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Risk-Informed Approach for Regulatory Approval of Microreactor Transport

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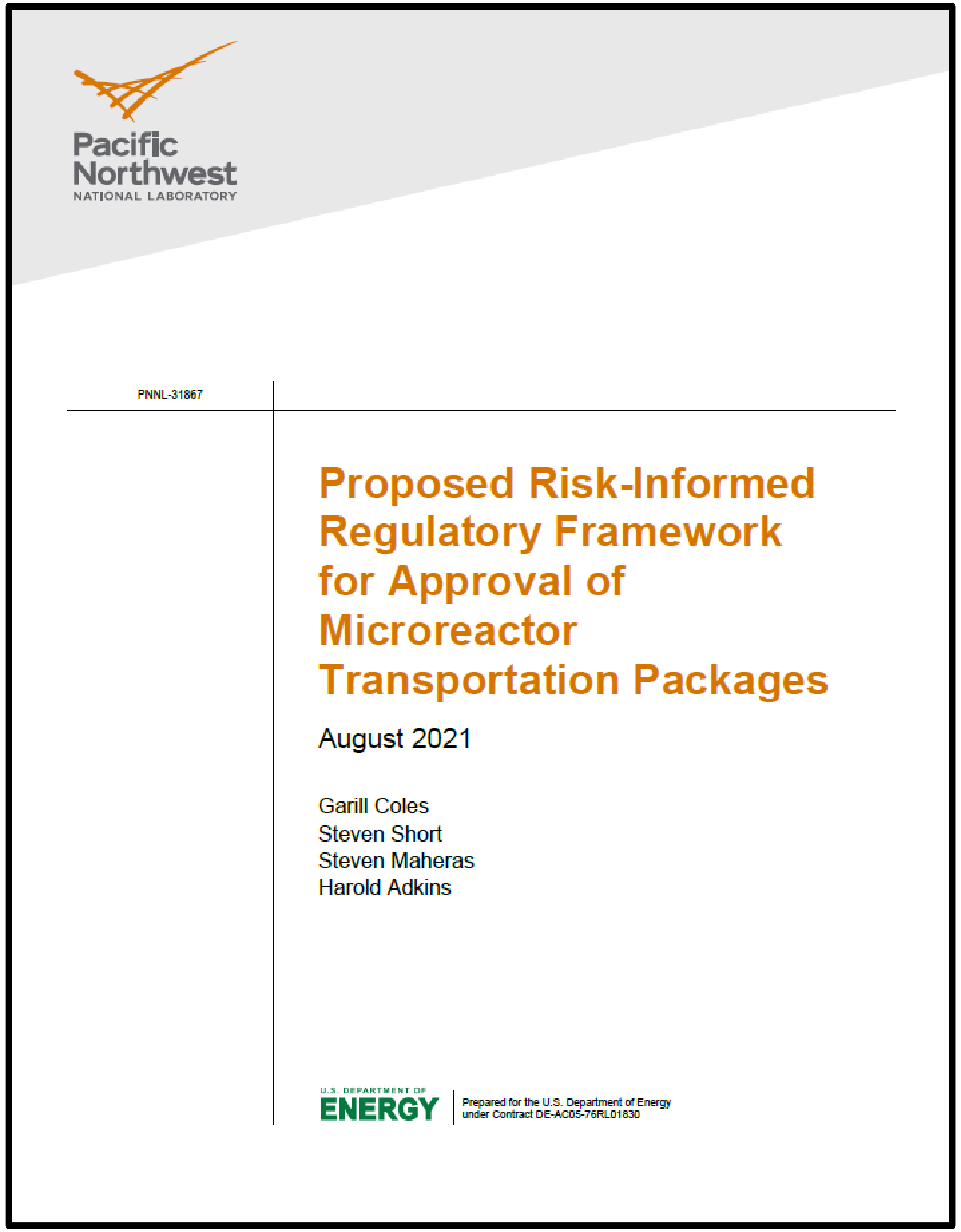
Overview

- Last year PNNL developed a risk-informed regulatory framework for licensing the transportation of a microreactor with its fuel contents (PNNL-31867)
  - Under Nuclear Regulatory Commission (NRC) review
- PNNL is currently performing trial implementation of a major element of the framework for the DOD Strategic Capabilities Office (SCO) Project Pele which is a PRA of transportation of the TRISO fueled microreactor
- Key elements discussed here today:
  - Proposed regulatory approach for initial unit
  - Proposed risk acceptance guidelines
  - Proposed risk assessment approach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PNNL-31867

Proposed Risk-Informed Regulatory Framework for Approval of Microreactor Transportation Packages

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Proposed Regulatory Approach

- US transportation regulatory requirements contained in 10 CFR Part 71 largely focus on the definition for thick-wall steel vessel (transportation package)
- A microreactor with its irradiated or unirradiated fuel contents is unlikely to meet the codified regulatory requirements in 10 CFR 71
- If Fissile Material or Type B package requirements cannot be directly met, then other package approval options are possible:
  - 10 CFR 71.41(c) Alternative Environmental and Test Conditions (10-160B and 8-120B Transportation Casks)
  - 10 CFR 71.41(d) Special Package Authorization (West Valley Melter Package)
  - 10 CFR 71.12 Exemption (Trojan Reactor Vessel)
- Preferred initial pathway identified by PNNL is the Exemption process that allows compensatory actions to protect basis of exemption if acceptable risk is demonstrated
  - Can apply to multiple shipments unlike Special Package Authorization
  - Flexibility in deviating from deterministic requirement compared to Alternative Environmental and Test Conditions
- Regulatory change may be needed in the future for more frequent or multiple transports

Proposed Risk Acceptance Guidelines

- Demonstration of acceptable risk will require a quantitative risk assessment given the complexities and uncertainties about package performance and potential risk to public:
- The benefit of risk acceptance guidelines is that they provide a key basis in support of risk-informed regulatory decisionmaking
- However, regulatory risk evaluations guidelines do not exist for transportation packages like they do for nuclear power plants (NPPs)
- NRC proposed guidance in a risk-informed decision making (RIDM) report for nuclear material and waste applications (ML08072038).
  - These are based on quantitative health objectives and guidelines developed from the Safety Policy Statement (QHOs and QHGs)
  - However, challenges remain in its implementation and the approach has not been endorsed for use by NRC as that would be a policy decision

Proposed Risk Acceptance Guidelines

NRC Proposed QHGs Based on Interpretation of Safety Policy Statement

Receptor	Acute Fatality	Latent Cancer Fatality	Serious Injury (Cancer Illness)
Public	QHG-1 - Public individual risk of acute fatality is negligible if it is less than or equal to 5×10^{-7} fatality per year.	QHG-2 - Public individual risk of a LCF is negligible if it is less than or equal to 2×10^{-6} fatality per year or 4 mrem per year	QHC-3 - Public individual risk of serious injury is negligible if it is less than or equal to 1×10^{-6} injury per year.
Worker	QHG-4 - Worker individual risk of acute fatality is negligible if it is less than or equal to 1×10^{-6} fatality per year.	QHG-5 - Worker individual risk of LCF is negligible if it is less than or equal to 1×10^{-5} fatality per year or 25 mrem per year.	QHG-6 - Worker individual risk of serious injury is negligible if it is less than or equal to 5×10^{-6} injury per year.

- The premise of the 1986 NRC Safety Goal Policy is that risk to people from a nuclear power pant should be very small compared to the sum other accident risk (e.g., 0.1% prompt fatality)
- The Safety Goal does not specifically address workers, so the RIDM report proposes that worker risk be small compared to other risk but not as small as for the public who are not trained in radiation protection

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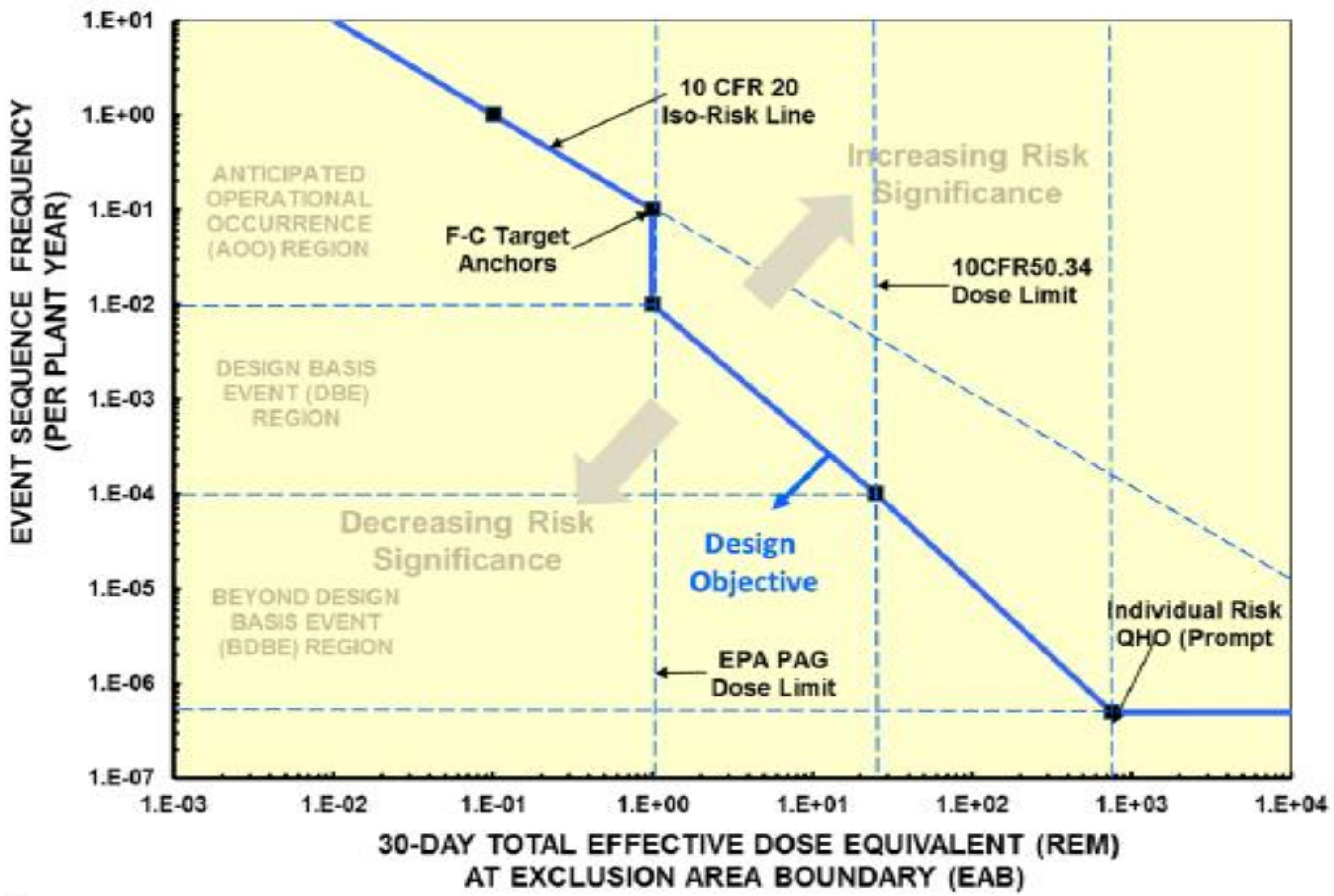
Surrogate Measures for Proposed Risk Acceptance Guidelines

- Levels of NPP PRA include Level I (CDF/LERF), II (release), and III (health effects)
- However, NPP PRAs (which are mature and well used) are not typically taken to Level III, but rather use the surrogates of CDF and LERF for risk informed applications because they are more attainable (see Regulatory Guide 1.200)
- PNNL proposes using surrogates for the QHGs suggested by the RIDM report by formulating goals in terms of radiological dose and likelihood:
  - Reduction in calculational burden by eliminating conversion to health effects
  - Dose limits can be compared to other federal/international dose limits used in related contexts
  - Determining likelihood and consequence separately provides a greater level of information for decisionmaking
- PNNL examined the use of dose consequence-likelihood pairs for other applications
  - Nuclear Energy Institute (NEI) 18-04 guidance for risk informed licensing basis development for advanced nuclear reactors
  - DOE-STD-3009 semi-quantitative risk ranking in support of nuclear safety basis for nonreactor facilities
  - IAEA Q system that defines radionuclide quantities allowed in Type A packages (A_1 and A_2 quantities)

Surrogate Measures for Proposed Risk Acceptance Guidelines

Frequency-Consequence Targets from NEI 18-04, Revision 1



- Illustration of the concept of risk evaluation guidelines based on the combination of radiological dose and likelihood

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Example Surrogate Measures for Proposed Risk Acceptance Guidelines

Annual Accident Frequency (per year)	Radiological Dose Consequence to the MOI	Radiological Dose Consequence to the Worker	Risk Acceptability
$\leq 5\times10^{-7}$	>750 rem TED	>750 rem TED	Acceptable
$<1\times10^{-6}$ and $>5\times10^{-7}$	≤750 and >25 rem TED	≤750 and >100 rem TED	Unacceptable
$\leq 1\times10^{-6}$ and $>5\times10^{-7}$	≤ 25 and >5 rem TED	≤100 and >25 rem TED	Acceptable
$<1\times10^{-4}$ and $>1\times10^{-6}$	≤ 25 and >5 rem TED	≤100 and >25 rem TED	Unacceptable
$\leq 1\times10^{-4}$ and $>1\times10^{-6}$	≤ 5 and >1 rem TED	≤25 and >1 rem TED	Acceptable
$<1\times10^{-3}$ and $>1\times10^{-4}$	≤ 5 and >1 rem TED	≤25 and >1 rem TED	Unacceptable
$\leq 1\times10^{-3}$ and $>1\times10^{-4}$	≤1 and >100 mrem TED	≤1 and >100 mrem TED	Acceptable
$>1\times10^{-3}$	≤1 and >100 mrem TED	≤1 and >100 mrem TED	Unacceptable
$\leq 1\times10^{-3}$	≤100 mrem	NA	Acceptable
$\leq 1\times10^{-2}$	NA	≤100 mrem TED	Acceptable

Note: The radiological dose consequence as presented as TED, based on Integrated Committed Dose to all organs thereby accounting for direct exposure as well 50-Year Committed Effective Dose Equivalent.

- This table is an aggregation of the limits from the cited sources but refined to ensure that no criterion is greater than proposed QHGs when converted to health effects

Proposed Risk Assessment Approach

- The NRC RIDM report advocates use of PRA when quantitative benefits are needed
- PRAs for NPPs typically involve event tree and fault tree analysis are not are proposed here
  - The value of fault tree analysis of complex engineered systems or event tree analysis to map accident sequences is limited because most of initiating events lead directly to failure (release of radiological material or loss of shielding)
- Rather PRA development will focus on:
  - Identification of accident scenarios
  - Development of the likelihood of those scenarios
  - Development of the consequence of those scenarios
- Like-kind accidents will be grouped be create representative bounding accidents.
  - Grouped primarily by accident phenomena
  - Bounding likelihood and consequence of accidents in the group used

PRA Trial Approach
Identification of Accident Scenarios

- Hazard Analysis provides broad understanding of accident possibilities – which is important given lack of experience in transporting a microreactor
  - (e.g., Hazard identification checklist and Hazardous condition evaluation)
- Hazardous condition evaluation worksheets was used to postulate accident conditions in which likelihood and consequence bins are assigned:
  - Fire hazard events, Explosion events (e.g., diesel fires)
  - Kinetic energy, Potential energy (e.g., collisions, drops to a lower elevation)
  - Loss of containment hazard events (e.g., human errors, road vibration)
  - Direct radiological exposure events (e.g., loss of shielding, increased routine exposure),
  - Criticality event (e.g., road accident that results in drop into body of water)
  - Man-made events, (e.g., human error in errors in disassembly or packaging)
  - Natural Phenomena events (e.g., high wind accidents, containment degradation due to extreme cold)
- Accident may involve scenarios beyond accidents typically considered

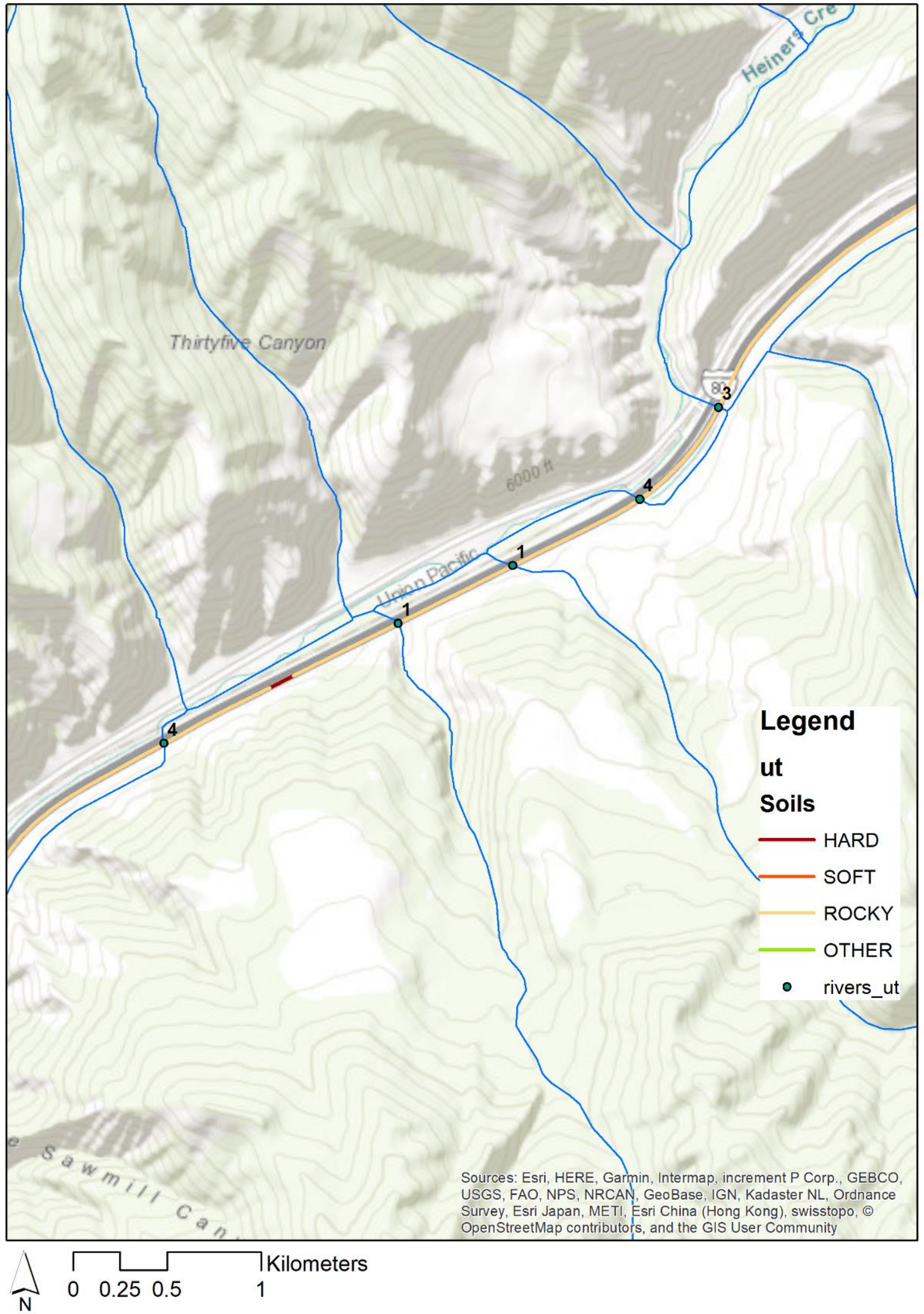
PRA Trial Approach – Identification of Accident Scenarios

Hazardous Condition Evaluation Worksheet – Fire Events					
Event Class/ Initiator	Hazardous Event Summary	Initiating Event Likelihood	Consequences	Risk Characterization	Preventive and Mitigative SSCs
Diesel fuel fire General fire in the Transport	Release of rad material from microreactor package to environ caused by damage to package due to fire that originates inside the transport container	Anticipated $F \geq 10^{-2}$ Unlikely 10-2 > F ≥ 10-4 Extremely Unlikely 10-4 > F ≥ 10-6 Beyond Extremely Unlikely $F < 10^{-6}$	Physical Consequence Material at Risk Potential damage to elements of the package and mechanism for release from….	Low Medium High Involved MAR (e.g., Rad material plated out in Primary Cooling System or Rad material diffused in core structures)	Non-flame propagating rated cable Fire detection and suppression Emergency response

Accidents defined and grouped into bounding representative accident as appropriate (representative but not overly conservative)

PRA Trial Approach
Determination of Accident Freq

- Likelihood determination
  - Truck accident data (failure frequency of impacts, rollover, drops) for specific route (augmented by national statistics from earlier transportation studies)
  - Specific routing information (distances, key features such as bridges, bodies of water)
  - Non-truck failure estimation (e.g., human error, containment failure)



PRA Trial Approach – Determination of Accident Consequences

- Consequence analysis will be based on estimating the impact from two sources:
  - Direct radiation dose to humans from material that becomes unshielded in a transportation accident
  - Radiological dose to a human through possible dose pathways from radiological material that is released
- Five Factor formula used to determine source term (e.g., MAR x DR x ARF x RF x LPF)
  - Material at risk, Damage ratio, Airborne release fraction, Respirable fraction, Leak path factor
- Estimation off these factors will be done for packaged reactor system elements, the TRISO fuel, and compacts holding the fuel particles (expected to be small for TRISO fuel)
  - Fuel analysis and testing for transportation is currently limited, and system thermal and impact fragility and testing analysis have not been completed– so initially efforts will use a bounding approach
- Estimation of radiological dose will be based on traditional methods for possible dose pathways (e.g., IAEA SSG-26 for transportation packaging, and DOE-STD-3009)
  - Such as inhalation dose, direct external radiation dose (gamma and beta), skin contamination, direct gamma and direct beta radiation dose, etc.

PRA Trial Approach – Modeling Uncertainty Challenges

- Fragility of the package to the impacts associated with different road accidents
- Mechanisms of release and characterization release fractions
- Characterization of material at risk:
    1. Nongaseous fission products from TRISO fuel and heavy metal contamination damaged an accident,
    2. Gases from TRISO fuel and heavy metal contamination damaged an accident,
    3. Radioactive material that has diffused and is held up the compact and other core structures
    4. Radioactive material that has plated-out in the Primary Cooling system,
    5. Noble gases in the pressure boundary of cooling system assuming (it’s not evacuated),
    6. Clean-up system inventory (if applicable),
    7. Contamination outside the reactor.
    8. Contamination on and outside the microreactor transportation package
- The PRA model provides a means to explore the sensitivity of the modeling uncertainties on the risk results to identify where to focus design, testing, or modelling refinement efforts.

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Credit or Identification of Compensatory Measures

- Specific permitting requirements (e.g., for heavy haul or superloading) vary by state and in some cases may require specific measures that could be considered compensatory measures
- Potential compensatory measures that may be credited in the PRA or identified as a defense-in-depth measure such as:
  - Real time health/fitness onboard monitoring/diagnostics of reactor package
  - Escort the reactor forward and aft for the entire route
  - Choose a route that avoids bodies of water (balanced by quality of road)
  - Controls for bridges over bodies of water (speed reduction, close bridge to other traffic)
  - Avoid shipping during known times of high traffic volume such as at night
  - Avoid shipping during severe weather
  - Conduct training for emergency responders along the route
- PRA provides a means to quantify the potential benefit of specific compensatory measures.

Summary

- In summary the approach:
  - Layouts a feasible regulatory pathway for licensing a first-of-kind transportation of microreactor with irradiated fuel based on risk information
  - Proposes a workable risk evaluation guidelines derived from QHGs proposed by NRC for these kinds of activities
  - Describes an applicable PRA approach to support the regulatory pathway consistent with the measures used in the proposed risk evaluation guidance
- We think the advantages of the approach are:
  - Increases the likelihood of successfully obtaining regulatory transportation package approval,
  - Can be used to inform the design on the relative risk significance of microreactor containment and shielding, and
  - Can be used to inform the need for and identification of transportation compensatory measures

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Thank you