SAND2010-3650P

Advanced Conceptual and Numerical Methods for Modeling Subsurface Processes Regarding Nuclear Waste Repository Systems

IAEA Network of Centers of Excellence

Sandia National Laboratories

Overview of Safety Assessment Methods

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Outline

- Definitions
- Basic Structure for Safety Assessments
- Iterative Process
  - Screen Features, Events and Processes
  - Develop Model
  - Characterize Uncertainty
  - Construct System Model
  - Evaluate System Performance
- Summary

Definitions

- Safety Case

  A collection of arguments and evidence to demonstrate the safety of a facility

  Developed in concert with the facility as scientific understanding advances

  Includes:

    Pre- and post-closure safety assessments

    Descriptions of barriers and their performance

    Supporting evidence (e.g., geologic analogues)

  Acknowledges unresolved issues

Geologic Disposal of Radioactive Waste, IAEA, 2006

Definitions

- Post-Closure Safety Assessment

  Systematic analysis of:

    the hazards associated with the facility and

    the ability of the site and the design of the facility to provide for the safety functions and meet technical requirements

  Quantifies performance and associated uncertainties

  Compares to relevant safety standards

  Safety assessments are site and design specific

  Constructed to address regulatory requirements

Geologic Disposal of Radioactive Waste, IAEA, 2006

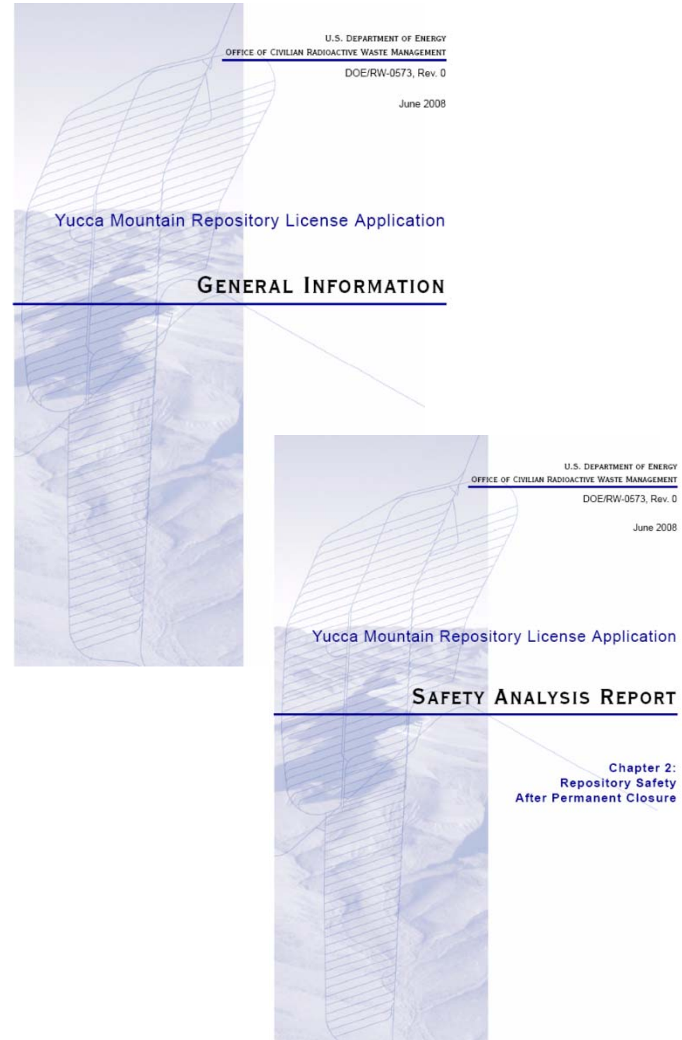
Safety Case Example: Yucca Mountain Repository License Application

DOE/RW-0573 Rev 0
June 2008

- General Information (GI)
  - General Description
  - Proposed Schedules for Construction, Receipt and Emplacement of Waste
  - Physical Protection Plan
  - Material Control and Accounting Program
  - Site Characterization

- Safety Analysis Report (SAR)
  - Repository Safety Before Permanent Closure
  - Repository Safety After Permanent Closure
  - Research and Development Program to Resolve Safety Questions
  - Performance Confirmation Program
  - Management Systems

- Available from the NRC (http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app.html#appdocuments)



Example

- Safety Case: Compliance Certification Application for the Waste Isolation Pilot Plant (and applications for recertification)

- Safety Assessment: 1996 (and 2004 and 2009) Performance Assessment for the WIPP

- Safety Case includes Safety Assessment(s)
  prepared by repository developer
  reviewed by regulator

Basic Structure for Safety Assessment

- Framework for quantitative risk assessment
  1. What events and processes can take place at the facility?
  2. How likely are these events and processes?
  3. What are the consequences of the events and processes?

     (Kaplan and Garrick (1979) 'risk triplet')
- How certain are the answers to these questions?

- Iterative process for answering these questions

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
- Abstraction of physical processes into models

Classification of Uncertainties

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 or model to use

− Alternative descriptors: reducible, subjective, state of knowledge, type B

− Examples:

- *Spatially averaged permeabilities, porosities, sorption coefficients, …*
- *Rates defining Poisson processes*

Steps in Iterative Performance Assessment

- *Screen Features, Events, and Processes (FEPs)* and develop scenario classes

  Answers first two questions: what can happen? How likely?

- *Develop models* and abstractions, along with their scientific basis, for logical groupings of FEPs within scenario classes

  Answers third question: what are the consequences?

- *Characterize uncertainty* in model inputs

  Answers fourth question: how certain are the answers?

- *Construct integrated system model* using retained FEPs and *perform calculations* for the scenario classes

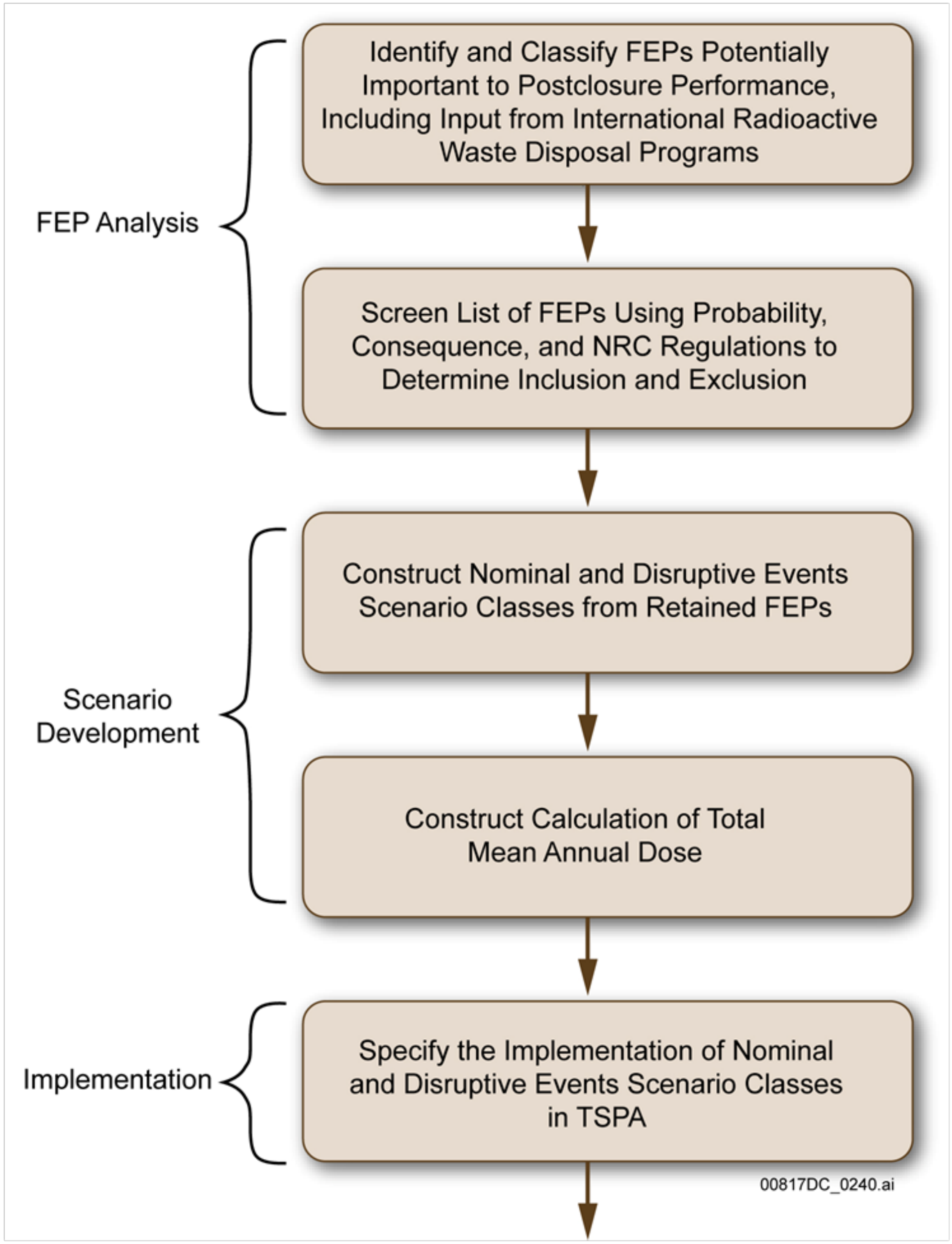
- *Evaluate system performance,* incorporating uncertainty

Definitions: FEPs

- Features
  - Elements of engineered or natural system that are important to represent in disposal system models
  - E.g., waste containers, fractures in host rock
- Events
  - Future occurrences that affect evolution of the disposal system
  - E.g., seismic events
- Processes
  - Physical processes that describe the evolution of the disposal system
  - E.g., water flow, metal corrosion, gas generation from chemical reactions

Evaluating FEPs: Yucca Mountain Example

- Probability and significance criteria for FEPs provided in 10 CFR 63.114
- 374 FEPs evaluated
  - 222 excluded
  - 152 included
- Relatively few Events, many more Features and Processes

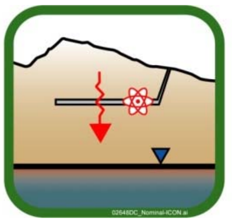


Form Scenarios: Yucca Mountain Example

Group events by similar effects to form Scenario Classes

Nominal Scenario Class

- **Nominal Modeling Case**

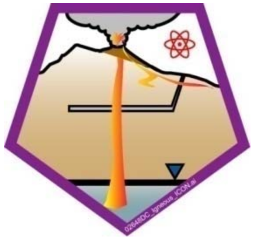


Early Failure Scenario Class

- **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**

Characterizing Aleatory Uncertainty

- What can happen? Define a vector **a** that describes an individual future, e.g.,

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

  - *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)

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

- How likely?

  Quantitative approach: characterize each element of **a** with a probability distribution

  Qualitative approach: consider a few subsets of $\mathcal{A}$ separately

Characterizing Aleatory Uncertainty

- Scenario-based approach
  - Define
    - *Reference* or *nominal* scenario – evolution of the disposal system in the absence of unlikely disturbances
    - *Altered evolution scenarios* – unlikely events
    - *Bounding scenarios* – extreme events
    - *Stylized scenarios* – events for which no likelihood can be expressed
  - Results from different scenarios are not combined; rather, are compared separately to safety standards
    - Undisturbed performance
    - Disturbed performance

Steps in Iterative Performance Assessment

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  Answers third question: what are the consequences?

- *Evaluate uncertainty* in model inputs

  Answers fourth question: how certain are the answers?

- *Construct integrated system model* using retained FEPs and *perform calculations* for the scenario classes

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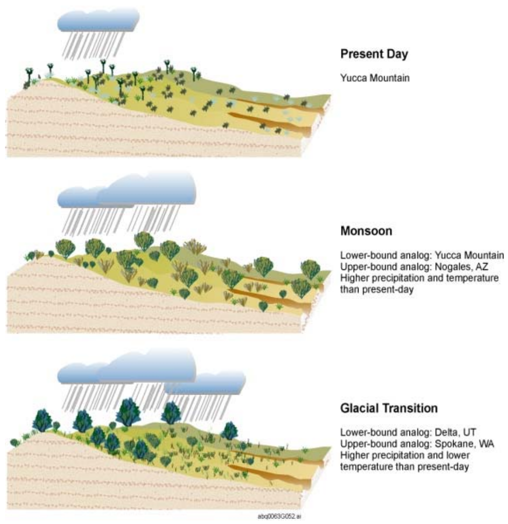
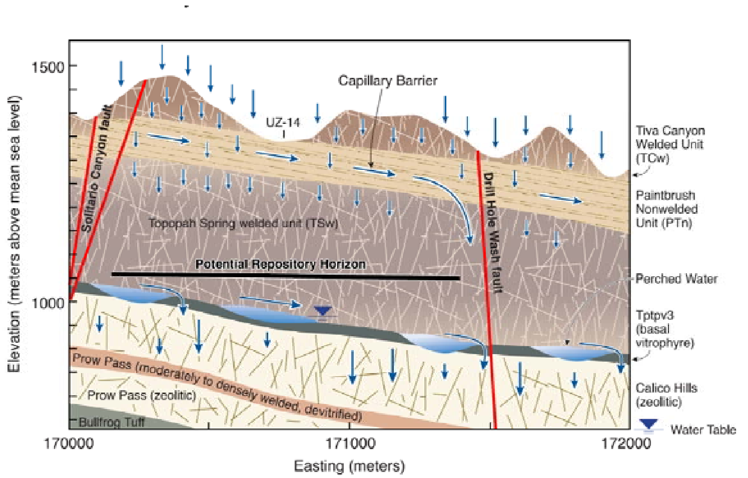
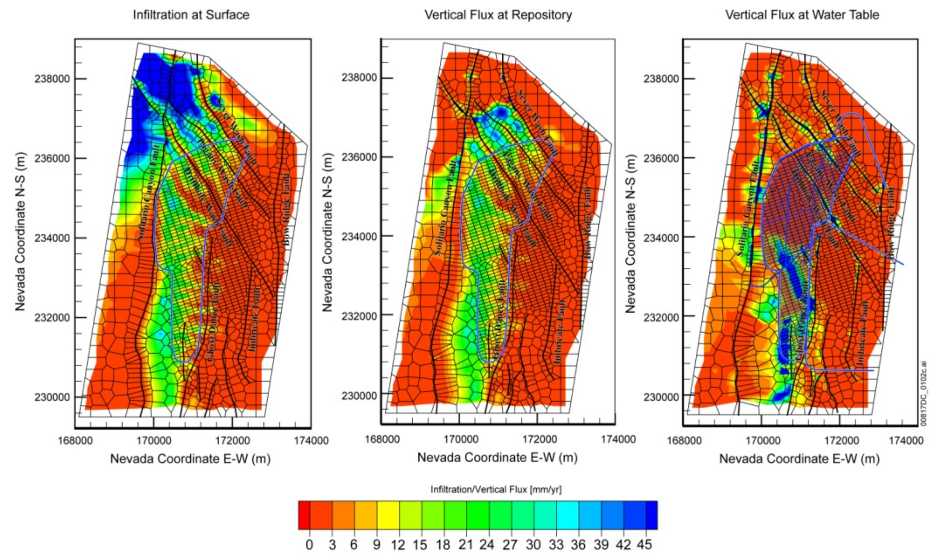
Example: Groundwater Flow at Yucca Mountain

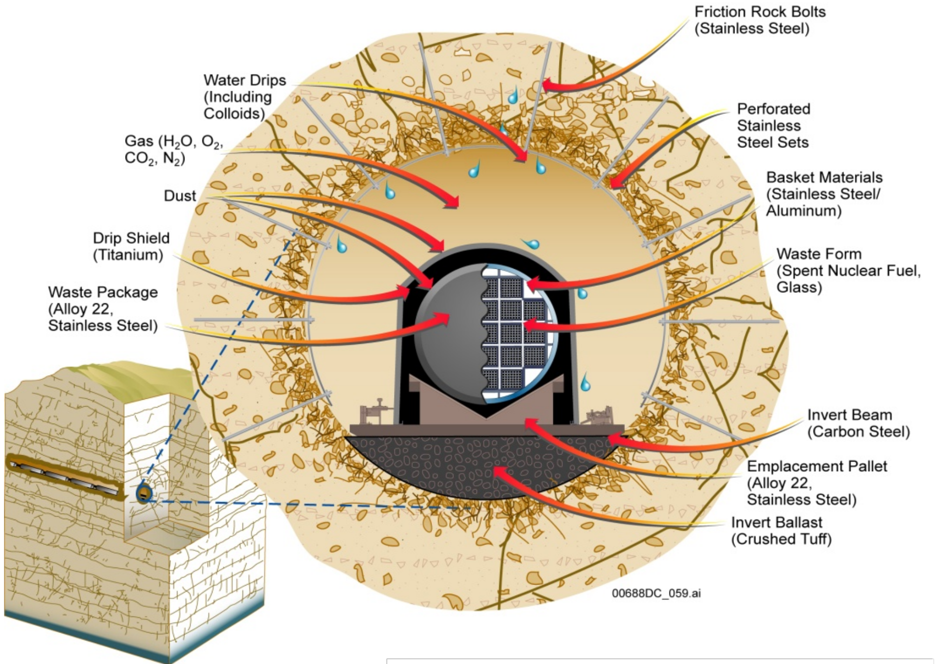


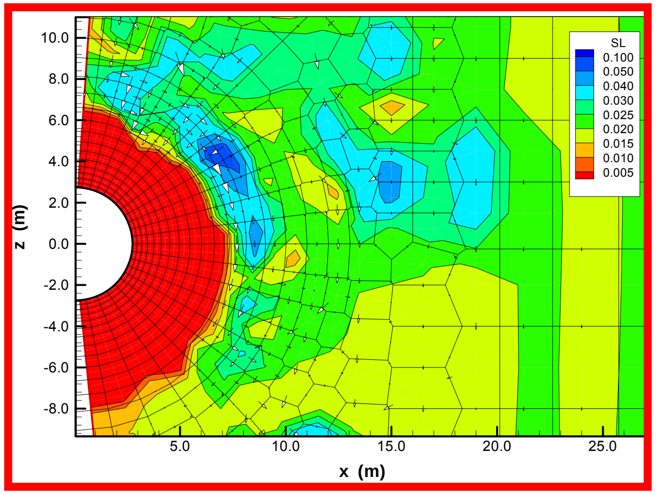


Field tests and models provide basis for understanding infiltration and flow in unsaturated rocks at Yucca Mountain

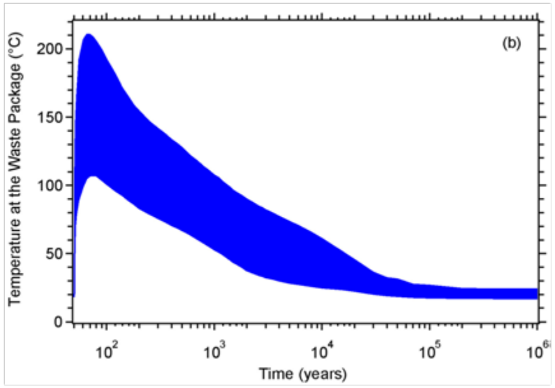


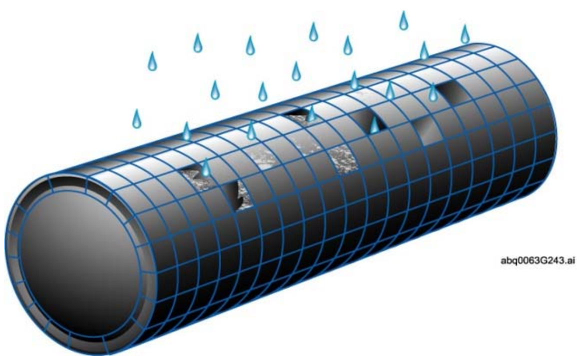
Example: Engineered Features at Yucca Mountain



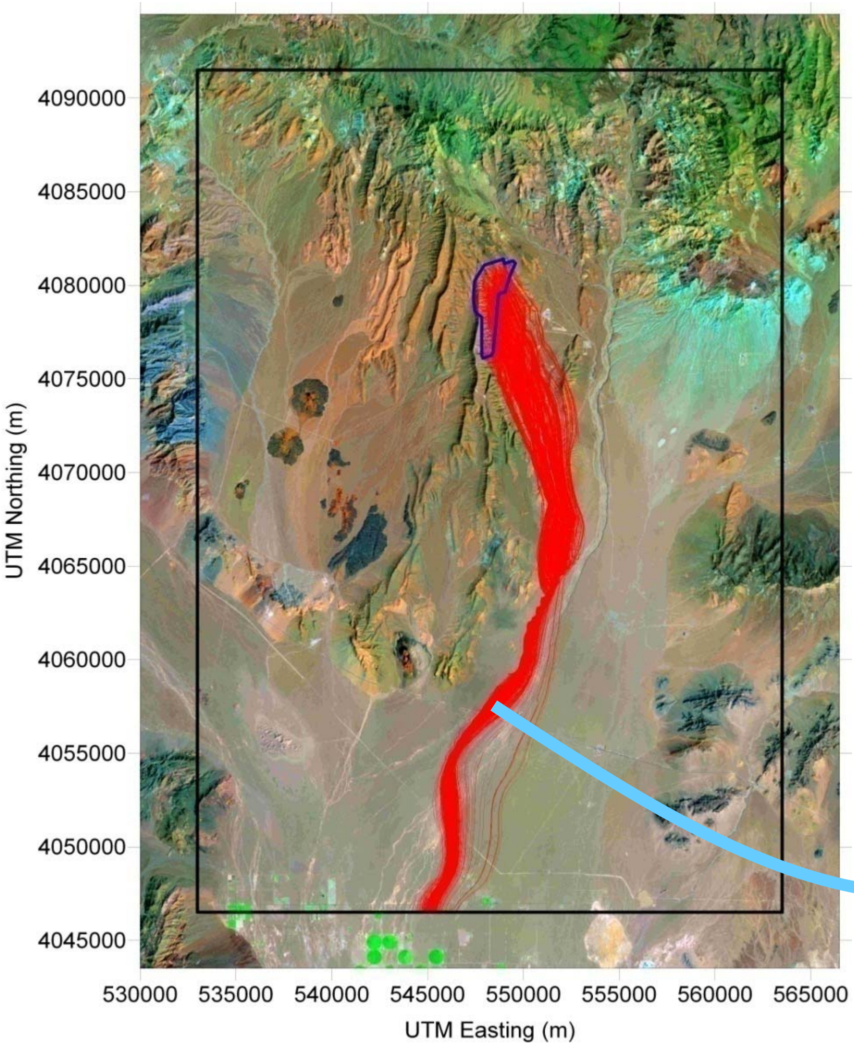


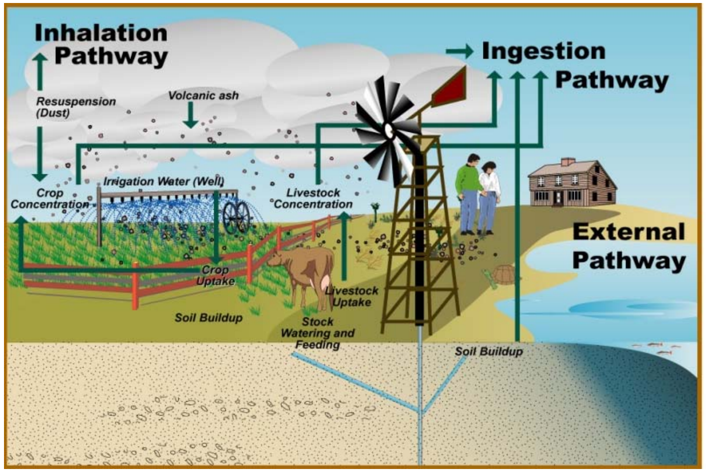
Material testing and models characterize performance of the engineered barriers





Example: Estimating Dose to Hypothetical Future Humans





Modeled groundwater flow paths and hypothetical exposure pathways

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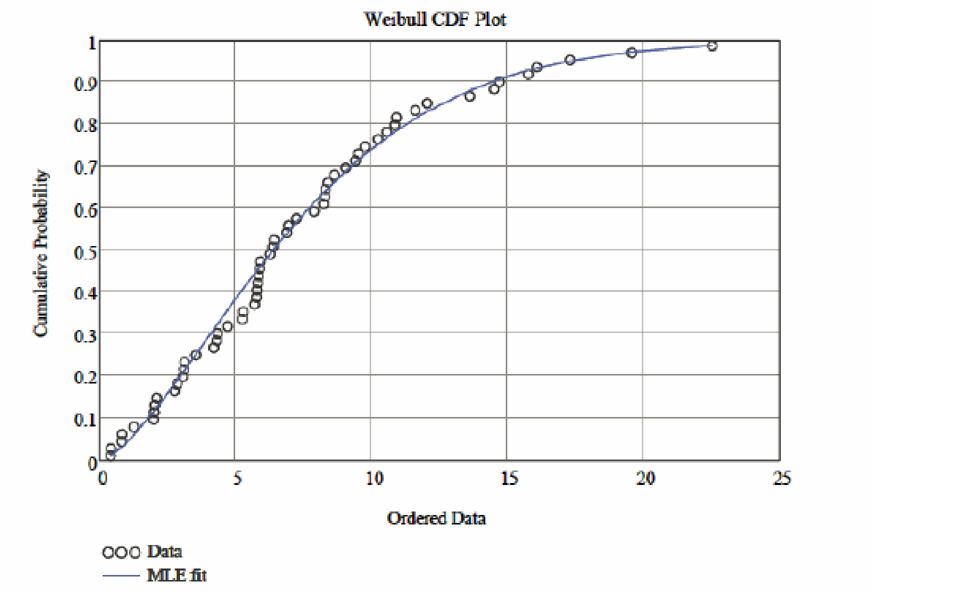
Characterizing Epistemic Uncertainty

Epistemic Uncertainty in
- Parameters (model inputs)
- Models



Parameter uncertainty is commonly represented by a probability space

Assign probability distribution to each uncertain input e_i

$$\mathcal{E} = \{\mathbf{e} : \mathbf{e} = [e_1, e_2, \ldots, e_N]\}$$

Model uncertainty is commonly addressed qualitatively

Comparison of alternative models

Use of a consensus model

Provide rationale for models that are selected

Steps in Iterative Performance Assessment

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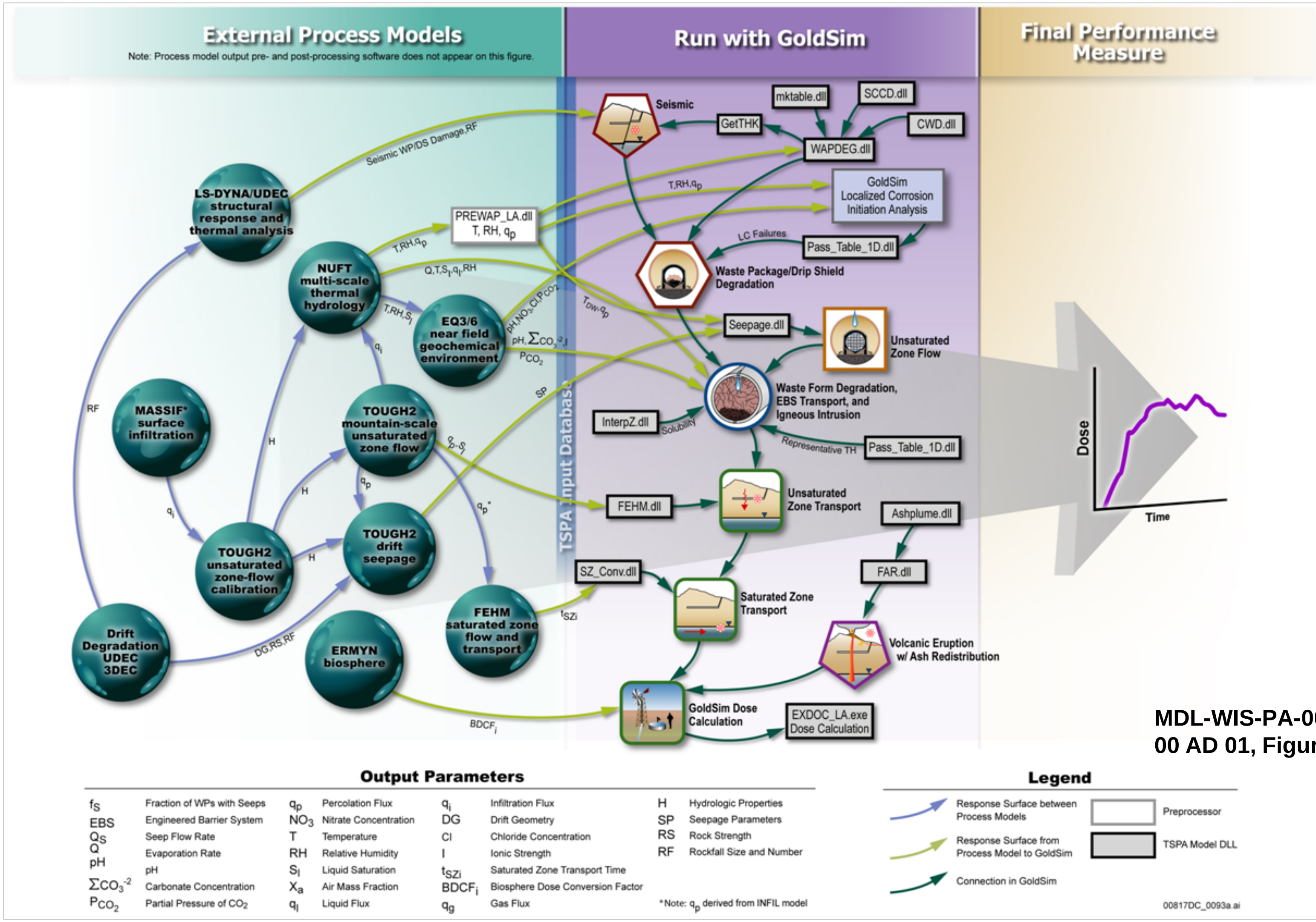
Example: Yucca Mountain TSPA



MDL-WIS-PA-000005 REV 00 AD 01, Figure 3-2[a]

Mathematical Structure

- Two (probability) spaces for inputs

  Aleatory uncertainty $\mathcal{A} = \{\mathbf{a} : \mathbf{a} = [nEW, nED, \ldots]\}$

  Epistemic uncertainty $\mathcal{E} = \{\mathbf{e} : \mathbf{e} = [e_1, e_2, \ldots, e_N]\}$
- Notionally, a function $D(\tau \mid \mathbf{a}, \mathbf{e})$ (dose) to be evaluated
- Example: mean value of $D(\tau \mid \mathbf{a}, \mathbf{e})$

$$\bar{\bar{D}}(\tau) = E_E\left[E_A\left(D(\tau \mid \mathbf{a}, \mathbf{e}_M) \mid \mathbf{e}_A\right)\right]$$

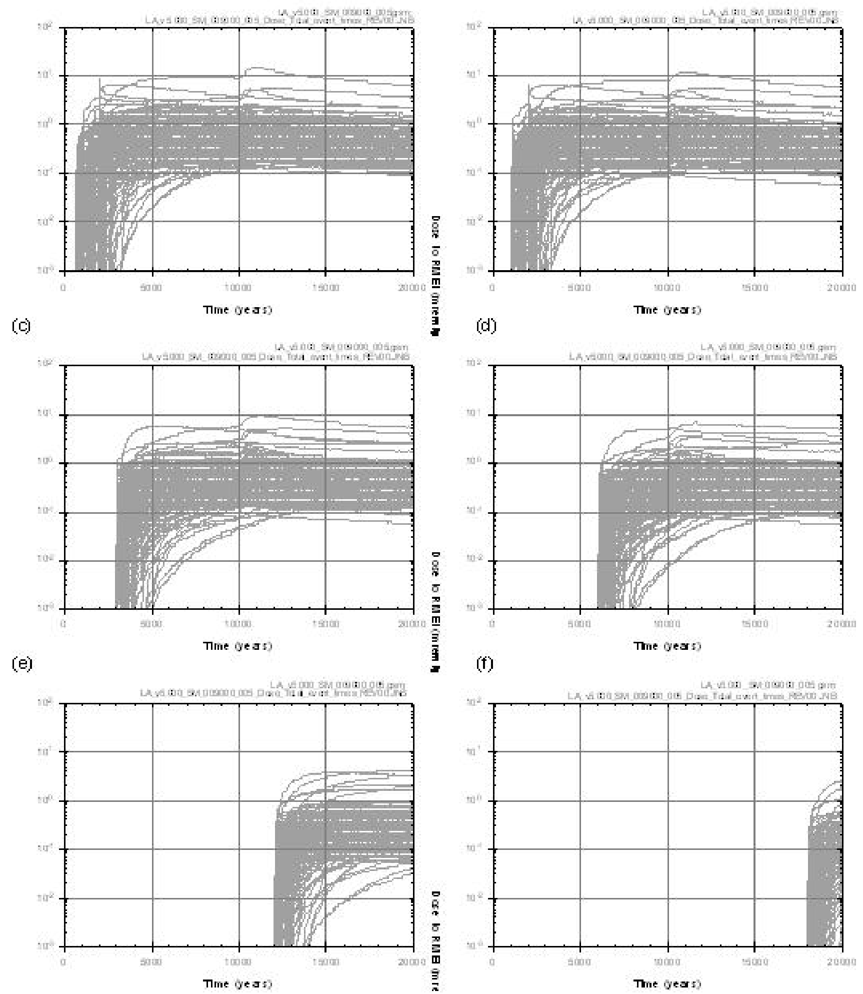
$$= \int_{\mathcal{E}}\left[\int_{\mathcal{A}} D(\tau \mid \mathbf{a}, \mathbf{e})\, d_A(\mathbf{a} \mid \mathbf{e})\, dA\right] d_E(\mathbf{e})\, dE$$

$$\cong \int_{\mathcal{E}}\left[\int_{\mathcal{A}}\left\{\sum_{\substack{MC \\ Scenarios}} D_{MC}(\tau \mid \mathbf{a}, \mathbf{e})\right\} d_A(\mathbf{a} \mid \mathbf{e})\, dA\right] d_E(\mathbf{e})\, dE$$

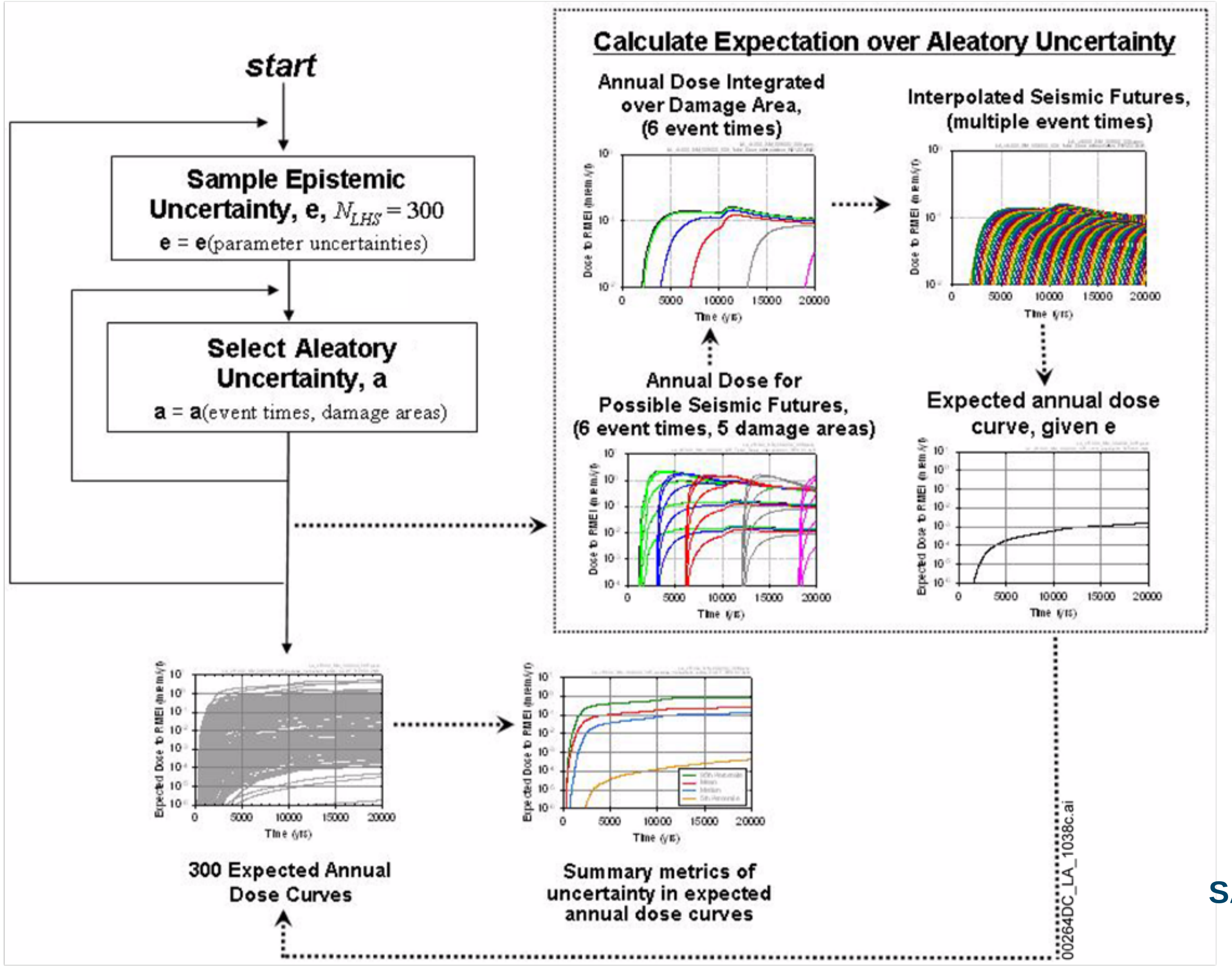
Example: Calculation of Dose
Yucca Mountain Seismic Ground Motion Scenario

- Sample values for epistemic uncertain inputs (parameters) **e** – 300 sample elements
- Select a few representative values for aleatory uncertain inputs **a** – seismic event time, level of damage
- For each combination (**a**,**e**) calculate dose over time

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



Example: Calculation of Expected Dose
Yucca Mountain Seismic Ground Motion Scenario



SAR Figure 2.4-8

Steps in Iterative Performance Assessment

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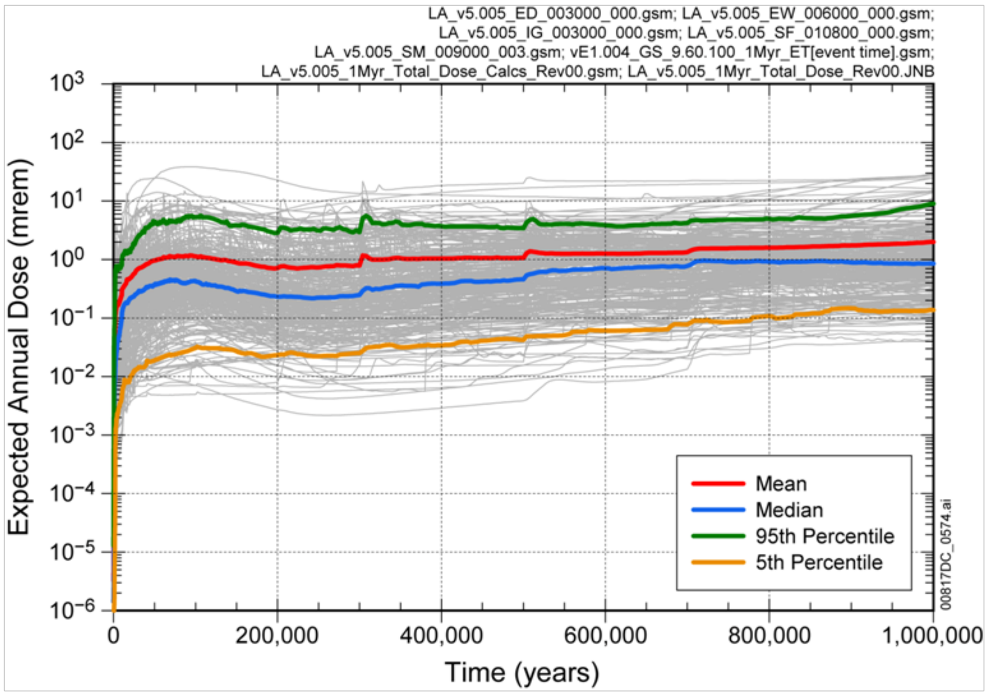
Analysis of Results

Example: Yucca Mountain Total Expected Dose

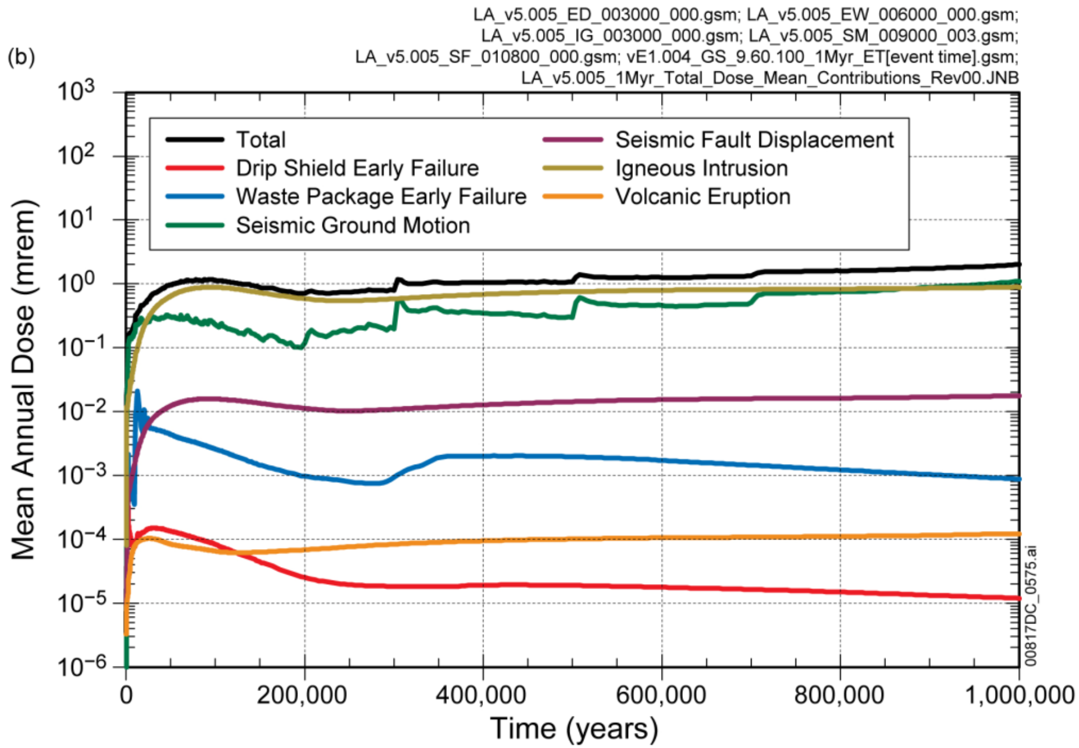


MDL-WIS-PA-000005 REV 00 AD 01, Figure 8.1-2[a]b

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>?

Modeling Cases Contributing to Total Mean Annual Dose



MDL-WIS-PA-000005 REV 00 AD 01, Figure 8.1-3[a]

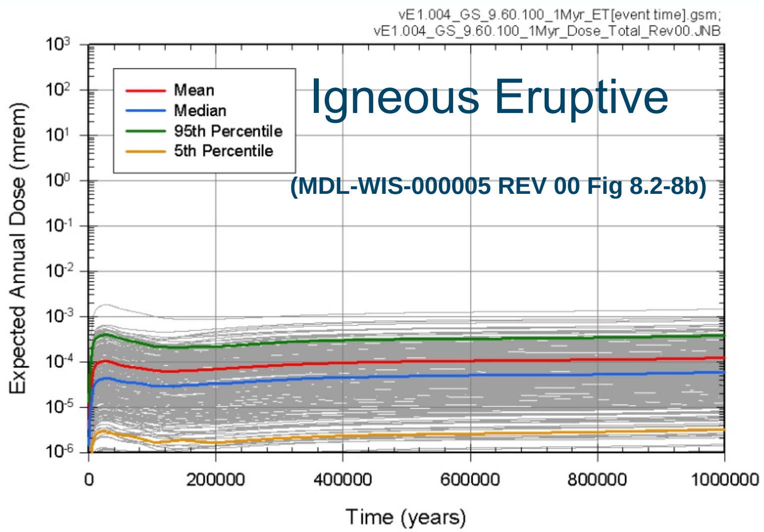
In order of importance:

Igneous Intrusion and Seismic Ground Motion (includes effects of nominal processes)

Seismic Fault Displacement

Early Failure, Volcanic Eruption

Construction of Total Expected Dose



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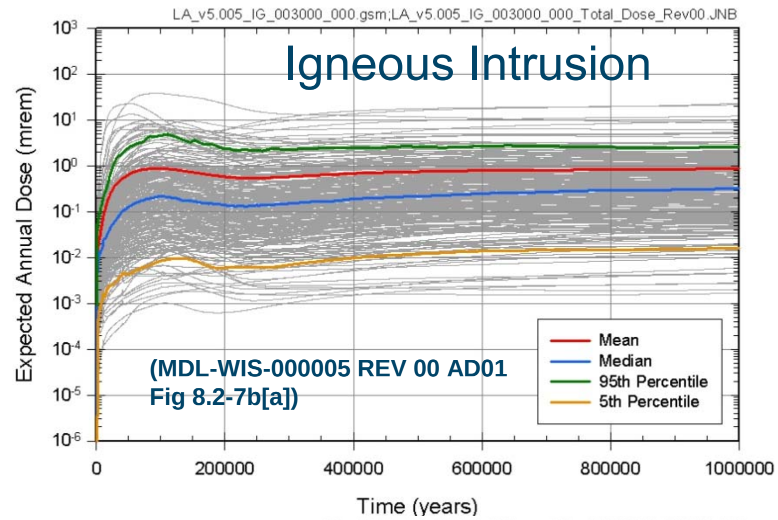

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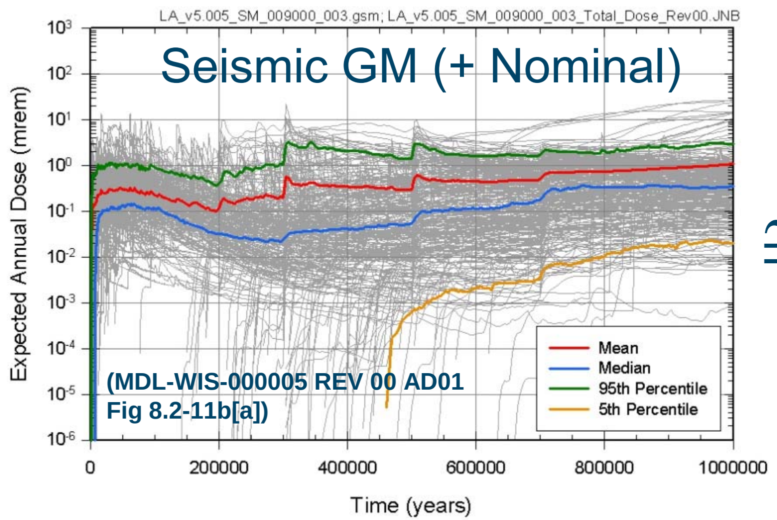

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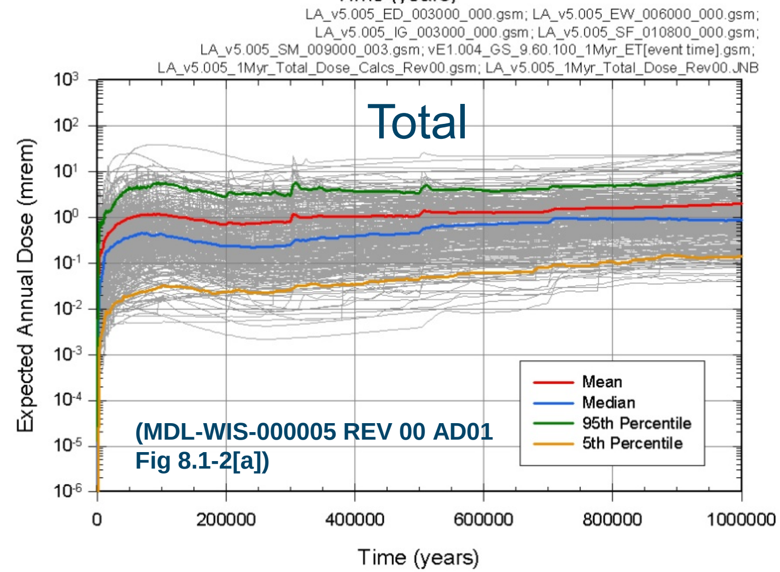
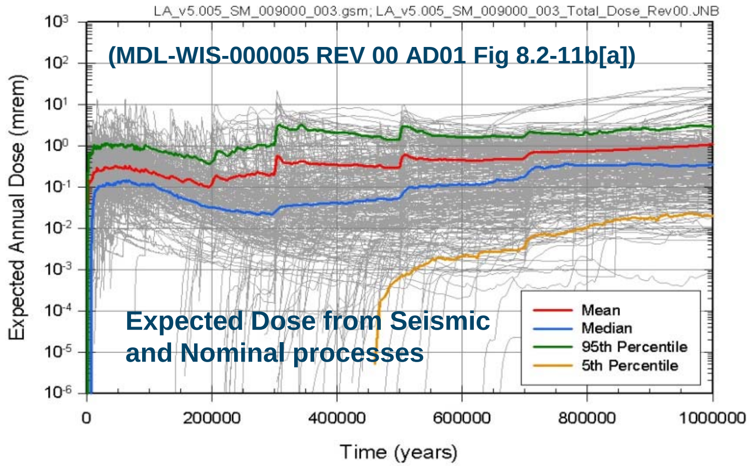
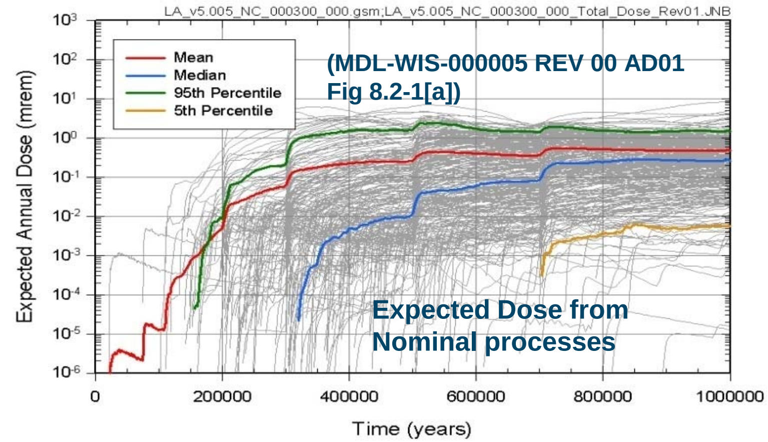
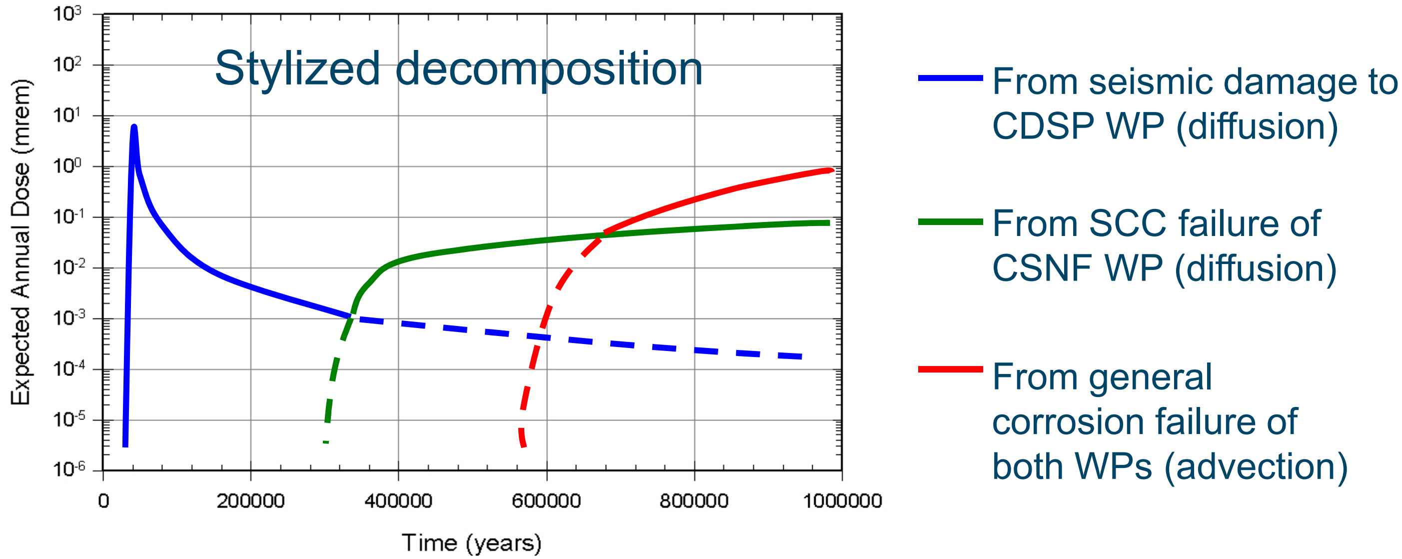


Decomposition of Seismic Ground Motion Dose

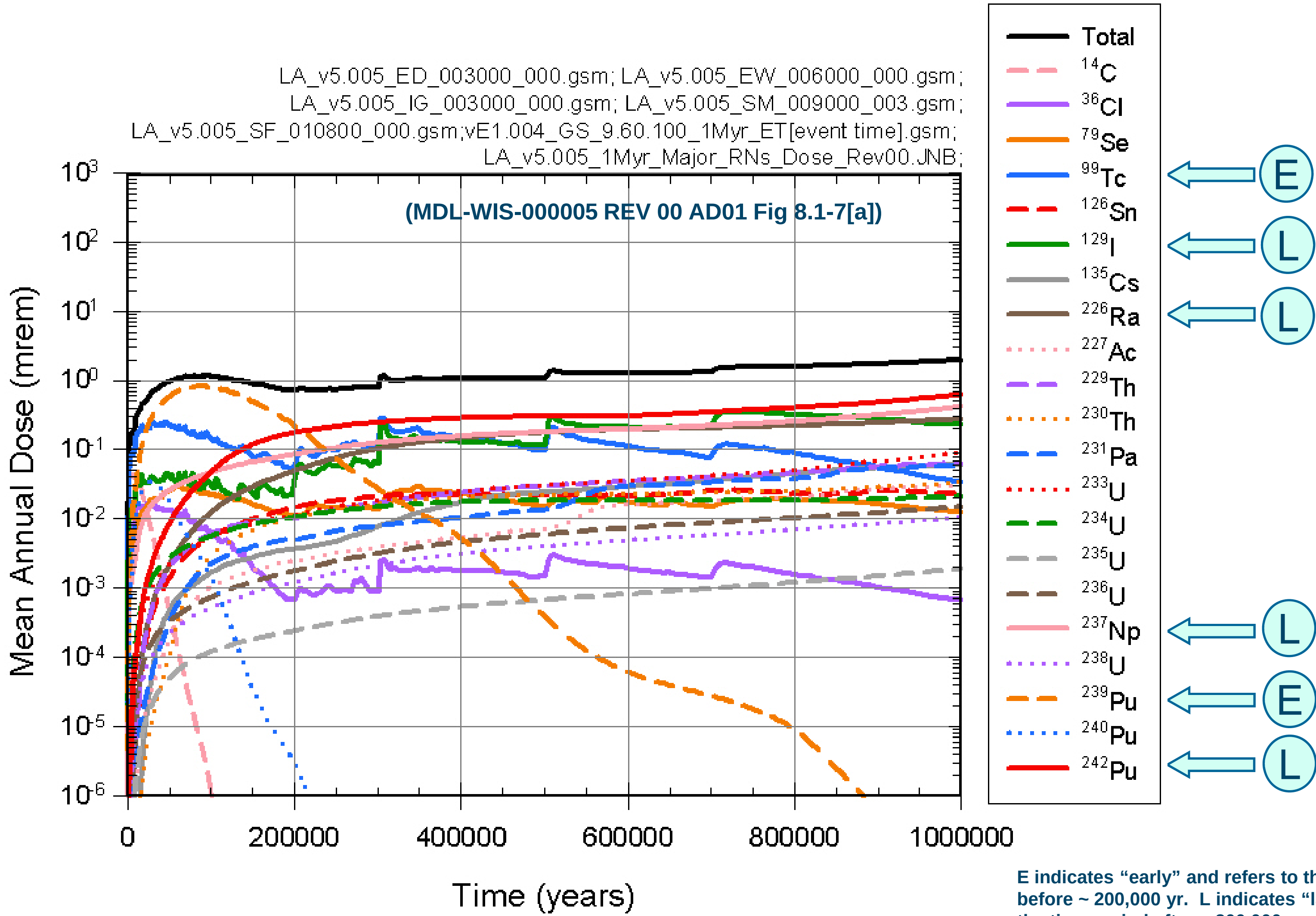


Included



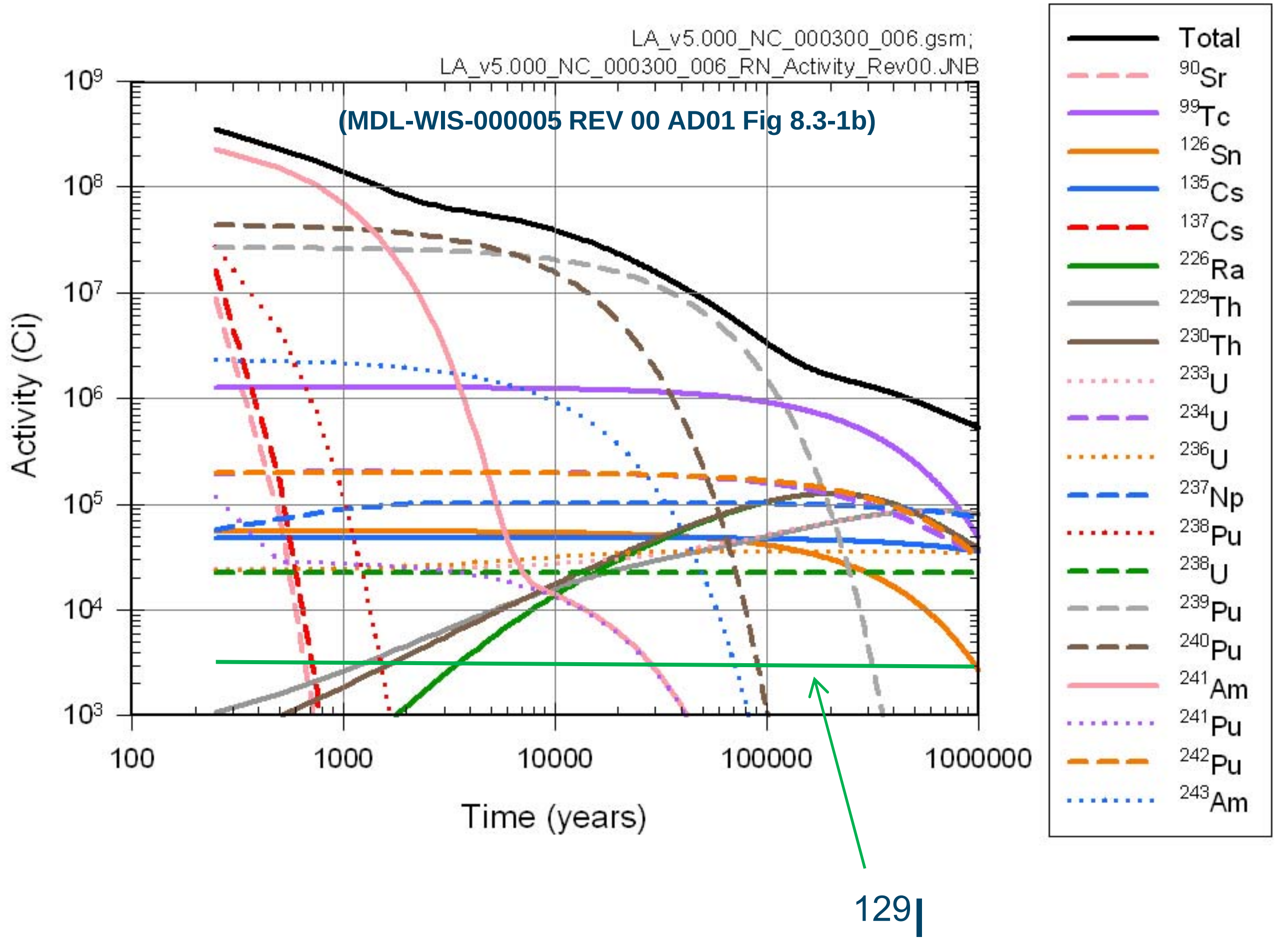


Radionuclides Important to Mean Dose



E indicates "early" and refers to the time period before ~ 200,000 yr. L indicates "late" and refers to the time period after ~ 200,000 yr

Radionuclide Inventory



Early (in order of total activity):

^{241}Am, ^{239}Pu, ^{240}Pu

Late (in order of total activity):

^{99}Tc, ^{237}Np

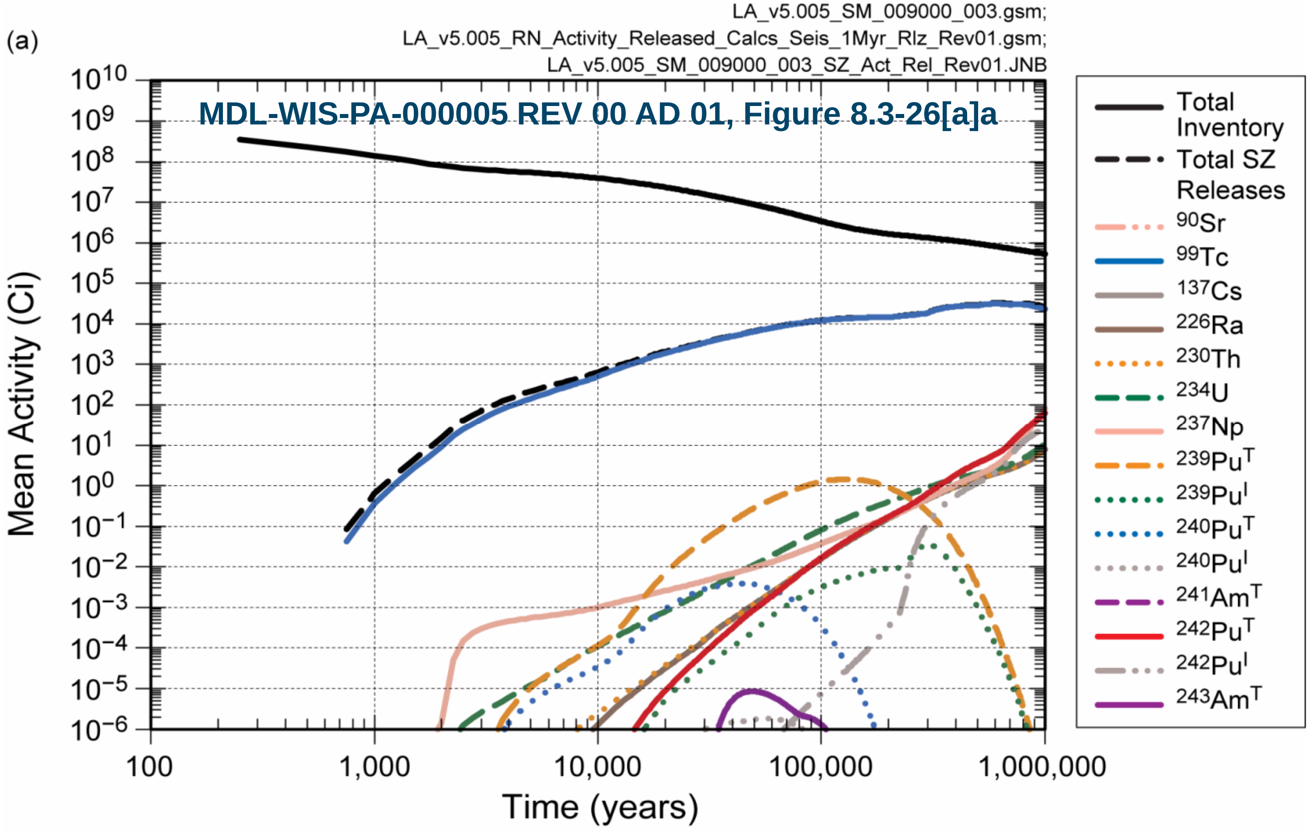
Note that activity in inventory does not necessarily correlate with importance to mean dose

Example Barrier Capability Illustration
Seismic GM + Nominal Processes

At 1M yr, total mean activity released from SZ is about 5 % of total inventory

Short-lived species (e.g., Sr-90, Cs-137) are fully contained

Maximum releases of intermediate-lived species (e.g, Pu-239) are a small fraction of the total activity and occur before 1,000,000 yr



Mean Activity Released from the Saturated Zone
Seismic Ground Motion Modeling Case
Representative Subset of all Radionuclides

Features and Processes Contributing to Repository Performance

- Precipitation → infiltration → seepage into repository drifts

Climate	Precipitation (mm/yr)	Infiltration (mm/yr)	Seepage (mm/yr)
Present-day[1]	150	4	0.04
Post-10k yr[2]	-	22	8.6

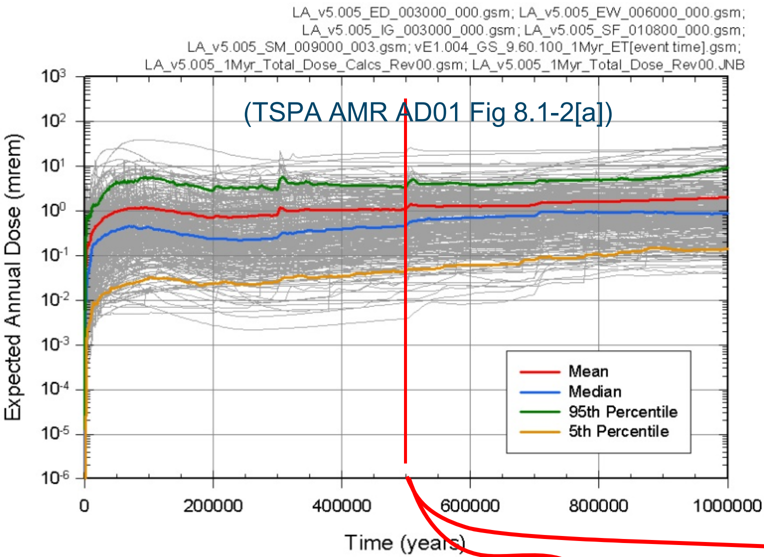
1) Nominal scenario, 10th percentile infiltration scenario, spatial averages, seepage converted from m3/WP/yr
2) Seismic + nominal, 10th percentile infiltration scenario, spatial averages, seepage converted from m3/WP/yr

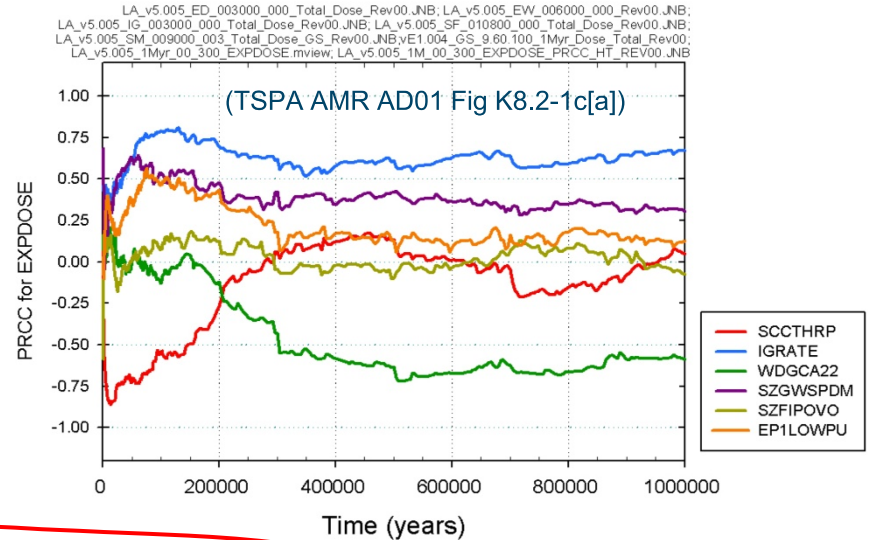
- Low likelihood of advection through WP outer barrier
  - WP outer barrier failure generally consists of stress corrosion cracking
  - Low likelihood of igneous events, rupture, general corrosion failures
  - Limited water available interior to WPs
- Iron oxyhydroxides from degraded WP materials sorb actinides, buffer water chemistry away from acidic conditions
- Travel times preclude transport of relatively short-lived radionuclides (e.g. ^{240}Pu), reduce concentrations of long-lived radionuclides

Sensitivity Analyses

- Inputs to TSPA-LA model are uncertain → model output is uncertain
- Monte Carlo analysis – sample from probability space describing inputs, for each sample element generate output
- Symbolically, for a vector $\mathbf{x}_i$ of sampled values for inputs, obtain a vector $\mathbf{y}_i = f(\mathbf{x}_i)$ of values for the outputs
- Sensitivity analyses examine the relationship between $\mathbf{x}_i$ and $\mathbf{y}_i$
- Explain which uncertain inputs cause uncertainty in output
- Correlation methods, graphical methods, global measures such as sample standard variation
- A. Saltelli et al – several textbooks on methods

Uncertainty in Total Expected Dose

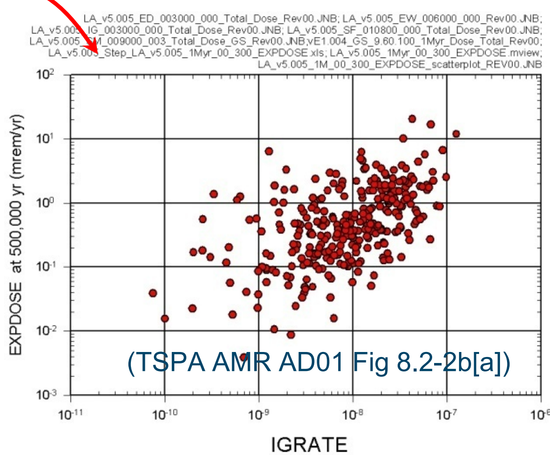


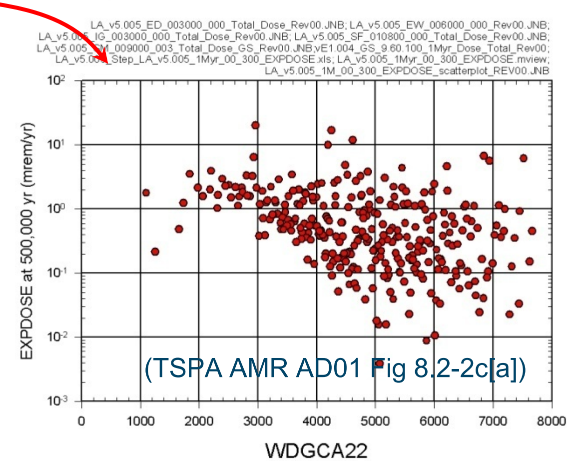


SCCTHRP – Stress threshold for SCC initiation

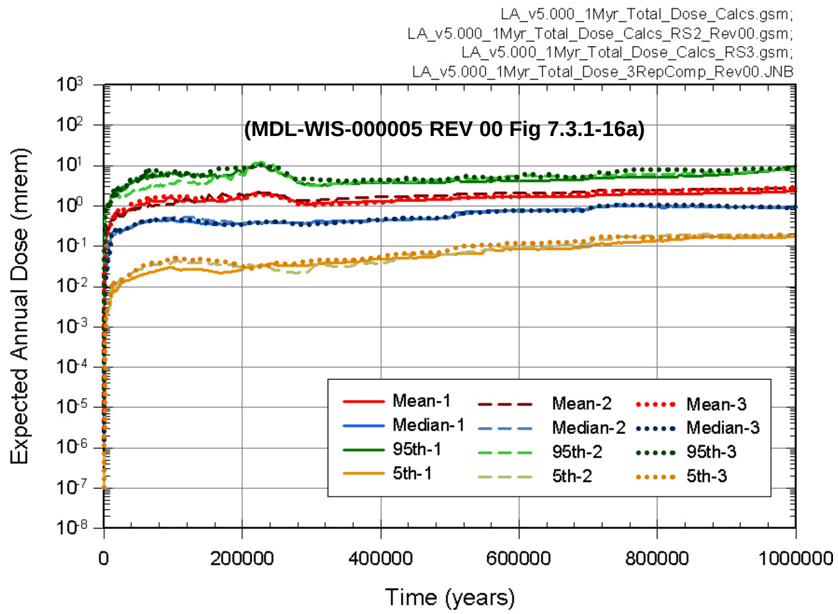
IGRATE – Frequency of igneous events

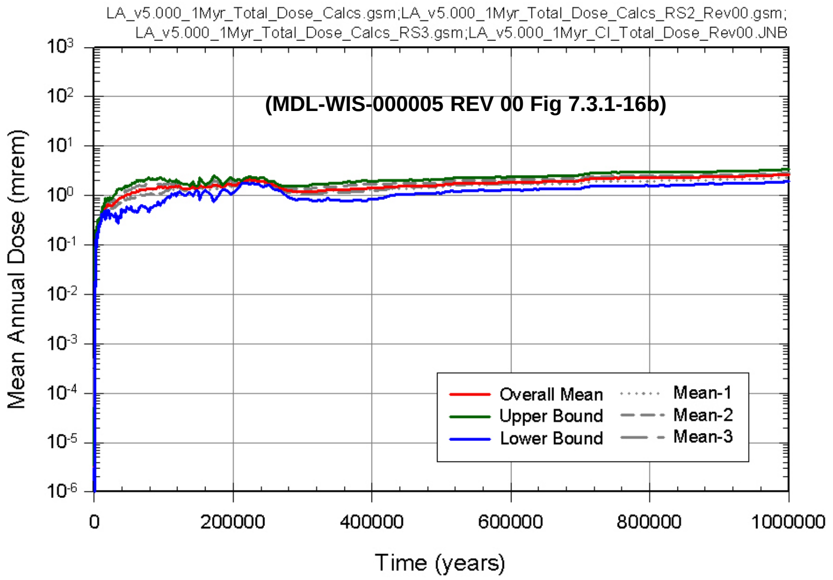
WDGCA22 – Temperature dependence in A22 corrosion rate





Stability of Total Dose





Replicated sampling demonstrates that sample size is sufficient

Confidence interval illustrates precision of estimate of total mean dose

Summary

- Basic Structure for Safety Assessments
  - Quantitative Risk Assessment
    - What can happen? How likely?
    - What are the consequences?
  - How certain are the answers?
- Iterative Process
  - Screen Features, Events and Processes
  - Develop Model
  - Characterize Uncertainty
  - Construct System Model
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