
Presentation to SUM 2010

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Waste for Yucca Mountain

Commercial Spent Nuclear Fuel:
63,000 MTHM (~7500 waste packages)

DOE & Naval Spent Nuclear Fuel:
2,333 MTHM
(~400 naval waste packages)
(DSNF packaged with HLW)

DOE & Commercial High-Level Waste:
4,667 MTHM
(~3000 waste packages of co-disposed DSNF and HLW)

Yucca Mountain
Total 70,000 MTHM

DSNF: Defense Spent Nuclear Fuel
HLW: High Level Radioactive Waste
MTHM: Metric Tons Heavy Metal
Proposed Repository at Yucca Mountain
Post-Closure Regulatory Requirements for proposed Yucca Mountain repository

- 10 CFR 63 and 40 CFR Part 197
  Maximum value of mean dose to the reasonably maximally exposed individual (RMEI) over time interval [0, \(10^4\) yr] less than 15 mrem/yr
- Maximum value of mean dose to the RMEI over time interval \([10^4, 10^6\) yr] less than 100 mrem/yr
- Take uncertainties and gaps in knowledge into account
- Requirements lead to Performance Assessment (PA) that
  - Computes measures of performance (e.g. mean dose)
  - Accounts for and quantifies uncertainty in measures of performance
Sources of Uncertainty

Lack of knowledge about the future state of the system probabilities of disruptive events

Incomplete data
  for example, limited hydrologic data from test wells

Spatial variability and scaling issues
  data may be available from small volumes (for example, porosity measurements from core samples), but may be used in the models to represent large volumes

Measurement error
  usually only a very minor source of uncertainty compared to uncertainty from incomplete data

Alternative conceptual models
## Categories of Uncertainty

<table>
<thead>
<tr>
<th>Aleatory Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Inherent randomness in events that could occur in the future</td>
</tr>
<tr>
<td>- Alternative descriptors: irreducible, stochastic, intrinsic, type A</td>
</tr>
<tr>
<td>- Examples:</td>
</tr>
<tr>
<td>&gt; <em>Time and size of an igneous event</em></td>
</tr>
<tr>
<td>&gt; <em>Time and size of a seismic event</em></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Epistemic Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Lack of knowledge about appropriate value to use for a quantity assumed to have a fixed value</td>
</tr>
<tr>
<td>- Alternative descriptors: reducible, subjective, state of knowledge, type B</td>
</tr>
<tr>
<td>- Examples:</td>
</tr>
<tr>
<td>&gt; <em>Spatially averaged permeabilities, porosities, sorption coefficients, …</em></td>
</tr>
<tr>
<td>&gt; <em>Rates defining Poisson processes</em></td>
</tr>
</tbody>
</table>
Four Questions Underlying PA

1. What events and processes can take place at the facility?

2. How likely are these events or processes?

3. What are the consequences of these events or processes?
   - Kaplan and Garrick (1979) “risk triplet”

4. How certain are the answers to the first 3 questions?
Mathematical Entities Underlying the YM PA

EN1: Probability space characterizing what can happen in the future
- Answers “What can happen” and “How likely”
- Provides formal characterization of aleatory uncertainty
  E.G. Assumption that igneous event occurrence is a Poisson process

EN2: Mathematical models for predicting consequences
- Answers “What are the consequences”
  E.G. Flow and Transport Models

EN3: Probability space characterizing uncertainty in TSPA inputs
- Basis for answering “How certain are the answers to the other three questions”
- Provides formal characterization of epistemic uncertainty
  E.G. Distribution assigned to rate for a Poisson process
Scenarios for the YM PA

Possible events are screened (10^{-8} yr^{-1} minimum) then grouped by event type to form four scenario classes (divided into seven modeling cases by effect of event on disposal system)

**Nominal Scenario Class**
- Nominal Modeling Case (included with Seismic Ground Motion for 1,000,000-yr analyses)

**Early Failure Scenario Class**
- Waste Package Modeling Case
- Drip Shield Modeling Case

**Igneous Scenario Class**
- Intrusion Modeling Case
- Eruption Modeling Case

**Seismic Scenario Class**
- Ground Motion Modeling Case
- Fault Displacement Modeling Case
EN1: Probability Space for Aleatory Uncertainty

Characterizes uncertainty in occurrence of future events

Define a vector that describes an individual future \( \mathbf{a} \)

\[
\mathbf{a} = [nEW, nED, nII, nIE, nSG, nSF, a_{EW}, a_{ED}, a_{II}, a_{IE}, a_{SG}, a_{SF}]
\]

where

- \( nEW = \) number of early WP failures
- \( nED = \) number of early DS failures
- \( nII = \) number of igneous intrusive events
- \( nIE = \) number of igneous eruptive events
- \( nSG = \) number of seismic ground motion events
- \( nSF = \) number of fault displacement events
- \( a_{EW} = \) vector defining \( nEW \) early WP failures
- \( a_{ED} = \) vector defining \( nED \) early DS failures
- \( a_{II} = \) vector defining \( nII \) igneous intrusive events
- \( a_{IE} = \) vector defining \( nIE \) igneous eruptive events
- \( a_{SG} = \) vector defining \( nSG \) seismic ground motion events
- \( a_{SF} = \) vector defining \( nSF \) fault displacement events

Form the set \( \mathcal{A} \) of all such vectors (description of all possible futures)

\[
\mathcal{A} = \{ \mathbf{a} : \mathbf{a} = [nEW, nED, nII, nIE, nSG, nSF, a_{EW}, a_{ED}, a_{II}, a_{IE}, a_{SG}, a_{SF}] \}
\]

Characterize each element of \( \mathbf{a} \) with a probability distribution
EN2: Models for Estimating Consequences

Conceptually represented by a function

\[ D(\tau | a, e) \]

\( \tau \) time
\( a \) future
\( e \) model inputs
EN3: Probability Space for Epistemic Uncertainty

- 392 epistemically uncertain analysis inputs
- \( \mathbf{e} = [e_1,e_2,...,e_{392}] \), \( \mathcal{E} = \{ \mathbf{e} : \mathbf{e} = [e_1,...,e_{392}] \} \)
- Example elements of \( \mathbf{e} \)

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
<th>Distribution</th>
<th>Range</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASHDENS</td>
<td>Tephra settled density (kg/m(^3)).</td>
<td>Truncated normal</td>
<td>300 to 1500</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>IGRATE</td>
<td>Frequency of intersection of the repository footprint by a volcanic event (yr(^{-1})).</td>
<td>Piecewise uniform</td>
<td>0 to 7.76E-07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>INFIL</td>
<td>Pointer variable for determining infiltration conditions: 10(^{th}), 30(^{th}), 50(^{th}) or 90(^{th}) percentile infiltration scenario (dimensionless).</td>
<td>Discrete</td>
<td>1 to 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MICPU239</td>
<td>Groundwater biosphere dose conversion factor (BDCF) for (^{239})Pu in modern interglacial climate ((Sv/year)/(Bq/m(^3))).</td>
<td>Discrete</td>
<td>3.49E-07 to 2.93E-06</td>
<td>9.55E-07</td>
<td></td>
</tr>
<tr>
<td>SZFISPVO</td>
<td>Flowing interval spacing in fractured volcanic units (m).</td>
<td>Piecewise uniform</td>
<td>1.86 to 80</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conceptual Calculation of Total Mean Dose

- Regulation requests “mean” values of dose to a reasonably maximally exposed individual
- Uncertainty in future events $\mathbf{a}$ and in model inputs $\mathbf{e}$ lead to a distribution of estimates of dose
- Calculation proceeds in three stages:

$$
\overline{D}(\tau) = E_E \left[ E_A \left( D(\tau | \mathbf{a}, \mathbf{e}) \right) \right]
$$

$$
= \int_E \int_A D(\tau | \mathbf{a}, \mathbf{e}) \, d_A(\mathbf{a} | \mathbf{e}) \, dA \, d_E(\mathbf{e}) \, dE
$$

$$
= \int_E \int_A \sum_{MC} D_{MC}(\tau | \mathbf{a}, \mathbf{e}) \, d_A(\mathbf{a} | \mathbf{e}) \, dA \, d_E(\mathbf{e}) \, dE
$$

$$
= \int_E \sum_{MC} \int_A D_{MC}(\tau | \mathbf{a}, \mathbf{e}) \, d_A(\mathbf{a} | \mathbf{e}) \, dA \, d_E(\mathbf{e}) \, dE
$$

- $E_E$ and $E_A$ denote expectations over the distribution of future events and model inputs, respectively.
Illustration of Calculation of Expected Dose

1. Start
2. Sample Epistemic Uncertainty, $e$, $N_{LHS} = 300$
3. $e = \theta$ (parameter uncertainties)
4. Select Aleatory Uncertainty, $a$
5. $a = a$ (event times, damage areas)

Calculate Expectation over Aleatory Uncertainty

- Annual Dose Integrated over Damage Area, (6 event times)
- Interpolated Seismic Futures, (multiple event times)
- Annual Dose for Possible Seismic Futures, (6 event times, 5 damage areas)
- Expected annual dose curve, given $e$

300 Expected Annual Dose Curves
Summary metrics of uncertainty in expected annual dose curves

National Nuclear Security Administration
Sandia National Laboratories
YM PA Results
Individual Protection Standard: 10,000 yr

Four questions:

1. What determines the **shape** of these curves?

2. What determines the **magnitude** of total mean dose?

3. What determines the **uncertainty** in total expected dose?

4. Are these results stable?
Total Mean Dose
Contributions By Modeling Case and Radionuclide

Note: Contribution from Nominal Modeling Case is zero within 10,000 years
Uncertainty in Total Expected Dose

**EXPDOSE**: 10,000 yr

<table>
<thead>
<tr>
<th>Step</th>
<th>Variable</th>
<th>$R^2$</th>
<th>SRRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SCCTHRP</td>
<td>0.69</td>
<td>-0.82</td>
</tr>
<tr>
<td>2</td>
<td>IGRATE</td>
<td>0.73</td>
<td>0.22</td>
</tr>
<tr>
<td>3</td>
<td>SZGWSPDM</td>
<td>0.76</td>
<td>0.17</td>
</tr>
<tr>
<td>4</td>
<td>MICTC99</td>
<td>0.78</td>
<td>0.14</td>
</tr>
<tr>
<td>5</td>
<td>WFDEGEXF</td>
<td>0.79</td>
<td>0.11</td>
</tr>
<tr>
<td>6</td>
<td>MCC14</td>
<td>0.80</td>
<td>0.10</td>
</tr>
<tr>
<td>7</td>
<td>UZGAM</td>
<td>0.81</td>
<td>-0.10</td>
</tr>
<tr>
<td>8</td>
<td>WDGCUA22</td>
<td>0.81</td>
<td>-0.07</td>
</tr>
<tr>
<td>9</td>
<td>HLGWGRNDS</td>
<td>0.82</td>
<td>-0.08</td>
</tr>
<tr>
<td>10</td>
<td>CSWFA0AC</td>
<td>0.82</td>
<td>-0.07</td>
</tr>
</tbody>
</table>

**SCCTHRP** – stress threshold for SCC initiation (90 to 105% of yield strength)

**IGRATE** – frequency of igneous events

**SZGWSPDM** – logarithm of uncertainty factor in groundwater specific discharge
Stability of Total Dose

Replicated sampling demonstrates that sample size is sufficient

Confidence interval illustrates precision of estimate of total mean dose
Quantifying Uncertainty

- Uncertainty in inputs (aleatory or epistemic) results from expert judgment
  - Empirical distribution
  - Model fit to data
  - Calibration with uncertainty range
- In some cases formal elicitation procedures are used
- Uncertainty in outputs results from propagating uncertain inputs through models
Addressing Uncertainty in Models

• Uncertainty in models arises from:
  an incomplete knowledge of the behaviour of engineered systems, 
  physical processes, or site characteristics, 
  representation of features, events and processes using simplified 
  mathematical models, 
  the inexact implementation of mathematical models in numerical form 
  and in computer codes.

• Addressed primarily by comparing alternative models
  Generally, one model is selected that overstates radionuclide releases 
  (as compared to alternative models)
  In some cases, several models are implemented and selected by 
  means of an uncertain pointer variable

• Other schemes exist (e.g., Bayesian updating) but not use for YM 
  PA was not practical
Summary

• Probabilistic structure used for performance assessment of a proposed nuclear waste disposal facility

• Analysis accounts for uncertainty in
  • Future events (aleatory)
  • State-of-knowledge as basis for modeling site performance (epistemic)

• Distinction between types of uncertainty aids in identifying source of uncertainty and its characterization
Estimating Dose to Hypothetical Future Humans

Modeled groundwater flow paths and hypothetical exposure pathways