Probabilistic Risk Analysis Methodology for Preclosure Operations at a Geologic Nuclear Waste Repository

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Objectives

- Evaluate risk from a potential repository during the preclosure period and account for the uncertainty in the risk using probability distribution functions
- Identify significant contributors to total risk
- Rank the reliance of the facility on the performance of individual structures, systems, and components (SSCs) based on risk

Implementation

- Methodology is general
- Full PRA is Not required by U.S. Nuclear Regulatory Commission (NRC) regulation applicable to Yucca Mountain
- Example problem shows application of the probabilistic methodology
- Application focuses on preclosure operations
  - Handling operations for emplacing waste in the repository
- Implementation via a computer code called the PCSA Tool developed by the CNWRA staff

Propagation of Uncertainty

- Basic methodology presented at the PSAM6 meeting assuming point-estimates for all parameters
- This paper accounts for uncertainty propagation through the risk calculation – generates a Complementary Cumulative Distribution Function (CCDF) for risk (dose in time period)

Basic Steps of the Methodology

1. Convert the initiating event frequencies into **initiating event probabilities**
2. Compute the **initiating event consequences**
   a. **Generate event sequences for each initiating event**
   b. **Estimate consequence for each event sequence.**
   c. **Estimate probability weighted consequence from all sequences.**
3. Identify the set of possible **scenario combinations**
4. Calculate the **risk of each scenario combination** and the **total risk**

Specific Objectives for the Example Application

- Identify the most likely scenario combinations
- Identify significant contributors to the facility risk
  - Functional areas
  - Individual scenario combinations
- Assess the significance of those combinations with more than one initiating event occurring in the same year
- Rank the facility reliance on the performance of individual structures, systems, and components

Simplified Example Problem

- Based on sample information and generic assumptions
- Intended for illustration only
- Considered 2 hazards
  - Operational (drops of spent nuclear fuel during handling)
  - Natural (seismicity)
- Considered 4 SSCs
  - Canister, surface aging cask, and waste package
  - High-Efficiency Air Particulate (HEPA) filtration

Example Initiating Events

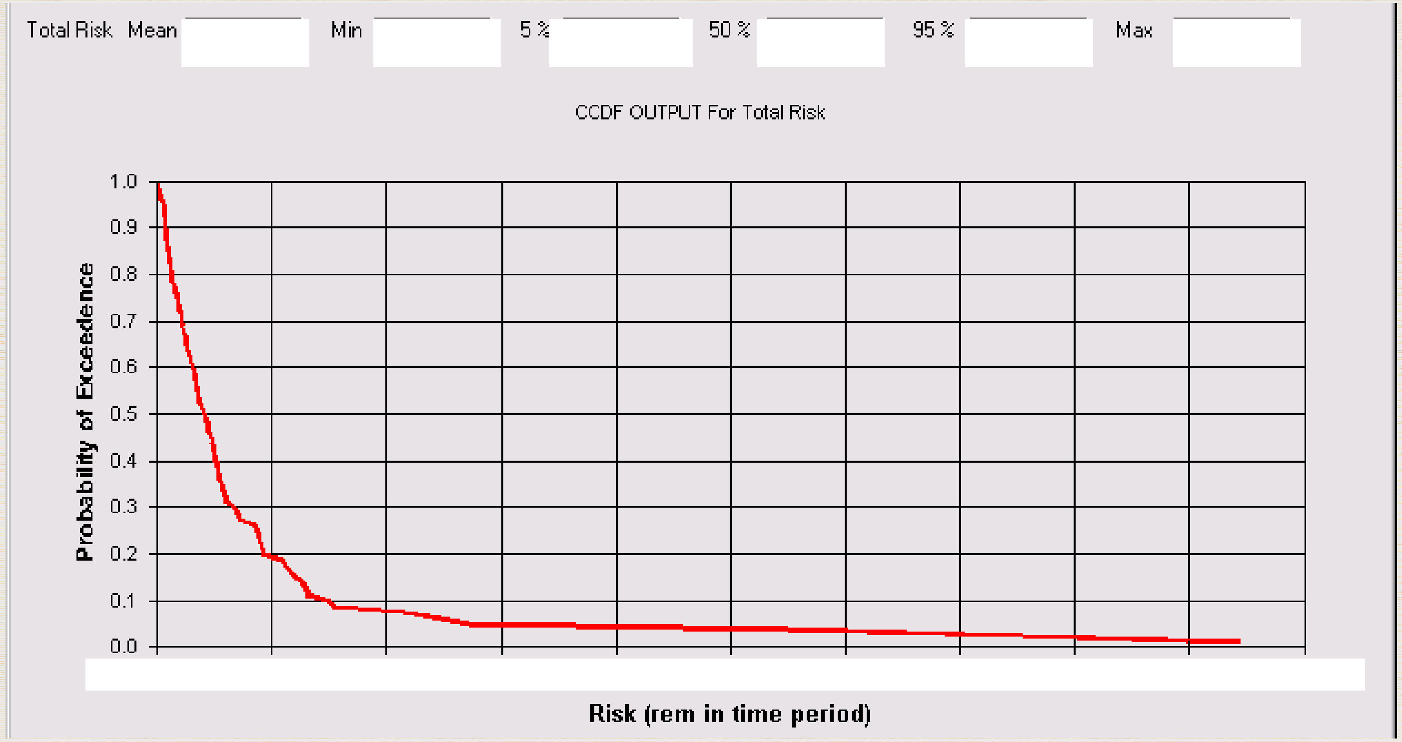
Scenario ID	Location	Number/ Type of Assemblies	Initiating Event Description
A	Dry Transfer Facility	1 PWR	Bare fuel assembly drops during handling
B		21 PWR	Canister drops during handling
C		68 BWR	Bare fuel assemblies experience dynamic mechanical loads during a seismic event
D		21 PWR	Canister experiences dynamic mechanical loads during a seismic event
E	Surface Aging Facility	44 BWR	Surface aging cask drops during handling
F	Onsite Transporter	21 PWR	Waste package experiences dynamic Mechanical loads from a seismic event

Example Event Sequences

Scenario ID	Initiating Event Frequency (1/yr)	Event Sequence Frequency (1/yr)	End State Description	Mean Consequence (Annual Public Dose) (Sv)*
A	0.2	2.0×10^{-1}	Release is HEPA filtered	1.6×10^{-7}
		2×10^{-6}	Release is not HEPA filtered	2.0×10^{-6}
B	0.005	5.0×10^{-3}	No canister breach, No release	0
		5.0×10^{-7}	Release is HEPA filtered	3.4×10^{-6}
		5×10^{-12}	Release is not HEPA filtered	4.3×10^{-5}
C	0.001	9.9×10^{-4}	Release is HEPA filtered	4.3×10^{-6}
		1×10^{-5}	Release is not HEPA filtered	1.2×10^{-4}
D	0.001	1.0×10^{-3}	No canister breach, No release	0
		9.9×10^{-8}	Release is HEPA filtered	3.4×10^{-6}
		1×10^{-9}	Release is not HEPA filtered	4.3×10^{-5}
E	0.0005	5.0×10^{-4}	No cask breach, No release	0
		5×10^{-8}	Defective cask breaches, Outdoor release	1.3×10^{-3}
F	0.001	1.0×10^{-3}	No waste package breach, No release	0
		1×10^{-7}	Defective waste package breaches, Outdoor release	3.6×10^{-4}

* Multiply by 100 to convert consequences from Sv to rem.

Illustration of Example Risk Output (PCSA Tool)



Example Scenario Combinations

Most likely scenario combinations

Largest contributions to total risk

Scenario Combination (partial list)	Probability of Scenario Combination in 1 yr (unitless)	Mean Consequence (Sv)*	Mean Risk, Probability × Consequence (Sv/yr)*
$A^-B^-C^-D^-E^-F^-$	8.1×10^{-1}	0	0
$A^+B^-C^-D^-E^-F^-$	1.8×10^{-1}	1.8×10^{-7}	3.2×10^{-8}
$A^-B^+C^-D^-E^-F^-$	4.1×10^{-3}	3.4×10^{-10}	1.4×10^{-12}
$A^+B^+C^-D^-E^-F^-$	9.0×10^{-4}	1.8×10^{-7}	1.6×10^{-10}
$A^-B^-C^+D^-E^-F^-$	8.1×10^{-4}	5.4×10^{-6}	4.4×10^{-9}
$A^-B^-C^-D^+E^-F^-$	8.1×10^{-4}	3.8×10^{-10}	3.1×10^{-13}
$A^-B^-C^-D^-E^-F^+$	8.1×10^{-4}	3.6×10^{-8}	2.9×10^{-11}
$A^-B^-C^-D^-E^+F^-$	4.1×10^{-4}	1.3×10^{-7}	5.1×10^{-11}
$A^+B^-C^+D^-E^-F^-$	1.8×10^{-4}	5.6×10^{-6}	1.0×10^{-9}
$A^+B^-C^-D^+E^-F^-$	1.8×10^{-4}	1.8×10^{-7}	3.2×10^{-11}
$A^+B^-C^-D^-E^-F^+$	1.8×10^{-4}	2.1×10^{-7}	3.8×10^{-11}
$A^+B^-C^-D^-E^+F^-$	9.0×10^{-5}	3.0×10^{-7}	2.7×10^{-11}
$A^-B^+C^+D^-E^-F^-$	4.1×10^{-6}	5.4×10^{-6}	2.2×10^{-11}
$A^-B^+C^-D^+E^-F^-$	4.1×10^{-6}	7.2×10^{-10}	2.9×10^{-15}
$A^-B^+C^-D^-E^-F^+$	4.1×10^{-6}	3.6×10^{-8}	1.5×10^{-13}
$A^-B^+C^-D^-E^+F^-$	2.0×10^{-6}	1.3×10^{-7}	2.6×10^{-13}

more than one initiating event occurs

* Multiply by 100 to convert consequences in Sv to rem.

Total Risk = 3.8×10^{-8} Sv/yr

Example Ranking of SSCs

- Hypothetical "take-away"analysis assumes the failure of an individual SSC
  - Rank the reliance on SSCs
  - Based on the increase in mean risk

Risk Metric Taken from the CCDF for Risk	Baseline Risk* (Sv/yr)	Take-Away Analysis, Risk* (Sv/yr)			
		HEPA Filtration	Canister	Surface Aging Cask	Waste Package
Mean value	3.8×10^{-8}	5.3×10^{-7}	5.8×10^{-8}	6.7×10^{-7}	3.9×10^{-7}

* Multiply by 100 to convert consequences in Sv to rem.

  - Surface aging cask
  - High-efficiency particulate air filtration
  - Waste package
  - Canister

Conclusions

- Methodology calculates the total facility risk and propagates the uncertainty in risk
- Hypothetical “take-away”analyses can rank individual SSCs based on risk
- Example problem insight: The SSC relied on most for limiting the risk was functioning in a <u>different</u> general location than the location that contributed the most to the total baseline risk
- Application highlights aspects of the facility design for a risk-informed regulatory review

Acknowledgement and Disclaimer

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- This presentation is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

Backup Material on the Steps of the Methodology

Step 1. Convert the initiating event frequencies into **initiating event probabilities**

- Poisson process describes the relationship between the initiating event frequency, f_x, and its probability of k occurrences
  - Large repetitions of handling operations
  - Low component failure rates for a bionomial process

$$p(k) = \frac{\left(f_x \cdot 1\mathrm{yr}\right)^k}{k!} e^{-\left(f_x \cdot 1\mathrm{yr}\right)}$$

Step 1. Convert the initiating event frequencies into **initiating event probabilities** (continued)

- Methodology divides the initiating event probabilities into two parts

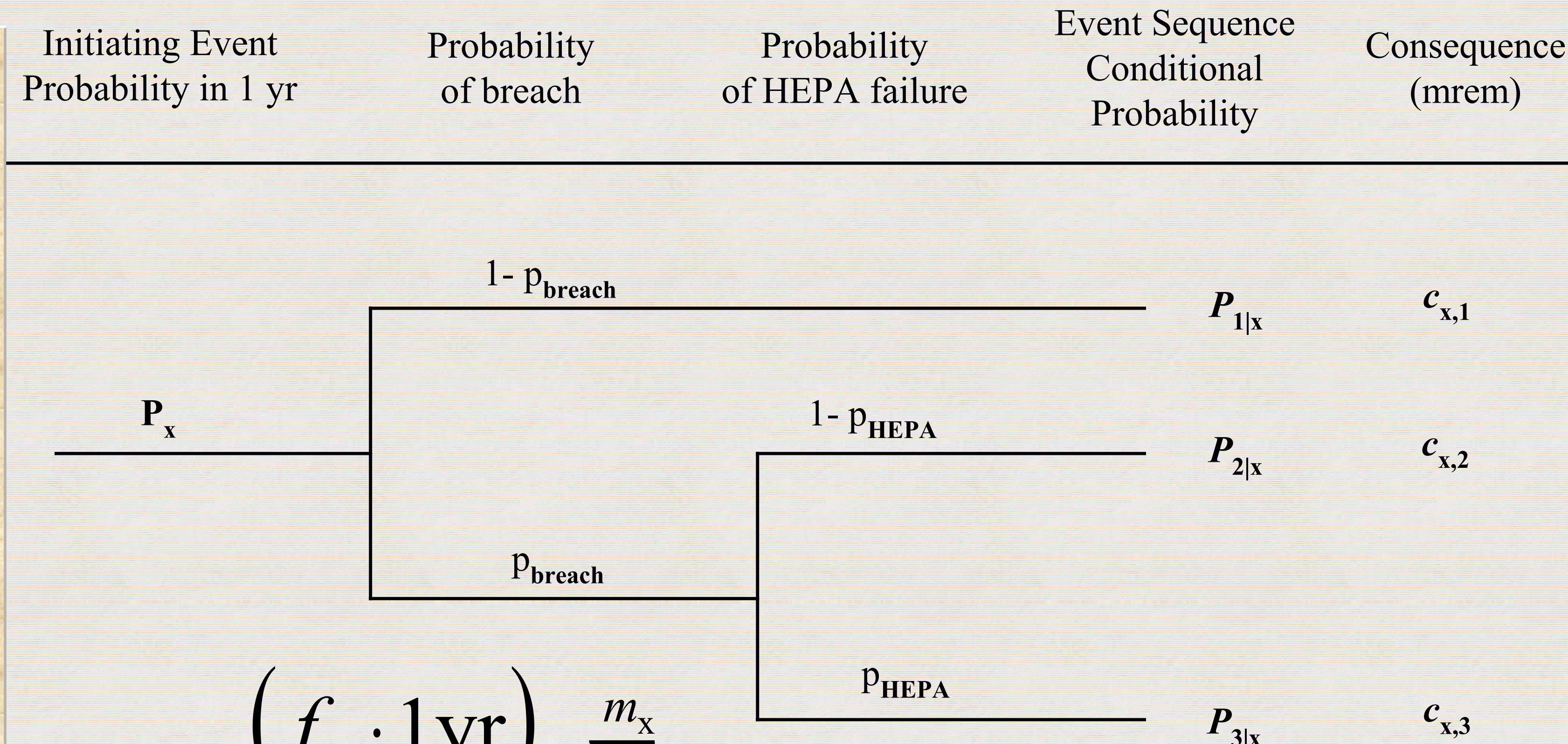
$$P(\text{Initiating Event x occurs at least once in 1 yr}) =$$

$$1 - e^{-\left(f_x \cdot 1\text{yr}\right)} = P_x$$

$$P(\text{Initiating Event x does not occur in 1 yr}) =$$

$$e^{-\left(f_x \cdot 1\text{yr}\right)} = 1 - P_X$$

Step 2. Compute **initiating event consequences**



$$C_x = \frac{\left(f_x \cdot 1\text{yr}\right)}{1 - e^{-\left(f_x \cdot 1\text{yr}\right)}} \sum_{i}^{m_x} p_{i|x} c_{x,i}$$

From Benke, et al. PSAM6 paper

Step 3. Identify the set of **scenario combinations**

- Example list of scenario combinations based on 4 initiating events

None
- $E_1^- E_2^- E_3^- E_4^-$

One
- $E_1^* E_2^- E_3^- E_4^-$
- $E_1^- E_2^* E_3^- E_4^-$
- $E_1^- E_2^- E_3^* E_4^-$
- $E_1^- E_2^- E_3^- E_4^*$

Two
- $E_1^* E_2^* E_3^- E_4^-$
- $E_1^* E_2^- E_3^* E_4^-$
- $E_1^* E_2^- E_3^- E_4^*$
- $E_1^- E_2^* E_3^* E_4^-$
- $E_1^- E_2^* E_3^- E_4^*$
- $E_1^- E_2^- E_3^* E_4^*$

Three
- $E_1^- E_2^* E_3^* E_4^*$
- $E_1^* E_2^- E_3^* E_4^*$
- $E_1^* E_2^* E_3^- E_4^*$
- $E_1^* E_2^* E_3^* E_4^-$

Four
- $E_1^* E_2^* E_3^* E_4^*$

From Benke, et al. PSAM6 paper

Step 4. Calculate the **risk of each scenario combination** and the **total risk**

- Risk = (Probability) × (Consequence)

$E_1^* E_2^- E_3^* E_4^-$ Example Scenario Combination

$$\left[P_1\left(1-P_2\right)P_3\left(1-P_4\right)\right]\left[C_1+C_3\right]$$

- Total Risk = Sum of all scenario combination risks