U.S. Department of Energy
Office of Civilian Radioactive Waste Management

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Criticality: Basis for Exclusion and Role of Burnup Credit

Presented to:
Nuclear Waste Technical Review Board

Presented by:
John C. Wagner, Ph.D.
Lead Laboratory
Oak Ridge National Laboratory

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Outline

- "Big Picture"
- Postclosure criticality control strategy
- Considerations for criticality evaluations
- Factors necessary for criticality to occur
- Criticality features, events and processes (FEPs)
- Use of design basis configuration in criticality evaluations
- Criticality FEP screening discussion and results

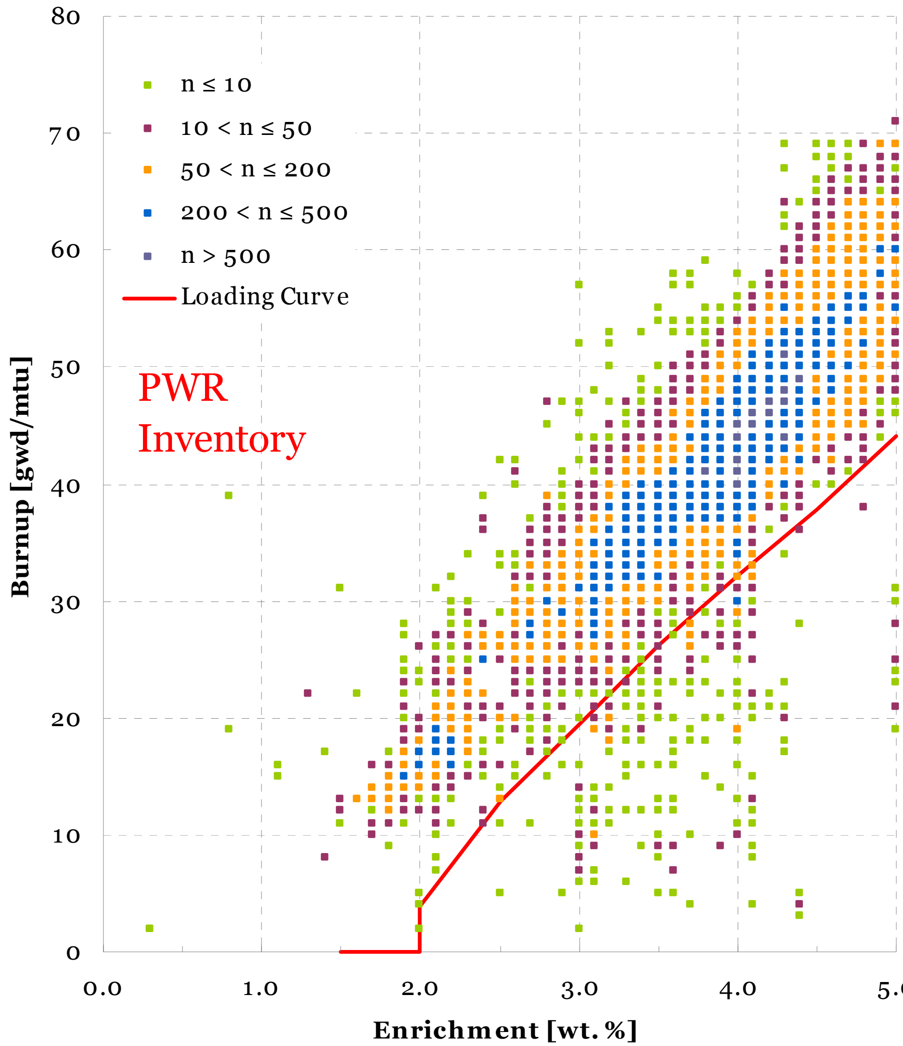
"Big Picture"

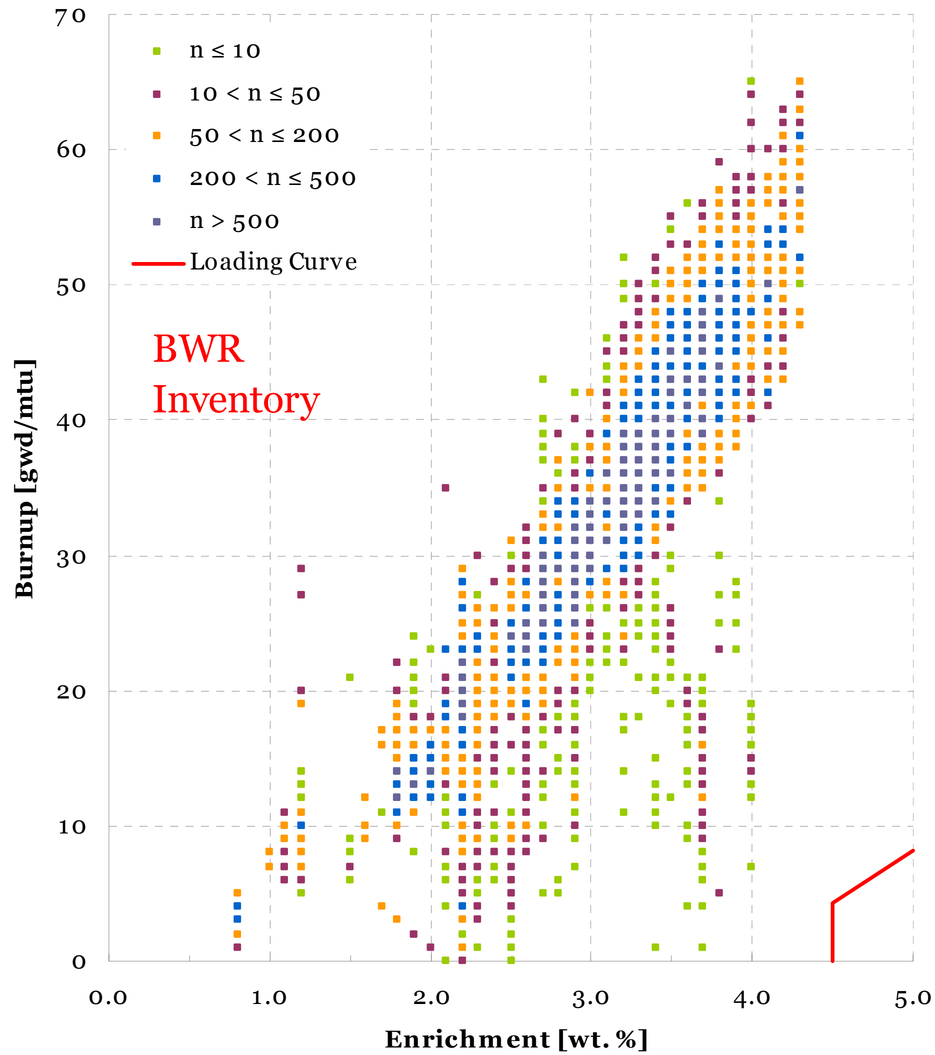
- Proposed 10 CFR 63.342(a) requires "DOE's performance assessments conducted to show compliance with 63.311(a)(1), 63.321(b)(1), and 63.331 shall not include consideration of very unlikely features, events, and processes, i.e., those that are estimated to have less than one chance in 10,000 of occurrence within 10,000 years of disposal (less than one chance in 100,000,000 per year)" (70 FR 53313, pp. 53319 to 53320)
- Criticality is considered an Event, and the criticality event has been screened out of the performance assessment on the basis of low probability of occurrence
  - Probability of criticality (POC) within disposal period $4.4 \times 10^{-5} < 1 \times 10^{-4}$

Postclosure Criticality Control Strategy Overview

- **Use NRC accepted methodology (*Disposal Criticality Analysis Methodology Topical Report*) for evaluating criticality features, events, and processes (FEPs)**
  - **SER for Rev 0 issued June 2000**
- **Reliance on engineered systems, natural systems, and waste form properties to ensure the POC is less than the threshold for inclusion in the performance assessment**
  - **In-package criticality control uses neutron absorbers and burnup credit (for commercial spent nuclear fuel, CSNF)**
    - **Burnup credit loading curves are developed such that they preclude criticality for waste packages loaded in accordance to design specifications under fully flooded conditions**
    - **Variations in the amount of burnup credit taken have little effect on the POC, but do affect the % of acceptable assemblies in the inventory**

CSNF Loading Curves

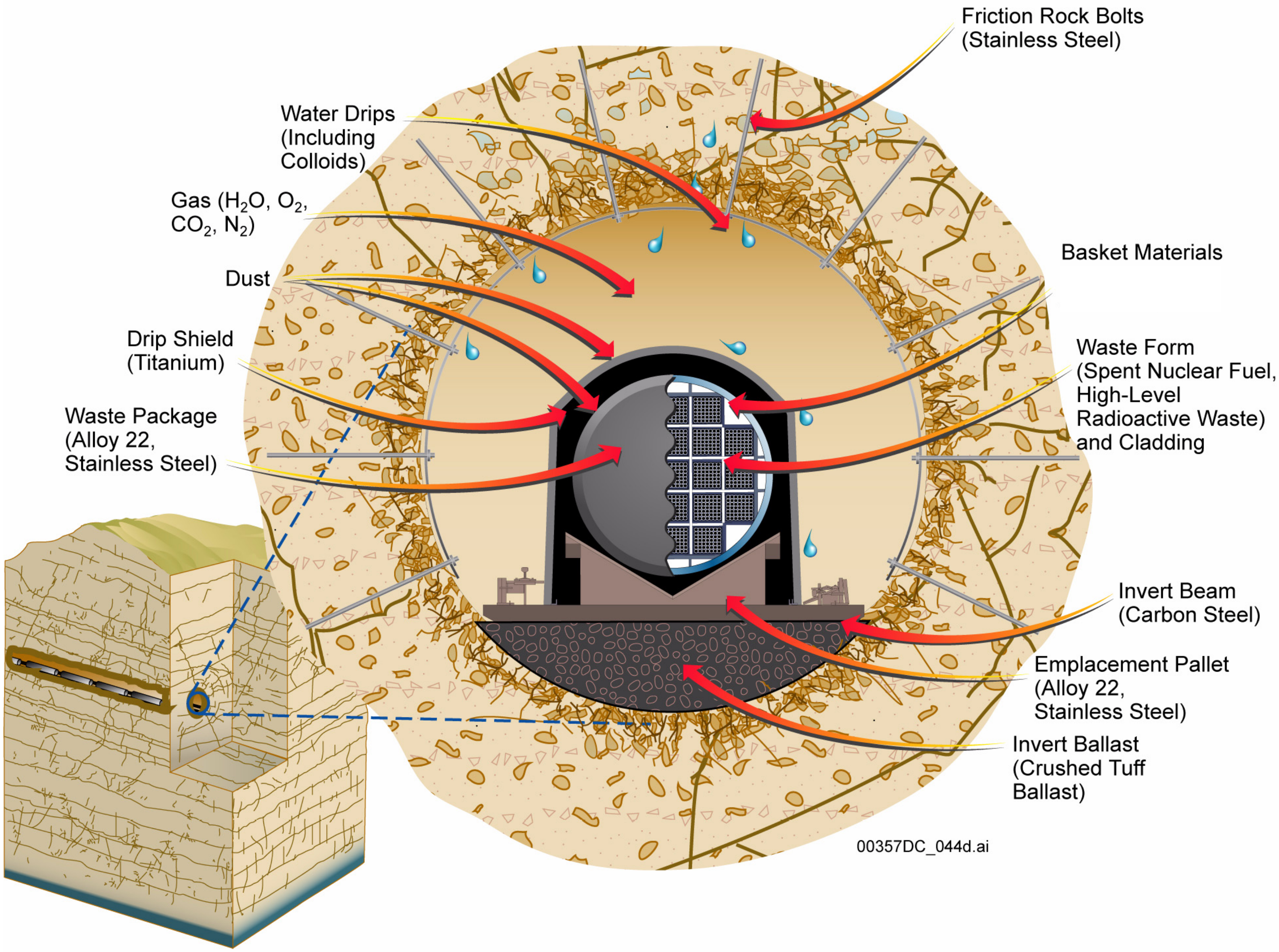




Repository Criticality Evaluation

- The occurrence of and conditions necessary for criticality in the repository have been thoroughly evaluated/studied
- Defendable parameter ranges, probabilities, probability distributions, and bounding values, where appropriate, have been determined and used to demonstrate compliance with applicable regulations

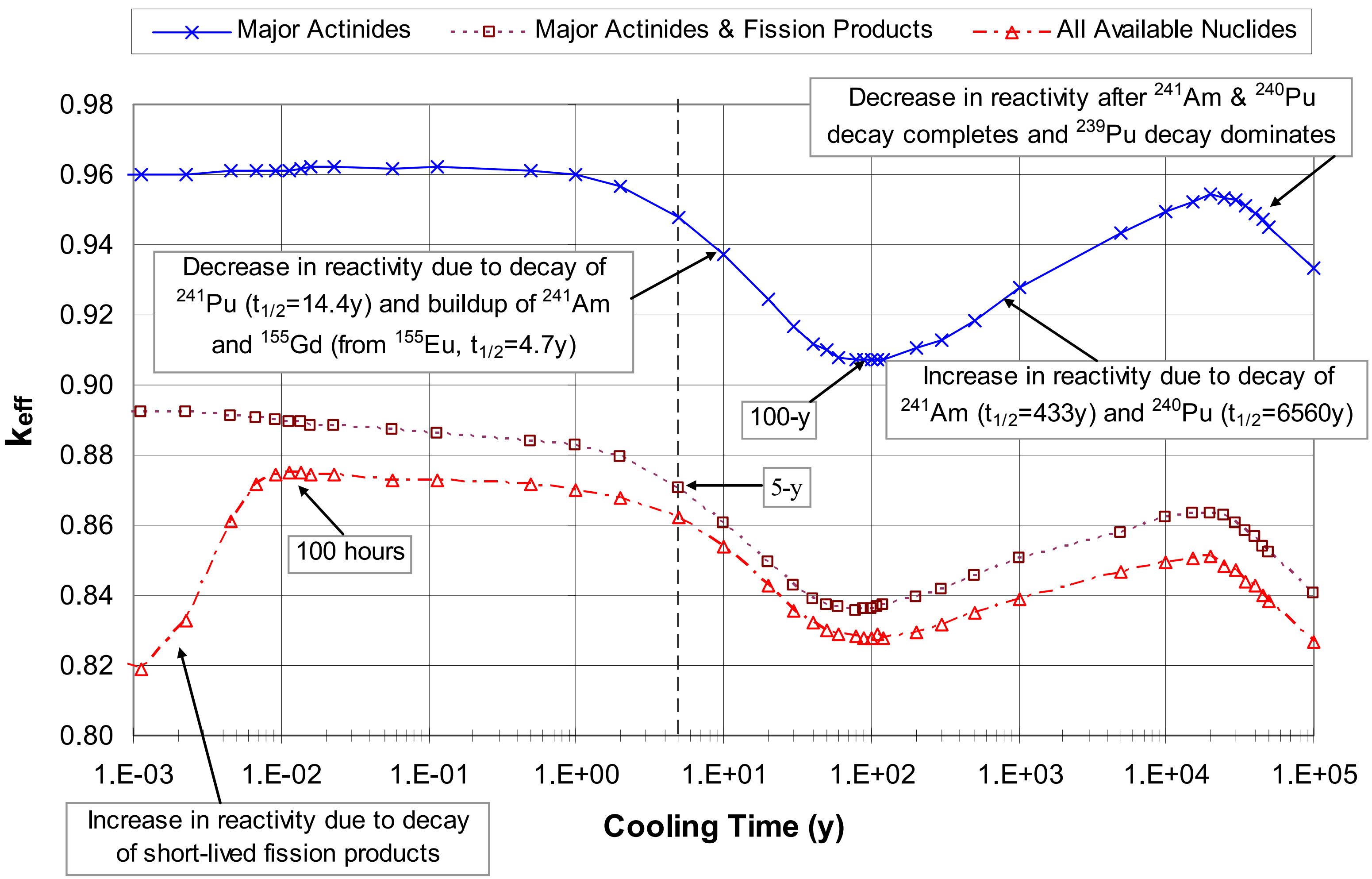
EBS in Emplacement Drift



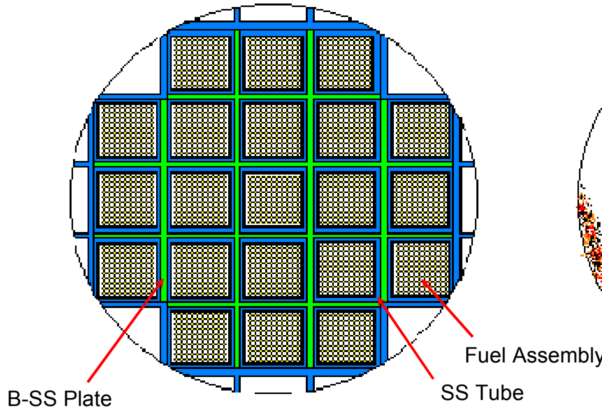
Considerations for Disposal

- Changing repository conditions
  - Temperature, humidity, and chemistry (effects degradation)
  - Water movement (moderator and transport mechanism)
- Changing waste package conditions
  - Material degradation (barriers and basket)
  - Changing of geometry (basket degradation)
- Changing spent fuel conditions
  - Waste form degradation (cladding and assembly structure)
  - Isotopic concentrations (decay and buildup)

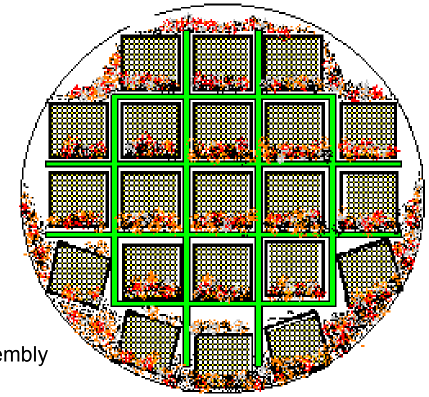
Reactivity of CSNF as a Function of Time



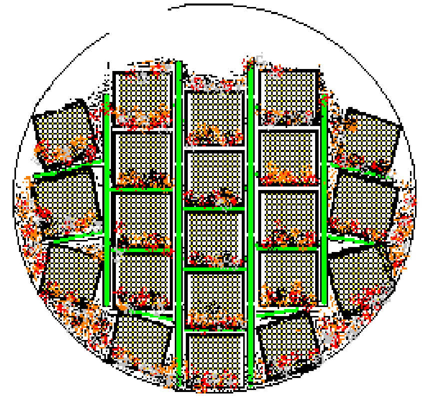
Visualization of Master Scenarios



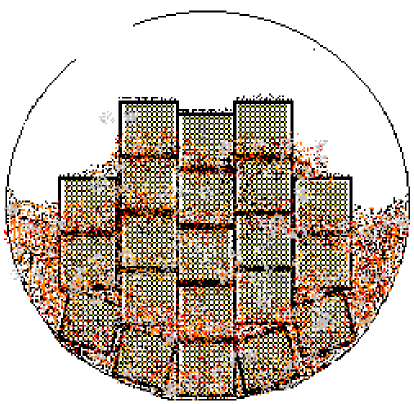
Initial Configuration



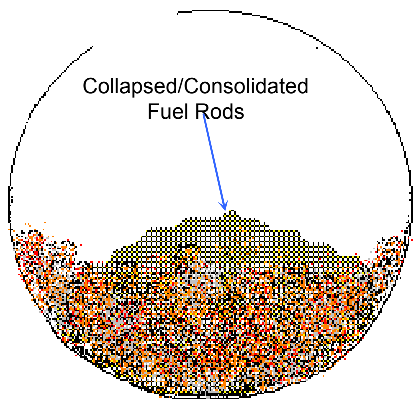
Side and Corner Guide Failure



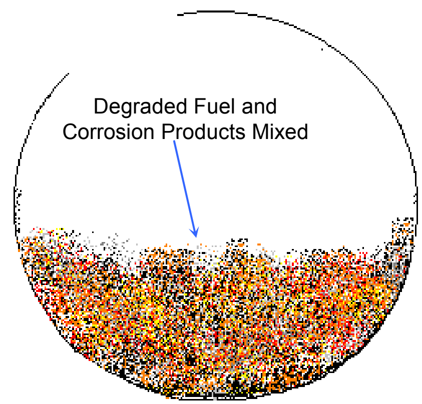
Fully Collapsed Basket



Fully Degraded Basket with Intact Assemblies



Fully Degraded Basket and Assembly Structure Intact Fuel Rods



Fully Degraded Basket and Fuel

Factors Necessary for Criticality

- **For in-package criticality to be possible, all of the following must occur:**
  - **Waste package damage (barriers breached)**
  - **Presence of a moderator (i.e., water)**
  - **Materials inside the package must degrade and/or reconfigure (e.g., separation of fissionable material from the neutron absorber material, or lack of absorber material)**
- **External criticality requires**
  - **Same processes for in-package criticality, <u>plus</u>**
  - **Sufficient accumulation of fissile material in a critical configuration (critical mass)**

Initiating Events

- **Criticality requires waste package failure in the event sequence**
- **Therefore, an initiating event must occur that causes a breach of the waste package before any other sequence of events on that waste package could lead to criticality**
- **Identified initiating events include:**
  - Early Failure (Drip Shield and Waste Package)
  - Seismic
  - Igneous
  - Rockfall

Criticality FEPs

- There are 16 criticality FEPs
- The criticality FEPs consider combinations of locations (intact in-package, degraded in-package, near-field (invert), and far-field) and conditions (nominal, rock fall, seismic, and igneous)
- Criticality is considered an Event, and the criticality event class (combination of all 16 FEPs) has been screened on the basis of low probability

Burnup Credit in Criticality FEPs

Location/ Initiating Event	Nominal/ Early Failure	Rock Fall	Seismic	Igneous
In-Package (Intact configuration)	➢ Burnup Credit ➢ Neutron Absorbers	**N/A**	➢ Burnup Credit ➢ Neutron Absorbers	**N/A**
In-Package (Degraded configuration)	➢ Burnup Credit ➢ Neutron Absorbers	**N/A**	➢ Burnup Credit ➢ Neutron Absorbers	**N/A**
Near-Field (Invert)	**N/A**	**N/A**	**N/A**	**N/A**
Far-Field (Unsaturated and Saturated Zones)	**N/A**	**N/A**	**N/A**	**N/A**

Criticality Calculations

- **Consistent with standard practice in criticality safety evaluations for licensing, design basis configurations have been developed and used in the postclosure criticality evaluation to bound, in terms of reactivity, possible relevant variations for each waste form**
- **Because it is not possible to definitively rule out the possibility of water and/or humid air entering and collecting in the waste package, the Design Basis configuration assumes a fully flooded system (probability of moderator presence is set to 1.0 if waste package is breached)**
  - **Humid air is expected to react with the waste form forming the mineral schoepite ($UO_3 \cdot 2H_2O$)**

    $UO_2(s) + ½\ O_2(aq) + 0.8\ H_2O(l) = UO_3 \bullet 0.8H_2O(s)$

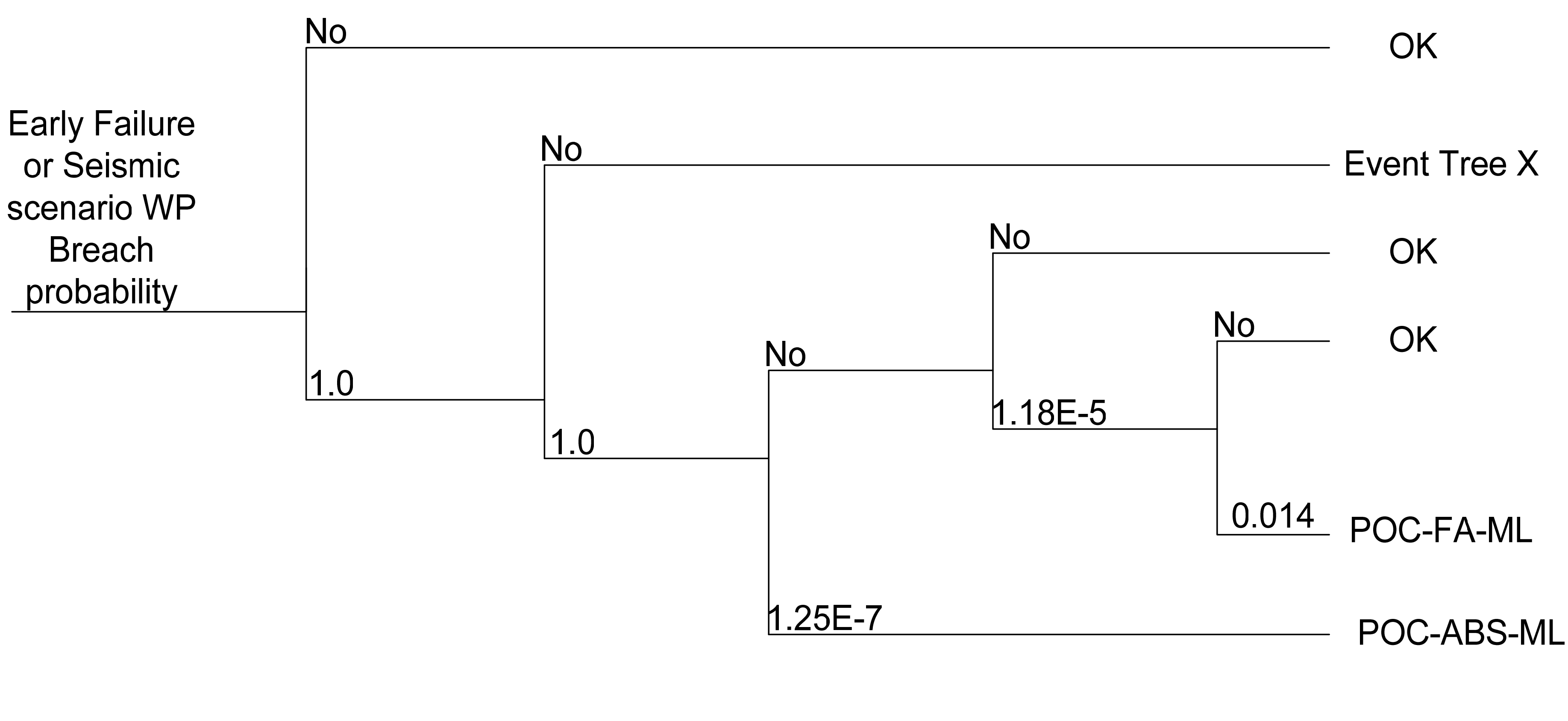
    $UO_2(s) + ½\ O_2(aq) + 2H_2O(l) = UO_3 \bullet 2H_2O(s)$

Common Events Dominate POC

- **As designed, the waste packages will remain subcritical even when fully flooded. Therefore, configurations not conforming to design specifications must be considered:**
  1. **Improper manufacturing resulting in the absence and/or loss of efficacy of neutron absorber**
  2. **Improper loading of fuel assemblies (CSNF)**
- **A detailed fault tree analysis was developed in the *Configuration Generator Model Report* which generated over 50,000 event sequences. A review of sequences with in-package criticality potential identified these two events as key elements**

Criticality Event Tree

Waste Package Outer Barrier Breach	Water Enters Waste Package	Design Basis Configuration	Neutron Absorber Misload	Waste Form Misload	Misloaded Assembly Exceeds CL	End-State



Early Failure Scenario

- Calculated based on presence of weld flaws in outer corrosion barrier or other early failure mechanisms, e.g., drip shield misplacement
- Assumes moderation present resulting in Design Basis configuration for k_{eff} calculations (fully flooded with water)
- Probability of localized corrosion is set to 1.0 if drip shield misplaced

Total sequence POC for the in-package location = 2.1×10^{-7} over 10,000 years

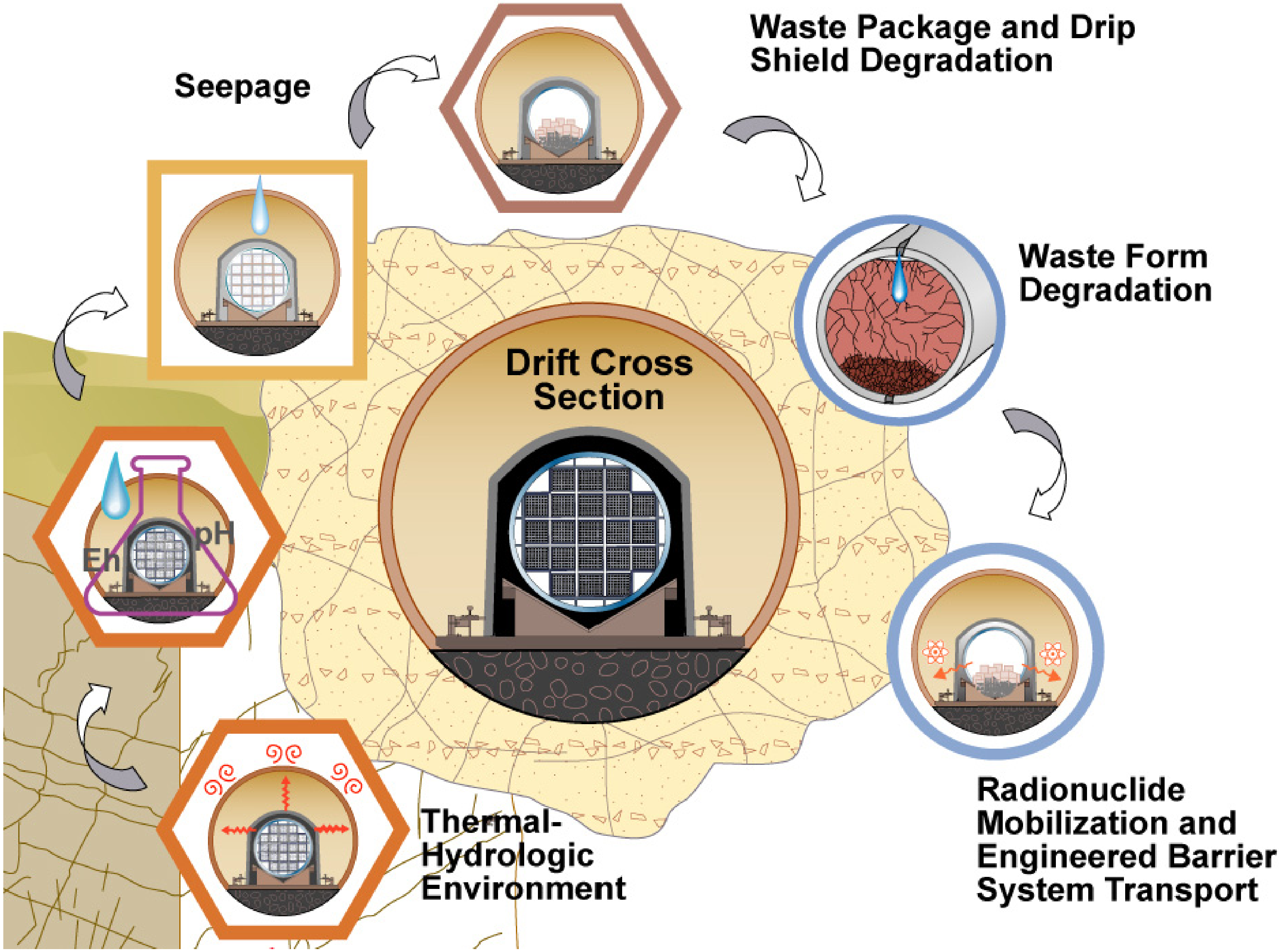
Seismic Scenario

- **Considered vibratory ground motion effects**
  - Repository POC = 4.5×10^{-7} for TAD packages and 3.7×10^{-5} for DOE SNF packages
  - Differences due to structural differences in packages
- **Considered fault displacement effects**
  - Repository POC = 4.7×10^{-9}
- **Considered multiple events that can result in breach and/or significant rockfall on the drip shield which could lead to localized corrosion of waste package**
  - Repository POC = 1.9×10^{-8}
- **Total seismic scenario probability of one or more DOE SNF or CSNF waste packages achieving criticality in the repository is 3.7×10^{-5} over 10,000 years (dominated by DOE SNF packages)**

Igneous Scenario

- **Screened out as insignificant contributor to total probability of criticality for in-package location**
  - **Dominant sequence for POC is DOE/SNF codisposal waste package subjected to seismic vibratory ground motion (probability of damage to a codisposal package over 10,000 years is 0.24)**
  - **Probability of damage from an igneous event is assumed to be 1.0, but the probability of an igneous event occurring in 10,000 years is 1.7 x 10^{-4}. More than a factor of 1400 below the dominating sequence for the total POC**

Principal Components of External Criticality



Criticality Analysis for External Locations

- Sensitivity studies performed to calculate minimum critical mass for near-optimized conditions
- Any material released from the package that is not uranium or plutonium is conservatively neglected from the mixture
- Each fuel modeled as as-manufactured enrichment (no credit for burnup)
- Moderation and reflection assumed at most reactive credible extents
- Results of waste forms evaluated indicate that the maximum mass released under optimized conditions is less than the minimum mass required for criticality, i.e.
  - Insufficient material is released to support external criticality

Probability of Criticality by Location

Location	Nominal	Seismic	Rockfall	Igneous	Total
In-Package	2.1×10^{-7}	3.7×10^{-5}	No breach	<<Seismic	3.7×10^{-5}
Near-Field	Insufficient mass released for accumulation into critical configuration				N/A
Far-Field	Insufficient mass released for accumulation into critical configuration				N/A
Naval SNF In-Package*					7.1×10^{-6}
Total Probability of Criticality					4.4×10^{-5}

*Classified Naval Technical Support Document (TSD)

Conclusion

- **Despite numerous and significant conservative analysis assumptions in the event sequences requisite to enabling criticality (i.e., analysis assumptions that increase the calculated probability of criticality), the probability of nuclear criticality during the postclosure performance period is very unlikely. Therefore, the criticality event class has been excluded on the basis of low probability**
  - **Each criticality FEP probability has been summed and the total is less than 1 chance in 10,000 of occurrence within 10,000 years after disposal. Accordingly, the criticality event sequence is excluded from performance assessments demonstrating compliance with proposed 10 CFR63.311 and 63.321, and with 10 CFR 63.331 on the basis of low probability**