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Sandia National Laboratories

General Training On Methodologies For Geological Disposal in North America

IAEA Network of Centers of Excellence

Total System Performance Assessment for Yucca Mountain

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Outline

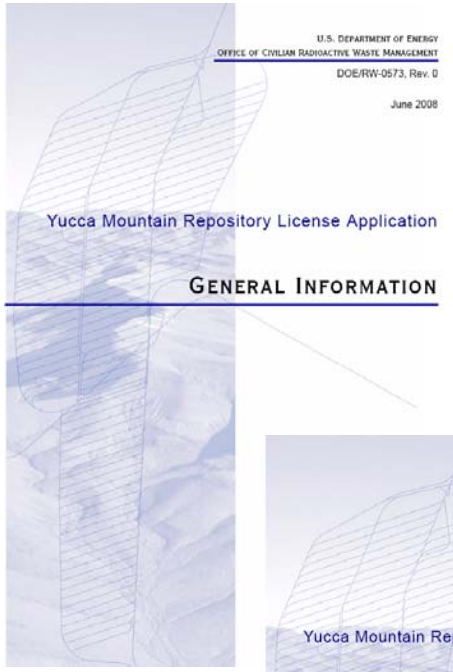
- Introduction to Total System Performance Assessment (TSPA)
- Regulatory Framework
- Steps in a Performance Assessment
  - Screening of Features, Events, and Processes (FEPs) and identification of scenarios
  - Development of models
  - Characterization of uncertainty
  - Construction of model
  - Evaluation of system results
- TSPA results for the Yucca Mountain License Application (LA)
- Conclusion

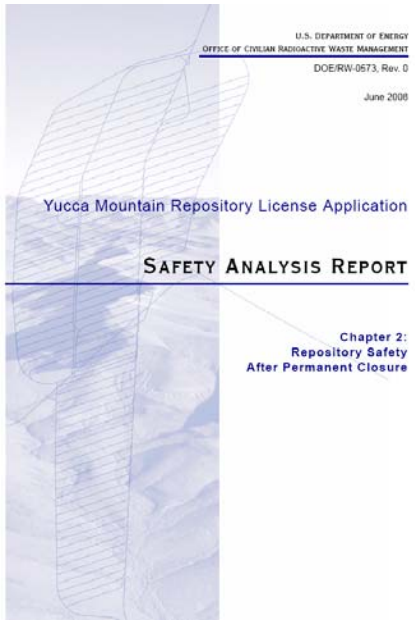
Yucca Mountain Repository License Application

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

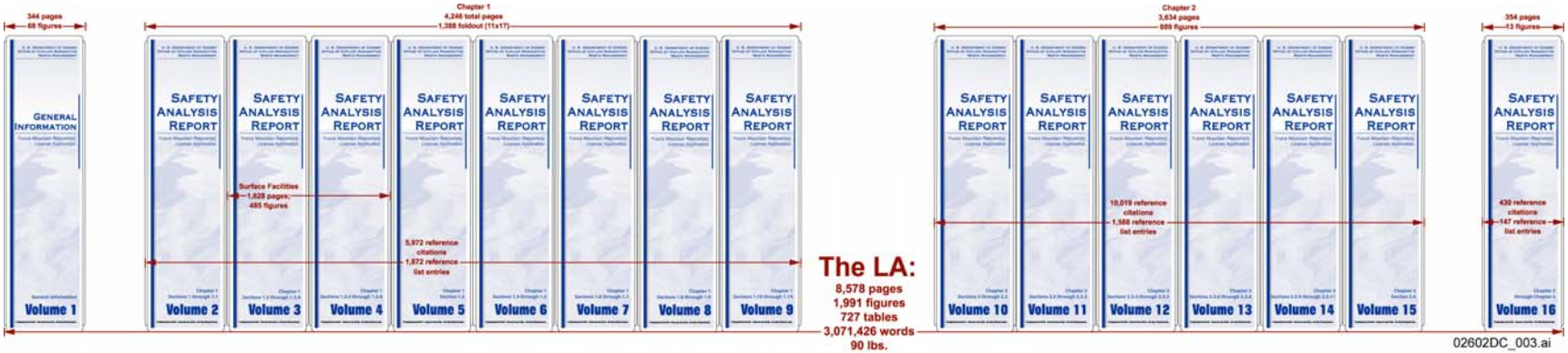
- Safety Analysis Report (SAR)
  - Repository Safety Before Permanent Closure
  - Repository Safety After Permanent Closure
  - Research and Development Program to Resolve Safety Questions
  - Performance Confirmation Program
  - Administrative and Programmatic Requirements





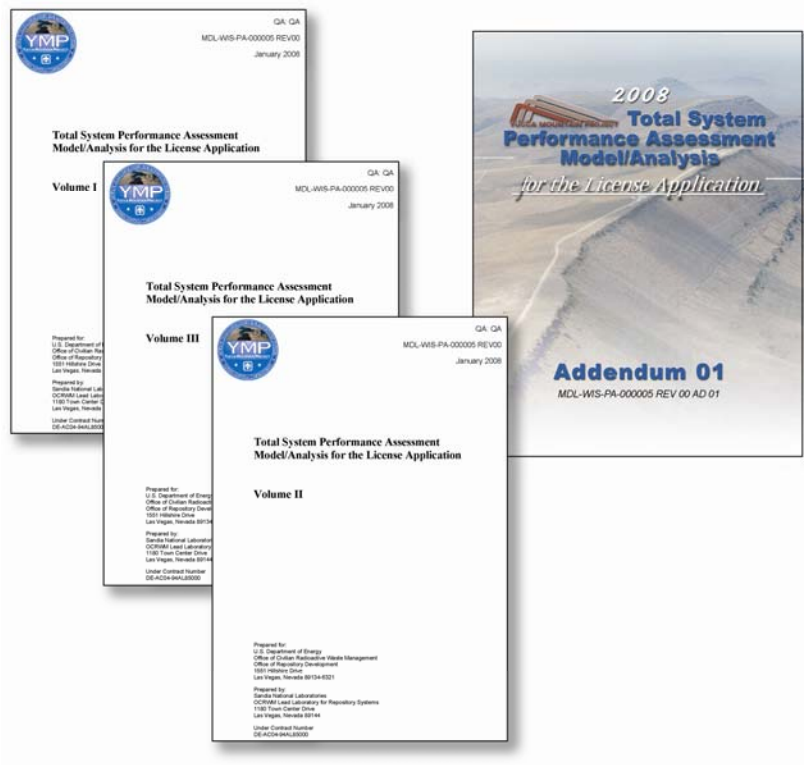
The Yucca Mountain License Application

- Available from the NRC (**http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app.html#appdocuments**)
- 17 volumes
  - Total number of pages – 8,646 (3M+ words)
  - Total number of figures – 2,830
  - Total number of tables – 930
  - Number of inches thick – 78
  - Weight of each complete copy – 110 lbs.
- The LA is accompanied by:
  - a Final Supplemental EIS (**http://ocrwm.doe.gov/ym_repository/seis/index.shtml**)
  - 198 key supporting documents (~38k additional pages)



TSPA-LA Documentation

SNL 2008, *Total System Performance Assessment Model/Analysis for the License Application*, MDL-WIS-PA-000005 REV 00 AD 01



Four volumes
4272 pages

11,843 pages of supporting technical documents that provide direct input

	Total Pages	Number of Tables	Number of Figures
Volume I	1111	183	255
Volume II	600	41	221
Volume III	1767	130	519
Addendum	794	34	321
TOTALS	**4272**	**388**	**1316**

Purpose of TSPA

- Performance Assessments provide answers to four questions:
  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?
  4. How reliable are the answers to the first 3 questions?
- TSPA evaluates the uncertainty in the evolution of the geologic setting and engineered barrier system
  - Predictive models are supported by field and lab tests, in-situ monitoring and natural analogs
  - Uncertainties in these models and associated parameters exist
- TSPA uses a range of defensible and reasonable parameter distributions and propagates the uncertainty to evaluate the effect and consequence

Representative Uses of TSPA

- Evaluate regulatory requirements
- Quantify performance margin and barrier capability
- Determine most sensitive models and parameters
- Prioritize information and testing needs
- Evaluate design options/alternatives
- Evaluate consequences of features, events and processes
- Determine significance of data, parameter and model uncertainty
- Prioritize repository risks

Regulatory Framework for the TSPA-LA

- United States Environmental Protection Agency (EPA) sets *Public Health and Environmental Protection Standards for Yucca Mountain*, 40 CFR Part 197
- United States Nuclear Regulatory Commission (NRC) defines licensing criteria for *Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, Nevada*, 10 CFR Part 63 consistent with the EPA Standard
- The TSPA-LA addresses the criteria established by the NRC in 10 CFR Part 63
- In the absence of final dose standards that apply beyond 10,000 years, the TSPA-LA addressed the criteria proposed by the NRC in *Implementation of a Dose Standard After 10,000 Years, proposed rule* (Federal Register v. 70, p. 53313) that implements the standards proposed by the EPA in 2005

  EPA final standard approved 30 September 2008

Definition of Performance Assessment

- Defined for Yucca Mountain by the U.S. Environmental Protection Agency at 40 CFR 197.12 (amended 30 September 2008)

  Performance assessment means an analysis that

  (1) Identifies the features, processes, (except human intrusion), and sequences of events and processes (except human intrusion) that might affect the Yucca Mountain disposal system and their probabilities of occurring;

  (2) Examines the effects of those features, events, processes, and sequences of events and processes upon the performance of the Yucca Mountain disposal system; and

  (3) Estimates the annual committed effected dose equivalent incurred by the reasonably maximally exposed individual, including the associated uncertainties, as a result of releases caused by all significant features, events, processes, and sequences of events and processes, weighted by their probability of occurrence.

Regulatory Framework (cont.)

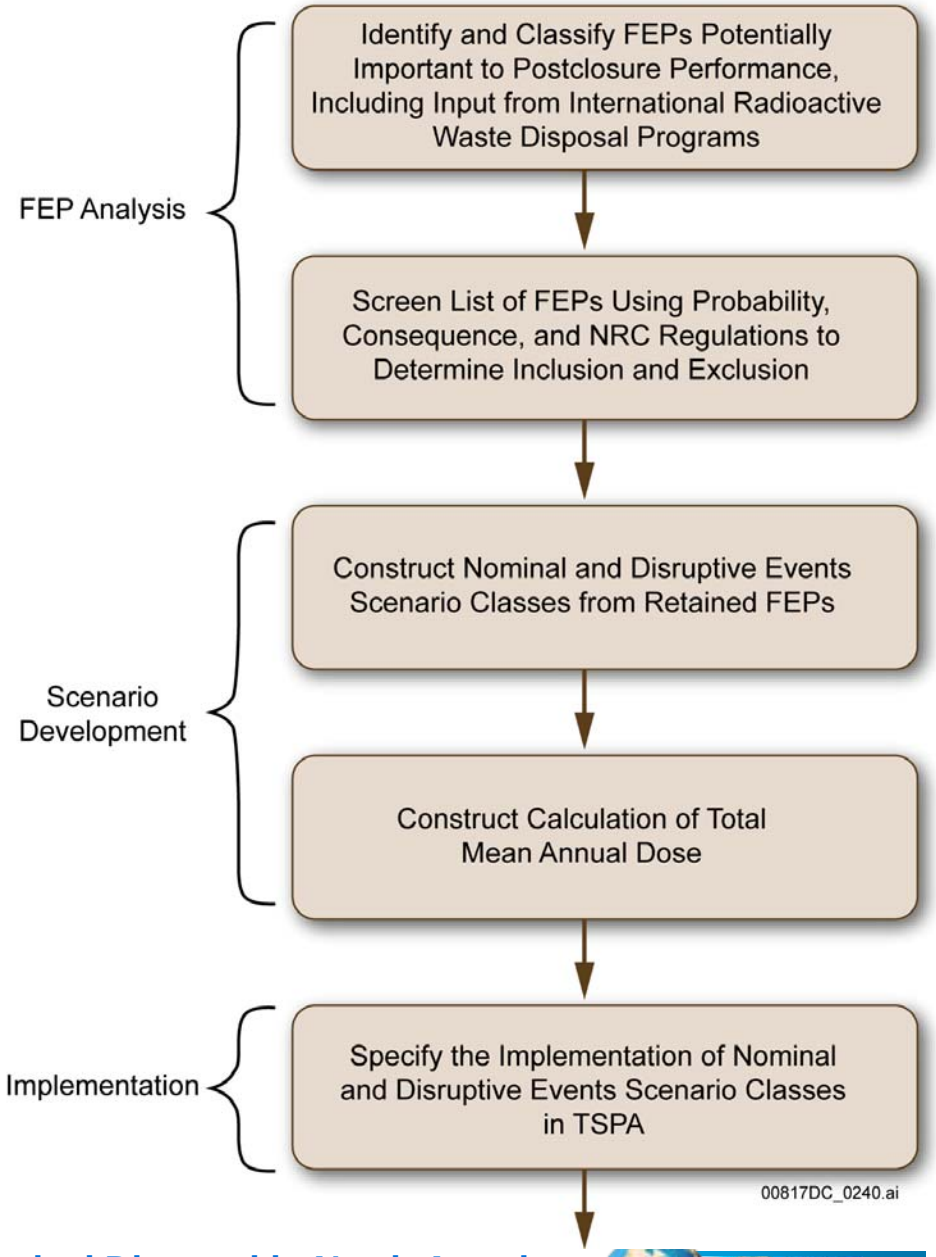
- Relevant to TSPA, EPA and NRC regulations define
  - The scope of the performance assessment
    - Criteria for the screening of FEPs
    - Characteristics of the “Reasonably Maximally Exposed Individual” (RMEI)
  - Probabilistic performance measures
    - Implemented through a Monte Carlo uncertainty analysis
  - A requirement for the identification and description of multiple barriers that contribute to waste isolation
  - Compliance limits for estimated mean annual dose and groundwater concentrations for
    - Individual protection
    - Individual protection following human intrusion
    - Groundwater protection

Steps in Iterative Performance Assessment

- *Screen Features, Events, and Processes (FEPs)* and develop scenario classes
- *Develop models* and abstractions, along with their scientific basis, for logical groupings of FEPs within scenario classes
- *Evaluate uncertainty* in model inputs
- *Construct integrated TSPA model* using all retained FEPs and *perform calculations* for the scenario classes and "modeling cases" within scenario classes
- *Evaluate total system performance,* incorporating uncertainty through Monte Carlo simulation

Evaluating FEPs and Defining Scenarios

- Probability and significance criteria for FEPs provided in 10 CFR 63.114
- 374 FEPs evaluated
  - 222 excluded from TSPA
  - 152 included
- Four scenario classes defined for analysis



FEP Screening Criteria

- 10 CFR 197.36(a)(1) (amended 30 September 2008)

  The DOE's performance assessments conducted to show compliance with §§197.20(a)(1), 197.25(b)(1), and 197.30 shall not include consideration of very unlikely features, events, or processes, i.e., those that are estimated to have less than one chance in 100,000,000 per year of occurring.

  …

  In addition, unless otherwise specified in these standards or NRC regulations, DOE's performance assessments need not evaluate the impacts resulting from features, events, and processes or sequences of events and processes with a higher chance of occurring if the results of the performance assessment would not be changed significantly in the initial 10,000-year period after disposal.

TSPA-LA Scenarios

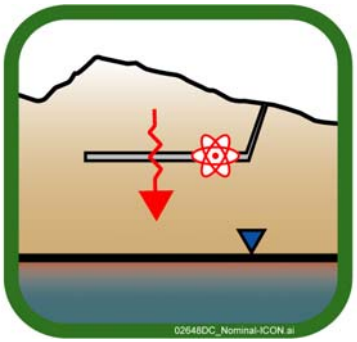
Four scenario classes divided into seven modeling cases

Nominal Scenario Class

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

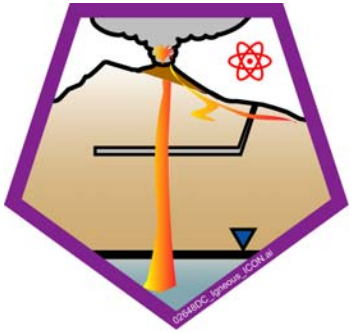
Early Failure Scenario Class

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



Igneous Scenario Class

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



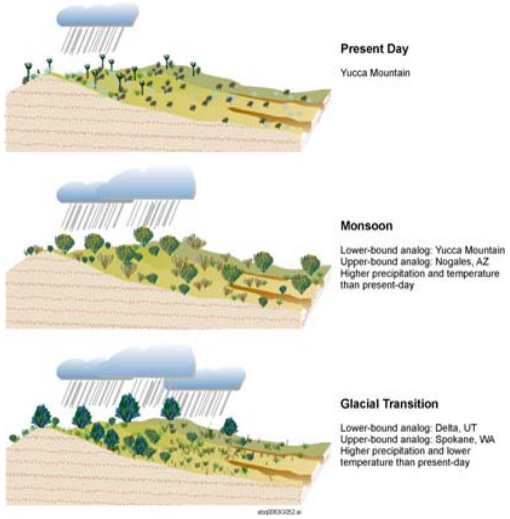
Seismic Scenario Class

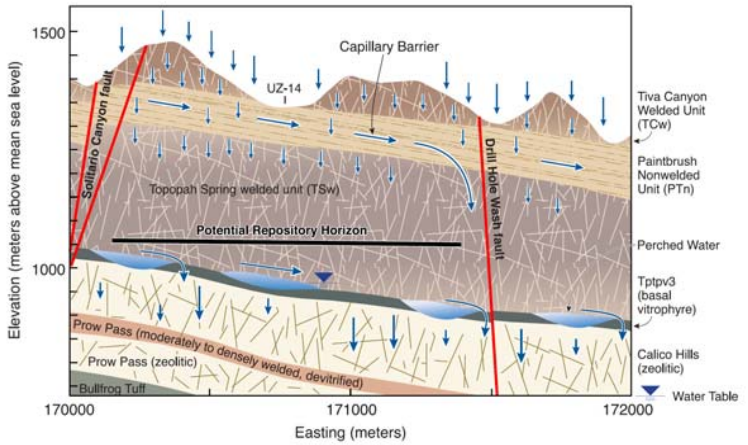
- **Ground Motion Modeling Case**
- **Fault Displacement Modeling Case**

Steps in Iterative Performance Assessment

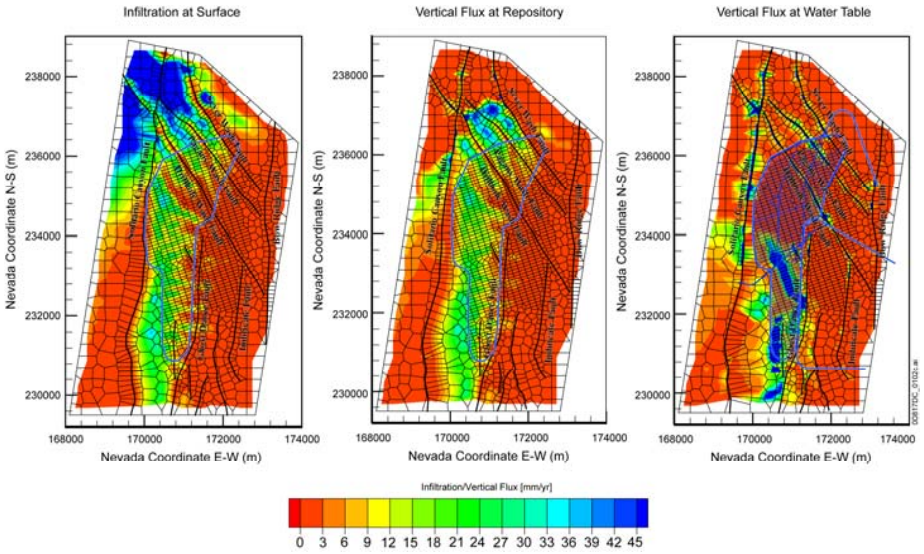
- *Screen Features, Events, and Processes (FEPs)* and develop scenario classes
- *Develop models* and abstractions, along with their scientific basis, for logical groupings of FEPs within scenario classes
- *Evaluate uncertainty* in model inputs
- *Construct integrated TSPA model* using all retained FEPs and *perform calculations* for the scenario classes and "modeling cases" within scenario classes
- *Evaluate total system performance,* incorporating uncertainty through Monte Carlo simulation

Groundwater Flow at Yucca Mountain

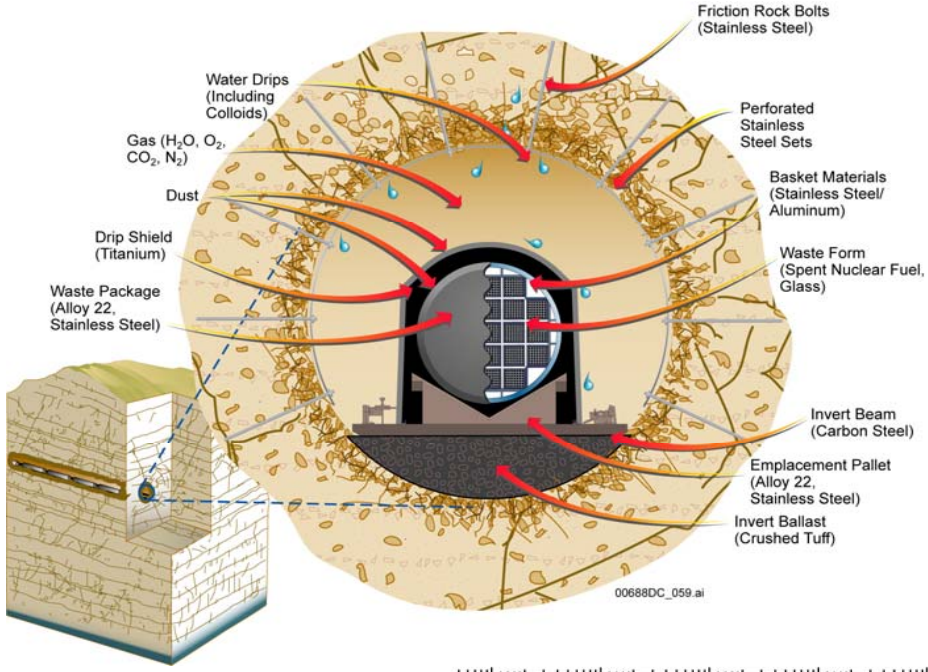


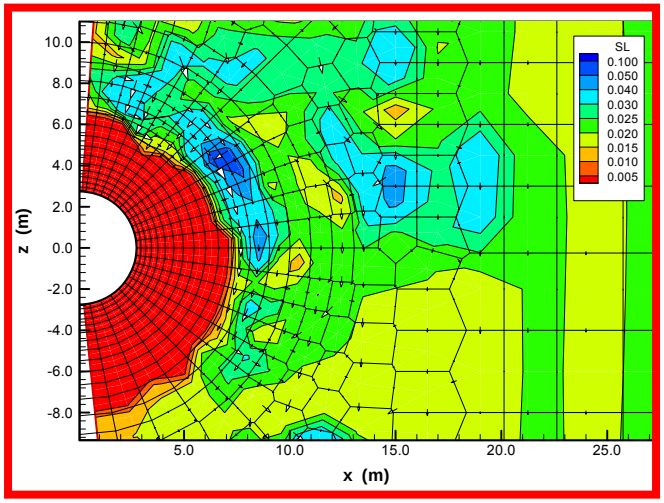


Field tests and models provide basis for understanding infiltration and flow in unsaturated rocks at Yucca Mountain

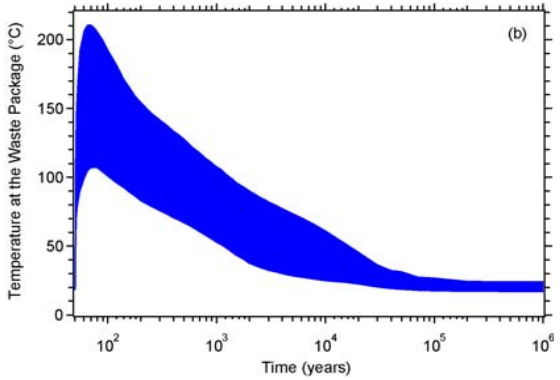


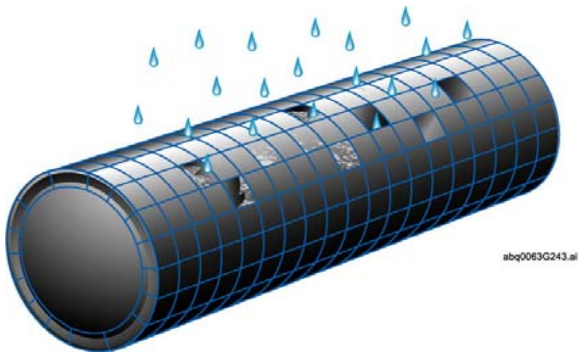
The Emplacement Environment at Yucca Mountain



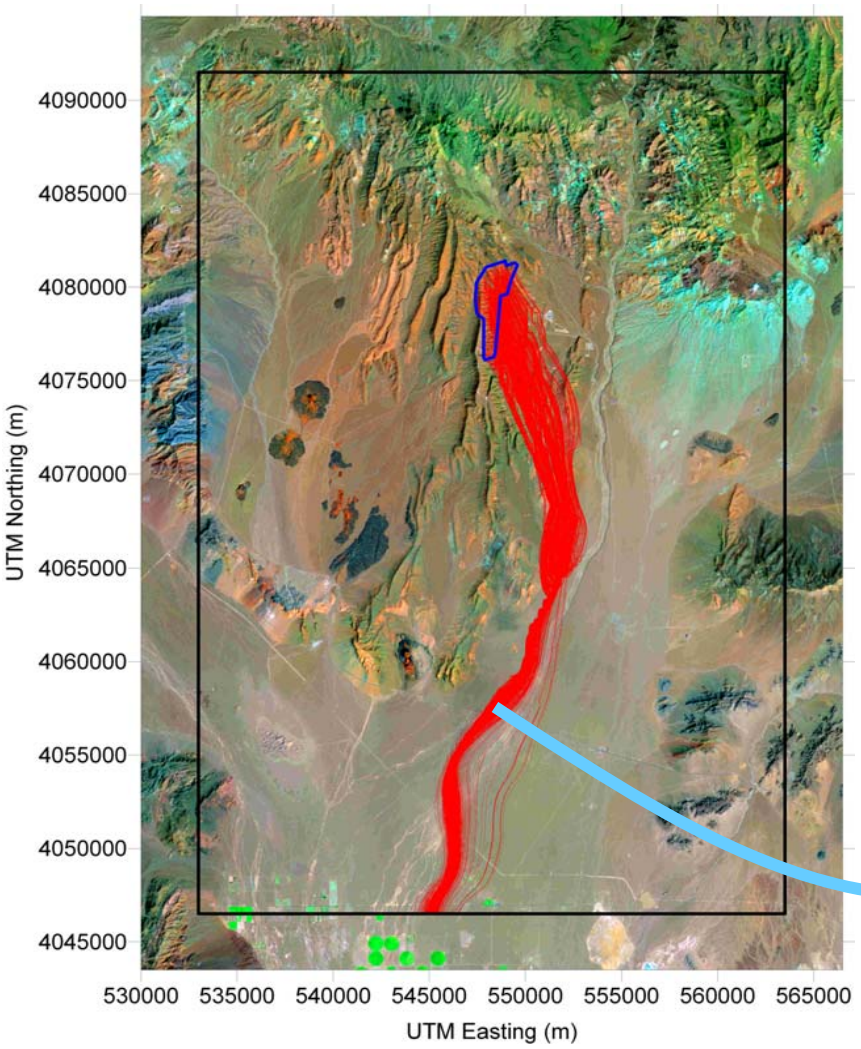


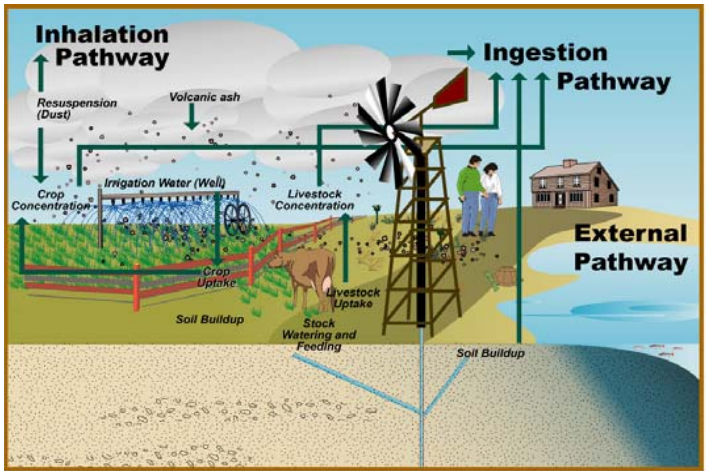
Material testing and models characterize performance of the engineered barriers





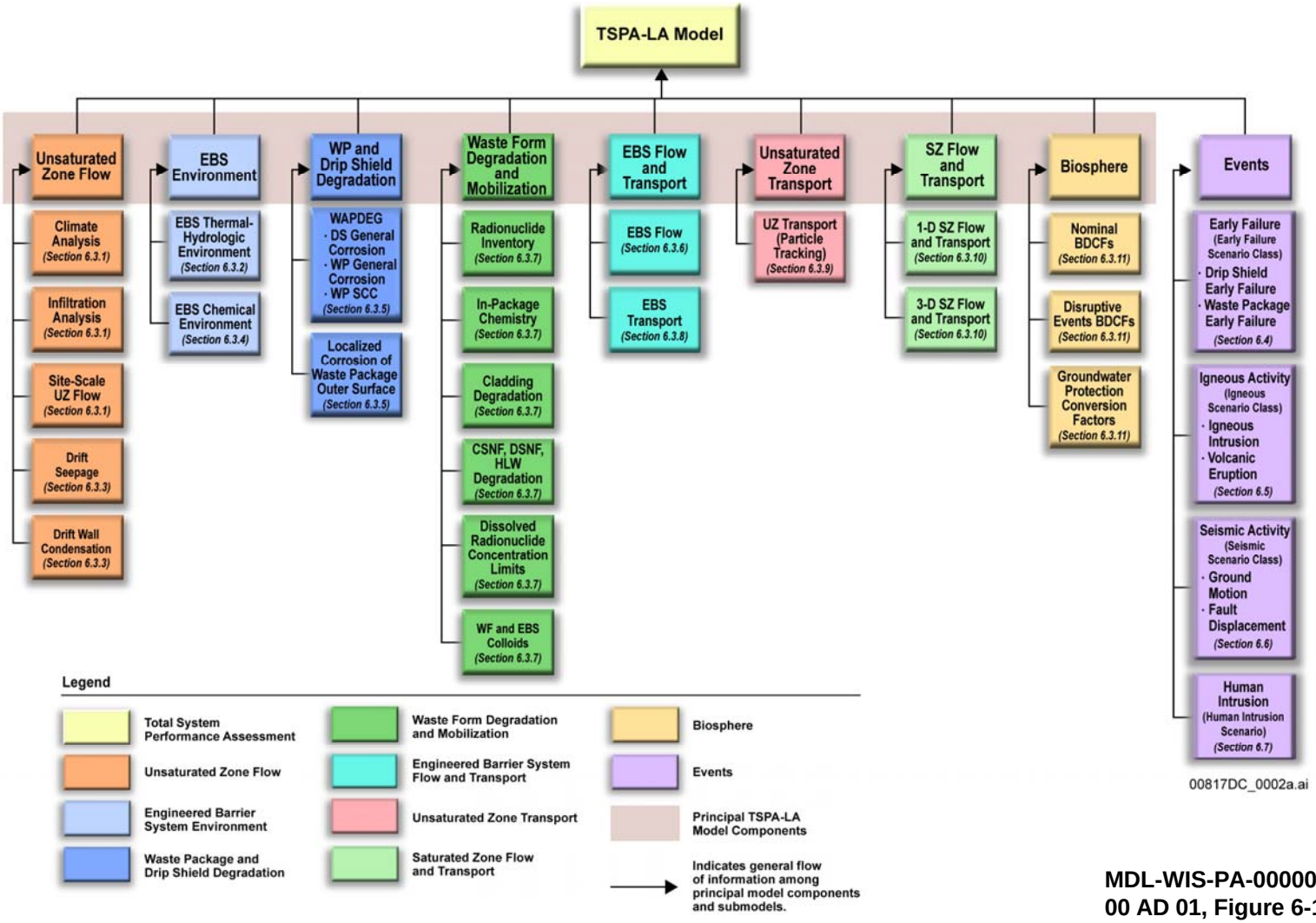
Estimating Dose to Hypothetical Future Humans





Modeled groundwater flow paths and hypothetical exposure pathways

Models and Submodels Supporting the TSPA



MDL-WIS-PA-000005 REV 00 AD 01, Figure 6-1

Steps in Iterative Performance Assessment

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

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

Lack of knowledge about the future state of the system

probabilities of disruptive events

Alternative conceptual models

Uncertainty in YM TSPA

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*

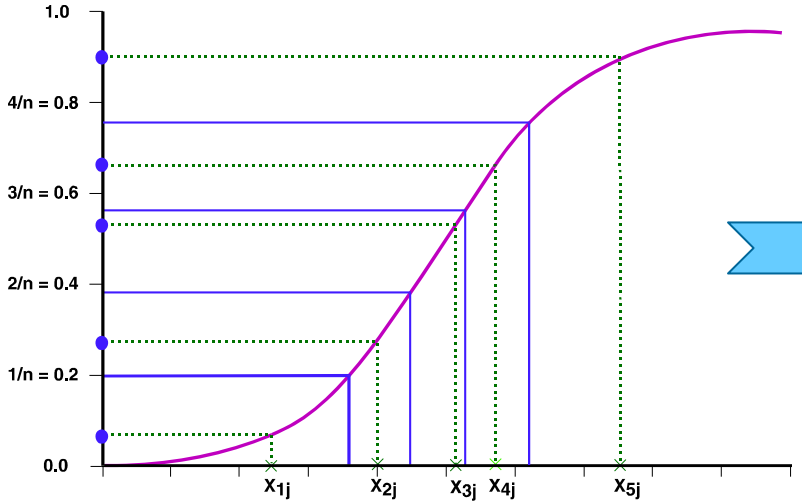
Epistemic uncertainty

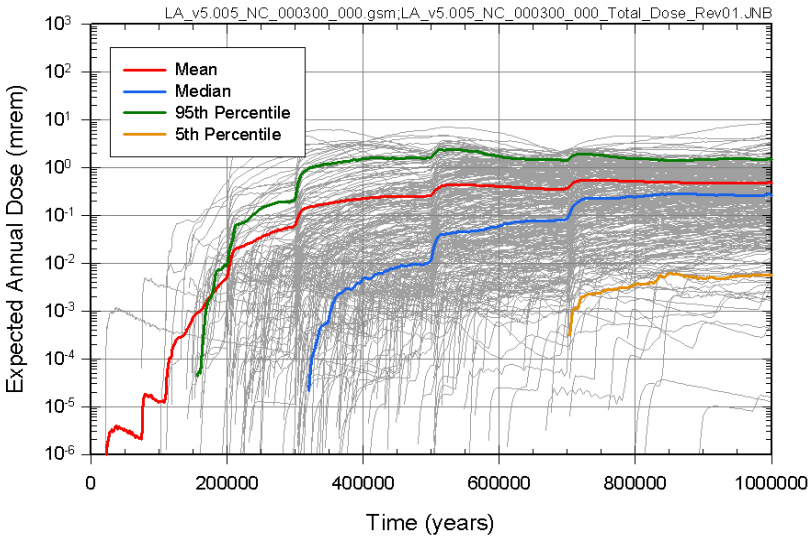
- Lack of knowledge about appropriate value to use for a quantity assumed to have a fixed value
- Alternative descriptors: reducible, subjective, state of knowledge, type B
- Examples:
  - *Spatially averaged permeabilities, porosities, sorption coefficients, …*
  - *Rates defining Poisson processes*

Uncertainty in YM TSPA (cont.)

Epistemic uncertainty incorporated through Latin hypercube sampling of cumulative distribution functions and Monte Carlo simulation with multiple realizations

(approx. 400 uncertain epistemic parameters in TSPA-LA)



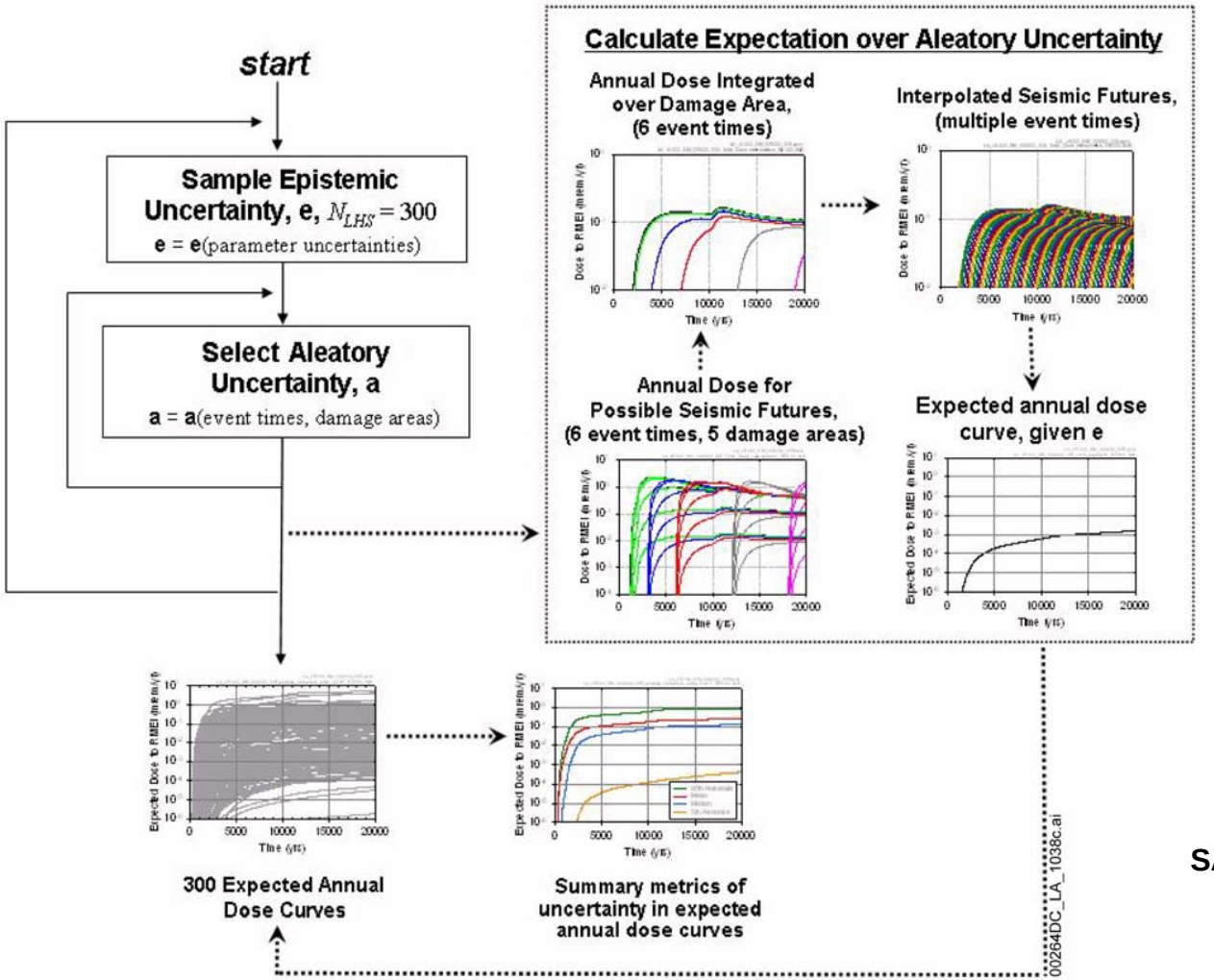


Aleatory uncertainty incorporated through the design of the analysis

Terminology

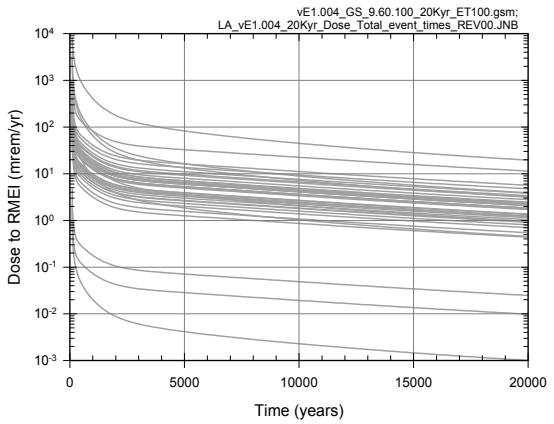
- **"Dose" – annual dose to the Reasonably Maximally Exposed Individual (RMEI) as a function of time** $D_{MC}(\tau|\mathbf{a},\mathbf{e})$
  - Depends on both aleatory and epistemic uncertainty
  - Summed over all radionuclides
- **"Expected Dose"** $\bar{D}_{MC}(\tau|\mathbf{e})$
  - Expectation is taken over aleatory quantities
  - Conditional on epistemic uncertainty
  - Calculated for each modeling case
- **"Mean Dose"** $\bar{\bar{D}}_{MC}(\tau)$
  - Expectation is taken over both epistemic and aleatory
  - Calculated for each modeling case
- **"Total Expected Dose"** $\bar{D}(\tau|\mathbf{e}) = \sum_{MC} \bar{D}_{MC}(\tau|\mathbf{e})$
  - Summed over modeling cases by epistemic vector
- **"Total Mean Dose"** $\bar{\bar{D}}(\tau) = \frac{1}{N}\sum_{i=1}^{N} \bar{D}(\tau|\mathbf{e}_i)$
  - Average of Total Expected Dose

Example: Calculation of Expected Seismic Dose

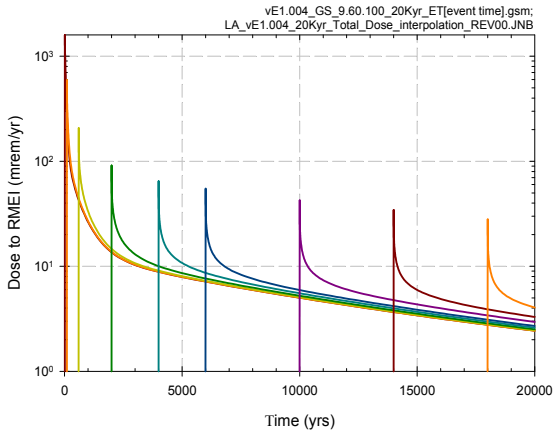


SAR Figure 2.4-8

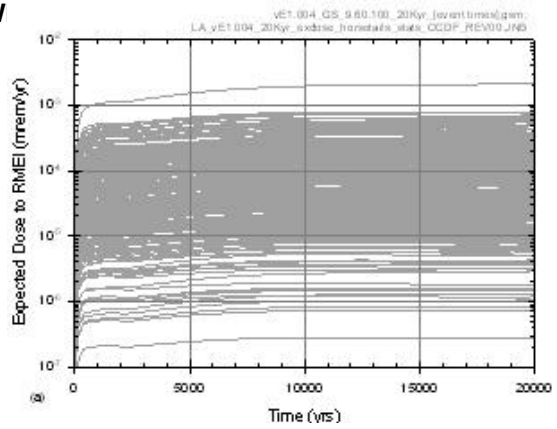
Example: Eruptive Dose



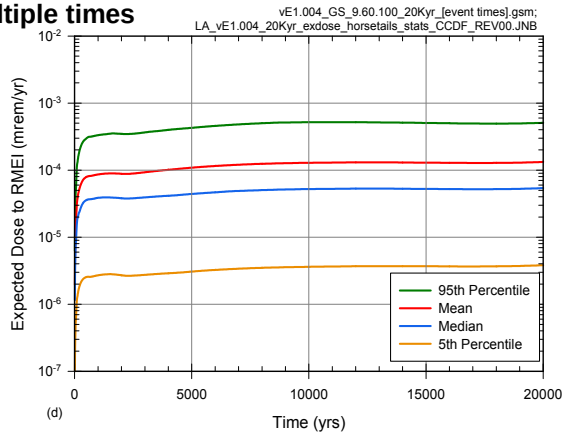
Eruptive dose: 40 realizations of aleatory uncertainty conditional on a single eruption of 1 W



Eruptive dose averaged over aleatory uncertainty associated with a single eruption of 1 WP, eruptions at multiple times



Expected eruptive dose; 300 realizations, each showing expected dose from a single sampling of epistemic uncertainty with events at all times



Summary curves showing overall mean dose from eruption

MDL-WIS-PA-000005 Rev 00, Figures J7.3-1, 2,&4

Steps in Iterative Performance Assessment

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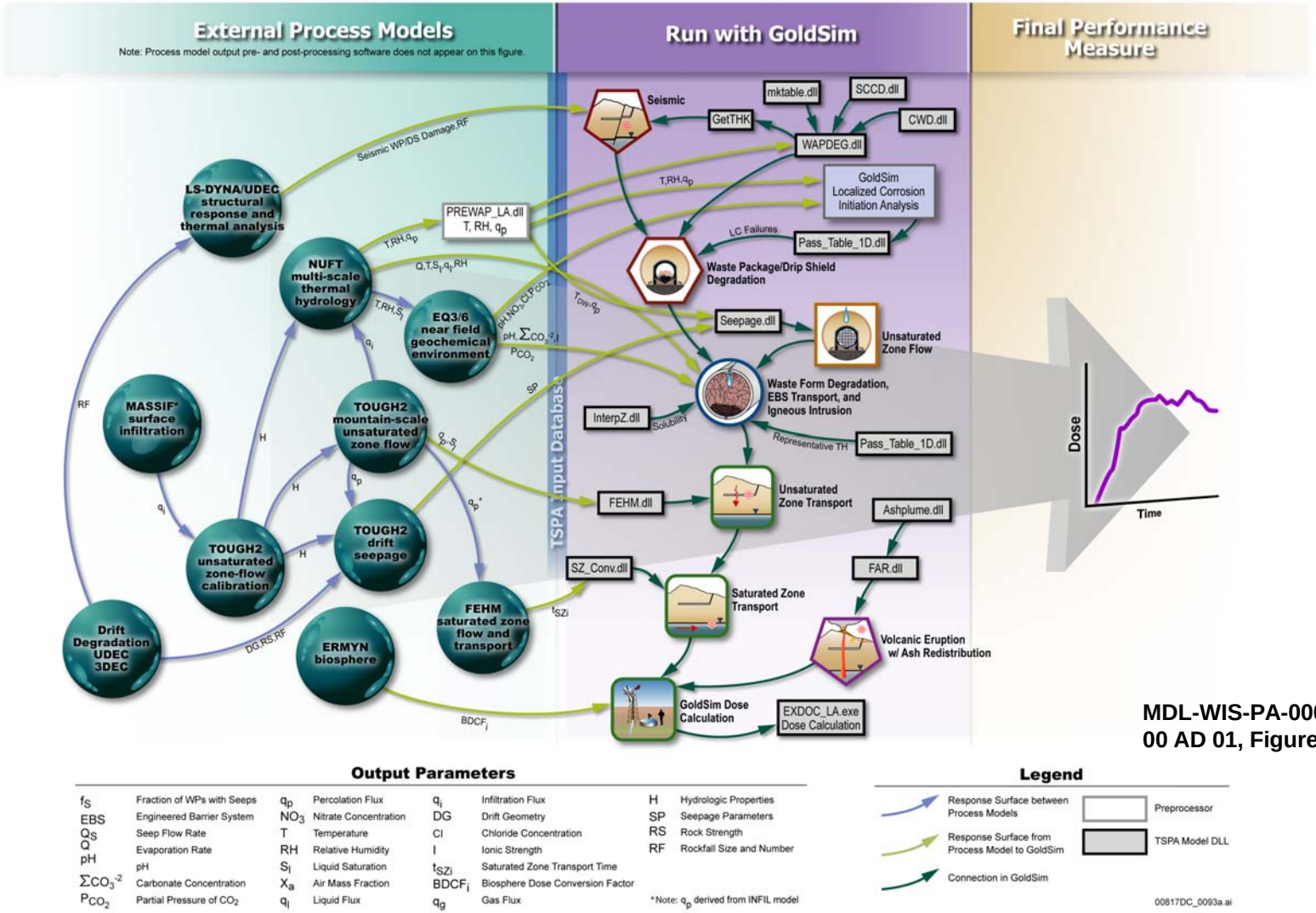
- *Develop models* and abstractions, along with their scientific basis, for logical groupings of FEPs within scenario classes
- *Evaluate uncertainty* in model inputs
- *Construct integrated TSPA model* using all retained FEPs and *perform calculations* for the scenario classes and "modeling cases" within scenario classes
- *Evaluate total system performance,* incorporating uncertainty through Monte Carlo simulation

TSPA Architecture



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

TSPA-LA Scenarios

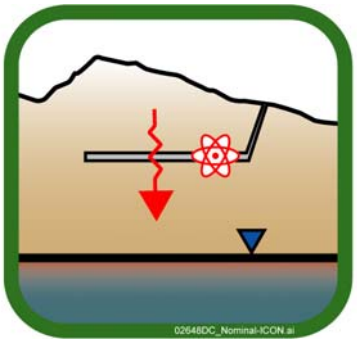
Four scenario classes divided into seven modeling cases

Nominal Scenario Class

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

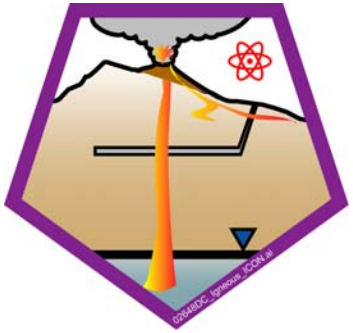
Early Failure Scenario Class

- **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**

TSPA Scenarios and Modeling Cases

- Nominal Scenario Class (1 modeling case)
  - No releases until waste package (WP) corrosion creates pathway
  - WP failures rare before 100,000 years
  - WP failures due to stress corrosion cracking (SCC) of closure welds occur as general corrosion removes annealed layer
    - SCC common by 500,000 years
    - Releases through SCC occur by diffusion only
  - Drip shield (DS) failures due to general corrosion occur between 270,000 and 340,000 years
  - WP "patch" failures due to general corrosion rarely occur before 500,000 years
    - Mean of 9% of WPs show patch failures at 1 million years
    - Patch failures allow advective releases

Scenarios and Modeling Cases (Cont)

- Early Failure Scenario Class (2 modeling cases)
  - Early Failure WP Modeling Case
    - Failures occur at time of repository closure
    - Median probability of early failure = 4.4×10^{-5} per WP
    - Probability of 1 or more early failure waste packages = 0.44
    - Expected number of early failure waste packages (given early failures occur) = 2.5
    - Diffusion until DS failure by corrosion
  - Early Failure DS Modeling Case
    - Failures occur at time of repository closure
    - Median probability of early failure = 4.3×10^{-7} per DS
    - Probability of 1 or more early failure drip shields = 0.017
    - Expected number of early failure drip shields (given early failures occur) = 1.1
    - Simplifying assumption: WP under early failed DS is also failed in seeping conditions
    - Transport by both advection and diffusion

Scenarios and Modeling Cases (Cont)

- Igneous Scenario Class (2 modeling cases)
  - Intrusion Modeling Case
    - Mean frequency 1.7 x 10^{-8}/yr (uncertain event frequency)
    - All waste packages and drip shields sufficiently damaged to provide no barrier to flow and transport
    - Seepage equal to percolation flux (no capillary barrier)
  - Eruption Modeling Case
    - Probability of waste intersection by eruption conditional on igneous event is 0.08
    - Mean number of waste packages intersected = 3.8
    - Mean fraction of waste package content ejected = 0.3
    - Ash redistribution by fluvial processes after deposition

Scenarios and Modeling Cases (cont.)

- Seismic Scenario Class (2 Modeling Cases)
  - Seismic Ground Motion (GM) Damage Modeling Case
    - Ground motions result in SCC that allow diffusive releases
      - Frequency of events that damage codisposal (CDSP) packages: ~ 10^{-5} / yr
      - Frequency of events that damage transportation, aging, and disposal (TAD) packages for commercial spent nuclear fuel (CSNF): ~ 10^{-8} / yr
    - Cracked area accumulates with additional seismic events
    - Repeated damage may cause WP rupture (<10^{-8} / yr)
    - Drip shield thins by general corrosion and fails due to dynamic loading of accumulated rockfall
  - Nominal corrosion processes included for million-year analyses
    - Corrosion affects EBS response to ground motion
      - Damage analyses consider thinning of Alloy 22 and titanium
      - SCC allows corrosion of internal steel components

Scenarios and Modeling Cases (cont.)

- Seismic Scenario Class (2 Modeling Cases) (cont.)

  Seismic Fault Displacement Modeling Case

  Annual frequency approximately 2 x 10^{-7} / yr

  Fault displacements rupture waste packages and drip shields, allowing advection and diffusion

  Size of rupture uncertain, 0 to cross-sectional area of WP

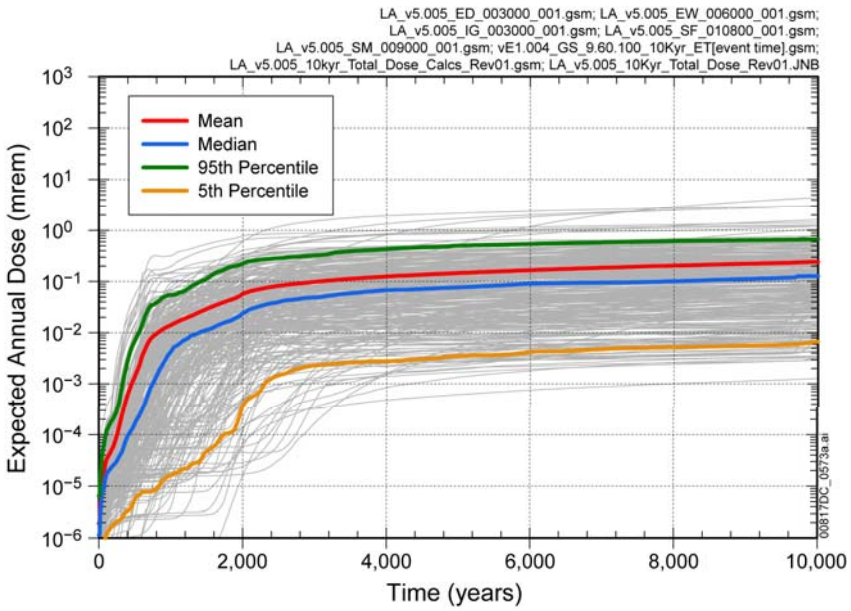
  mean of ~ 47 waste packages and drip shields damaged

Steps in Iterative Performance Assessment

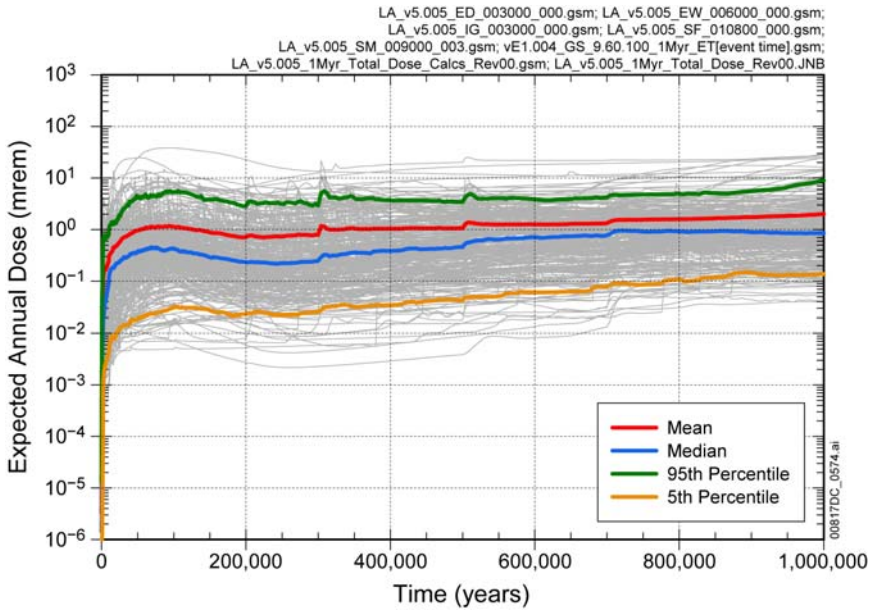
- *Screen Features, Events, and Processes (FEPs)* and develop scenario classes
- *Develop models* and abstractions, along with their scientific basis, for logical groupings of FEPs within scenario classes
- *Evaluate uncertainty* in model inputs
- *Construct integrated TSPA model* using all retained FEPs and *perform calculations* for the scenario classes and "modeling cases" within scenario classes
- *Evaluate total system performance,* incorporating uncertainty through Monte Carlo simulation

Total System Performance Assessment Results

Total Mean Annual Dose



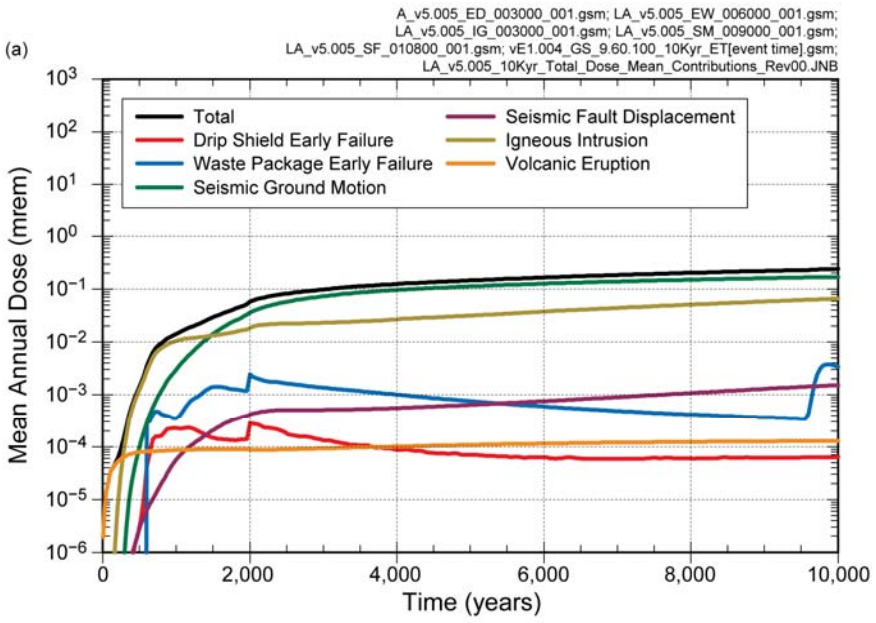
10,000 years

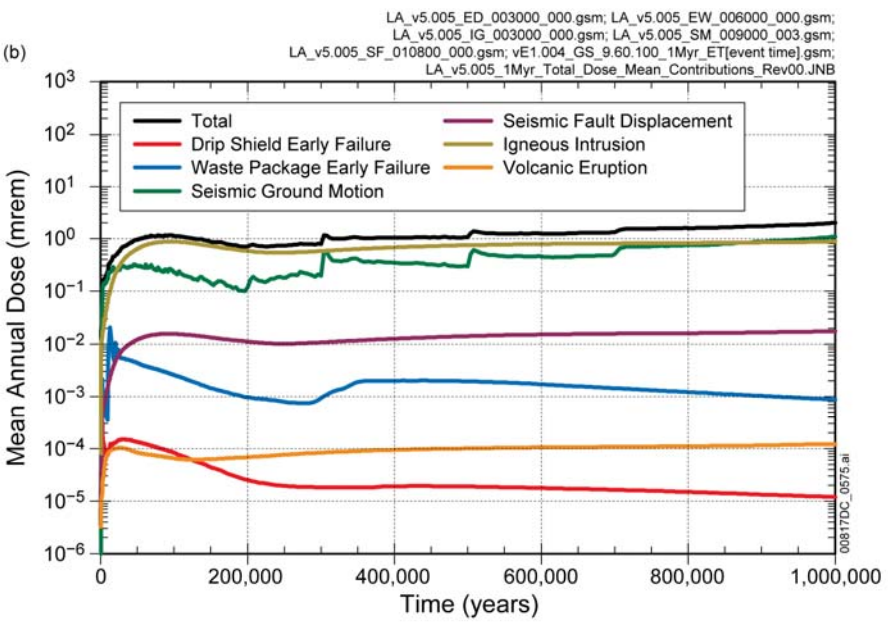


1,000,000 years

MDL-WIS-PA-000005 REV 00 AD 01, Figure 8.1-1[a] and Figure 8.1-2[a]

Modeling Cases Contributing to Total Mean Annual Dose



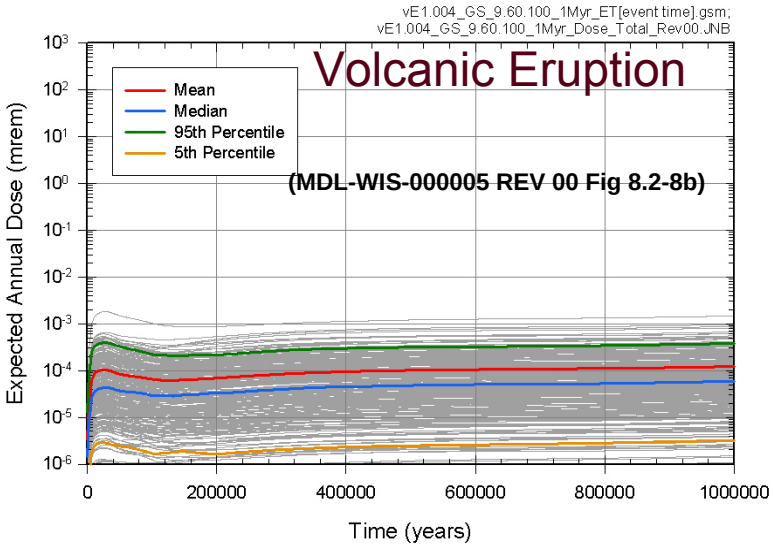


10,000 years

1,000,000 years

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

Construction of Total Dose



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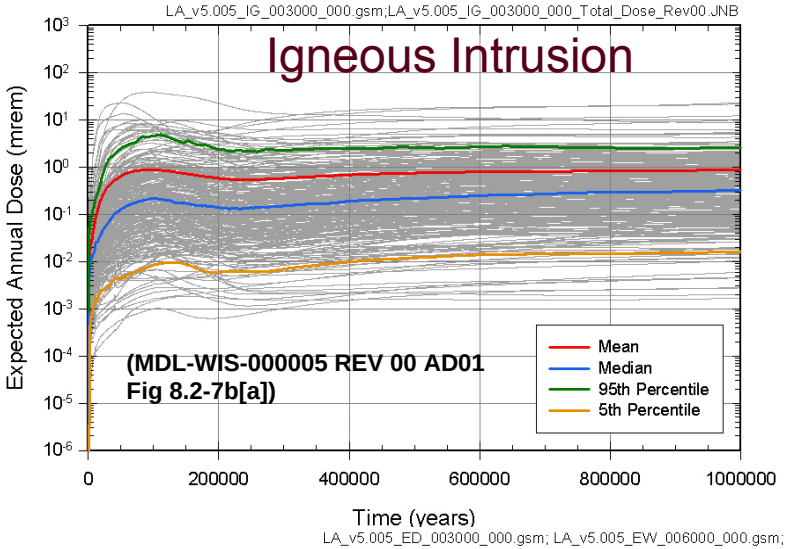

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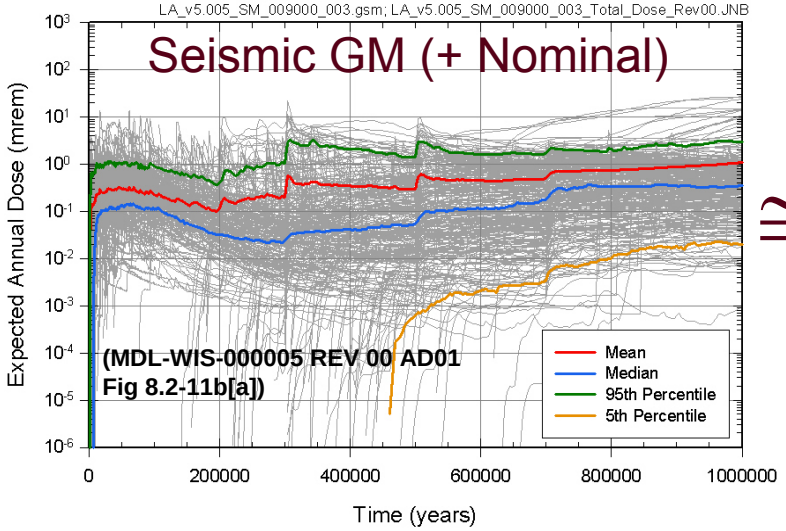

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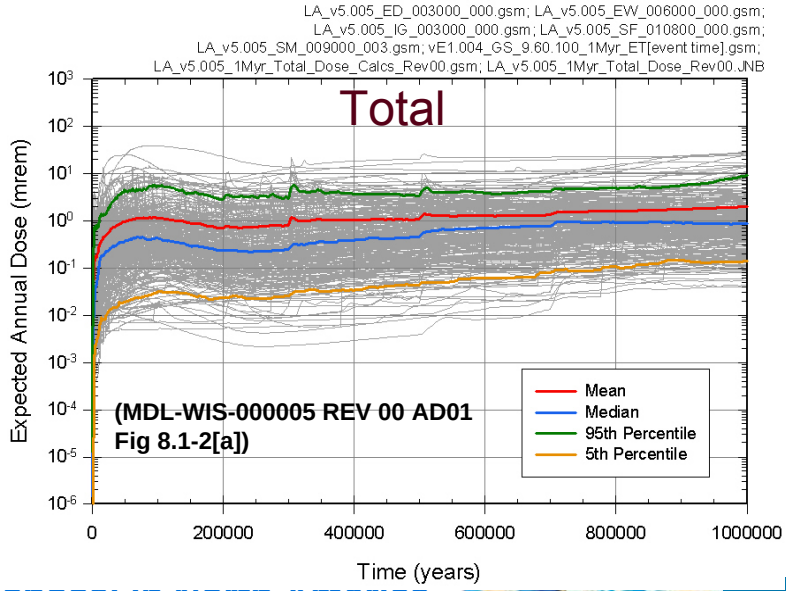
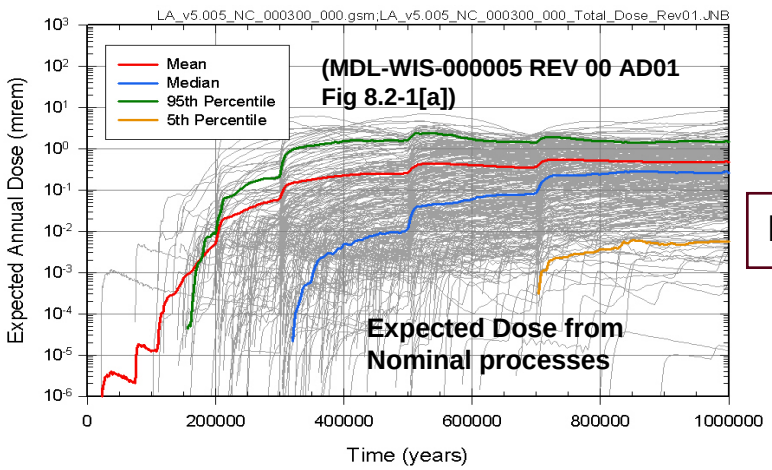
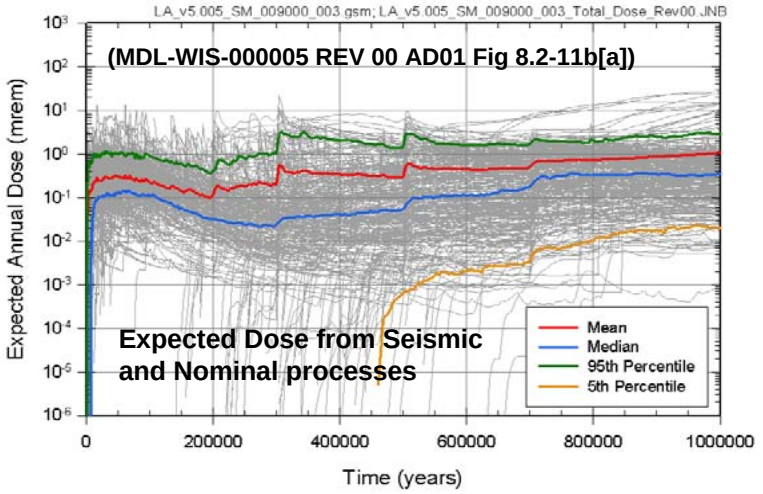
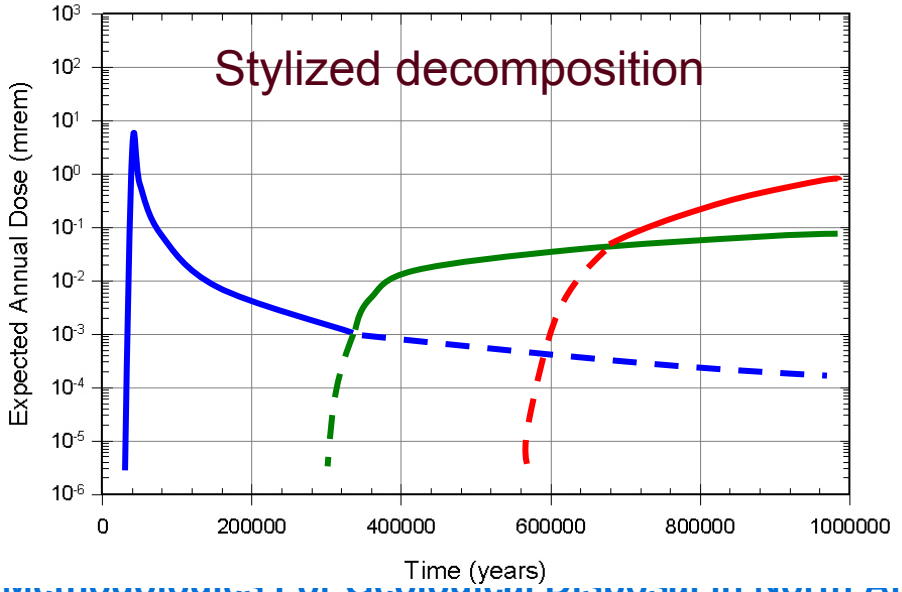


Composition of Seismic Ground Motion Dose



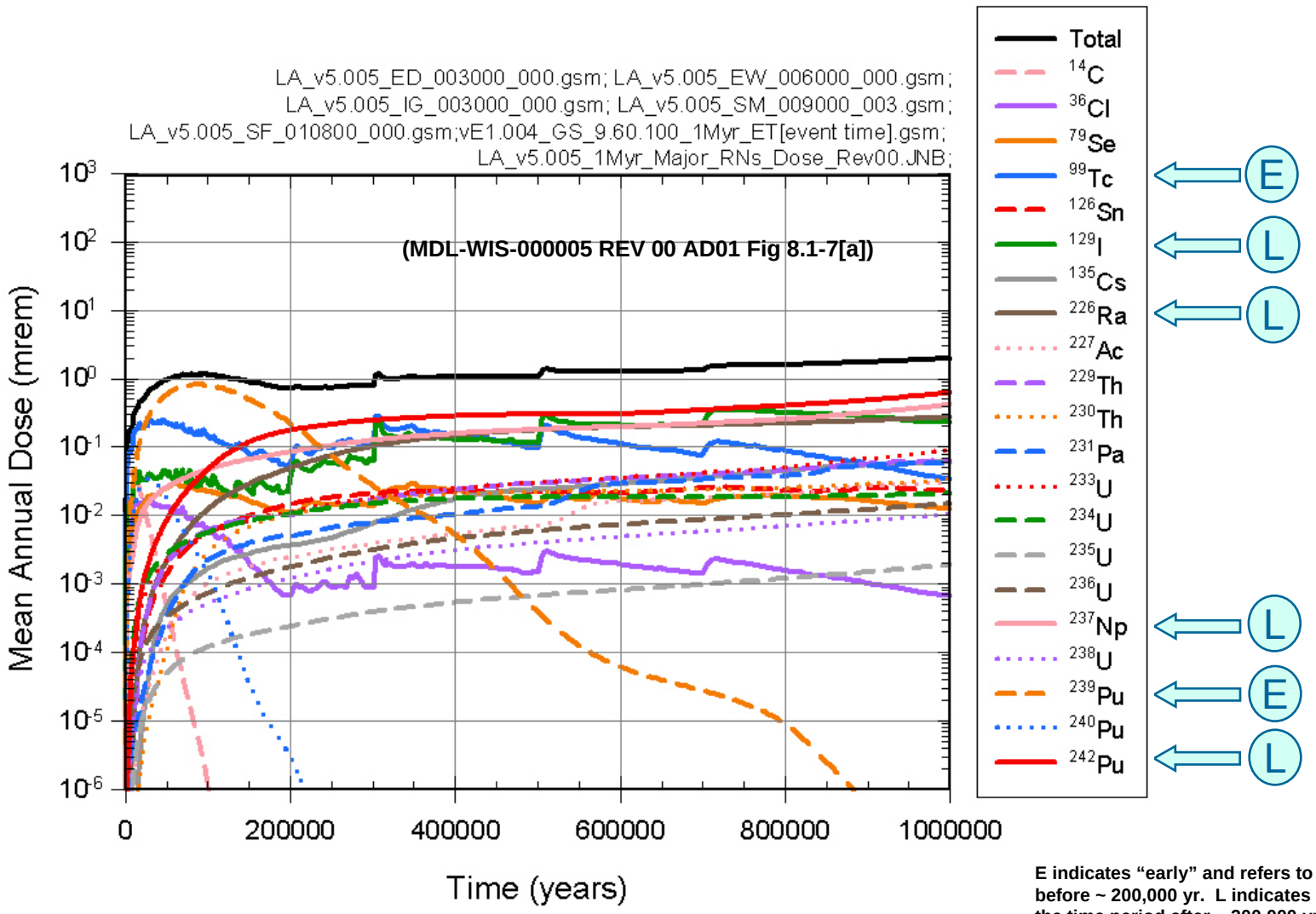
Included





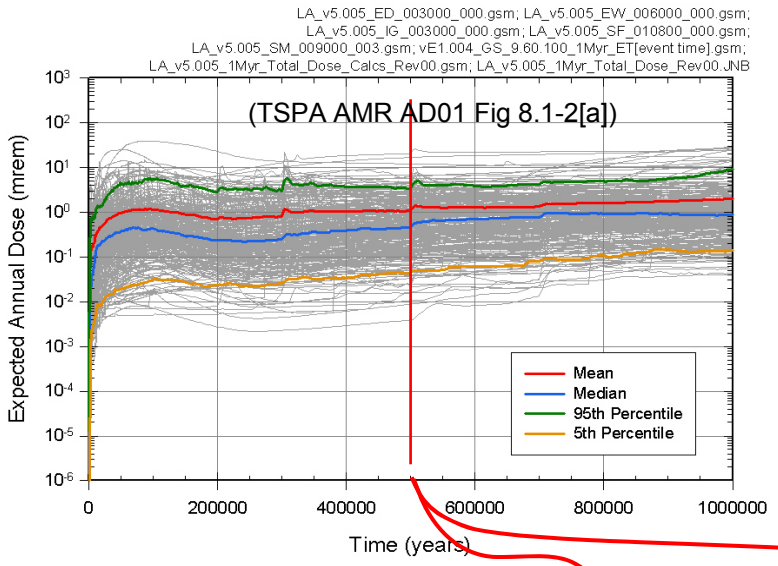
- From seismic damage to CDSP WP (diffusion)
- From SCC failure of CSNF WP (diffusion)
- From general corrosion failure of both WPs (advection)

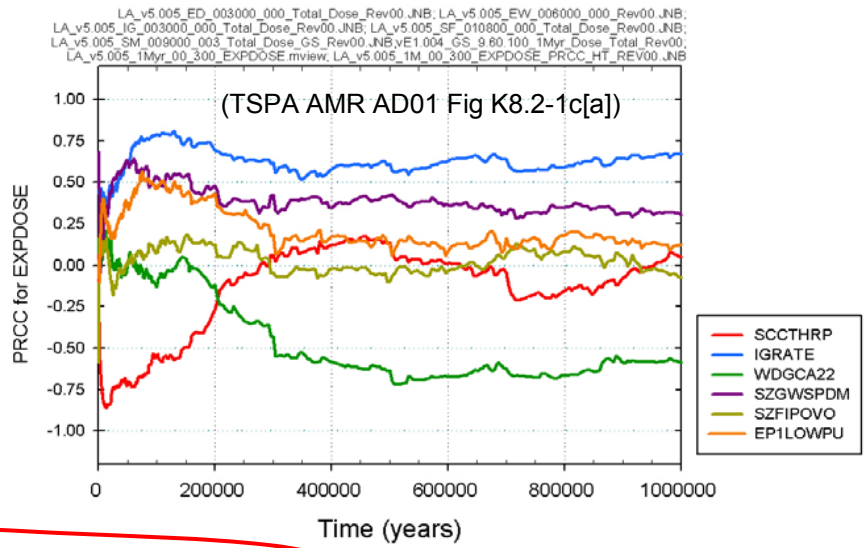
TSPA-LA Radionuclides Important to Mean Dose



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

Uncertainty in Total Expected Dose

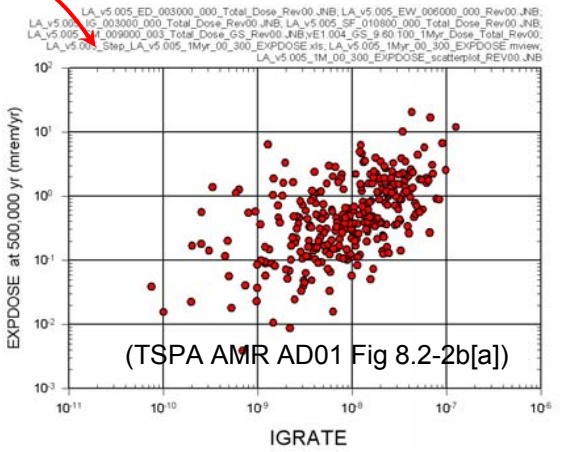


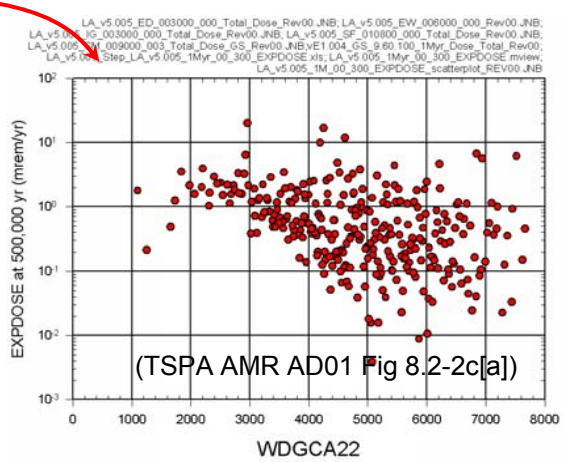


SCCTHRP – Stress threshold for SCC initiation

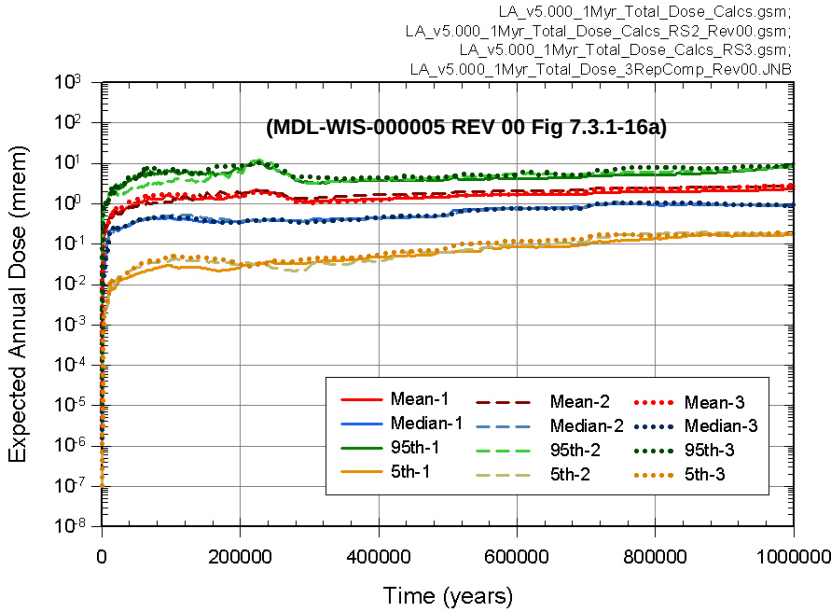
IGRATE – Frequency of igneous events

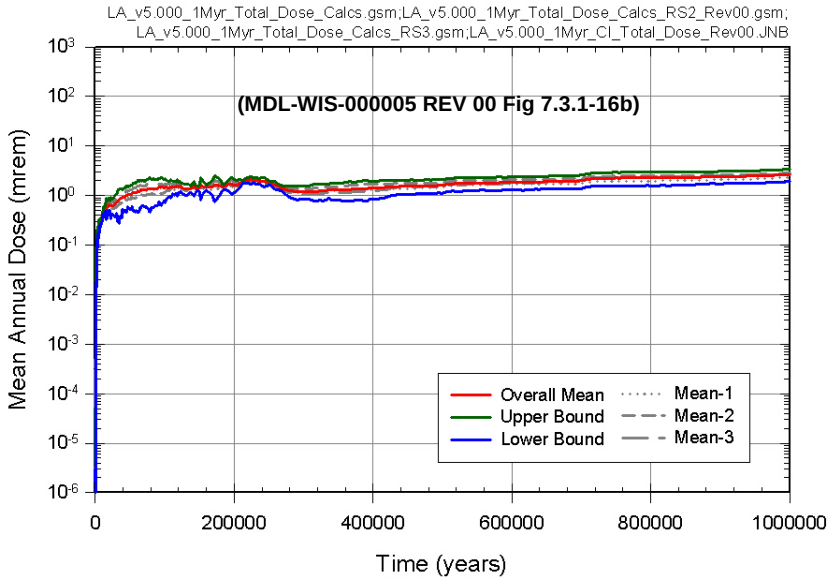
WDGCA22 – Temperature dependence in A22 corrosion rate





Stability of Total Dose (million-year example)



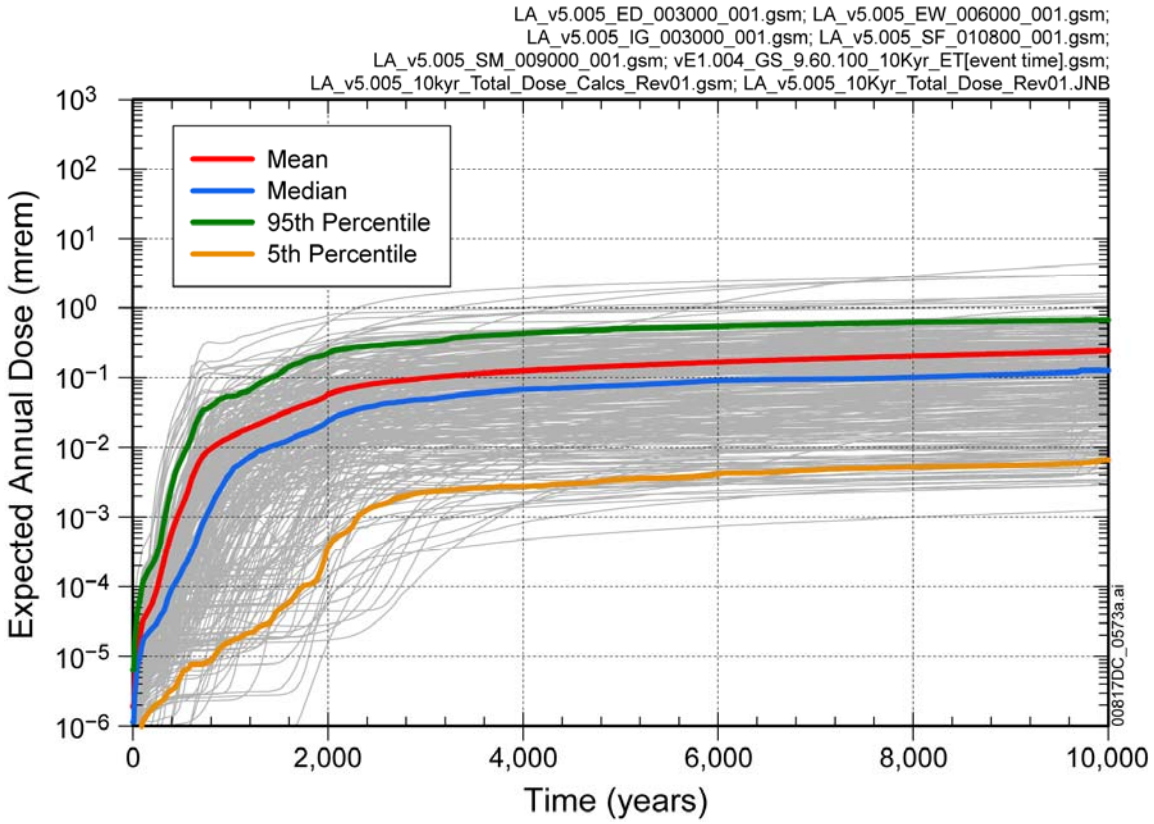


Replicated sampling demonstrates that sample size is sufficient

Confidence interval illustrates precision of estimate of total mean dose

Total System Performance Assessment Results

Individual Protection Standard: 10,000 yr



MDL-WIS-PA-000005 REV 00 AD 01, Figure 8.1-1[a]

10,000-year Standard:

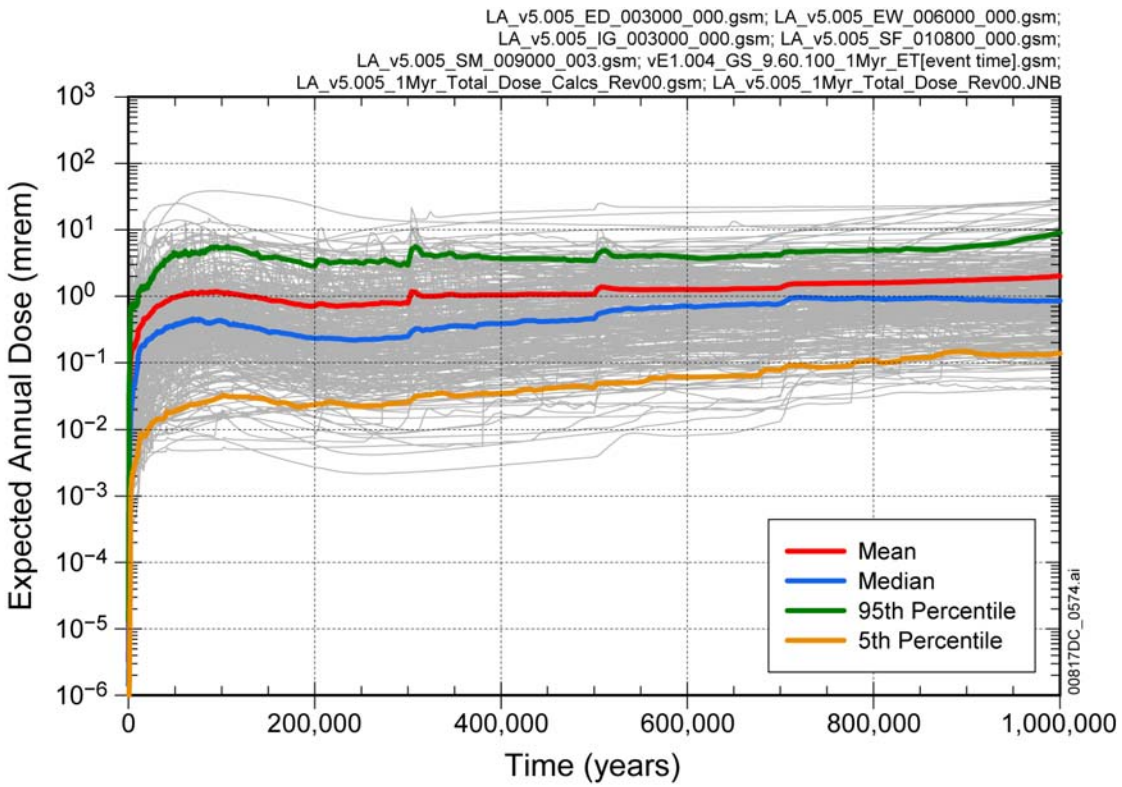
Mean annual dose no more than 0.15 mSv (15 mrem)

TSPA-LA estimated 10,000 yr maximum mean annual dose:

0.0024 mSv (0.24 mrem)

Total System Performance Assessment Results

Individual Protection Standard: 1,000,000 yr



1,000,000-year Standard:

Mean annual dose no more than 1 mSv (100 mrem)

TSPA-LA estimated 1,000,000- yr maximum mean annual dose:

0.02 mSv (2.0 mrem)

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

Conclusions

- The TSPA-LA supports the DOE's License Application to the NRC for authorization to construct a repository at Yucca Mountain
- The TSPA provides probabilistic estimates of long- term performance, consistent with supporting technical information and taking into account uncertainties in the future occurrence of disruptive events
- All performance measures are well below regulatory limits

Backup

Multiple Barriers Contribute to Waste Isolation

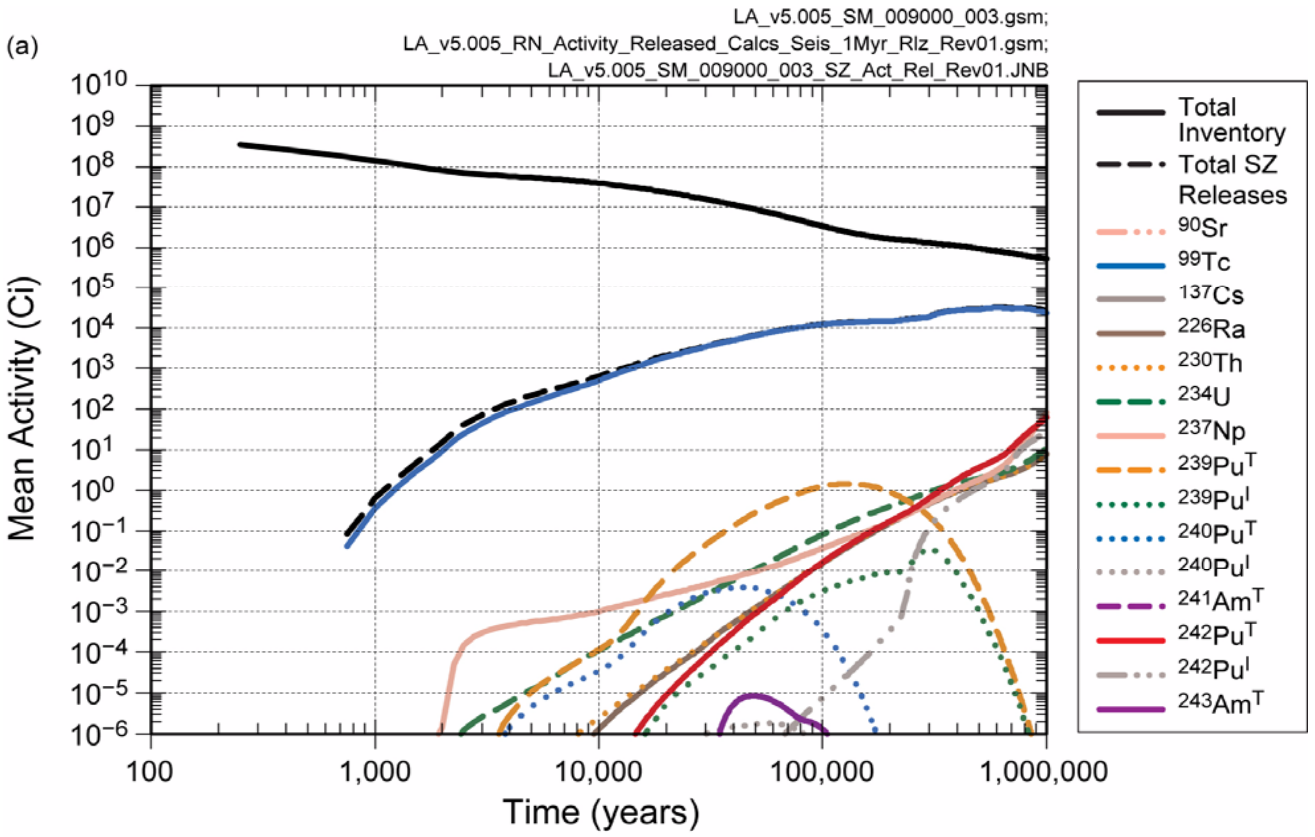
- Upper Natural Barrier System
  - Topography and surficial soils
  - Unsaturated zone above the repository
- Engineered Barrier System
  - Drift environment
  - Drip Shield
  - Waste Package
  - Waste forms and associated shipping containers
  - Emplacement pallet
  - Drift invert
- Lower Natural Barrier System
  - Unsaturated zone below the repository
  - Saturated zone between the repository and the accessible environment

Example Barrier Capability Analysis

At I million 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
MDL-WIS-PA-000005 REV 00 AD 01, Figure 8.3-26[a]a

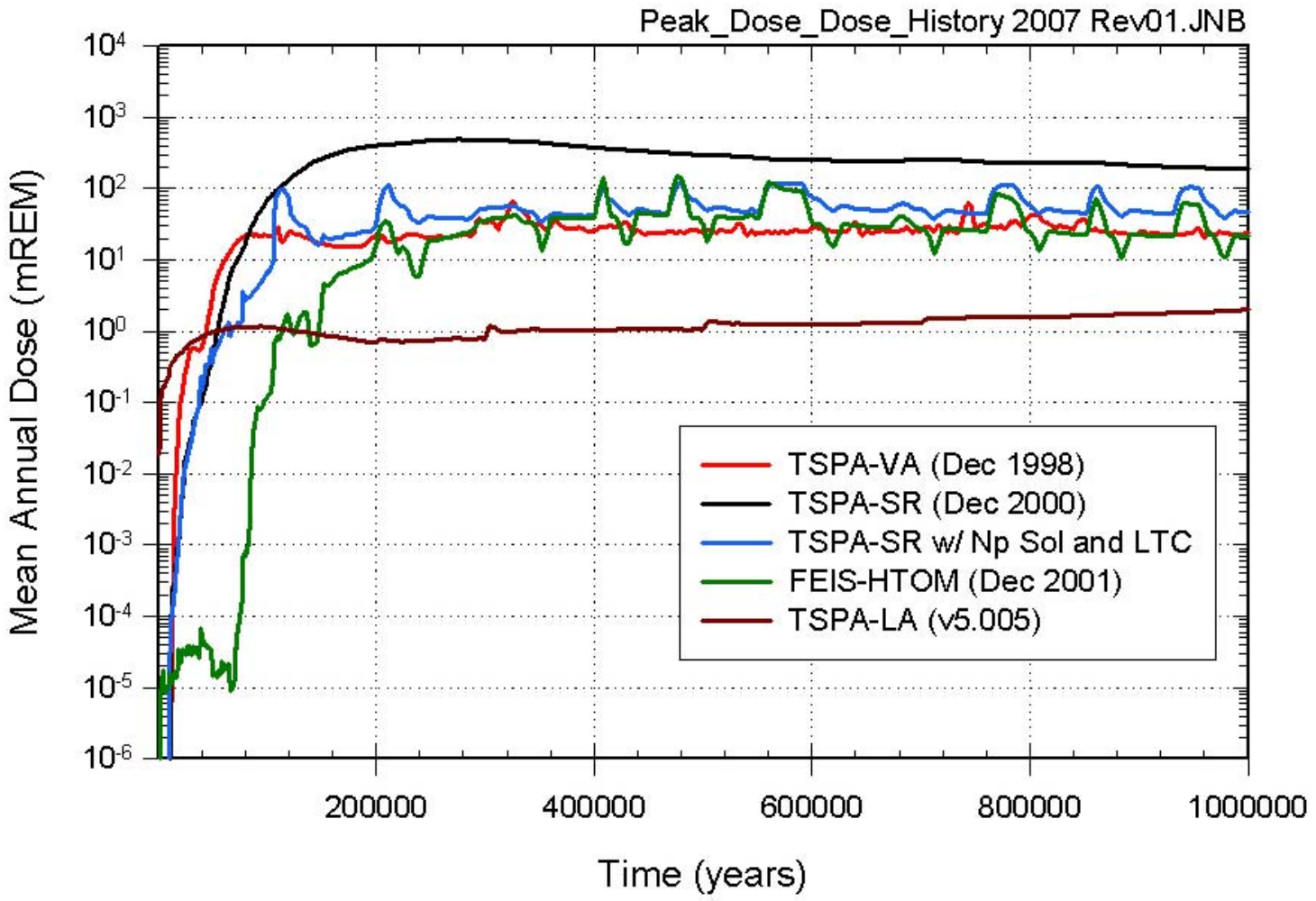
Iterative TSPAs for Yucca Mountain

Advances have occurred over the last ten years in scientific understanding, design concepts, modeling capability, and regulatory requirements, and results from prior iterations of Yucca Mountain TSPA are not directly comparable to the TSPA-LA

Understanding changes in model results helps build confidence in the TSPA-LA

- Multiple iterations of TSPA prior to 1998
- 1998: TSPA to support the Viability Assessment (TSPA-VA)
- 2000: TSPA to support the Site Recommendation (TSPA-SR)
- 2001: TSPA to support the Final Environmental Impact Statement (TSPA-FEIS)
- 2008: TSPA-LA

Yucca Mountain Mean Annual Dose Estimates 1998-2008



w/ Np Sol and LTC indicates "with neptunium solubility limits reduced by sequestration in secondary mineral phases and with long-term climate change."
"HTOM" indicates "high-temperature operating mode."

Source: Figure 1 of Swift et al., 2008, "Broader Perspectives on the Yucca Mountain Performance Assessment," 2008 IHLRWMC, Las Vegas, NV, Sept. 7-11, 2008

Major Changes in TSPA from VA to LA

- TSPA-VA
  - Selected relevant design aspects
    - 28-meter drift spacing
    - Alloy-22 waste package inner vessel
    - No drip shield
  - No disruptive events or early failures included in total dose
  - Cladding failure occurred by rockfall and corrosion, cladding remained intact in most waste packages throughout simulation
  - Dose was release-rate limited rather than solubility-limited
  - Long-term dose dominated by Np-237, Pu-242 from general corrosion failures of commercial spent nuclear fuel packages (CSNF) in dripping regions (Tc-99 important at earlier times)

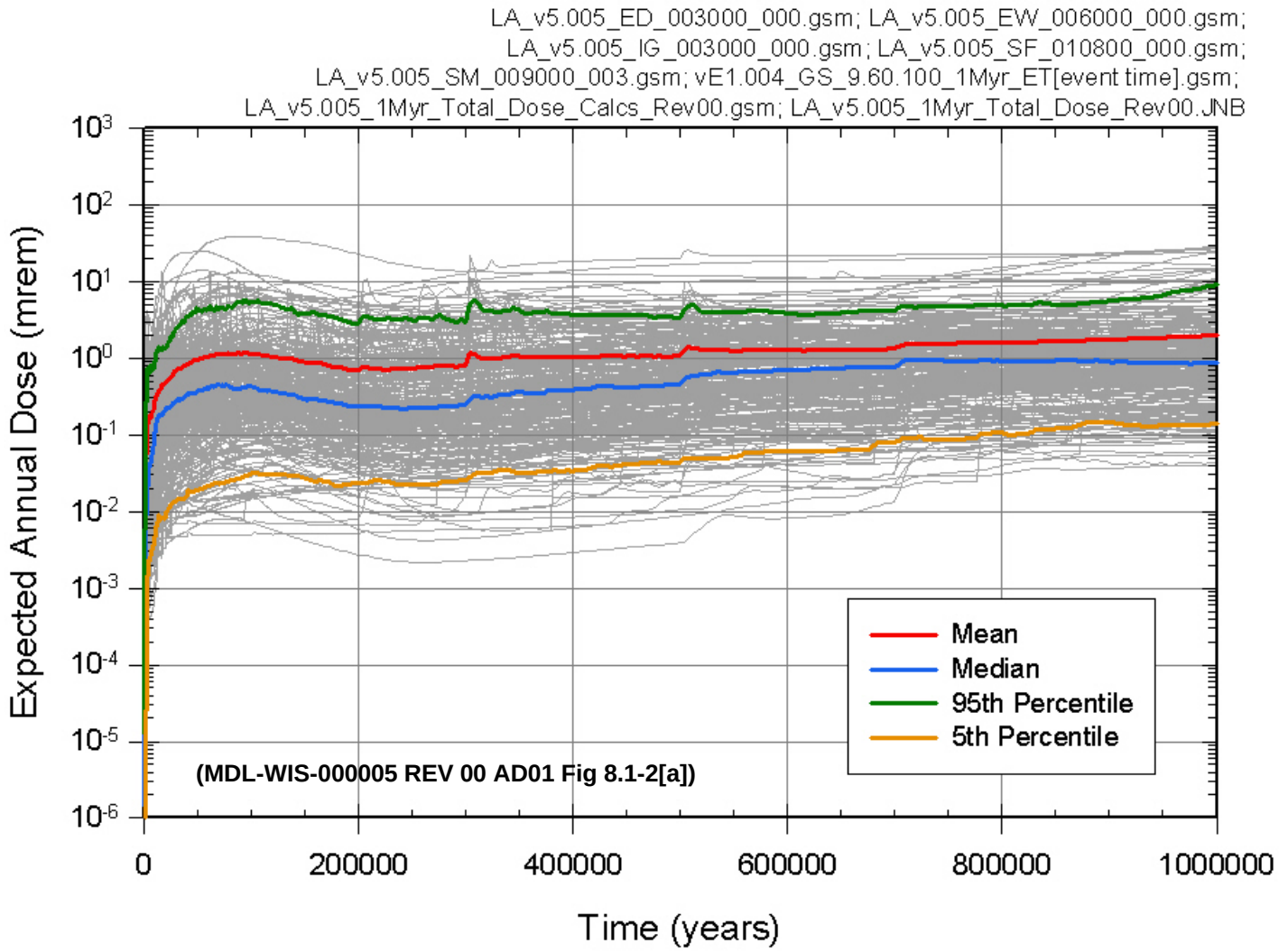
Major Changes in TSPA from VA to LA (cont.)

- TSPA-SR
  - Design changes
    - 81-m drift spacing
    - Alloy-22 waste package outer barrier
    - Addition of drip shield
  - Cladding failure occurs due to ground motion as well as rockfall
  - Igneous disruption evaluated for 100,000 yr, not shown for 1,000,000 yr
  - Solubility-limited dose, increase of ~10× over TSPA-VA
  - Long-term dose dominated by Np-237 from general corrosion failures of CSNF packages in dripping regions
- TSPA-SR with secondary mineral phases and long-term climate change
  - Including secondary phases in Np solubility model lowered dose ~10×
  - Including full-glacial climates at fixed times caused cyclic peaks
- TSPA-FEIS
  - Modified general corrosion model resulted in later waste package failures
  - Early waste package failures caused releases prior to general corrosion failure

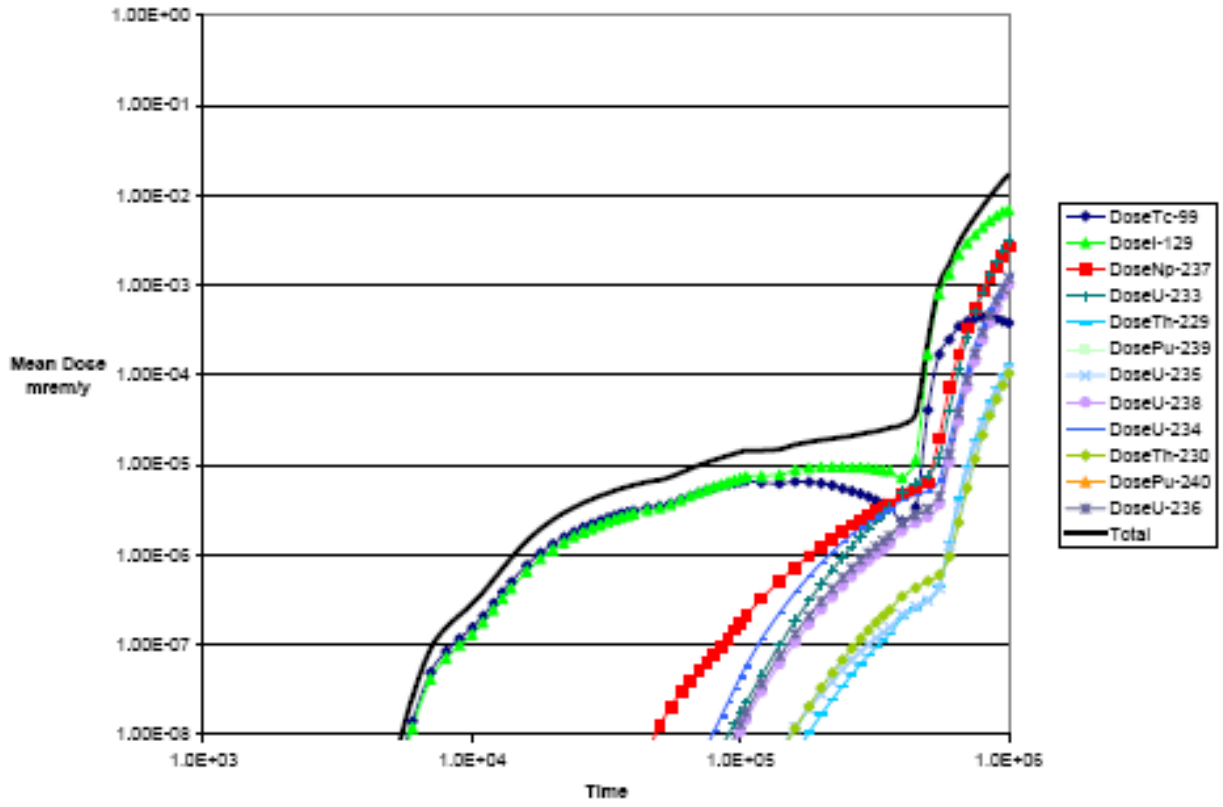
Major Changes in TSPA from VA to LA (cont.)

- TSPA-LA
  - Total dose includes igneous and seismic disruption
    - Consequences of disruptive events are weighted by their probability of occurrence
  - Design includes Transport, Aging and Disposal (TAD) canisters
  - Average long-term climate specified by proposed EPA, NRC regulations
  - Dose ~10× lower than previous analyses
    - General corrosion failure is rare before 500,000 yr (approx. 9% of waste packages show general corrosion failure at 1 million yr)
    - Diffusive releases from stress-corrosion cracking following ground motion are a dominant contributor
    - Modifications to dose conversion factors, source term, transport in engineered barrier system (e.g., sorption on corrosion products), no credit for cladding
  - Tc-99, I-129 are major contributors at later times than in prior TSPAs because of relative importance of diffusion
  - Pu-242 from advective transport following waste package failure by general corrosion is the largest single contributor to the maximum mean annual dose, occurring at 1 million years

TSPA-LA Total Expected Dose



2005 EPRI Results for Yucca Mountain



Maximum total dose estimated by the EPRI IMARC 9 model:

0.02 mrem/yr, at 1,000,000 yr

Maximum total mean dose estimated by the TSPA-LA model:

2.0 mrem/yr, at 1,000,000 yr

Source: Figure 5-10 of Apted and Ross 2005, "Program on Technology Innovation: Evaluation of a Spent Fuel Repository at Yucca Mountain, Nevada, 2005 Progress Report, EPRI 1010074, Electric Power Research Institute

Comparison of EPRI and TSPA-LA models

- EPRI IMARC 9 Model
  - Nominal performance only
    - Disruptive events evaluated separately, not included in full performance assessment
  - Maximum dose at 1,000,000 years, due to general corrosion failure
  - CSNF only
  - I-129 is dominant contributor
  - Relative to TSPA-LA
    - Smaller seepage fraction
    - Lower corrosion rate
    - Lower solubility limits for Pu, Np, Th
    - Lower specific discharge in saturated zone
- TSPA-LA model
  - Nominal and disruptive performance
  - Disruptive events dominate total mean annual dose for most of the 1,000,000 period
  - Maximum dose at 1,000,000 years, due to general corrosion failure from nominal processes
  - CSNF, DOE spent fuel, and defense high-level waste
  - Relative to IMARC 9, largest contributors to difference in maximum dose are
    - Larger seepage fraction
    - Higher solubility limits for Pu, Np, and Th
    - Maximum I-129 mean dose ~10× larger than IMARC 9

Recent Performance Assessments for Potential Repository Sites in Sweden and France

- Differences among programs preclude direct comparisons to Yucca Mountain without extensive caveats
- Sweden – Forsmark site
  - Granite host rock, robust engineered barriers
    - Less than 1% of copper canisters have failed by 1,000,000 years
  - Estimated maximum risk at 1,000,000 yr for conservative modeling assumptions is ~6×10^{-6}, corresponding to ~0.08 mSv/yr (~8 mrem/yr)
    - Source: Section 12.12 and Figure 12-20 of SKB 2006, *Long-term Safety for KBS-3 Repositories at Forsmark and Laxemar—a First Evaluation,* TR-06-09
- France – Meuse/Haute Marne site
  - Clay host rock, emphasis on low-permeability natural barriers
  - Estimated maximum dose to a conservatively chosen critical group, at approximately 330,000 years is ~0.02 mSv/yr (~2 mrem/yr)
    - Source: Table 5.5-8, ANDRA 2005, *Dossier 2005: Argile. Tome: Safety Evaluation of a Geological Repository*
- All three disposal concepts have the potential to offer highly effective long-term isolation of radioactive waste

Conclusions

- Iterative TSPAs for Yucca Mountain in the past decade have responded to new scientific understanding, improved modeling techniques, and advances in the conceptual design for the repository
- Difference in results from the TSPA-LA and the EPRI IMARC-9 model are consistent with different approaches to models and inputs
- Qualitative observations from assessments perfomed in Sweden and France indicate that multiple disposal concepts can offer effective long-term isolation of radioactive waste

History of DOE Yucca Mountain TSPAs

TSPA Iteration	Summary of Key Results
1988 Site Characterization Plan	• Applied basic methodology for Monte Carlo uncertainty analyses based on scenarios.
TSPA-1991	• Demonstration of TSPA approach. • Models limited to UZ and SZ, and volcanism identified importance of uncertainty in UZ flow paths.
TSPA-1993	• Improved models for UZ, SZ, early models for coupled processes, EBS, biosphere. • Importance of uncertainty in thermal hydrology, UZ flow, corrosion of engineered materials.
TSPA-1995	• Incorporate new science and design, evaluate alternative models. • Importance of robust process models for WP degradation, seepage, UZ and SZ transport.
TSPA-VA	• Supported the 1998 Viability Assessment, models based on best current information. • Ranked importance of uncertainty in each of the major components for 10,000, 100,000, and 1,000,000 years. • Emphasis on seepage, water chemistry, corrosion, and SZ.
1999 License Application Design Selection (LADS)	• TSPA tools used to evaluate relative merits of design alternatives. • Demonstrated that multiple designs were viable for long-term performance.
TSPA for Site Recommendation (2000)	• Robust modeling system using fully qualified inputs • Conservative approach to some components. • Regulatory importance of volcanism identified. • Conservative treatments of uncertainty complicated realistic understanding.
FY 2001 Supplemental Science and Performance Analyses (SSPA)	• More realistic treatment of uncertainty. • Incorporation of new information since TSPA-SR. • Confirmed potential suitability. • Confirmed importance of volcanism and EBS performance for 10,000 years. • Insights into EBS and natural system effects on peak dose.
TSPA for the Final Environmental Impact Statement (2001)	• Updated SSPA to include new information, revised regulatory boundary.
2002 Sensitivity Analyses (one-on and one-off)	• Insight into barrier performance. • Risk-importance information regarding model components. • Importance of volcanic disruption for 10,000-yr regulatory compliance.
TSPA-LA	• Models updated to current information.