Microreactor Risk-Informed Transportation Package Approval Methodology

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Microreactor Topics

- Introduction
- Microreactor transportation
- Risk-informed transportation package approval process
- Maritime Scoping Study
- Marine Retrofit Study

Microreactors – Introduction

- Microreactors are a class of very small modular reactors targeted for non-conventional nuclear markets
  - Also known as transportable nuclear power plants (TNPPs)
- There are a variety of TNPP/microreactor/advanced reactor designs, including gas, liquid-metal, molten-salt, and heat-pipe-cooled concepts
- Potential microreactor/TNPP applications are:
  - Data centers
  - Remote communities
  - Mining sites
  - Remote defense bases
  - Back-up generation for power plants
  - Humanitarian aid and disaster relief missions

Key Attributes of Microreactors/TNPPs

- Microreactors/TNPPs have key features enabled by their small size that distinguish them from other reactor types mainly large reactors (LWRs) and small modular reactors (SMRs).
- These are:
  - Typically produce less than 50 MW electrical power
    - ✓ < 20 MW thermal (7 MW electric) regarded as transportable
  - Smaller footprint and emergency planning zone
  - Factory fabrication and fueling
  - Self-regulating (enabling remote and semi-autonomous microreactor operation)
  - Rapid deployability and availability during emergency response
  - Possible operation up to 10 years or more

Commercial TNPP Developers and Types

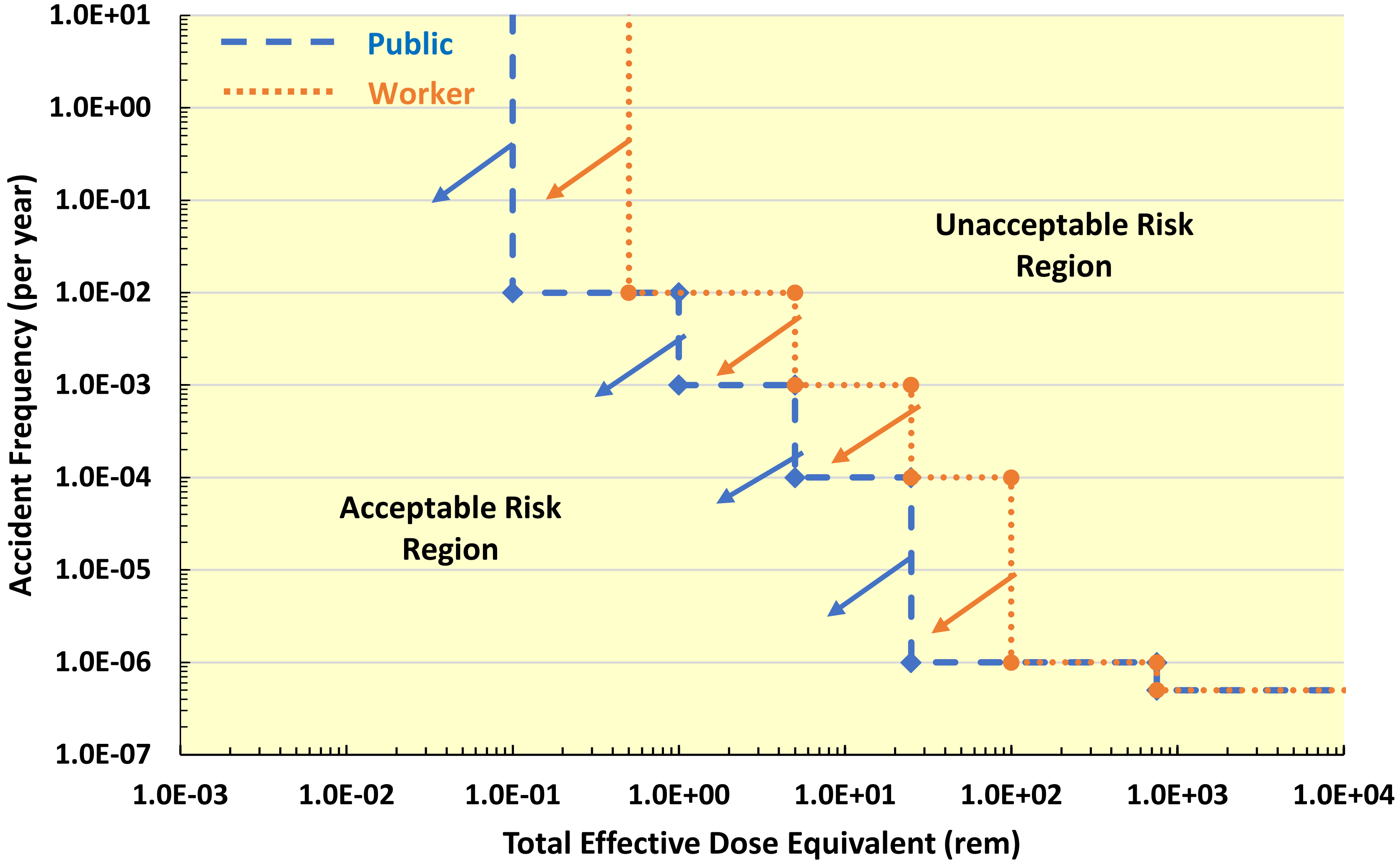
Developer	Name	Type	Power Output (MWe/MWth)	Fuel	Coolant	Moderator	Refueling Interval
Aalo Atomics	Aalo One	STR	7 MWe/20MWth	UO2	Sodium	H	3-5 years
Alpha Tech Research Corp	ARC Nuclear Generator	MSR	12 MWe/30 MWth	LEU	Flouride salt		intermittent
Antares Industries	R1	Sodium Heat Pipe	1.2 MWth	TRISO	Sodium	Graphite	
BWXT	BANR	HTGR	17 MWe/50 MWth	TRISO	Helium	Graphite	5 years
Deep Fission	DB-PWR	PWR	1-15 MWE	LEU	Water	Water	4-6 years
General Atomics	GA Micro	HTGR	1-10 MWe		Gas		
HolosGen	HolosQuad	HTGR	13 MWe	TRISO	Helium/CO2		10 years
Micro Nuclear, LLC	Micro Scale Nuclear Battery	MSR/Heat Pipe	10 MWe	UF4	FLiBe	YH	10 years
Nano Nuclear	Zeus/Odin	HTGR/MSR	1.0 MWe/2.5 MWth	UO2	Helium		
Nano Nuclear	LOKI MMR	HTGR	1.5-5 MWe	TRISO	Helium	Graphite	
NuCube	NuSun	Heat Pipe	1 MWe/3 MWth	TRISO	Sodium	Graphite	10+ years
NuGen, LLC	NuGen Engine	HTGR	2-4 MWe	TRISO	Helium		
NuScale Power	NuScale Microreactor	LMTM/Heat Pipe	<10 MWe	Metallic	Liquid Metal	Liquid Metal	10 years
Oklo	Aurora	SFR	15 MWe	Metallic (U-Zr)	Sodium		10+ years
Radiant Nuclear	Kaleidos Battery	HTGR	1.2 MWe	TRISO	Helium	Graphite	4-6 years
Nano Nuclear (formerly Ultra Safe Nuclear)	Kronos (formerly Micro Modular Reactor)	HTGR	3.5-15 MWe/10-45 MWth	TRISO	Helium	Graphite	20
Westinghouse	eVINCI	Sodium Heat Pipe	5 MWe/15 MWth	TRISO	Sodium	Graphite	8 years
X-Energy	XENITH	HTGR	5 MWe/10 MWth	TRISO	Helium	Graphite	3+ years

Microreactor Transportation

- Efficient, timely, and cost-effective deployment of microreactors requires that they be deployed containing their unirradiated (fresh) and irradiated (spent) fuel
- Transport of a microreactor containing its unirradiated or irradiated fuel raises many unique transportation regulatory issues
  - U.S. Nuclear Regulatory Commission transportation regulations in 10 CFR Part 71 largely revolve around shipping irradiated fuel in thick-wall pressure vessels *(transportation casks)*
  - A microreactor with its irradiated or unirradiated fuel contents is unlikely to meet the entire suite of NRC transportation regulatory requirements using traditional analytical methods
- Use of a *risk-informed transportation package approval process* coupled with Transportation Probabilistic Risk Assessment (PRA) methods will likely be needed to provide a regulatory licensing pathway through which microreactors containing their unirradiated and irradiated fuel will be demonstrated to protect public health and safety while being transported
  - Will require the use of compensatory measures
- Approach builds on well-established uses of PRA and adapts them to the transportation package approval process

Proposed Risk Evaluation Guidelines

- Phase 1: develop proposed risk evaluation guidelines
- Developed based on NRC and DOE risk guidance for licensing nuclear facilities
- Proposed guidelines are compatible with NRC nuclear safety goals, Qualitative Health Objectives, and NRC-proposed Quantitative Health Guidelines

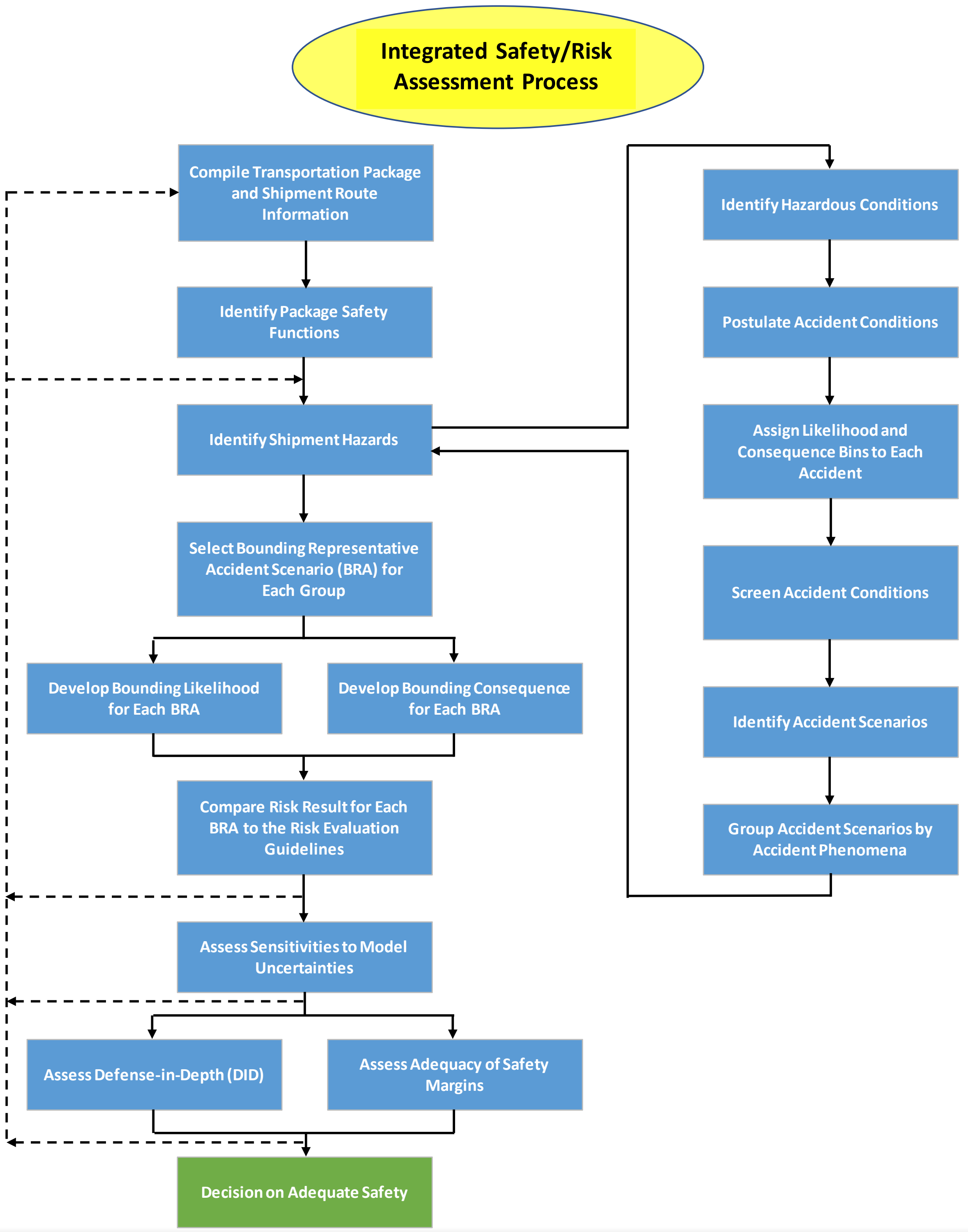


Proposed Risk Evaluation Guidelines

Acronyms: NRC – U.S. Nuclear Regulatory Commission; DOE – U.S. Department of Energy

Integrated Risk Assessment Process

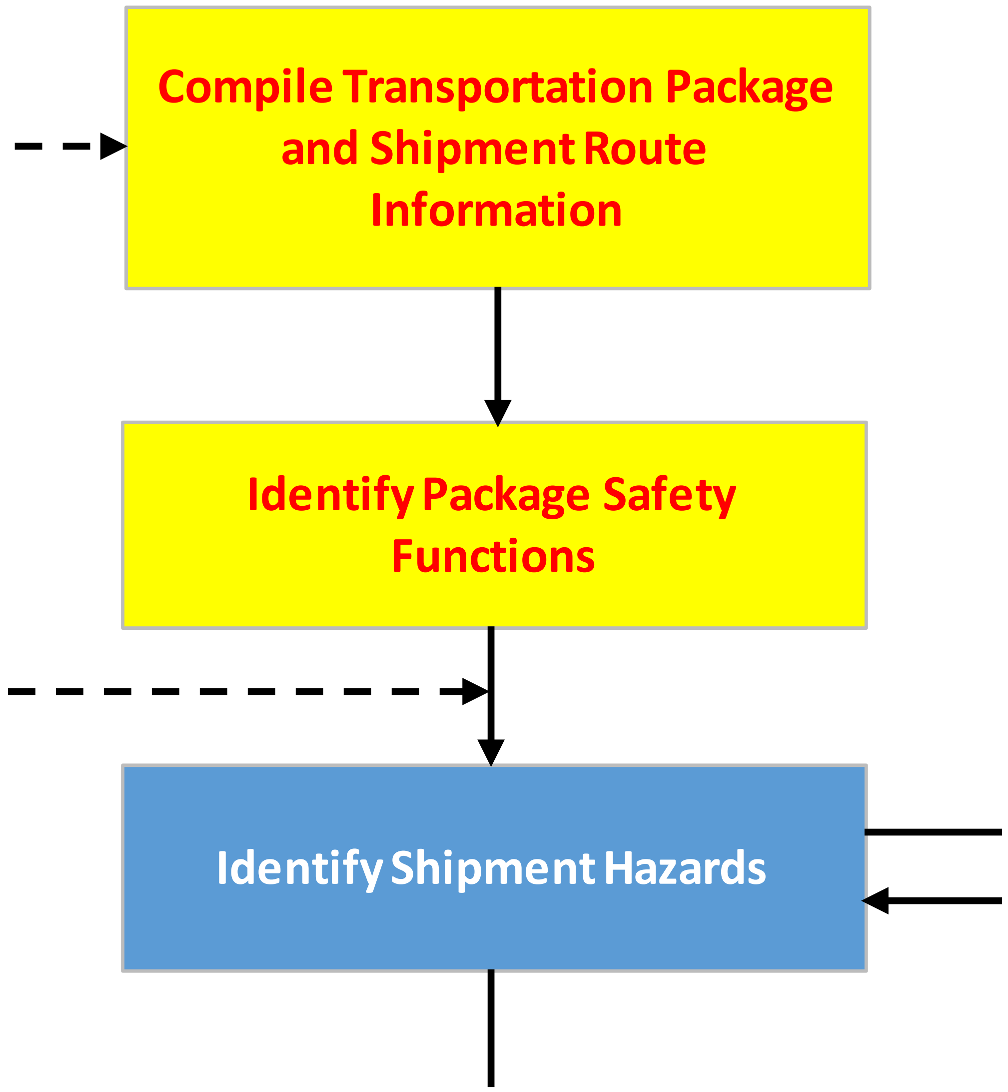
- Phase 2: develop an integrated risk assessment process
  - Based on probabilistic risk assessment (PRA) approaches and methods
- Uses standard methods acceptable to both NRC and DOE for assessing the risk of nuclear facilities
- Phase 3: demonstration implementation of the integrated risk assessment process on a hypothetical shipment of a TNPP/microreactor



Probabilistic Risk Assessment Development Process

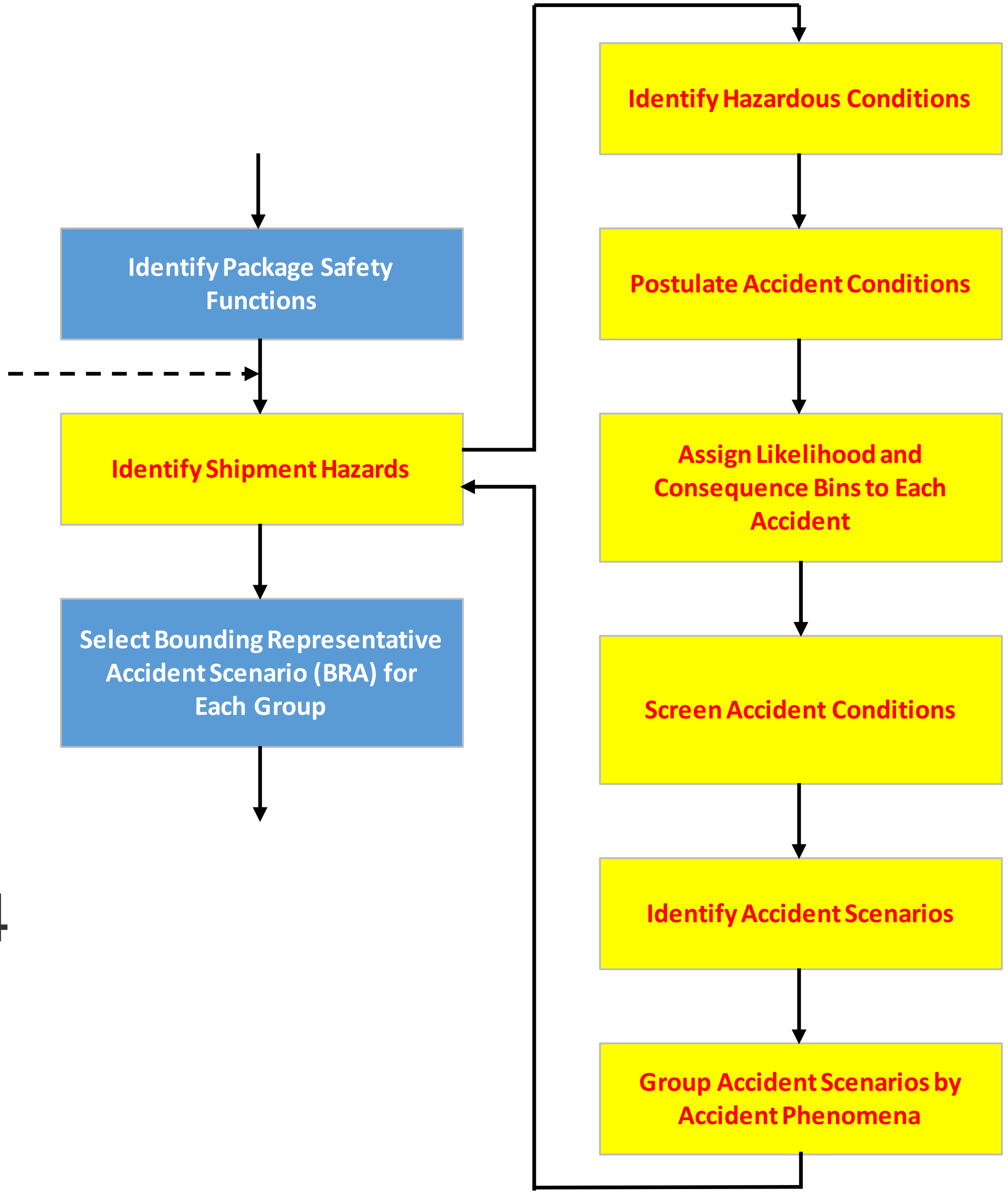
Step 1 – Compile TNPP and Shipment Route Information and Step 2 - Identify Package Safety Functions

- Step 1, Information Collection
  - TNPP transportation package (Reactor Module only)
    - ✓ system design and configuration information, estimated radionuclide inventory at various time periods following reactor shutdown, information on the process for preparing the module for shipment
- Step 2, Package Safety Functions
  - provide containment of radiological materials
  - provide radiation shielding
  - maintain a criticality-safe configuration
  - maintain adequate passive cooling

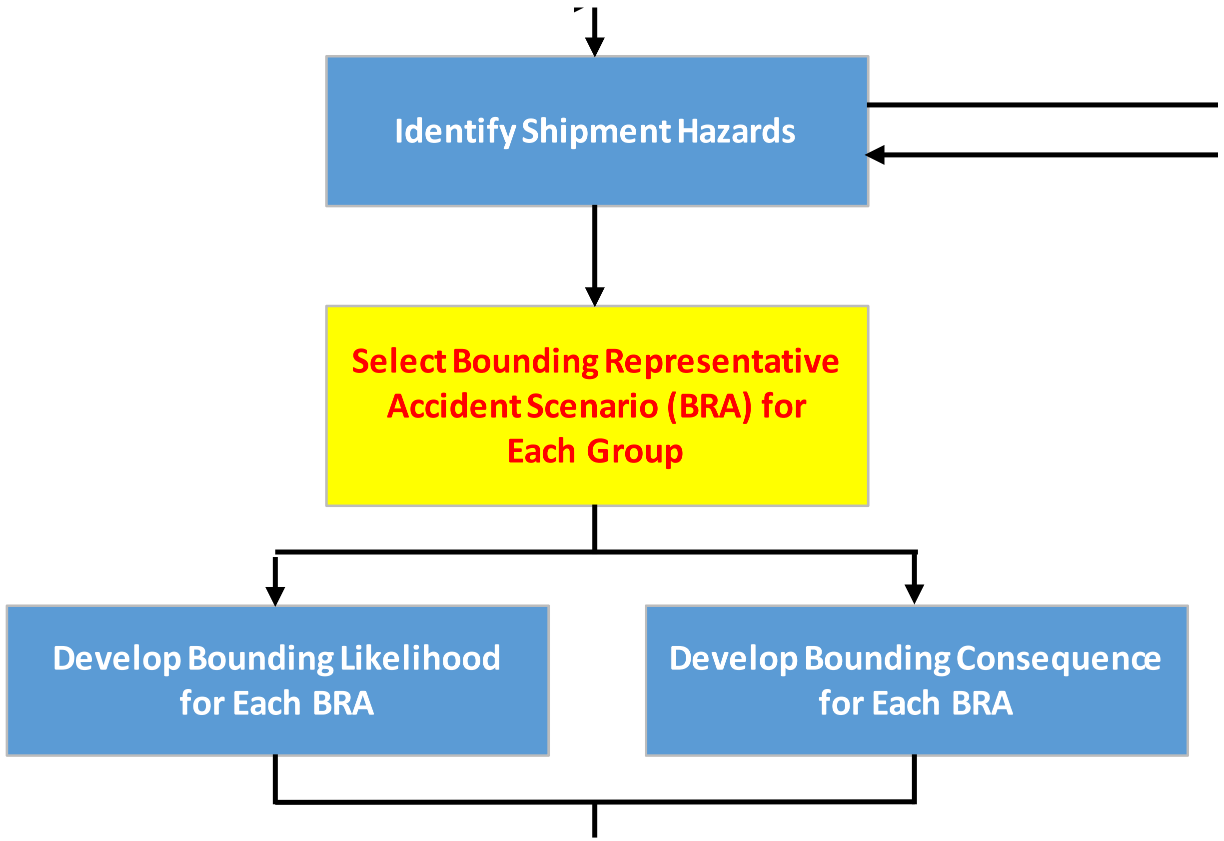


Step 3 – Identify Shipment Hazards

- Utilize standard hazards analysis (HA) approach
- Use of expert panels to identify and assess hazardous conditions that could occur during TNPP transport
- Complete hazardous condition evaluation worksheets
- Formulate hazardous conditions to contain information needed to define accident scenarios
- Total of 5 accident scenarios representing 4 accident phenomena classes were defined



Step 4 – Select Bounding Representative Accident Scenarios (BRAs) for Each Accident Phenomena Group

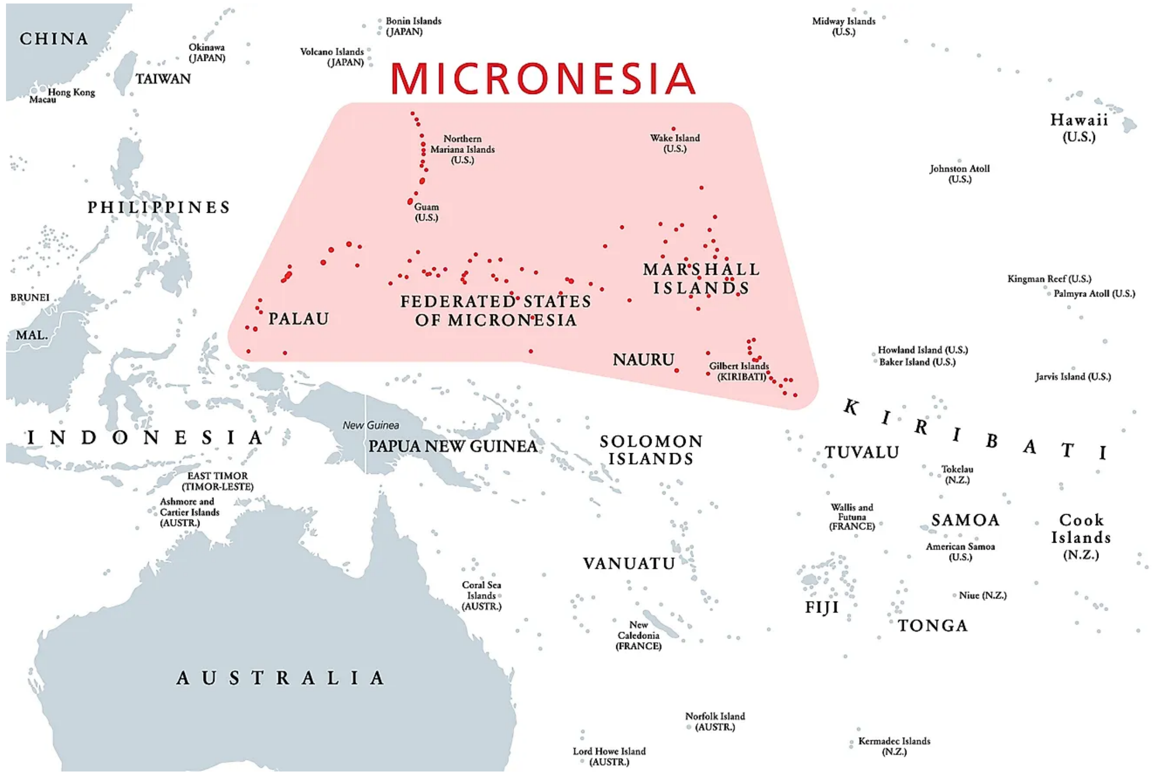


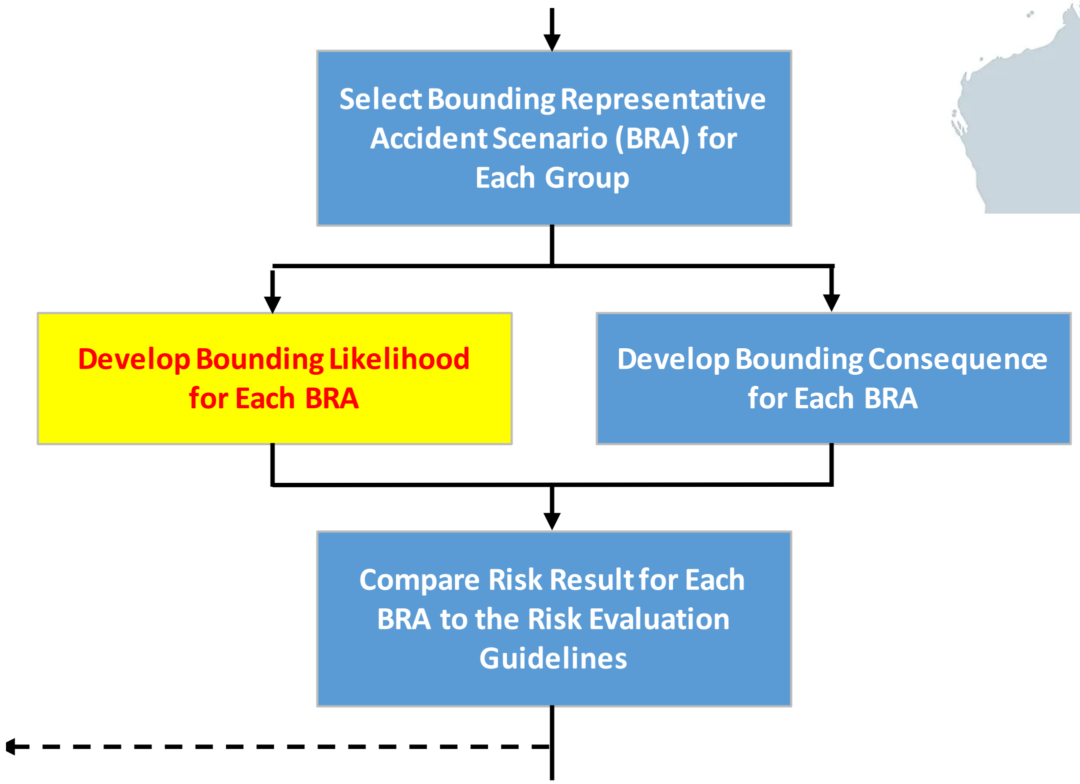
BRA ID	Description
1	Collision event.
2	Fire-only event.
3	Collision with fire event.
4	Crane drop during loading/unloading.

- Representative of a group of accident scenarios that are phenomenologically similar
  - But not overly conservative
- Bounds the risk of all accident scenarios in the group

Step 5 – Develop Bounding Likelihood for Each BRA

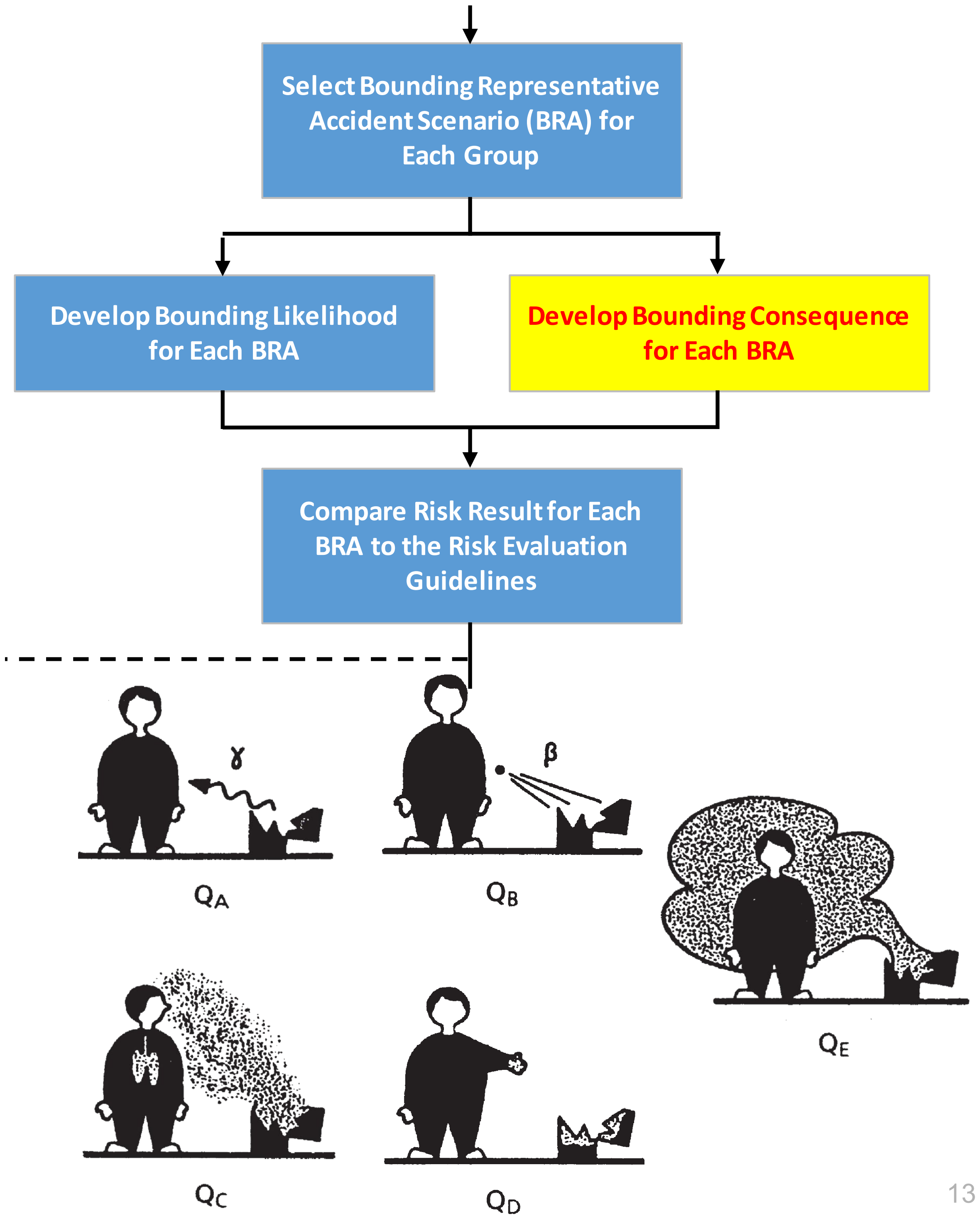
- Specific routing information
  - Route assumed transport from Military Ocean Terminal Concord (MOTCO) to Micronesia
- Maritime transportation accident rate data
  - Largely derived from LNG cargo ships
- Package-specific failures not in accident rate data
  - Internal-initiated fires, random failures, human error



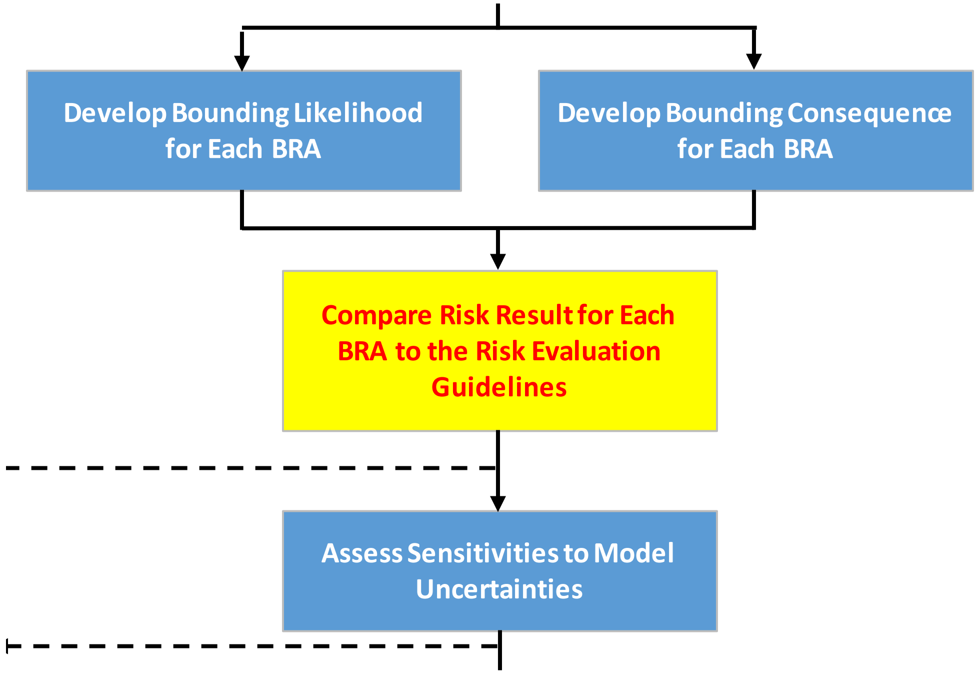


Step 6 – Develop Bounding Consequence for Each BRA

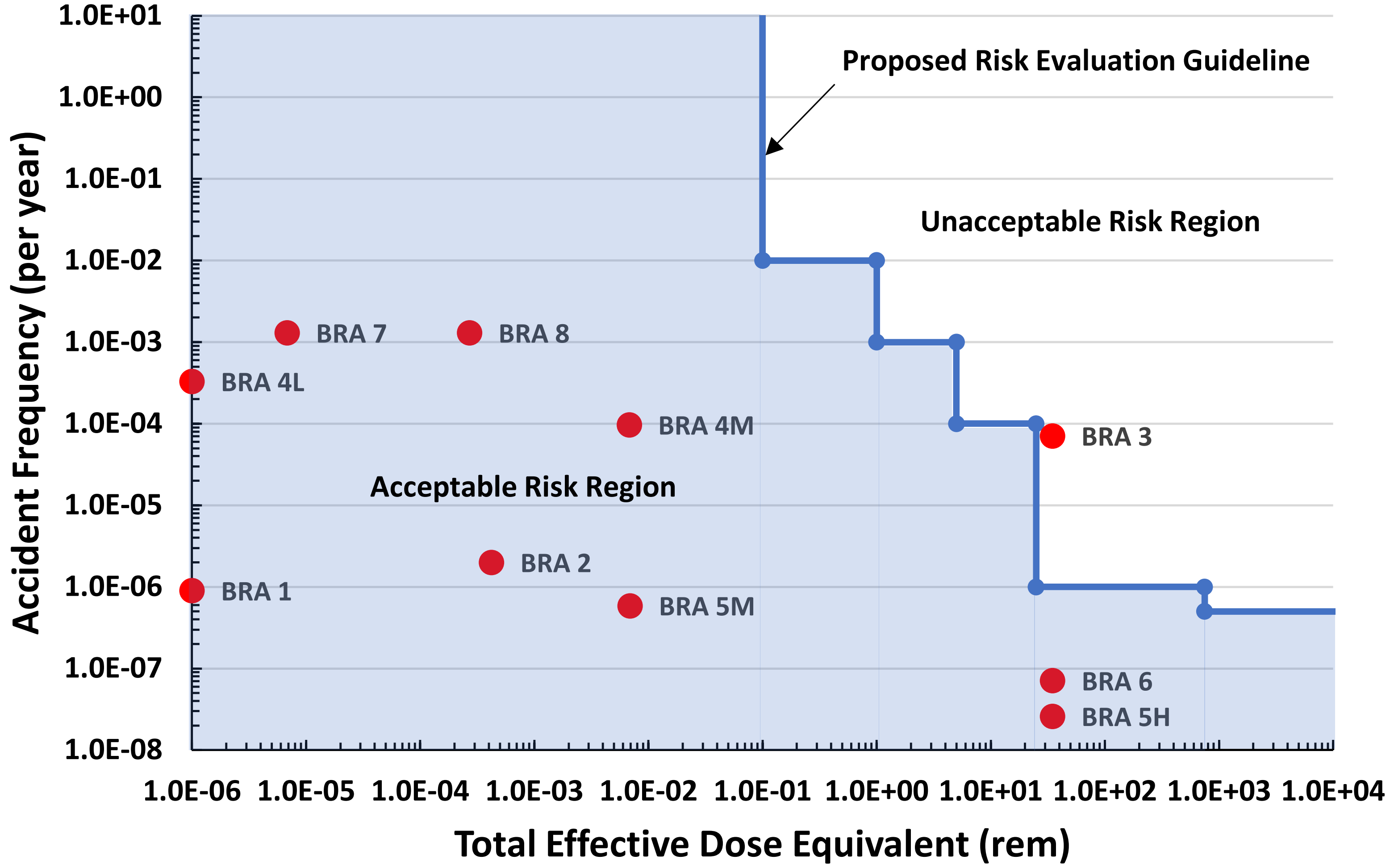
- Radiological dose pathways from IAEA SSG-26 (Q System) for developing A1 and A2 values (which are the same as in NRC regulations)
- Estimated effective doses for each pathway based on IAEA SSG-26 methods/data, with some refinements used to estimate the consequences for the public and from inhalation
- Used DOE/NRC methods/data to determine source term (e.g., MAR × DR × ARF × RF × LPF)
- Source term includes spent fuel inventory and inventories diffused during reactor during operation
  - Fuel (concerns about performance under mechanical impact)
  - Core/compact (concerns about fuel qualification)
  - Pressure Boundary (concerns about plating)



Step 7 – Compare Risk Results to Proposed Risk Evaluation Guidelines



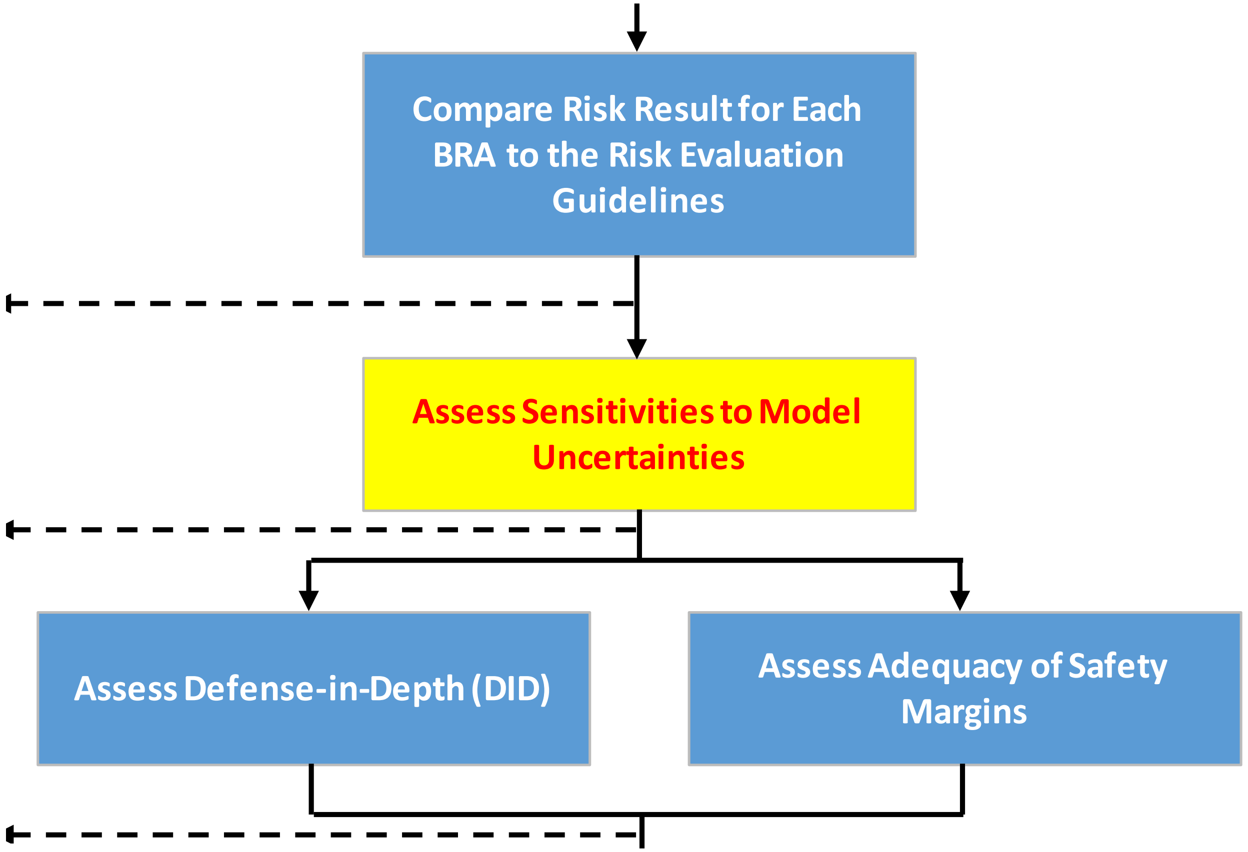
- Sum the likelihood of all accident scenarios included in each BRA
- Consequence is the maximum of the accident scenarios included in each BRA



Notational PRA Results for the Public

Step 8 – Assess Sensitivities to Model Uncertainties

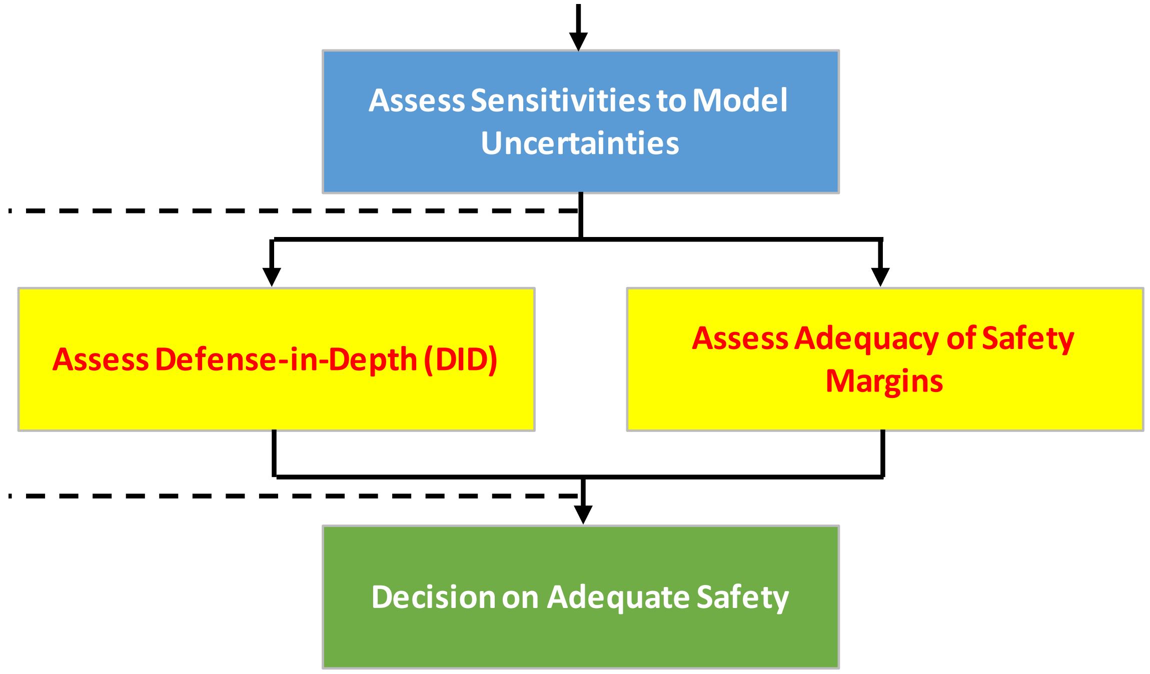
- Parameter uncertainty analysis (e.g., Monte Carlo analysis) typical of PRAs is not included in the methodology
  - Because each BRA is evaluated with a bounding estimate of the likelihood and consequence
- Sensitivity studies are to be performed to address the impact of key assumptions and sources of uncertainty



- For the demonstration implementation, the results of sensitivity studies were not available in time for this paper, but are currently being performed
  - Time after reactor shutdown when the reactor is shipped
  - Distance between the public and the TNPP transportation package
  - Variations in source term factors

Step 9 – Assess Defense-in-Depth
Step 10 – Assess Adequacy of Safety Margins

- DID is a design and operational philosophy that calls for multiple layers of protection to prevent and mitigate accidents
  - use of controls
  - multiple physical barriers to prevent release of radiation
  - redundant and diverse key safety functions
  - emergency response measures



- Safety margin is defined as a measure of the conservatism that is employed in a design or process to assure a high degree of confidence that it will perform a needed function
  - One approach often used is to demonstrate adherence to acceptable codes and standards

U.S. Department of Defense (DoD) Strategic Capabilities Office (SCO)

- Risk Informed Transportation Package Approval for Domestic Highway Shipment of a TNPP Methodology Document
  - Final report published and docketed
    - ML24268A101 - 1. PNNL-36380, "Development and Demonstration of a Risk Assessment Approach for Approval of a Transportation Package of a Transportable Nuclear Power Plant for Domestic Highway Shipment August 2024" (8/21/2024)
    - ML24268A102 - 2. List of Updates to 2024 Version of Pele PRA Report (8/21/2024)
  - Endorsement letter published and docketed
    - Endorsement of the Risk Assessment Approach for Transportation Package Approval of the Project Pele Transportable Nuclear Power Plant for Domestic Highway Shipment. Docket No. 71-9396. U.S. Nuclear Regulatory Commission. Washington, D.C. October 7, 2024. https://www.nrc.gov/docs/ML2427/ML24271A054.pdf

Why Is Maritime Transport Necessary?

- Many deployment scenarios for microreactors involve transport to locations outside the continental U.S.
  - Deployment outside of the continental U.S. of an unirradiated microreactor could be by air or ship
  - Redeployment or return back to the U.S. would require transport by ship
    - ✓ Radiation dose rates and shielding weights
    - ✓ Pu air transport regulations
  - This would be the case for civilian or military microreactors
- For these scenarios, the microreactor is considered cargo and does not provide propulsion or is a component of a floating nuclear power plant (FNPP)

Photo courtesy of World Nuclear Transport Institute (WNTI)

Risk-Informed Maritime Transport

- PNNL developed a plan for establishing a licensing pathway for a transportable nuclear power plant, containing its unirradiated and irradiated fuel, as a transportation package for maritime transport using a PRA framework to meet the regulatory requirements of 10 CFR Part 71
- Plan addresses
  - Maritime transportation PRA methodology, information, and data
    - ✓ Safety goals and risk evaluation guidelines
    - ✓ Potential accident scenarios
    - ✓ Maritime accident rate data and event trees
    - ✓ Maritime accident consequence analysis
  - Modeling uncertainties for maritime transport
  - Potential compensatory measures for maritime transport
  - Defense-in-depth and safety margin considerations
- PNNL currently conducting a scoping study to demonstrate the viability of a risk-informed approach for transportation package approval for maritime transport of a microreactor
- Scoping study being conducted for DoD SCO and Office of Chief Engineers, Nuclear Power Branch

Pacific Northwest NATIONAL LABORATORY

PNNL-34962 Rev. 1

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 | Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

Scoping Study Content (I)

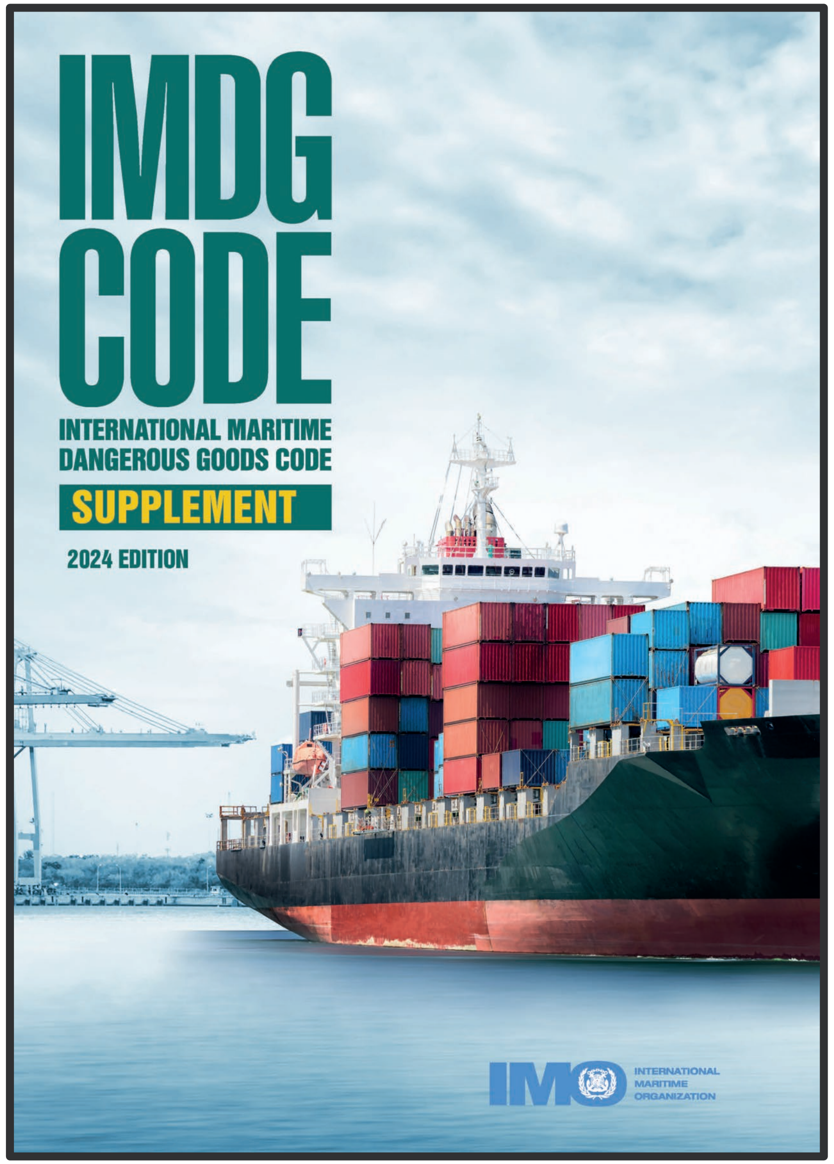
- Scoping study assumes the use of an INF Code ship
  - INF Code – International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Waste on Board Ships
- Content of scoping study
  - Discussion of the regulatory approach for licensing the TNPP package for maritime transportation
  - Description of the specific TNPP package and the marine transport vessel used in the demonstration scoping study
  - Presentation of the quantitative risk evaluation guidelines used to determine whether the level of maritime TNPP transportation risk is acceptable
  - Demonstration of the PRA methodology for the maritime transportation accidents selected for the scoping study
  - Discussion of selection of a set of dominant maritime TNPP transportation accident sequences developed for the scoping study
  - Discussion of determination of the likelihood of occurrence of the maritime TNPP transportation accidents selected for the scoping study

Scoping Study Content (II)

- Content of scoping study (continued)
  - Discussion of determination of radiological dose consequences from the maritime TNPP transportation accidents selected for the scoping study
  - Presentation of the maritime TNPP transportation PRA baseline results for the scoping study and evaluation of the results of a TNPP package maritime transportation accident by comparing them to the proposed risk evaluation guidelines
  - Presentation of the uncertainty analysis and sensitivity studies and their results and identification of insights generated by these analyses for the demonstration
  - Description and evaluation of how the defense-in-depth and safety margin philosophies are incorporated into a risk-informed approach for maritime TNPP Package transportation
  - Discussion of the insights gained from the demonstration of the viability of the risk informed approach for package approval of a TNPP for maritime shipment

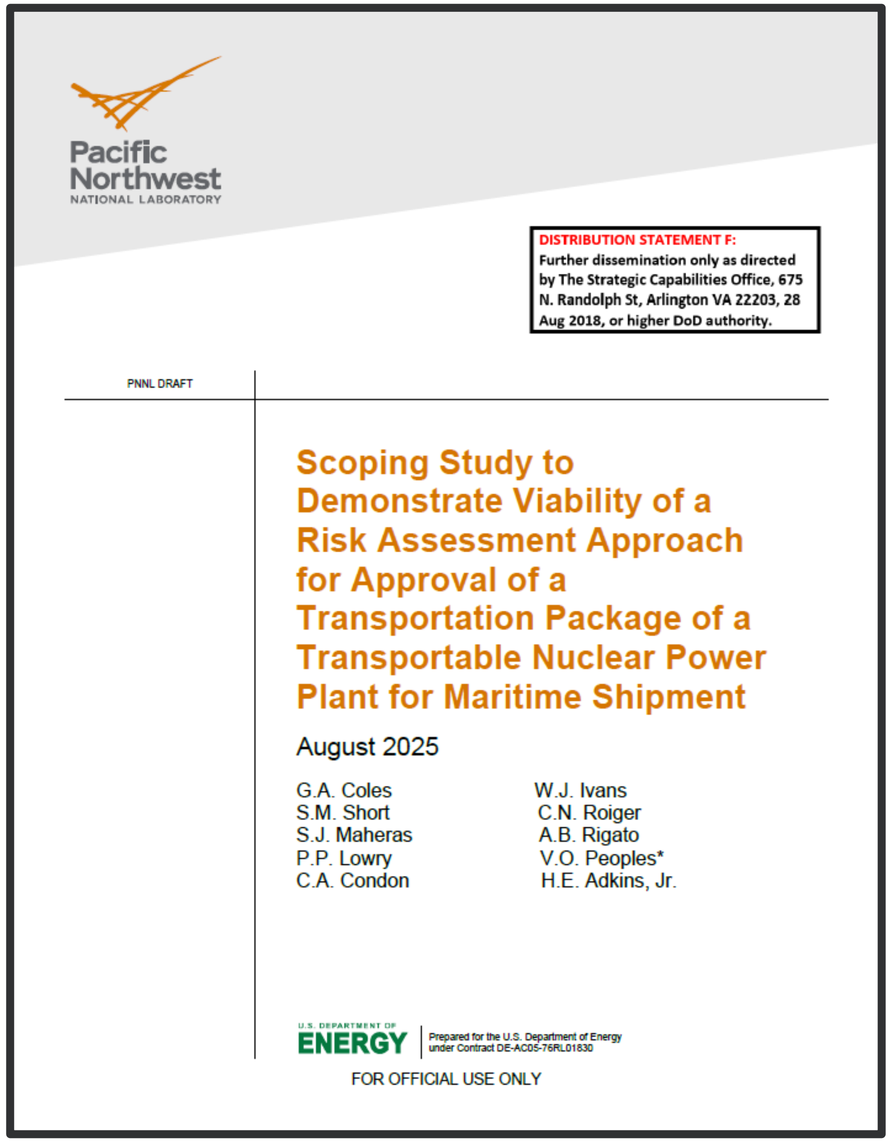
INF Code Requirements

- Damage stability
- Fire safety measures
- Temperature control of cargo spaces
- Structural considerations
- Cargo securing arrangements
- Electrical power supplies
- Radiological protection
- Management and training
- Shipboard emergency plan
- Notification in the event of an accident involving INF cargo
- It is possible to refit existing ships to meet INF 1 or INF 2 requirements, but an INF 3 ship will likely need to be purpose-built
    - The MCL Trader was refit in 2009 to meet INF 2 requirements for the Russian Research Reactor Fuel Return (RRRFR) Program



U.S. Department of Defense (DoD) Strategic Capabilities Office (SCO)

- Risk Informed Transportation Package Approval for OCONUS Maritime Shipment of a TNPP Methodology Document
  - Completed draft document and submitted to NRC 8/18/2025 for review
  - Engagement meetings with NRC to commence in early 2026 (schedule affected by govt shutdown)
  - Applied concepts and lessons learned from the domestic highway study to maritime shipment of TNPP/microreactor as cargo
  - Endorsement targeted for end of CY26



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PNNL DRAFT

Scoping Study to Demonstrate Viability of a Risk Assessment Approach for Approval of a Transportation Package of a Transportable Nuclear Power Plant for Maritime Shipment

August 2025

G.A. Coles, S.M. Short, S.J. Maheras, P.P. Lowry, C.A. Condon, W.J. Ivans, C.N. Roiger, A.B. Rigato, V.O. Peoples*, H.E. Adkins, Jr.

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

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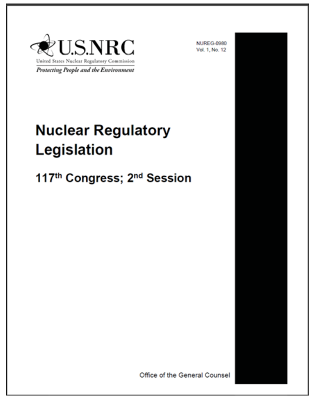
DoD Operational Energy Capability Improvement Fund (OECIF)

- Maritime Nuclear Asset Transportation Capability Development (MNATC)
  - In-Depth Study to Analyze Maritime Options Available to the DoD To Transport Nuclear Reactors
  - Subset of Study will also Examine Options to Retrofit a DoD Cargo Vessel or Procure Vessels to Meet INF Code Requirements and DoD Objectives
- Legal and Regulatory Taxonomy for Maritime Nuclear Defense Applications (TMNDA)
  - In-Depth Study to Analyze Legal and Regulatory Frameworks, Gaps and Seams Relevant to DoD Maritime Nuclear Reactors
  - Subset of Study will also Examine Options and DoD Objectives
  - Goal is to meet requirements to achieve sustainable, reliable and scalable microgrid with reserve power capability for operations and expeditionary support
- Target completion for both studies end of FY26

Nuclear Transport Solutions (NTS)/Pacific Nuclear Transport Limited (PNTL) Vessel (Pacific Egret)

DoD Large-Medium, Speed, Roll-On/Roll-Off ships (LMSRs) Cargo Vessel


U.S.NRC

Nuclear Regulatory Legislation

117th Congress; 2nd Session

Office of the General Counsel

IAEA

IMO

Retrofit Options

- Study will examine retrofit options for 3 types of ships from the Military Sealift Command (MSC) and the Maritime Administration (MARAD)
  - Large-Medium Speed RO/RO (LMSR) Ship
  - Roll-On/Roll-Off (RO/RO) Ship
  - Fast Sealift Ship (FSS)
- MSC Fleet
  - MSC owns, operates, and maintains 15 reserve ships within its sealift fleet in reduced operating status; these are among the first ships to activate when additional capacity is needed during peacetime/wartime.
- MARAD Fleet
  - MARAD, owns and maintains 46 reserve sealift ships in reduced operating status within its Ready Reserve Force. Together, the MSC and MARAD ships in reduced operating status comprise the 61-ship surge sealift fleet

Thank you