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Characterization, Propagation and Analysis of Aleatory and Epistemic Uncertainty in the 2008 Performance Assessment for the Proposed Repository for Radioactive Waste at Yucca Mountain, Nevada

Presentation to SUM 2010

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Waste for Yucca Mountain

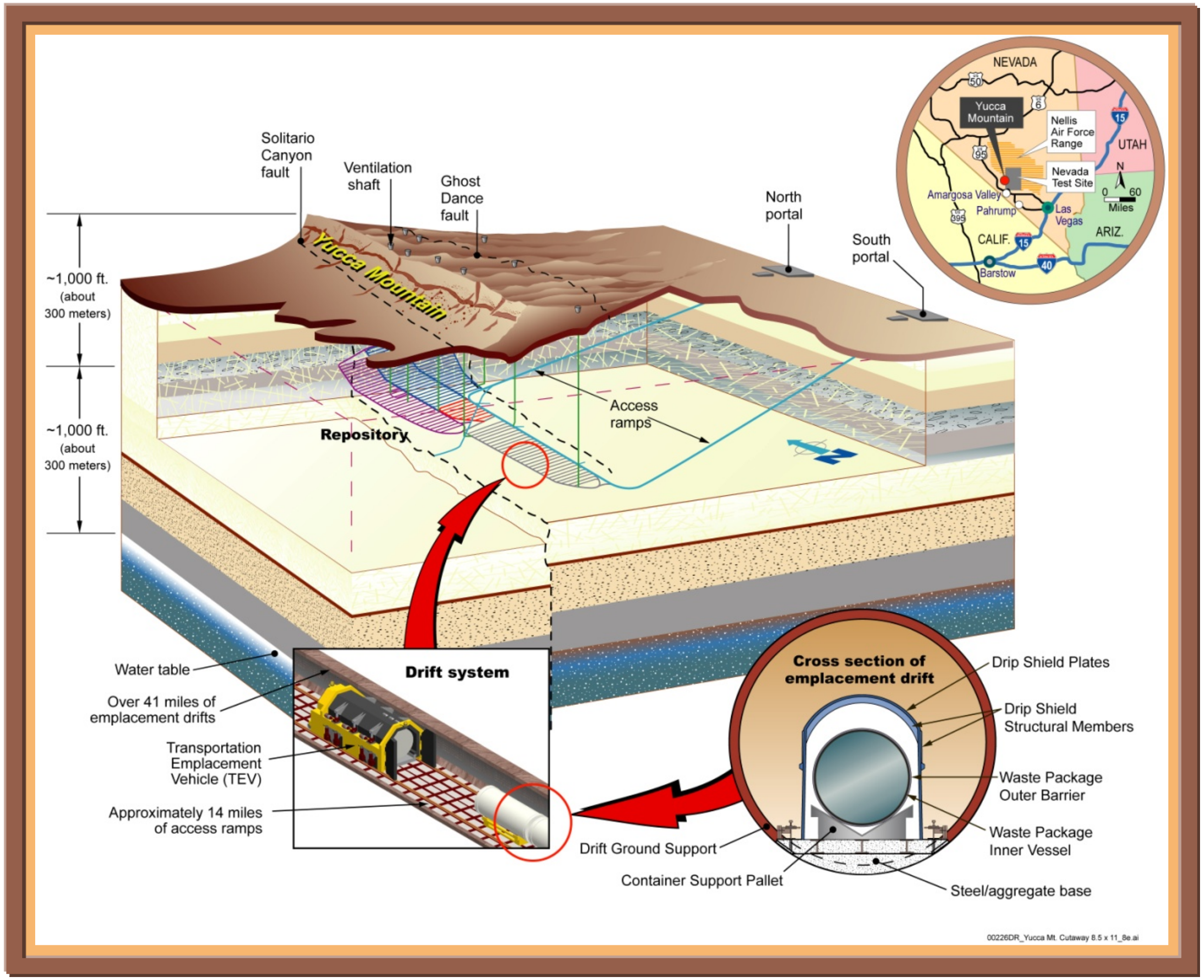
Commercial Spent Nuclear Fuel:
63,000 MTHM (~7500 waste packages)

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)

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

Aleatory Uncertainty
− Inherent randomness in events that could occur in the future
− Alternative descriptors: irreducible, stochastic, intrinsic, type A
− Examples:
➢ *Time and size of an igneous event*
➢ *Time and size of a seismic event*

Epistemic uncertainty
− Lack of knowledge about appropriate value to use for a quantity assumed to have a fixed value
− Alternative descriptors: reducible, subjective, state of knowledge, type B
− Examples:
➢ *Spatially averaged permeabilities, porosities, sorption coefficients, …*
➢ *Rates defining Poisson processes*

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

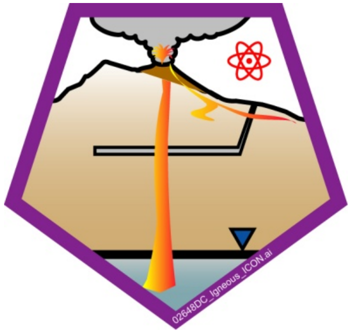
Possible events are screened (10^{-8} yr^{-1} minimum) then grouped by event type to form four scenario classes (divided into seven modeling cases by effect of event on disposal system)

Nominal Scenario Class

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

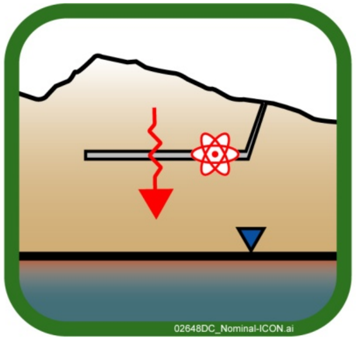
Igneous Scenario Class

- **Intrusion Modeling Case**
- **Eruption Modeling Case**



Early Failure Scenario Class

- **Waste Package Modeling Case**
- **Drip Shield 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 **a**

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

where

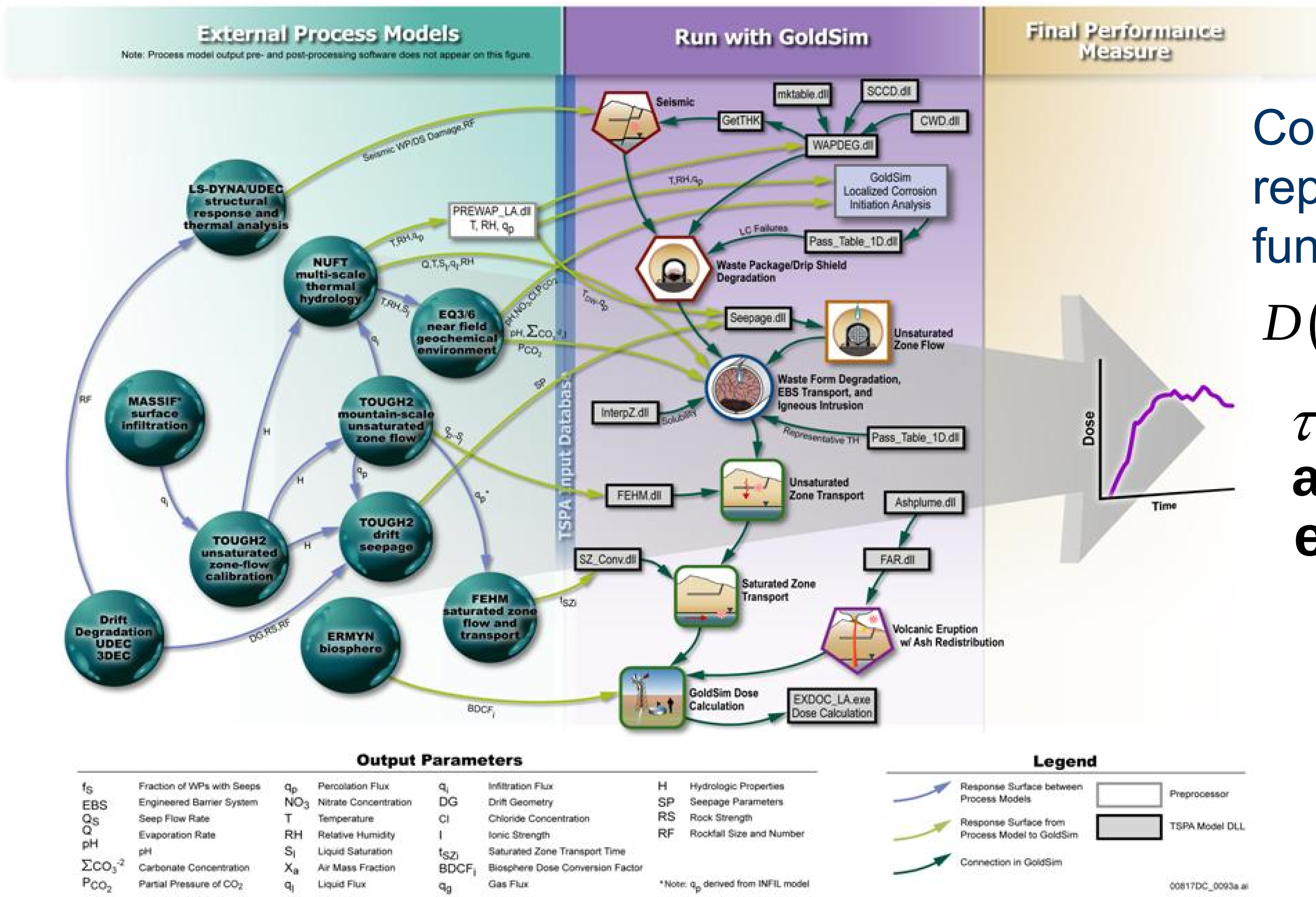
- nEW = number of early WP failures
- nED = number of early DS failures
- nII = number of igneous intrusive events
- nIE = number of igneous eruptive events
- nSG = number of seismic ground motion events
- nSF = number of fault displacement events
- a_{EW} = vector defining nEW early WP failures
- a_{ED}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

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

Characterize each element of **a** with a probability distribution

EN2: Models for Estimating Consequences



Conceptually represented by a function

$$D(\tau \mid \mathbf{a}, \mathbf{e})$$

τ time

a future

e model inputs

EN3: Probability Space for Epistemic Uncertainty

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

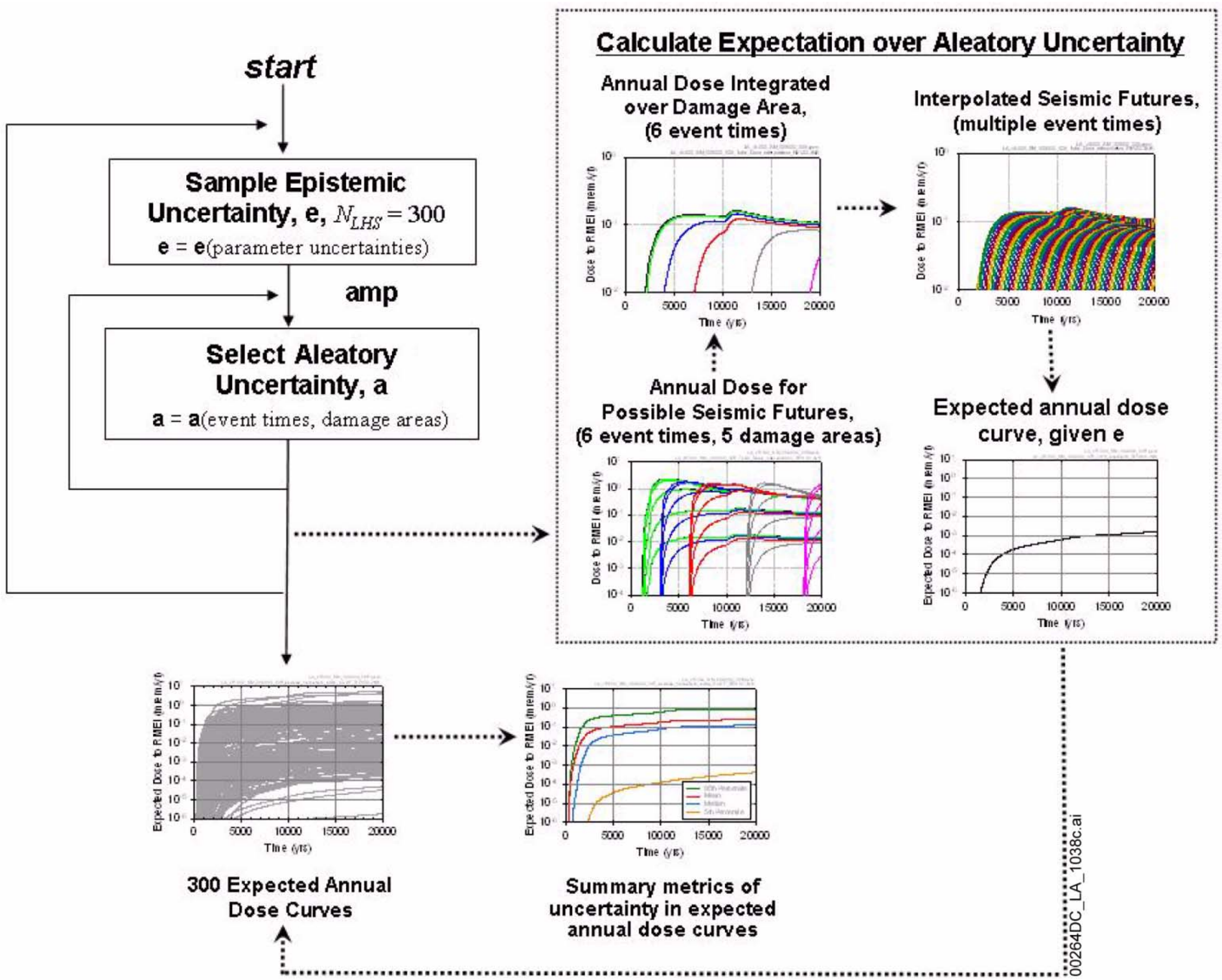
ASHDENS - Tephra settled density (kg/m^3). *Distribution:* Truncated normal. *Range:* 300 to 1500. *Mean:* 1000. *Standard Deviation:* 100.
IGRATE - Frequency of intersection of the repository footprint by a volcanic event (yr^{-1}). *Distribution:* Piecewise uniform. *Range:* 0 to 7.76E-07.
INFIL -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

Conceptual Calculation of Total Mean Dose

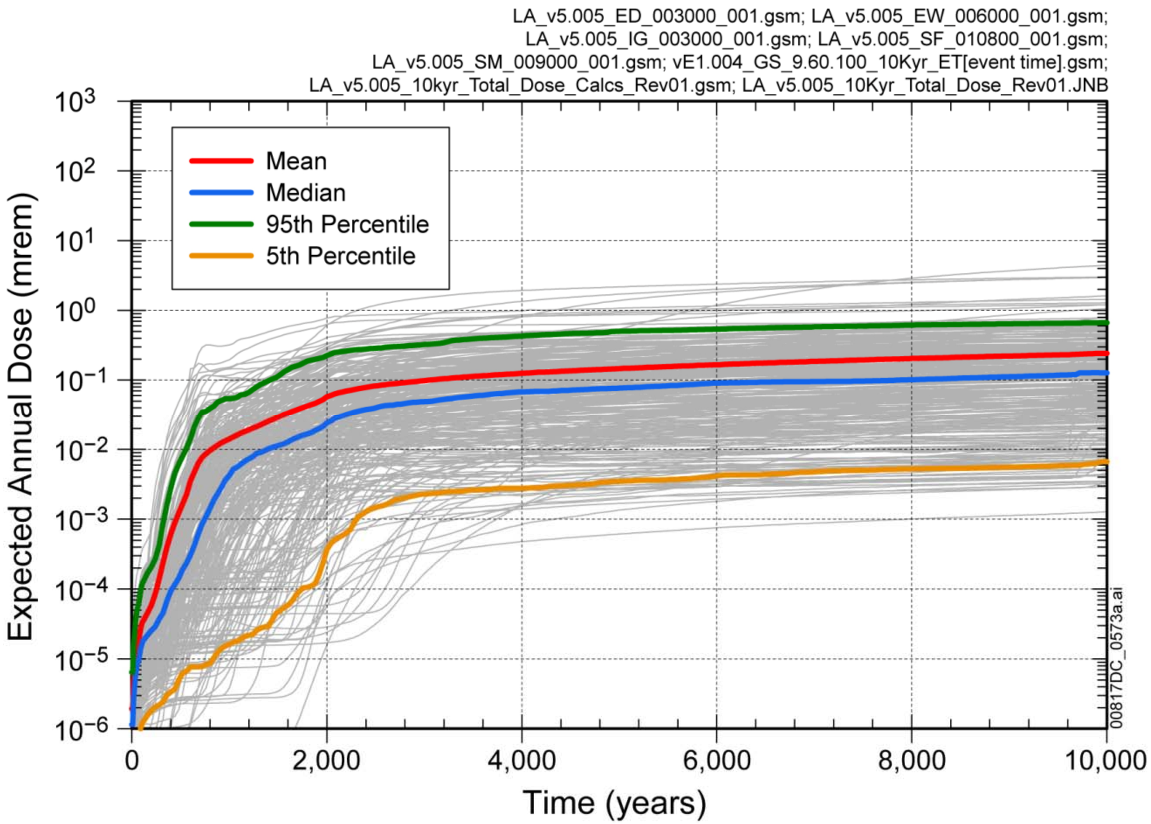
- Regulation requests "mean" values of dose to a reasonably maximally exposed individual
- Uncertainty in future events **a** and in model inputs **e** lead to a distribution of estimates of dose
- Calculation proceeds in three stages:

$$
\begin{aligned}
\bar{\bar{D}}(\tau) &= E_E\left[E_A\left(D(\tau \mid \mathbf{a}, \mathbf{e})\right)\right] \\
&= \int_{\mathcal{E}}\left[\int_{\mathcal{A}} D(\tau \mid \mathbf{a}, \mathbf{e})\, d_A(\mathbf{a} \mid \mathbf{e})\, dA\right] d_E(\mathbf{e})\, dE \\
&\cong \int_{\mathcal{E}}\left[\int_{\mathcal{A}}\left\{\sum_{MC} D_{MC}(\tau \mid \mathbf{a}, \mathbf{e})\right\} d_A(\mathbf{a} \mid \mathbf{e})\, dA\right] d_E(\mathbf{e})\, dE \\
&= \int_{\mathcal{E}} \sum_{MC}\left[\int_{\mathcal{A}} D_{MC}(\tau \mid \mathbf{a}, \mathbf{e})\, d_A(\mathbf{a} \mid \mathbf{e})\, dA\right] d_E(\mathbf{e})\, dE
\end{aligned}
$$

Illustration of Calculation of Expected Dose



YM PA Results
Individual Protection Standard: 10,000 yr

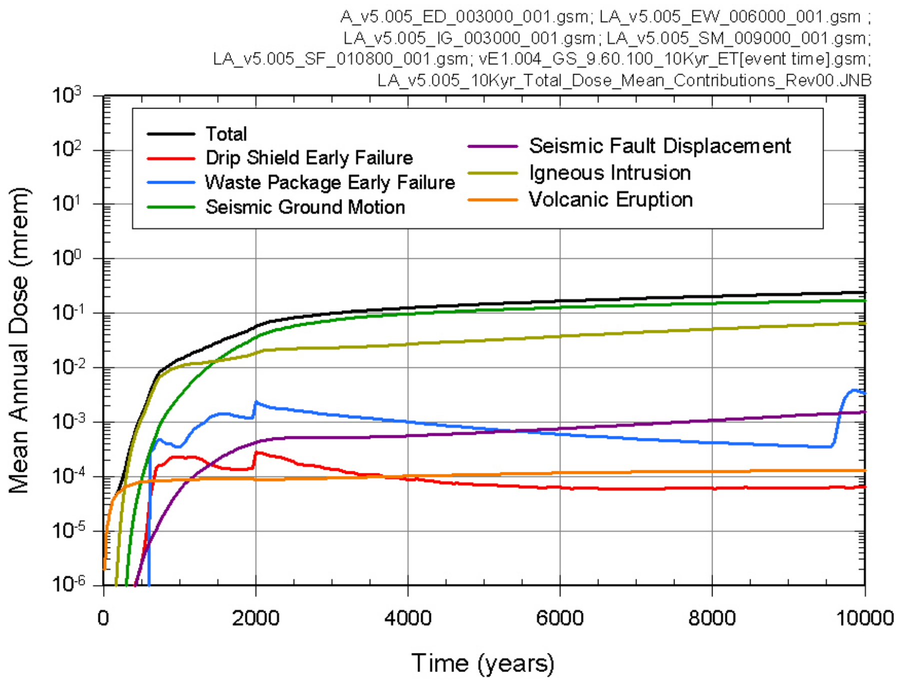


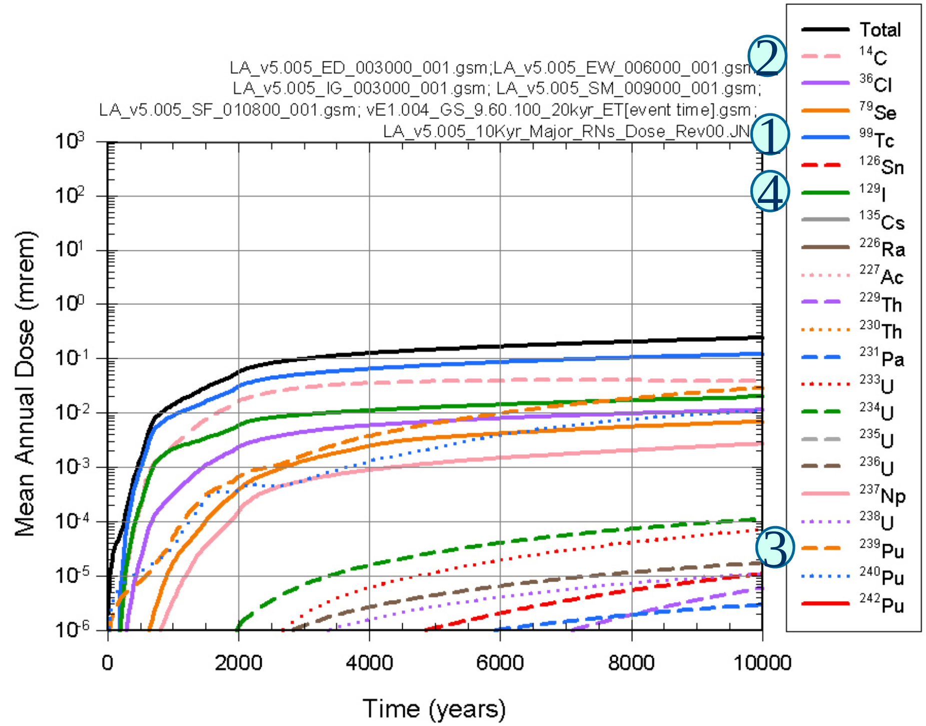
Four questions:

1. What determines the <u>shape</u> of these curves?
2. What determines the <u>magnitude</u> of total mean dose?
3. What determines the <u>uncertainty</u> in total expected dose?
4. Are these results <u>stable</u>?

Total Mean Dose

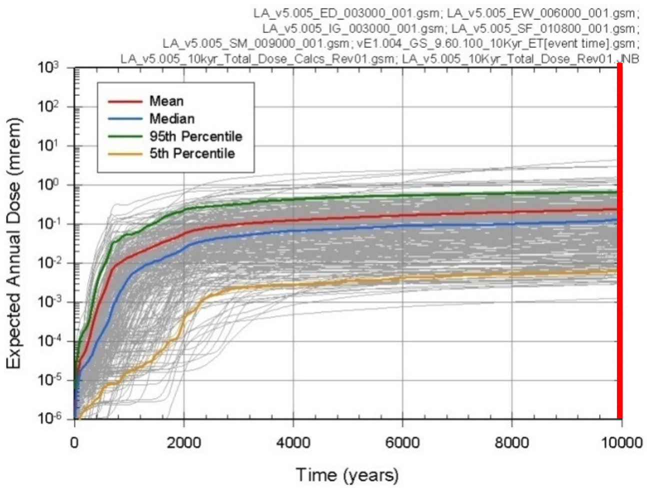
Contributions By Modeling Case and Radionuclide

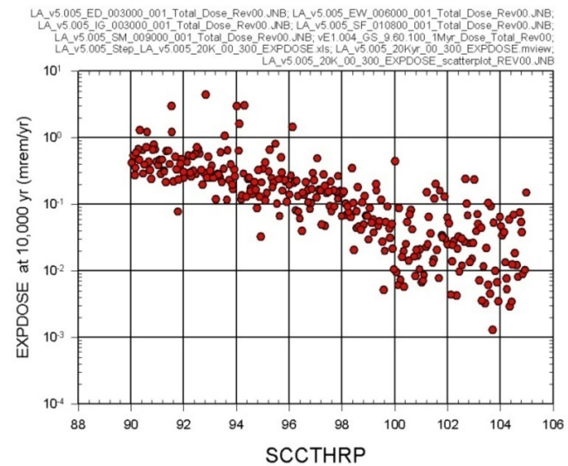


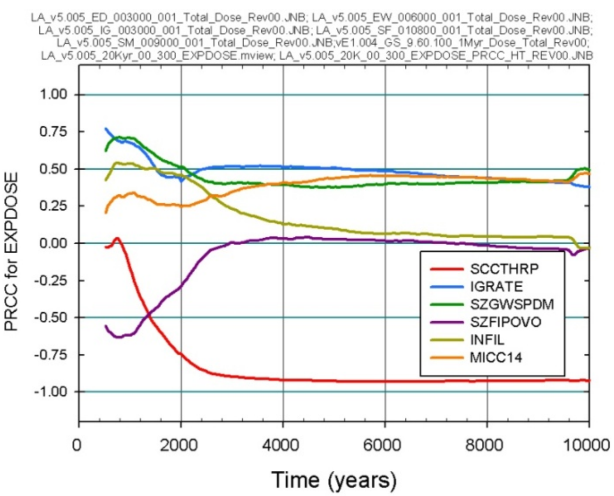


Note: Contribution from Nominal Modeling Case is zero within 10,000 years

Uncertainty in Total Expected Dose



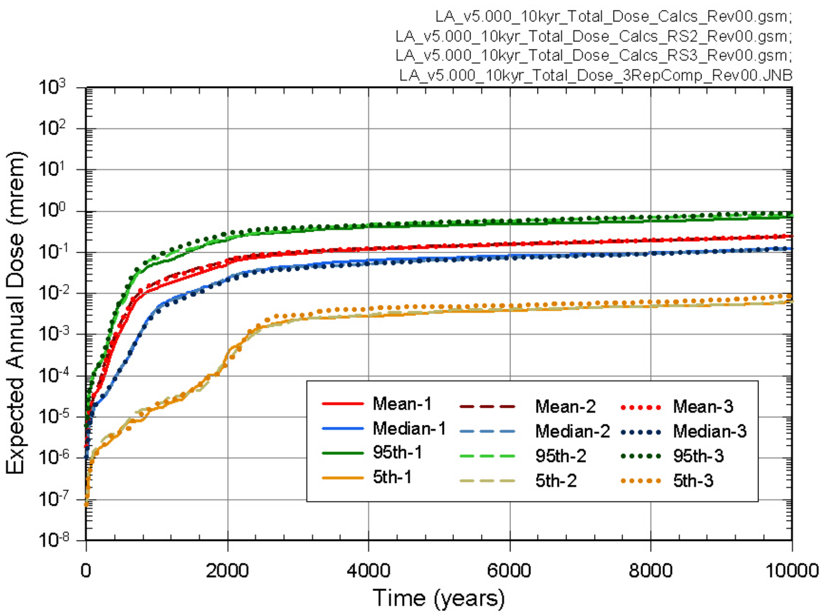


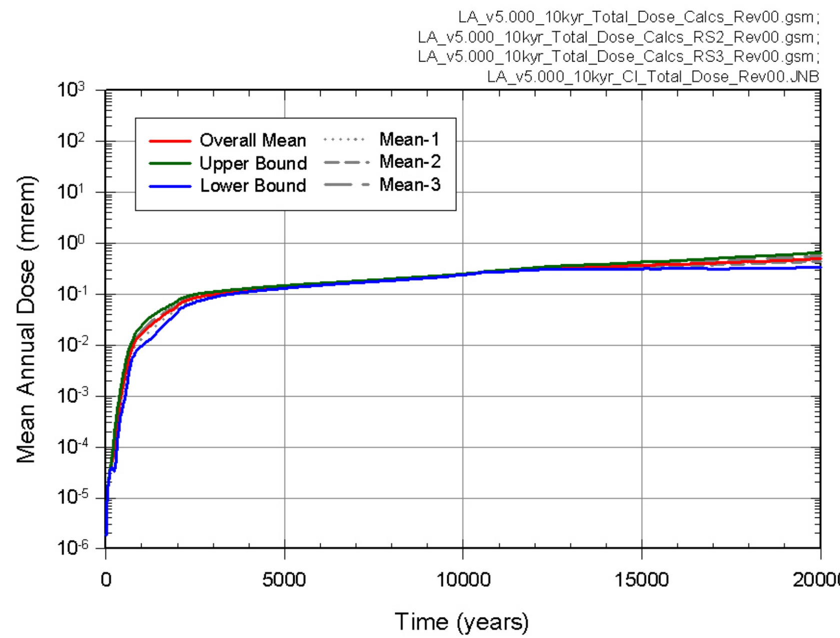


	EXPDOSE: 10,000 yr		
Step	**Variable**	**R^2**	**SRRC**
1	SCCTHRP	0.69	-0.82
2	IGRATE	0.73	0.22
3	SZGWSPDM	0.76	0.17
4	MICTC99	0.78	0.14
5	WFDEGEXF	0.79	0.11
6	MICC14	0.80	0.10
7	UZGAM	0.81	-0.10
8	WDGCUA22	0.81	-0.07
9	HLWGRNDS	0.82	-0.08
10	CSWFA0AC	0.82	-0.07

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

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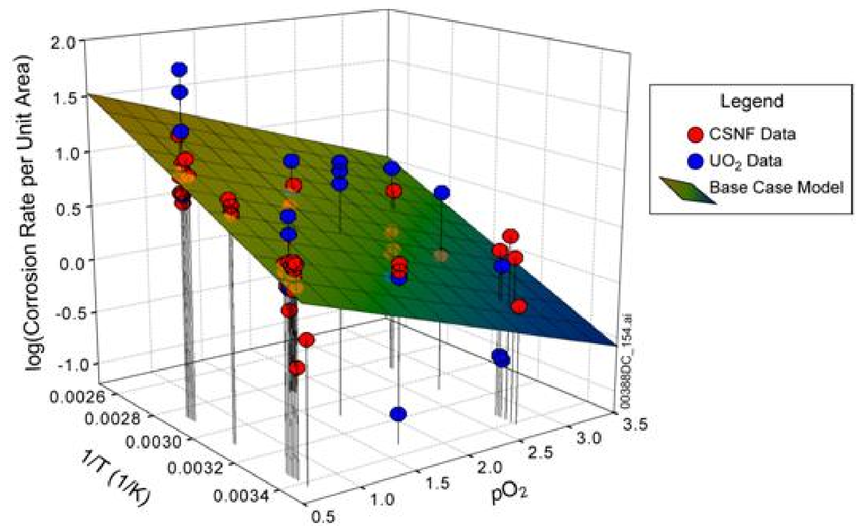
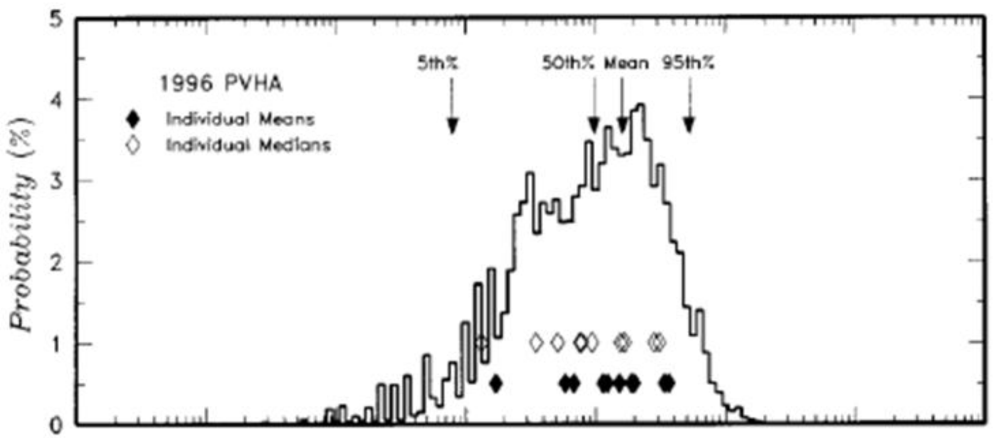
Quantifying Uncertainty

- 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





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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

Backup Slides

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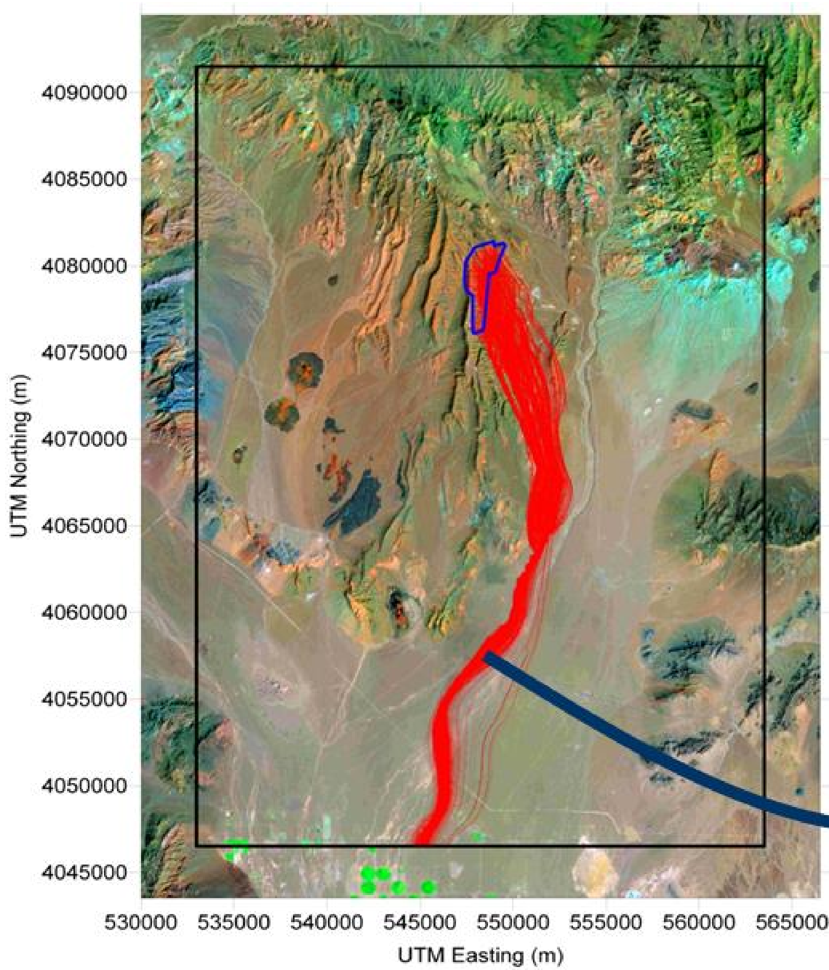
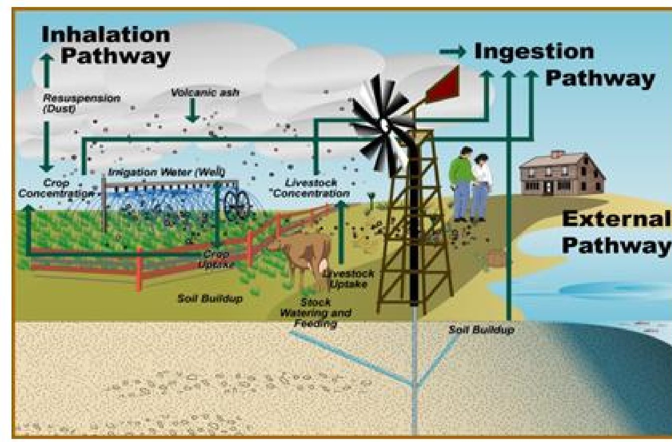
Estimating Dose to Hypothetical Future Humans





Modeled groundwater flow paths and hypothetical exposure pathways