LNG and LPG events (collision and fire/explosion) above were divided by the sum of all estimated nautical miles sailed by LNG (669,350,272 NM) and LPG (553,161,237 NM) tankers during 2008-2022. The results are captured in Table 13.

Table 13. Incident/Accident Rates per Nautical Mile for Liquefied Natural Gas and Liquefied Petroleum Gas Tankers Using S&P Global Casualty Data from 2008-2022

Quantity	Accident/Nautical Mile
Liquefied Natural Gas (LNG) Fire Rate	3.0×10^{-9}
Liquefied Propane Gas (LPG) Fire Rate	6.5×10^{-8}
LNG Collision Rate	2.8×10^{-8}
LPG Collision Rate	1.4×10^{-7}
Nuclear Fuel Carrier Collision Rate	0.0
Nuclear Fuel Carrier Fire Rate	0.0

Incident rates per nautical mile using S&P Global casualty data compares to SAND98-1171 and Gucma and Mou (2022) for LNG and LPG tankers. No further screening of these events were made, so most likely the number of events that could actually challenge cargo (such as a TNPP) is less than the above making the values presented in Table 13 conservative. Fewer incidents were noted to have occurred in the last 10-15 years despite overall fleet size expansion which is perhaps due to advances in technology/logistics like GPS since the publication of SAND98-1171. NTS reported no incidents in comparison.

2.3.4 Development of a Maritime Scenario Event Tree

This section discusses the development of a maritime scenario event tree which are dominated by accidents involving ship to ship collisions and onboard ship fires (initiated by ship-to-ship collisions or otherwise). This approach is similar to the one described in SAND98-1171, which established that while other types of accidents such as the ship ramming into a fixed structure such as a bridge pier, dry dock, etc. or grounding may significantly damage the ship's bow, they would be unlikely to damage the RAM cargo onboard. However, SAND98-1171 assumed that the cargo being transported was radioactive material and not a TNPP, which may be more inherently sensitive to large decelerations depending on TNPP design requirements. When more data becomes available about the specific TNPP itself, these event trees could be refined and updated.

For maritime purposes, the generic event trees developed for the TNPP transportation PRA are very similar to the event trees developed for radioactive material in SAND98-1171, such as SNF (domestic or foreign), plutonium dioxide, vitrified high level waste, etc. carried in transportation casks, as shown in Figure 8 through Figure 11.

Figure 8 tracks whether there is a collision or fire for a ship carrying radioactive material (TNPP). The RAM (radioactive materials) ship branch would represent the ship carrying the TNPP in this figure. Figure 9 continues the logic tree from the top right RAM ship branch of Figure 8. Figure 10 continues the oil tanker logic branch from Figure 8 on the right, while Figure 10 covers the Fire/Sink branches on the right of Figure 8.

Specifically, Figure 9 takes into account the location of the cargo/cask (TNPP) when the ship carrying a TNPP is struck by another ship. Depending on the location where the striking boats hull is, additional analysis would be needed to determine if the TNPP would be damaged or not.

The oil tanker branch displayed in Figure 10 is an event (fire) that was not found to have occurred during the writing of SAND98-1171 nor was it found to have happened according to S&P Global data. In this scenario, the ship carrying the TNPP would strike the oil hold of an oil tanker. This scenario could lead to a long duration fire, despite there being no record of such an incidence when SAND98-1171 was published. This improbable scenario does provide insight into the conservative construction of the event tree.

These event trees were developed for SAND98-1171, but are still generally applicable to data from S&P Global and NTS, even though neither has never recorded such an incident.

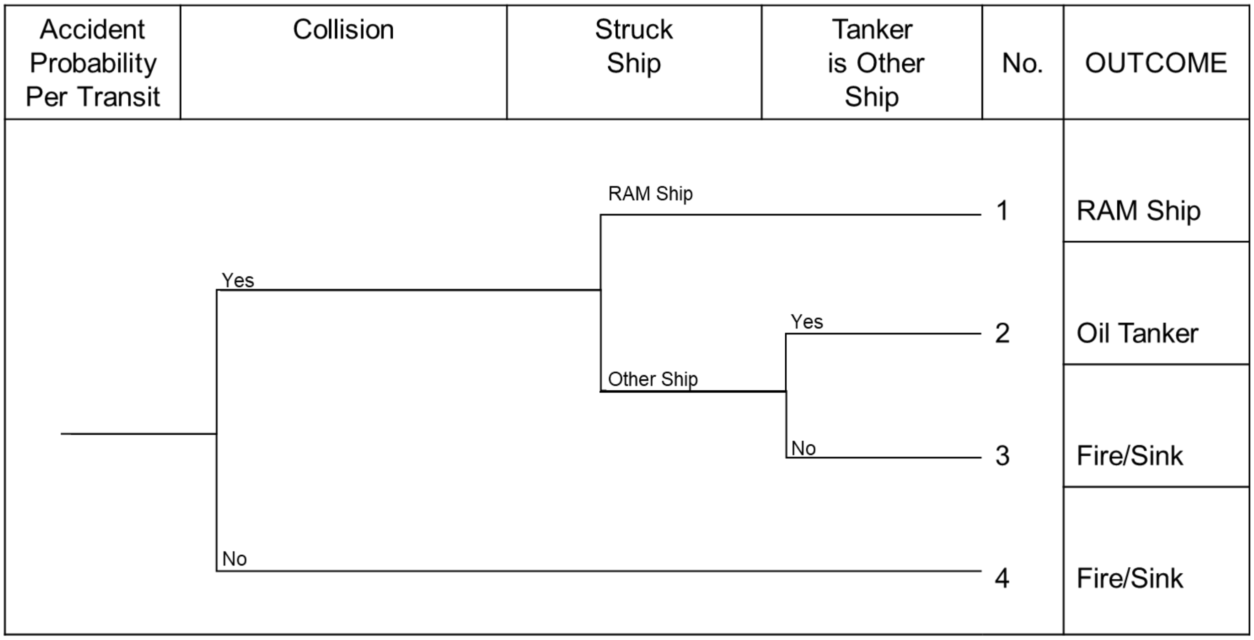

Figure 10. Ship Tree (SAND98-1171)

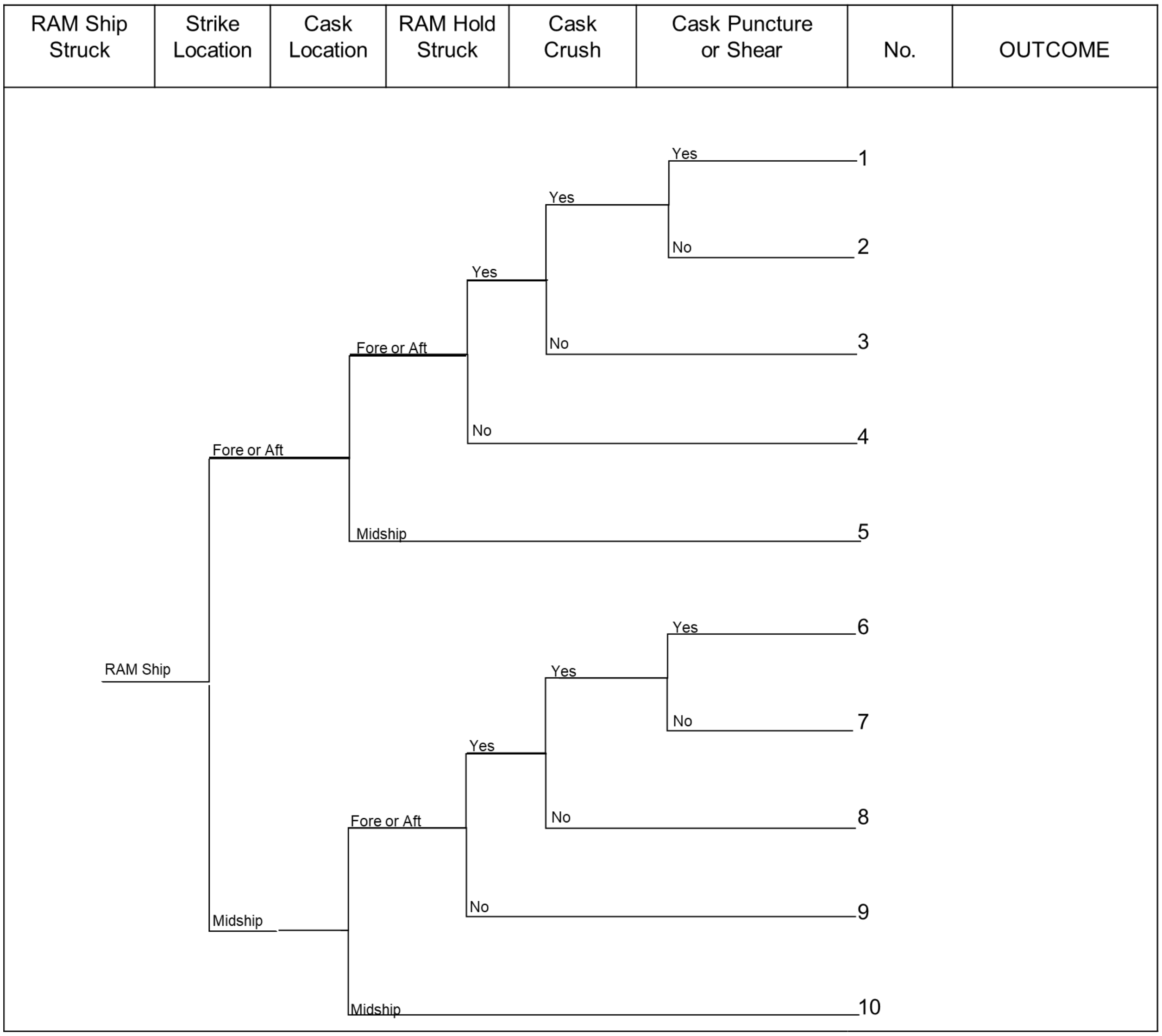

Figure 11. Radioactive Material Ship Tree (SAND98-1171)

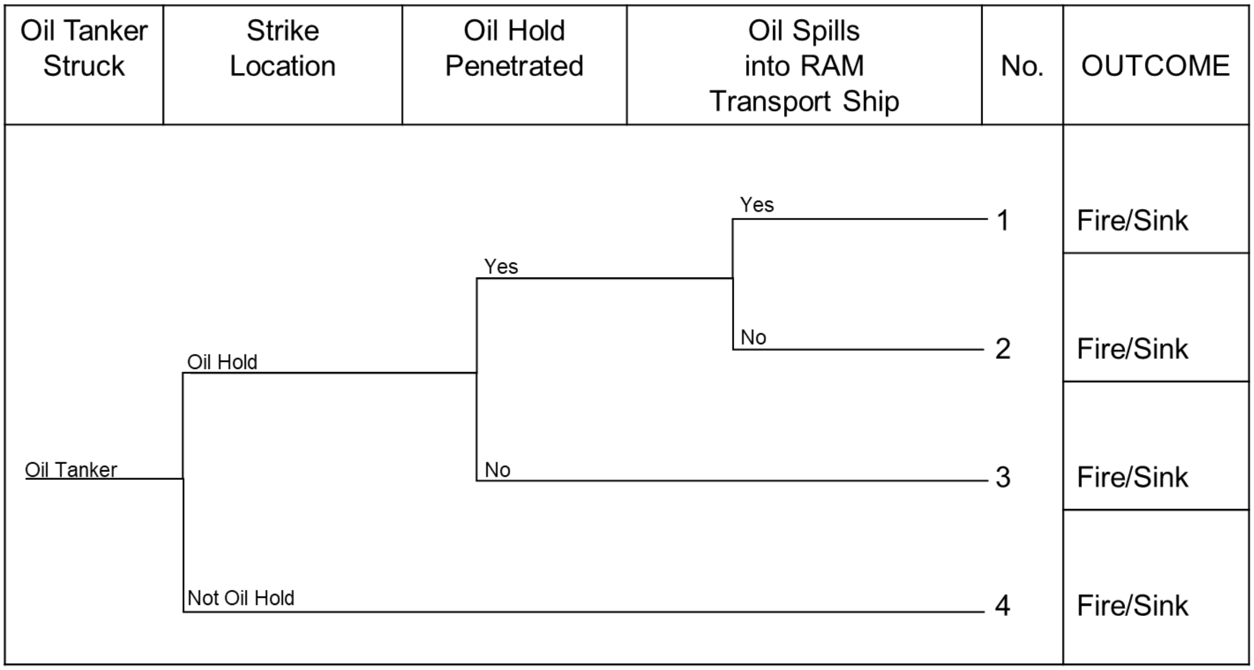

Figure 12. Oil Tanker Tree (SAND98-1171)

Finally, Figure 11 looks at fire as an accident scenario whether caused by a ship strike or otherwise and the possibility of damaging the TNPP and potentially sinking the ship.

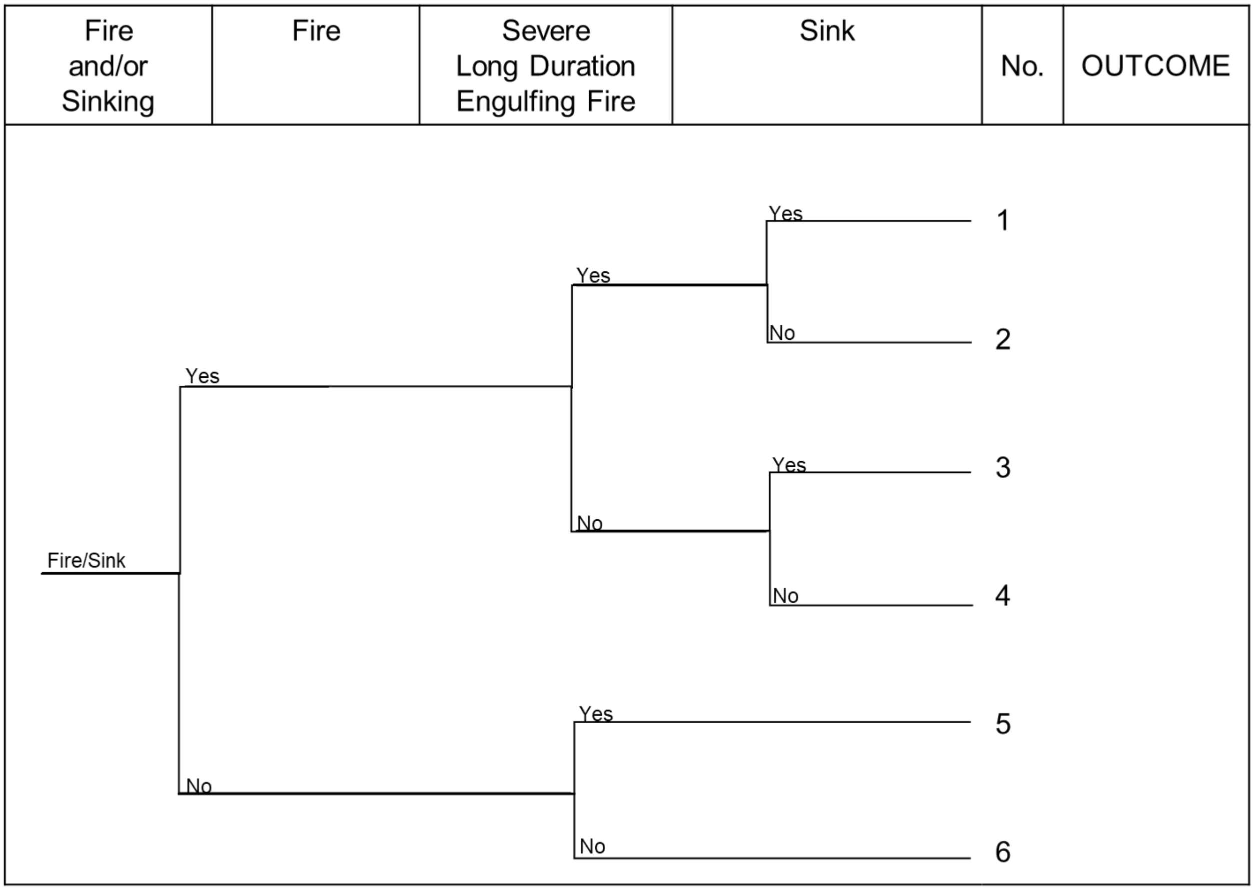

Figure 13. Fire/Sink Tree (SAND98-1171)

Dozens of scenarios are possible from Figure 8 through Figure 11. It is noted that these event trees were not originally developed for transportation of a TNPP, but for traditional radioactive material such as SNF, so it is conceivable that new accident scenarios are possible based on the TNPP design itself and its potential safety functions beyond containment, shielding, or subcriticality such reactor cooling. In such a case, events trees could be adjusted with custom TNPP needs.

2.3.5 Development of Maritime Branch Scenario Probabilities

Probabilities are intended to be assigned to the branches depicted in Figure 8 through Figure 11 above using individual event values previously calculated from NTS, S&P Global, and SAND98-1171 data. Specifically, ship collision, hull penetration, TNPP strike probabilities, fire spread, etc. can be assigned to the branches. Table 14 is an example where the ship carrying the TNPP is struck, and the potential for the TNPP to be significantly crushed, sheared etc. is brought to light.

Table 14. Scenario Event Probabilities (Table 8-1 from SAND98-1171)

Event	Probability
A ship collision occurs	$P_{collision}$
The radioactive material (RAM) ship is the struck ship	$P_{RAM\ ship\ struck}$
The strike location is midship	$P_{strike/midship}$
The RAM cask location is midship	$P_{cask/midship}$
The RAM hold is struck	$P_{RAM\ hold\ struck}$
Cask crush occurs	P_{crush}
Cask puncture or shear occurs	$P_{puncture/shjear}$
A fire starts on the RAM ship, spreads to the RAM hold, engulfs the cask, and then burns hot enough and long enough to increase radioactive release from the failed cask	$P_{severe\ engulfing\ fire}$
The RAM ship sinks	P_{sink}

2.3.5.1 Collision Probabilities

As mentioned previously, the work by Christian and Kang 2017b proposed a more sophisticated model when examining ship to ship collisions based on Monte Carlo simulation and examined the crossing of sea routes between ships and congested waterways. This methodology was not validated with actual casualty data. A sophisticated model for this recent work is not recommended for two reasons: (1), data from NTS, SAND98-1171, and S&P Global indicate little to no incidents of this type for LNG and LPG tankers and provide conservative estimates as surrogates to INF 3 ships, and (2), NTS, SAND98-1171, and S&P Global casualty records don’t provide enough information to support such a model. Thus, the same modelling approach used for ship to ship collision applied in SAND98-1171 of simply calculating collisions/nautical mile for LNG and LPG tankers is deemed acceptable. No ship to ship collisions involving INF 3 vessels were reported according to NTS.

Assuming that the ship carrying the TNPP is struck, the probability that the TNPP will be affected depends on the hold in which it is located and the potential for breach. Previous work (SAND98-1171) assumed that a cask would be placed along the centerline of the ship in midship hold. It also assumed that the chances that the ship carrying radioactive material has a 50-50 chance of being the struck ship, and the chances that a given hold is struck is proportional to the hold length divided by the length of the ship. Specifically, if the ship carrying the TNPP is struck by another ship, the probability that the TNPP will get crushed/overrun depends on its location within a hold and the ability of striking ship to penetrate the hull of the ship carrying the TNPP. A hull penetration methodology was presented in SAND98-1171 based on research by Minorsky (Minorsky 1959). This was then used to calculate pertinent probabilities of striking cargo like a TNPP. Here, the same could be done assuming that INF 3 vessel/TNPP characteristics were available. Thus, the same approach developed in SAND98-1171 is recommended here for INF 3 vessels carrying an TNPP. A resulting set of probabilities like those shown in Table 15 for a ship weighing 1,740 tonnes that is assumed to have been struck while transporting RAM could be developed for an INF 3 ship assuming data of TNPP and vessel characteristics were available.

Table 15. Probability of Initiating a Cask Crush Event in the 1,740 Tonne (1,050 TDW) Freighter Given That a Collision Has Occurred and Cask Tiedowns Hold. (Table 6-14a from SAND98-1171)

Event	No Cargo	Light Cargo	Medium Cargo	Heavy Cargo
Cask Overrun	0.152	0.152	0.000	0.147
Cargo Goes Solid	0.000	0.000	0.124	0.000
Total Probability	0.152	0.152	0.124	0.147

However, the methodology in SAND98-1171 can be improved using newer research results found in Christian and Kang (Christian and Kang 2017a). Their research indicates that the worst location for a SNF cask in terms of impact energy in a collision is when the SNF cask is located closest to the center of mass of the ship carrying it (SNF casks stored at the bow were found to have a reduced risk of damage). The same research varied stowage location, loading order, and number of SNF casks, as well as the speed of the ship carrying the casks and found that the damage that a SNF cask may suffer is proportional to the velocity of the ship transporting the SNF cask. Damage odds were found to increase as number of casks were increased and certain impact angles were found to impart more impact energy than others. This work, and the work done by SAND98-1171, assumed that impact angles between ships is random, and thus impact angles have a uniform distribution, although, both works indicate that ship captains try to alter direct strikes between ships, thus reducing the force experienced by the SNF casks but this could not be verified with S&P Global data or SAND98-1171 data.

Since TNPP prepared for transport are expected to share similarities to a transported SNF cask, a specific ship/TNPP configuration carrying a TNPP with altered stowage location, speed, angle of collision etc. could be studied (for say an INF 3 ship) using these latest developments in order to demonstrate lower probabilities of release if desired. Such an effort is left to future work.

2.3.5.2 Fire Probabilities

Incidents of fire per nautical mile were calculated above. Values based on LNG and LPG tankers are conservative when compared to INF 3 (NTS data) as no incidents were recorded by NTS to date.

While data from S&P Global, NTS, and SAND98-1171 indicate no fires have been recorded aboard LNG and LPG tankers, if a fire were to occur on a INF 3 vessel, the approach described in Chapter 7 of SAND98-1171 for fire spreading is reasonable. It is based on the number of holds the ship has, the chance that fire started in one hold and spread to another, whether the fire equipment on board is successful in mitigating fire, etc. Resulting fire probabilities were calculated for a given ship per SAND98-1171, however, no casualty data was used to verify the model. The equation for this probabilistic approach is:

$$P_{Fire} = P_{\text{System}} P_{St,L_{22}} \left(P_F P_{O_2} P_{Ex}\right)_{L_{22}} \left(P_F P_{O_2} P_{Ex}\right)_{L_{32}} \left(P_F P_{O_2} P_{Ex}\right)_{L_{31}} P_{Csk,L_{31}} \quad \text{Equation 1}$$

P_{System} = the probability that the ship is equipped with a fire suppression system

$P_{St,L_{22}}$ = the probability that the fire starts in compartment L22

$P_{Csk,L_{31}}$ = the probability that the RAM cask is located in compartment L31

P_F = the probability required fuel is present in the indicated compartment Lhd

P_{O_2} = the probability required air is present in the indicated compartment Lhd

P_{Ex} = the probability that the fire suppression system in compartment L_{hd} doesn't operate

Where L_{hd} represents the location of the compartment at deck *d*, and hold *h*. For this approach to be feasible, the specifics of the INF 3 vessel and TNPP would have to be known. It is noted that NTS INF 3 ships have additional firefighting capabilities which may minimize/mitigate any major fire damage resulting in significant release probabilities.

2.3.5.3 Probability of an Accident Leading to Release

Ultimately, the consequence that is being tracked via event trees is the probability of release of a source term denoted as $\mathrm{P_{release}}$. The methodology recommended in this plan to determine release is the same as that described in SAND98-1171. Event probabilities are used to calculate scenario probabilities which lead to accident consequences and is expressed in the equation below. Here, a sequence of events that could lead to a potential release of source term is noted as:

$$\mathrm{P_{STj}} = \mathrm{P_{Acc}} \prod_{k=1}^{n} \mathrm{P_{jk}} = \mathrm{P_{Acc}} F_{\mathrm{Sev,j}} \quad \text{Equation 2}$$

where:

$\mathrm{P_{STj}}$ = probability that a maritime accident leads to the release of a radioactive source term of specific composition and size.

$\mathrm{P_{Acc}}$ = probability of the initiating event

$\mathrm{P_{jk}}$ = probability of the n events in the sequence of events initiated by the accident culminates in the release of the j^{th} radioactive source term

$F_{\mathrm{Sev,j}}$ = product of all the events in the sequence that follow the initiating event.

Using the two scenarios which form the basis of Table 14, the above equation can be broken out specifically for each of the two events: The scenario in which the vessel that is carrying the TNPP is struck (RAM ship struck in Table 14) and fails to crush, puncture or shear the TNPP, and an extension of the previous scenario, where severe fire engulfs the TNPP (RAM cask) but does not sink the ship that is carrying it. Figure 13 shows what the equation looks like for each event.

$$P_{\text{release/collision only}} = P_{\text{collision}}\, P_{\text{RAM ship struck}}\, P_{\text{strike/midship}}\, P_{\text{cask/midship}}\, P_{\text{RAM hold struck}}\, P_{\text{crush}}$$
$$= P_{\text{collision}}\, F_{\text{severity/ collision only}}$$

where

$$F_{\text{severity/ collision only}} = P_{\text{RAM ship struck}}\, P_{\text{strike/midship}}\, P_{\text{cask/midship}}\, P_{\text{RAM hold struck}}\, P_{\text{crush}}$$

and

$$P_{\text{release/collision + fire}} = P_{\text{collision}}\, P_{\text{RAM ship struck}}\, P_{\text{strike/midship}}\, P_{\text{cask/midship}}\, P_{\text{RAM hold struck}}\, P_{\text{crush}}$$
$$\times P_{\text{puncture/shear}}\, P_{\text{severe engulfing fire}}\, (1.0 - P_{\text{sink}})$$
$$= P_{\text{collision}}\, F_{\text{severity/ collision + fire}}$$

where

$$F_{\text{severity/ collision + fire}} = P_{\text{RAM ship struck}}\, P_{\text{strike/midship}}\, P_{\text{cask/midship}}\, P_{\text{RAM hold struck}}\, P_{\text{crush}}$$
$$\times P_{\text{puncture/shear}}\, P_{\text{severe engulfing fire}}\, (1.0 - P_{\text{sink}})$$

Figure 14. Release Probabilities Using Equation 1 for Two Scenarios (EQ 8.1-8.4 of SAND98-1171)

2.3.6 Maritime Accident Consequence Analysis

In transportation PRAs performed for highway transport, consequence analysis is based on determining the source term for the release[27], 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):

$$\text{Source Term} = \text{MAR} \times \text{DR} \times \text{ARF} \times \text{RF} \times \text{LPF} \qquad \text{Equation 3}$$

where, MAR = material at risk, DR = damage ratio, ARF = airborne release fraction, RF = respirable fraction, and LPF = leak path factor.

The five-component equation, while traditionally developed for non-reactor nuclear facilities, can be applied to a TNPP transportation accident analysis.

Section 4.6.1 in Coles et al. (2022) contains a detailed discussion of the use of the five-component equation to estimate source terms in a highway transportation PRA.

For maritime transport, consequence analysis is expected to be similar to what has been provided in SAND98-1171, which has been stated as:

[27] Airborne release assumes population centers are nearby, as is often found near ports. An analysis to address release into the marine environment (due to ship foundering say) is not addressed in this report and may not be necessary if the release is assumed to occur far enough away from population centers, or if the package can be shown to be able to withstand hydrostatic pressures at depth due to the local bathymetry near population centers.

$$M_{ST} = \sum_i M_{STi} = \sum_i I_i F_{mci} F_{cei}$$ Equation 4

where M_{ST} is the release to the environment, I_i is the inventory of a given radionuclide, F_{mci} is the fraction that is released to the cask interior (e.g., the TNPP reactor vessel in our example) for that given radio nuclide, and F_{mci} is the fraction released from the cask to the environment from a failed cask (e.g., failed TNPP containment boundary).

The source term analysis will require information such as leak path factor or attenuation factors, damage probabilities, and release fractions for TRISO particles, compacts, or the TNPP 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.

3.0 Discussions of Modeling Uncertainties for Maritime Based Transport

This section discusses 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 decision making. 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 decision making.

With respect to casualty data, the primary source of the maritime PRA effort presented here is from NTS. Having no recorded incidents, sensitivity studies for this source of data are not quite as useful as source data contained within SAND98-1171 or newer S&P Global data which does report just a handful of incidents[28]. Previous work has shown that fire/ship collisions are far less frequent with ships that share INF 3 characteristics such as being double hulled and having experienced crew such as LNG and LPG tankers. That is, LNG and LPG tankers have fewer incidents per nautical mile of travel as compared to the general fleet. SAND98-1171 reported for the general fleet of vessels that collisions occur close to approach waters near ports, a natural conclusion given the closer proximity to other ships based on ship traffic in the area as shown in Figure 7. SAND98-1171 found that the size of the port made no difference. In essence performing a PRA with LNG and LPG tanker data is in effect a sensitivity study in and of itself. The incidents reported by S&P Global occurred at port and are too sparce to perform further analysis.

It is anticipated that the damage model used for the TNPP will be sensitive to not just TNPP characteristics but colliding ship characteristics such as dimensions, speed, and weight. A sensitivity study with respect to damaging the TNPP could be performed in this case but is beyond the scope of this plan and would require additional INF 3 vessel and TNPP design specifics and is thus left as potential future work. Regardless, the damage model of the TNPP itself can be thought of as less of a factor in this PRA study because work by NTS indicates not a single incident has occurred, while S&P Global data reports three incidents occurred 25+ years ago, and LNG and LPG incidents which serve as conservative surrogate estimates are very low. That is in terms of a licensing strategy, it may not be necessary to model a specific TNPP if reported/calculated accident rates are accepted as being exceedingly low by the regulator to then not warrant additional investigation. Thus, dependent release rates may not need to be modeled either. However, a damage model may still be desired by the regulator to demonstrate reasonable assurance of safety. In this case, a sensitivity/uncertainty study model could be employed for the damage model used to represent the TNPP.

[28] The event described earlier in this report for the Mont-Louis was captured by S&P Global. The Mont-Louis is described as a cargo ship in their system (not a nuclear fuel carrier ship) which is the focus of this report. This highlights the important fact that not all radioactive material is shipped just by nuclear fuel carriers.

4.0 Identification of Potential Compensatory Measures for Maritime Transport

This section discusses potential compensatory measures that could be credited in the TNPP transportation PRA or as a defense-in-depth measure for both highway and maritime transport.

In Coles et al. (2022) and Maheras et al. (2023), potential compensatory measures were identified for highway transport of a TNPP:

- TNPPs containing irradiated fuel shipped by highway would contain a HRCQ of radioactive materials (> 3000 A2) and would need to meet the routing requirements in 49 CFR Part 397. This requires transport to be conducted using interstates, beltways around cities, and State identified preferred routes. Transport on these types of roads would be a potential compensatory measure because these types of roads are typically of higher quality and capacity than other roads.

- A TNPP containing irradiated fuel shipped by highway would also likely be subject to a CVSA Level VI inspection (CVSA, 2020). This inspection would also be considered as a potential compensatory measure.

- TNPPs transported by highway would also likely be overweight/over-dimension loads and would require state permitting when transported by highway. Typical permit conditions include maximum length, width, and height requirements; escort vehicle requirements; pole car requirements; law enforcement escort requirements; and route survey requirements. These permit conditions would be considered as potential compensatory measures.
- Real-time health/fitness onboard monitoring/diagnostics of microreactor package.
- Escort the TNPP forward and aft for the entire route.
- 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.
- Consider rolling road closures.
- Avoid shipping during known times of high traffic volume.

- Conduct training for emergency responders along the route.

The potential compensatory measures that have been developed for highway transport can be adapted for maritime transport. A list of possible compensatory measures is provided below; this list can be modified and implemented based on the results of the maritime transportation PRA.

- Class INF 3 ships are purpose-built ships with many safety features that other vessels may not have. There are existing transportation packages certified to carry nuclear material, however, not all require INF 3 ships for transport. Some features of a Class INF 3 ship include:
  - Improved damage stability
  - Improved fire protection measure
  - Temperature control of cargo
  - Structural enhancement above typical cargo ships
  - Enhanced cargo securing requirements
  - Electrical supplies (spare electrical generators for firefighting)
  - Radiological protection equipment
  - Management training and shipboard emergency plan
- Navy/U.S. Coast Guard to provide escorts.
- Although NTS data has no incidents, ship sailing route could be chosen to be between ports that are less frequented, minimizing ship collision.
- Avoid shipping from congested areas.
- Ship at various times or days of the year to avoid other traffic vessel traffic.
- Conduct training for emergency responders at port facilities.
- Operate INF 3 Class ships in pairs to provide mutual support if necessary.

In addition, NTS (PNTL) ships were designed with wide consultation with Lloyd’s of London, the Salvage Association and leading salvage companies. They have cargo compartments protected by a double hull configuration and duplication and separation of all essential systems. This means that if any important system fails during a voyage, there is always a back-up ready to be brought into operation. In addition, Each PNTL ship undergoes regular maintenance inspections and operational equipment is checked and tested prior to each voyage from PNTL’s home port of Barrow, England.

5.0 Defense-in-Depth and Safety Margin Considerations

The 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 TNPPs.

The primary defense in depth considerations come from the design features of NTS' INF 3 vessels themselves. Per PNTL (2013), their fleet of INF 3 ships have the following back up safety features:

- Double hulls and hull reinforcement to withstand collision damage.
- Enhanced buoyancy to ensure the ship will continue to float even in extreme circumstances.
- Dual navigation, communications, cargo monitoring and cooling systems.
- Satellite navigation and tracking.
- Twin engines, rudders and propellers.
- Additional firefighting equipment, including a hold flooding system and spare electrical generators.
- Operating the INF 3 Class ships in pairs to provide mutual support if necessary could also be considered a defense-in-depth measure.

In addition to manual radiation monitoring, there are fixed radiation monitors for each hold that are linked to an alert system on the bridge. The PNTL ships are equipped with a satellite weather routing system and also use professional shore-based maritime services that provide up to the minute local meteorological data. These enable the ships to follow the safest routes and avoid severe weather patterns.

Defense in depth also comes in the form of training which is conducted every year to test the company's overall response activities, the communication system, the expertise of team members and the ships' crews and the performance of equipment.

6.0 Conclusions

From a maritime point of view, a PRA licensing strategy should be to present results on NTS data as a corner stone of the application (supported by S&P Global data for nuclear fuel carriers). NTS' track record suggests that their maritime shipments of nuclear material is extremely safe as no events/casualties have ever been recorded over its 50 years of experience shipping a variety of nuclear materials including plutonium and SNF, covering 5,000,000+ nautical miles and over 180 shipments using INF 3 ships. Thus, the PRA licensing strategy should be based not only on NTS' incident free history, but on its current use of INF 3 vessels that already meet the requirement to perform a RAM packaging shipment by sea as TNPP containing its SNF would be highly similar.

However, PRA results based on data from SAND98-1171 and Gucma and Mou (2022) for LNG or LPG vessels should also be presented as a conservative estimate of accident rates since as compared to the general fleet, LNG or LPG accident rates are lower and thus safer. This may be attributed to commonalities in build and crew capabilities with INF 3 ships. Recent results based on S&P Global data indicates that incident rates per nautical mile of travel for LNG or LPG vessels are very low and comparable to what was developed for SAND98-1171.

6.1 Future Work

For maritime transport, further work could be done to develop the damage model to the TNPP if a collision and/or fire were to occur when design information of the TNPP becomes available. Until then, probabilities developed here that would be used in determining release rates are conservative. Once developed, damage models can only strengthen the argument of a PRA based licensing approach since they are expected to further lower release probabilities. For maritime transport, the TNPP damage model would be expected to be sensitive to parameters such as velocity, materials of construction, etc. and could be further explored to minimize release probabilities and fractions. Additional information about the conveyance (INF 3 class vessel) would most likely be needed. For maritime efforts as described above, ship/TNPP configuration could be studied while varying stowage location, speed, angle of ship collision etc. in order to demonstrate lower probabilities of release.

As discussed in Coles et al. (2022), development of the highway transportation PRA for the Project Pele demonstration reactor is currently in its initial stages and has yet to be endorsed. However, the methodology, data, and results presented in Coles et al. (2022) are the most advanced to date and should be used to inform the development of a maritime transportation PRA.

While this plan has focused on the transportation of a TNPP via highway or by sea, the next two logical modes of transport not yet considered are rail and air transport. In the U.S., rail transport of TNPPs could potentially be viable if several TNPPs were being shipped from a factory to a depot or port. Air transport of a TNPP could potentially be viable for remote locations with limited highway or rail access and or/nonexistent navigable waterways, or for humanitarian and disaster relief. Of course, additional investigation and acquisition of data would be needed to develop the event trees and scenario probabilities to support resulting accident probabilities, release fractions, and accident consequences.

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