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Sandia National Laboratories

Yucca Mountain Project Performance Assessment Methodology

Clean. Reliable. Nuclear.

PRESENTED BY

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NEFC Knowledge Management Deep Dive
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Outline – YMP PA Methodology

- **Description of Yucca Mountain (YM) repository concept**
- **Regulatory basis for Yucca Mountain Project (YMP)**
- **Major steps in a Performance Assessment (PA)**
  - Screen Features, Events, and Processes (FEPs) and develop scenario classes
  - Develop (process) models and abstractions for logical groupings of FEPs within scenario classes
  - Estimate uncertainty in model inputs (Uncertainty Quantification – UQ)
  - Construct integrated Total System Performance Assessment (TSPA) model and run simulations
  - Evaluate total system performance, including use of Uncertainty Analysis/Sensitivity Analysis (UA/SA)
- **TSPA model "validation" approach**
- **TSPA iteration timeline**

Waste for Yucca Mountain

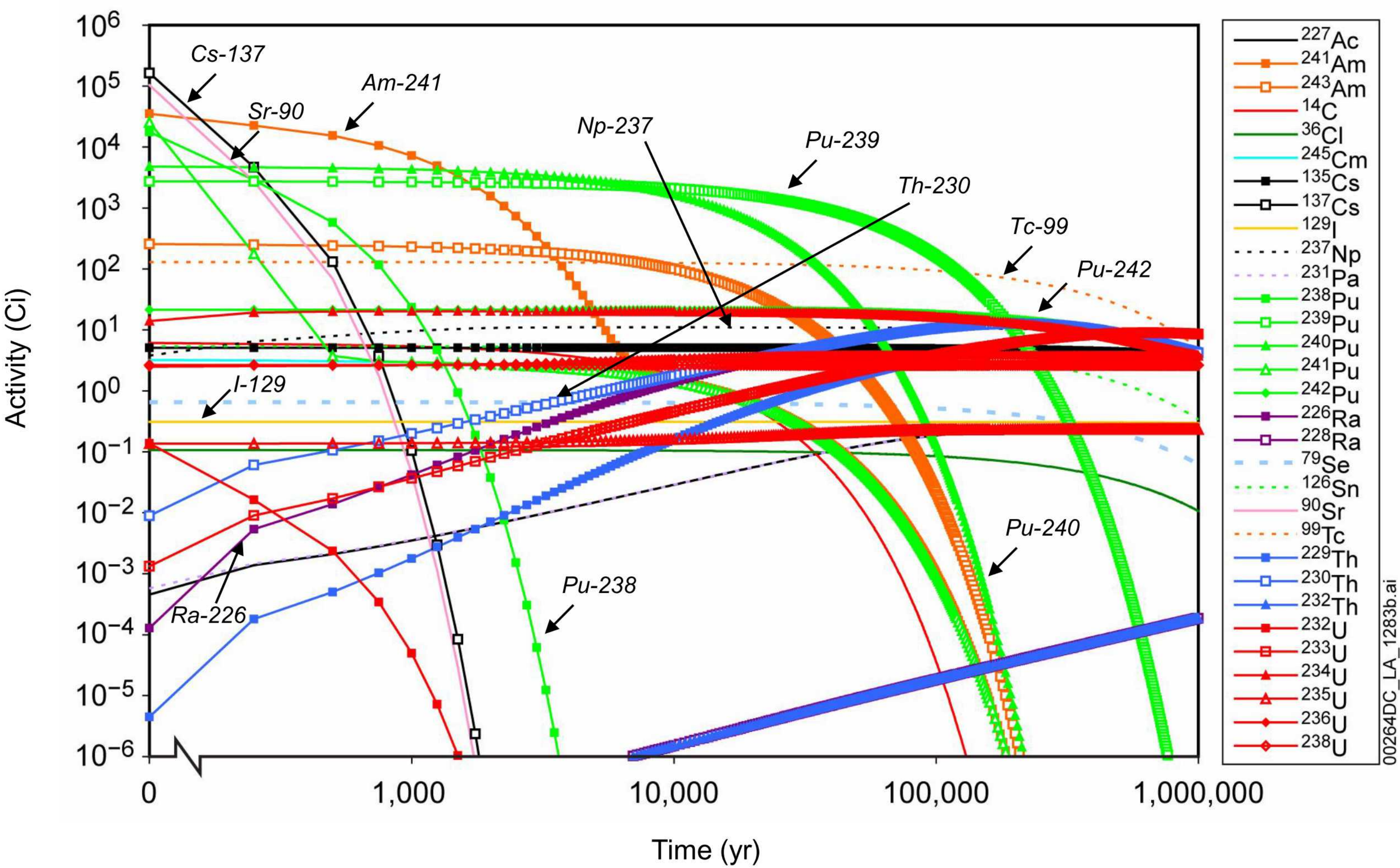
Commercial Spent Nuclear Fuel:
*63,000 MTHM**

DOE & Naval Spent Nuclear Fuel:
2,333 MTHM

DOE & Commercial High-Level Waste:
4,667 MTHM

*Metric Ton Heavy Metal

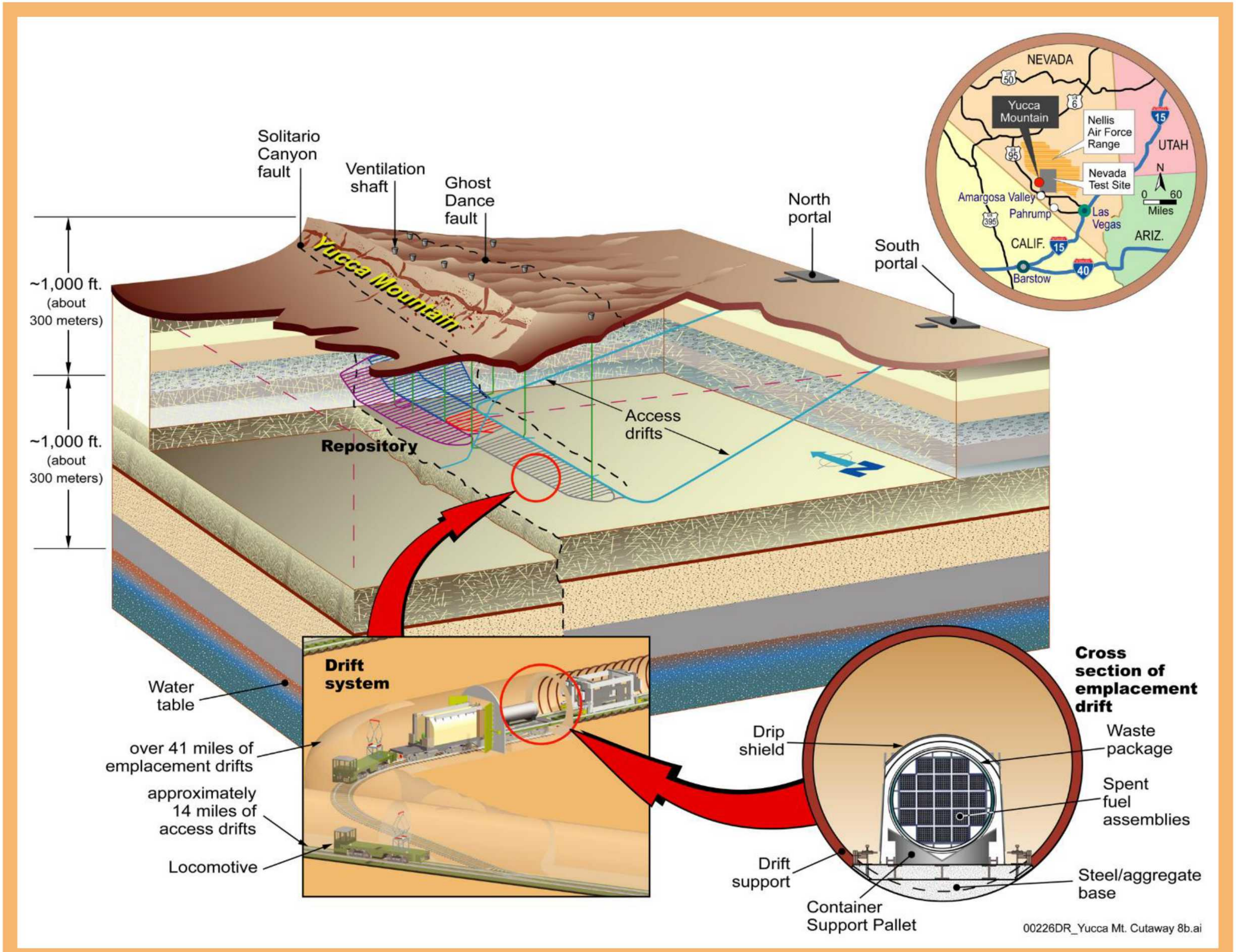
Yucca Mountain Radionuclide Inventory 1 million years



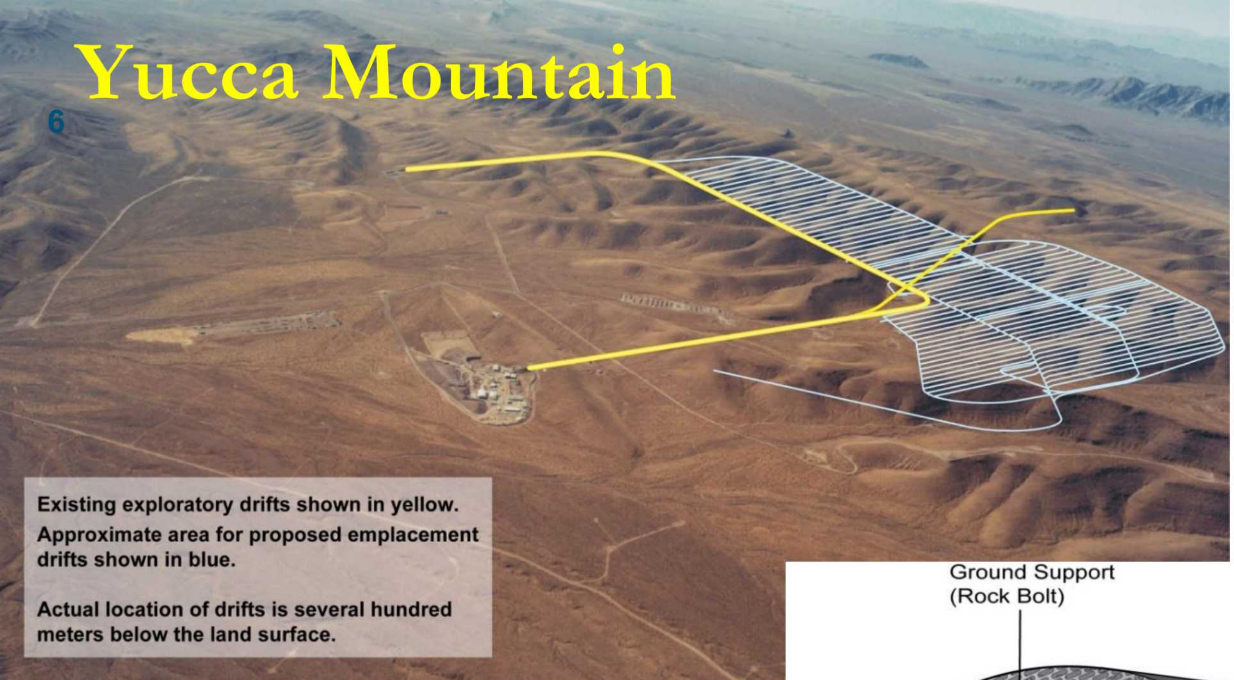
DOE/RW-0573 Rev 1, Figure 2.3.7-11, inventory decay shown for an single representative Yucca Mountain used fuel waste package, as used in the Yucca Mountain License Application, time shown in years after 2117.

DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application: Safety Analysis Report*, DOE/RW-0573, Revision 1

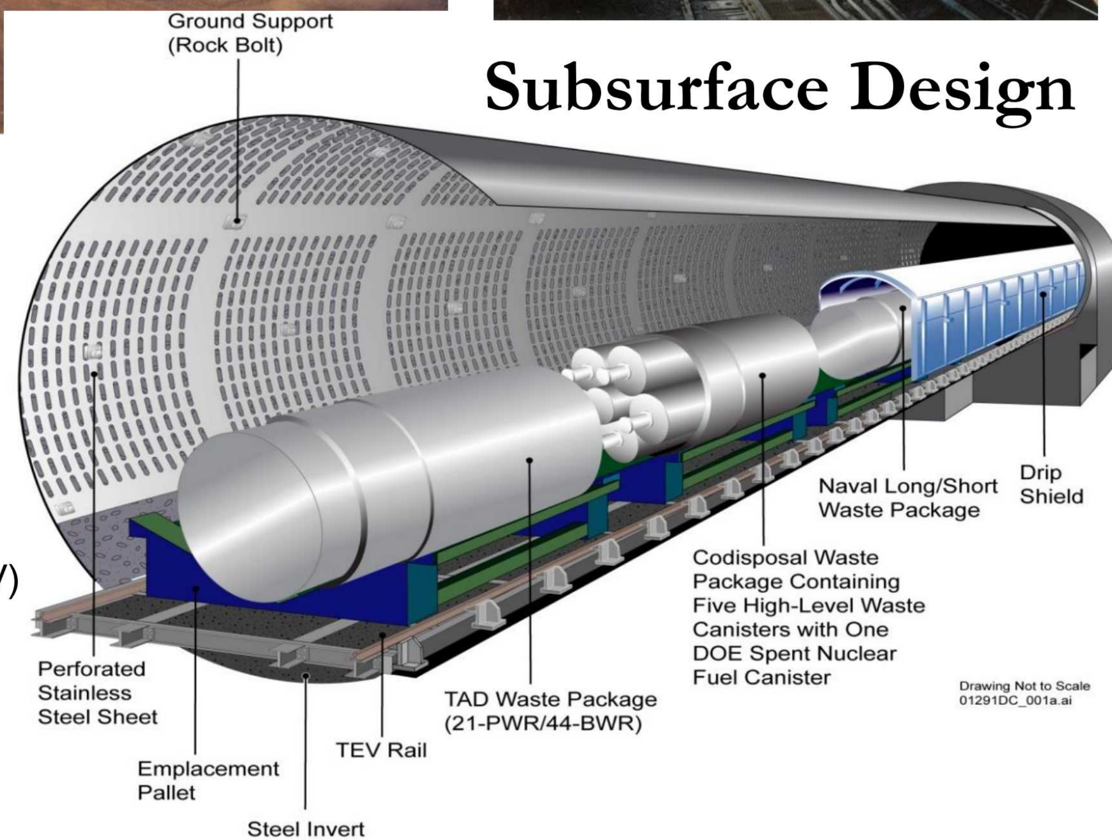
The Natural and Engineered Barrier Systems



Yucca Mountain



Subsurface Design



Emplacement drifts
- 5.5 m diameter
- approx. 100 drifts, 600-800 m long

Waste packages
- ~11,000 packages
- ~ 5 m long, 2 m diameter
- outer layer 2.5 cm Alloy 22 (Ni-Cr-Mo-V)
- inner layer 5 cm stainless steel

Drip shields
- free-standing 1.5 cm Ti shell

Groundwater Transport Pathways in the Saturated Zone

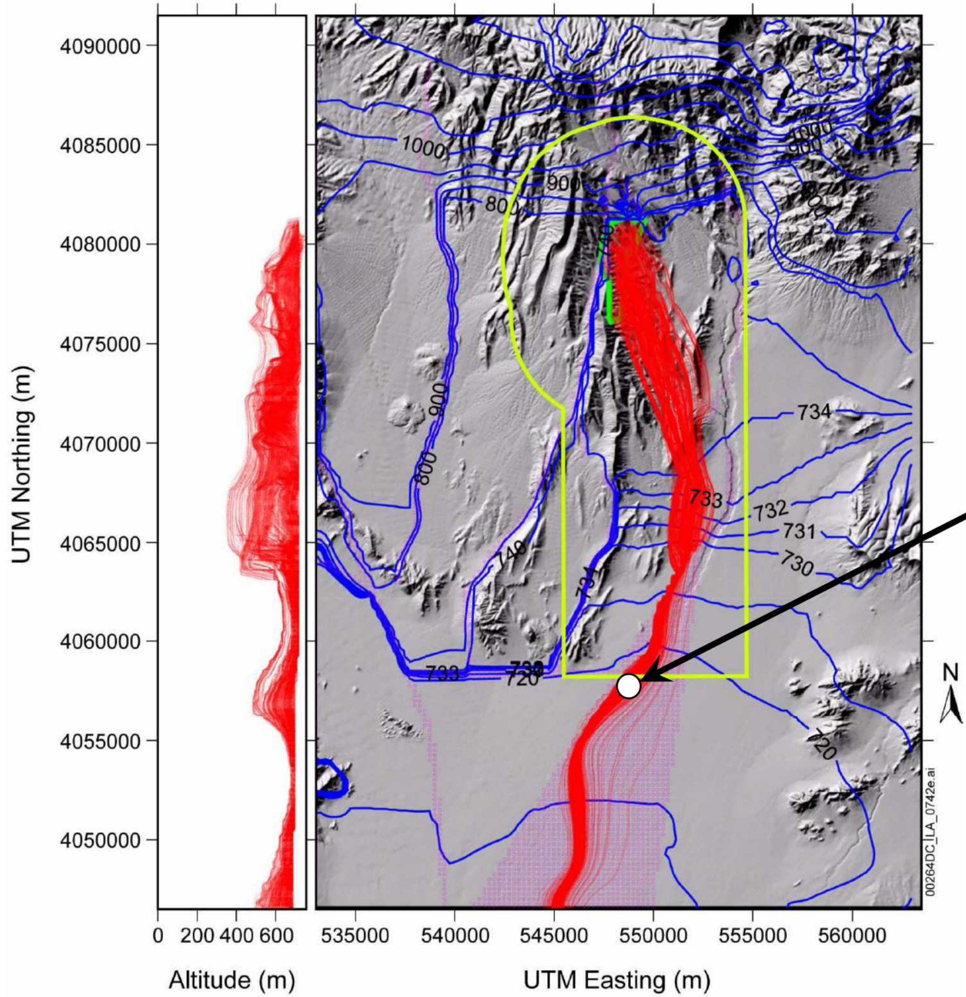


Figure 2.3.9-14. Simulated Groundwater Paths from Beneath the Repository with Hydraulic Heads Simulated with the Site-Scale Saturated Zone Flow Model

NOTE: Blue lines refer to head contours; red lines refer to particles. The left panel plots all flow paths projected onto a north–south vertical plane; the right panel plots the flow paths in plan view. The 0 in the left panel corresponds to sea level elevation. Particle paths are simulated using a value of 5.0 for horizontal anisotropy in permeability. Postclosure controlled area boundary is shown with the chartreuse line.

- **Location of RMEI (reasonably maximally exposed individual) just outside the controlled boundary, 18 km south of repository**
- **Location of dose calculation at highest concentration in plume (see next slide)**

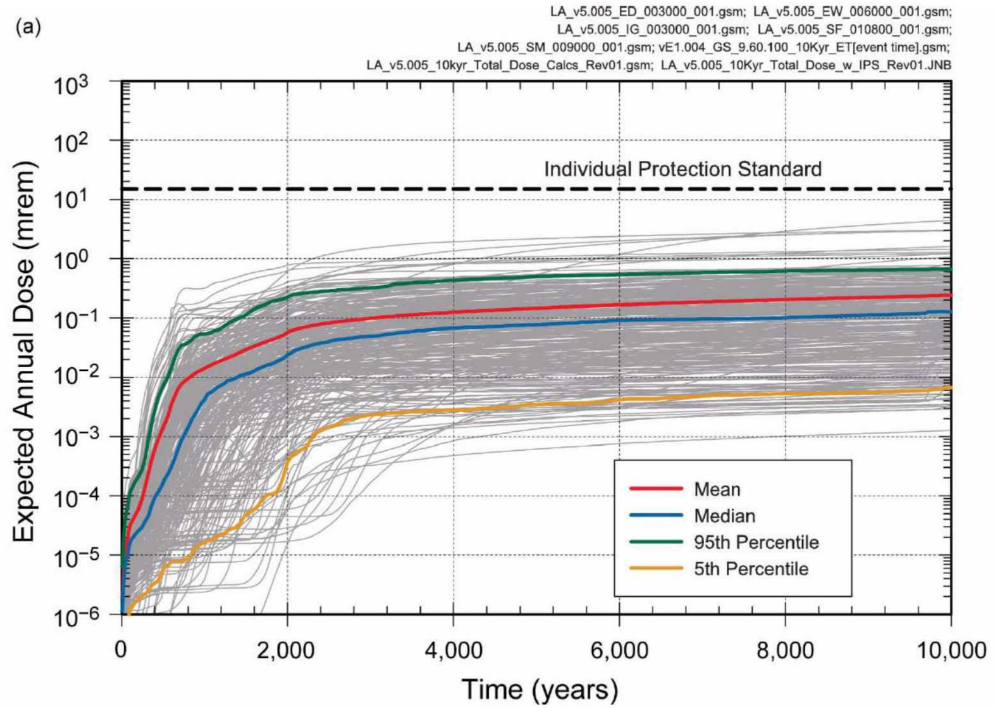
DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application: Safety Analysis Report*, DOE/RW-0573, Revision 1

Individual Protection Requirements – Proposed 10,000-year Standards (in June 2008 at time of LA* submittal)

<u>10 CFR 63.311:</u>

"DOE must demonstrate, using *performance assessment*, that there is a reasonable expectation that, for 10,000 years following disposal, the reasonably maximally exposed individual receives no more than an annual dose of 0.15 mSv (15 mrem) from releases from the undisturbed Yucca Mountain disposal system. DOE's analysis must include all potential pathways of radionuclide transport and exposure"

(Emphasis added.)



DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application: Safety Analysis Report*, DOE/RW-0573, Revision 1, Fig. 2.4-10

***License Application**

Reasonable Expectation (10 CFR 63.304)

- ***Reasonable Expectation* means that the Commission is satisfied that compliance will be achieved based upon the full record before it. Characteristics of reasonable expectation include that it:**
  1. Requires less than absolute proof because absolute proof is impossible to attain for disposal due to the uncertainty of projecting long-term performance
  2. Accounts for the inherently greater uncertainties in making long-term projections for the performance of the Yucca Mountain disposal system
  3. Does not exclude important parameters from assessments analyses simply because they are difficult to precisely quantify to a high degree of confidence; and
  4. Focuses performance assessments and analyses on the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values

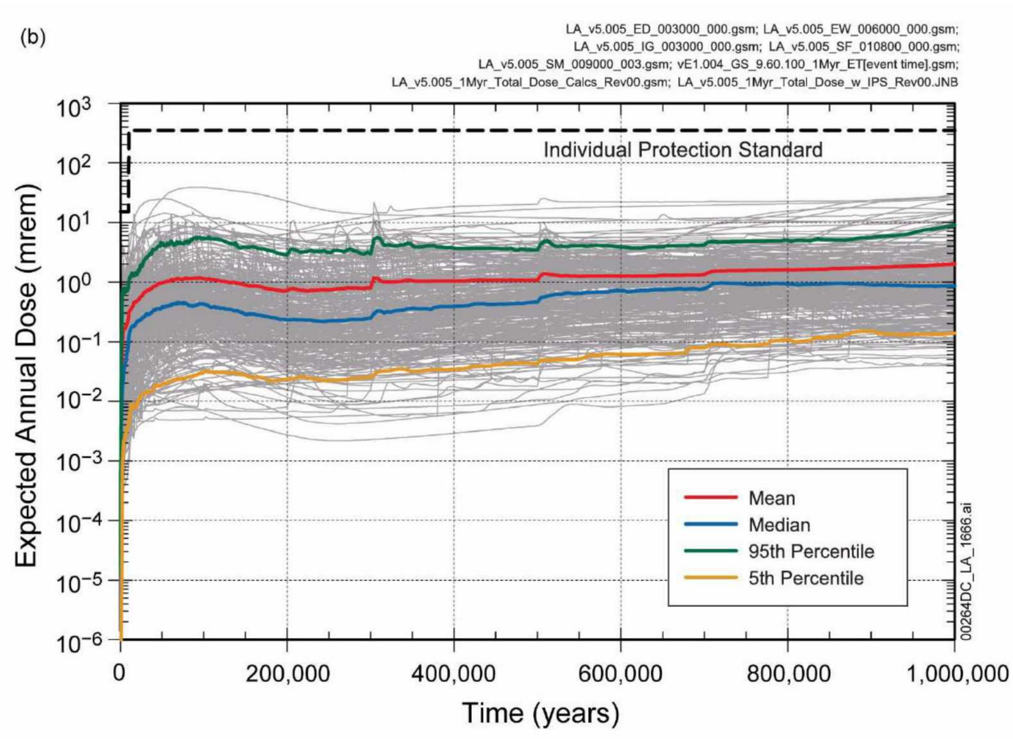
Individual Protection Requirements – Proposed 1,000,000-year Standards (in June 2008 at time of LA submittal)

<u>Proposed 10 CFR 63.303(b):</u>

"Compliance is based upon the *median* of the projected doses from DOE's performance assessments for the period after 10,000 years of disposal and through the period of geologic stability…"

<u>Proposed 10 CFR 63.311(a)(2):</u>

"DOE must demonstrate…a reasonable expectation… [of an annual dose no more than] …
3.5 mSV (350 mrem) after 10,000 years but within the period of geologic stability."



DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application: Safety Analysis Report*, DOE/RW-0573, Revision 1, Fig. 2.4-10

(Emphasis added.)

Individual Protection Requirements – Amended Final Rule (74 FR 10811; March 13, 2009)

Final 10 CFR 63.303(a):

"Compliance is based upon the *arithmetic mean* of the projected doses from DOE's performance assessments for the period within 1,000,000 years after disposal…"

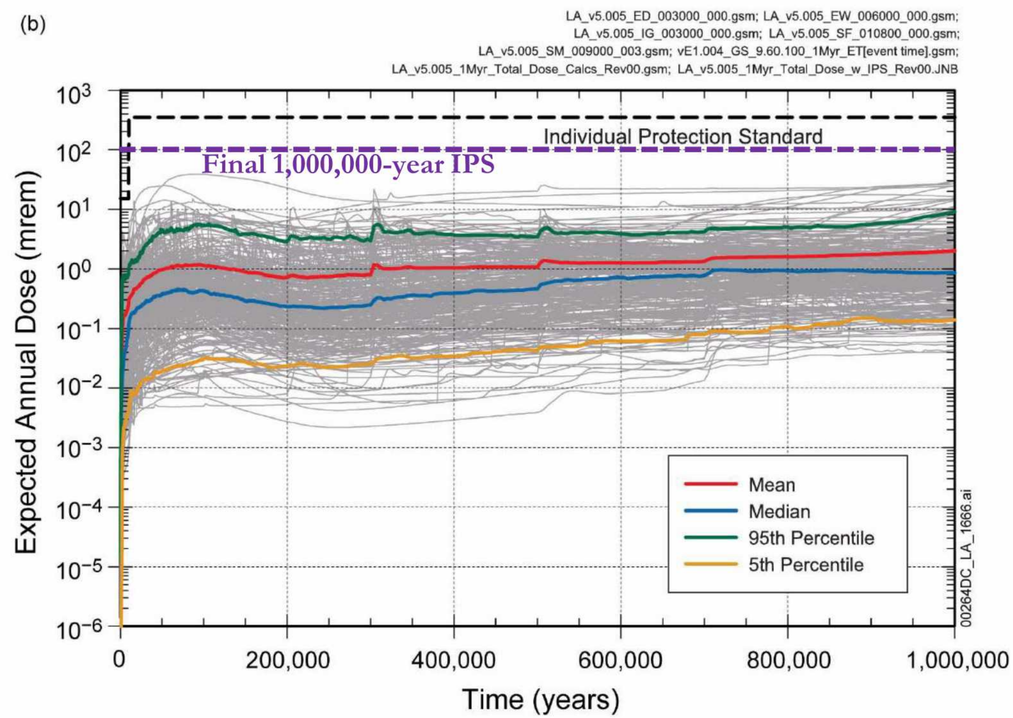
Final 10 CFR 63.311(a):

"DOE must demonstrate, using performance assessment, that there is a reasonable expectation that the reasonably maximally exposed individual receives no more than the following annual dose from releases from the undisturbed Yucca Mountain disposal system:

(1) 0.15 mSv (15 mrem) for 10,000 years following disposal; and

(2) *1.0 mSv (100 mrem) after 10,000 years*, but within the period of geologic stability."

(Emphasis added.)



DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application: Safety Analysis Report*, DOE/RW-0573, Revision 1, Fig. 2.4-10. ("Final 1,000,000-year IPS" added)

Other Post-closure Regulatory Standards

- **Groundwater Protection Standard 10 CFR 63.331**
  - Sets limits on concentrations of radionuclides in groundwater
  - Applies to undisturbed performance only (no disruptive events with annual probabilities less than 10^{-5})
- **Human Intrusion Standard 10 CFR 63.321**
  - Applies same Individual Protection Standards to the conditional consequences of a single, stylized borehole intrusion
  - Applies to undisturbed performance only (no disruptive events with annual probabilities less than 10^{-5})
  - Does not include direct releases to the surface

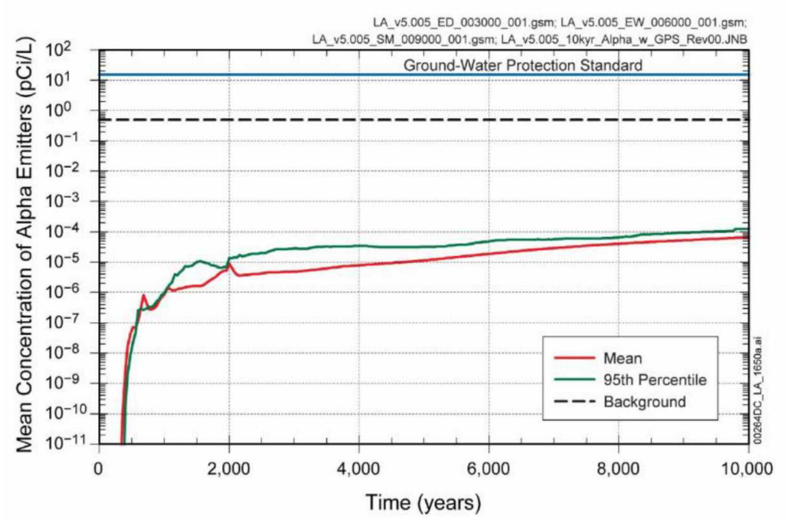


Figure 2.4-13. Summary Statistics for Activity Concentration of Gross Alpha (Including ^{226}Ra but Excluding Radon and Uranium) in Groundwater for 10,000 Years after Repository Closure

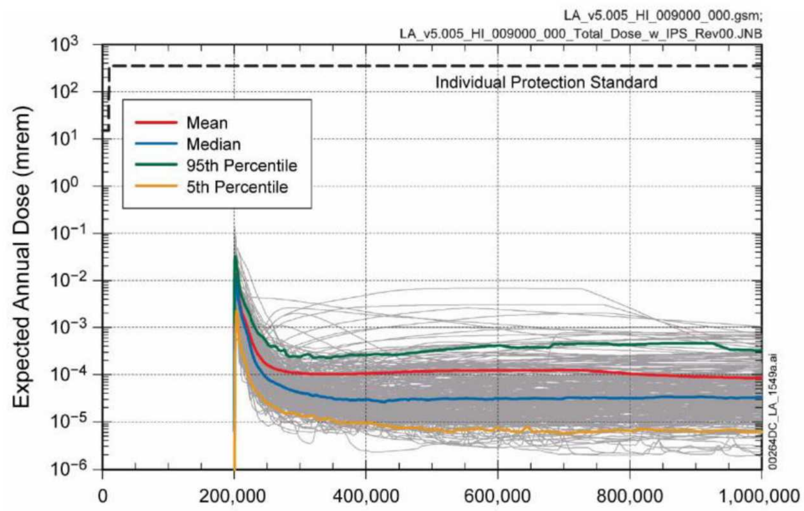


Figure 2.4-11. Distribution of Expected Annual Dose for the Human Intrusion Modeling Case for the Post-10,000 Year Period after Permanent Closure, with Drilling Intrusion Event at 200,00 Years

DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application: Safety Analysis Report*, DOE/RW-0573, Revision 1

Other Post-closure Regulatory Standards

- **Multiple Barrier Requirement 10 CFR 63.115**
  - DOE must identify barriers and describe capabilities to limit water flow, radionuclide release, or radionuclide transport
  - No quantitative subsystem requirements; this is a descriptive requirement rather than a performance standard
  - But, DOE's post-closure chapter of the SAR* included a large section (the first section, 2.1) devoted to "…the technical basis for the description of the capability of barriers, identified as important to waste isolation, to isolate waste. The technical basis for each barrier's capability shall be based on and consistent with the technical basis for the performance assessments used to demonstrate compliance…"

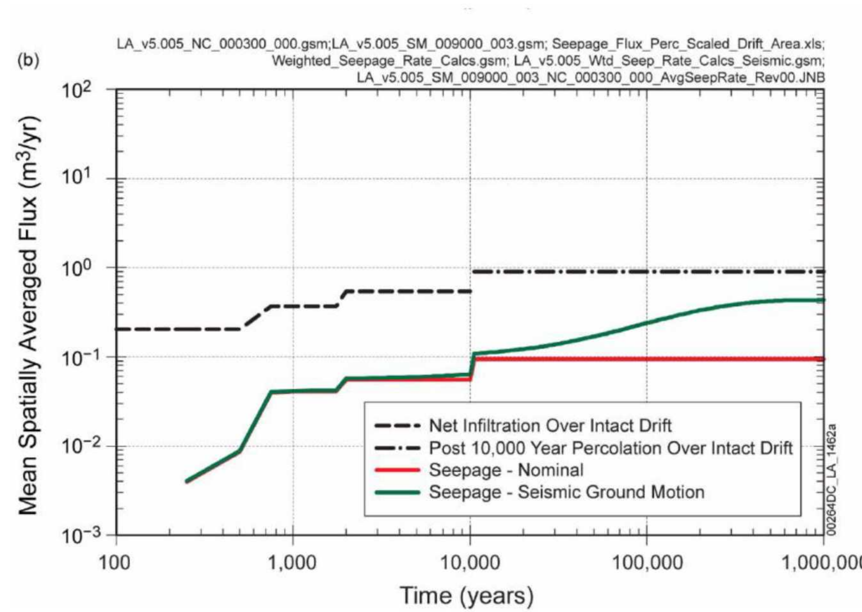


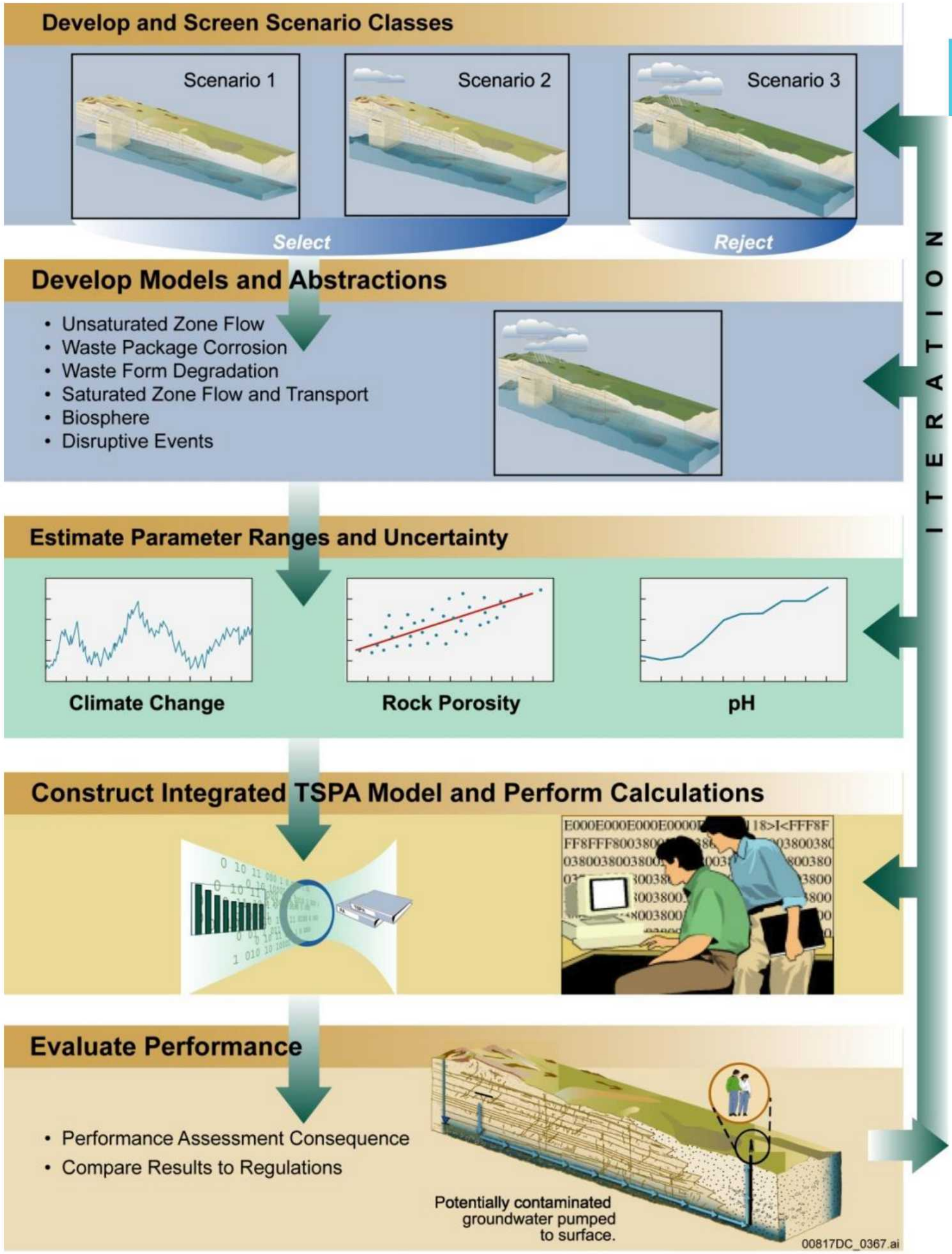
Figure 2.1-5. Upper Natural Barrier Capability to Prevent or Substantially Reduce the Rate of Water Movement to the Waste for the Mean Spatially-Averaged (a) Annual Precipitation, Net Infiltration, and Post-10,000-Year Percolation and (b) Drift Seepage Fluxes for the Combined Nominal/Early Failure Modeling Case and Seismic Ground Motion Modeling Case—1,000,000 Year Period

DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application: Safety Analysis Report*, DOE/RW-0573, Revision 1

*Safety Analysis Report

Major Steps in a 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**
- ***Estimate uncertainty*** **in model inputs (UQ or uncertainty quantification)**
- ***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**
- **<u>Iterate</u>**



SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Figure ES-4.

Definition of 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

Processes/events act upon or within features:

Characteristics, Processes, and Events / Features / Components		Processes											Events		
	Characteristics	Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (Long Timescale)	Other	Nuclear Criticality	Early Failure	Seismic
Glossary / Definitions	CP	TM	TH	TC	TB	TT	TL	RA	LG	CL	HP	OP	NC	EF	SM
Surface Features															
(BP) Biosphere															
(01) Natural Surface and Near-Surface Environment															
(02) Flora and Fauna															
(03) Humans															
(04) Food and Drinking Water															
(05) Dwellings and Other Man-Made Surface Features/Materials															
Geosphere Features															
(OU) Other Geologic Units															
(01) Overlying / Adjacent Units (including Caprock, Aquifers)															
(02) Underlying Units															
(HR) Host Rock															
(01) Disturbed Rock Zone (DRZ)															
(02) Emplacement Unit(s)															
(03) Other Host Rock Units															
Waste and Engineered Features															
(BB) Buffer/Backfill															
(01) Waste Package Buffer															
(02) Drift/Tunnel Backfill															
(WP) Waste Package and Internals															
(01) SNF															
(02) Vitrified HLW															
(05) Other HLW															
(06) Metal Parts															
(WF) Waste Form and Cladding															
(01) SNF and Cladding															
(02) Vitrified HLW															
(05) Other HLW															
(06) Metal Parts from Reprocessing															

Regulatory Basis for the Analysis of Features, Events, and Processes

The definition of Performance Assessment

From EPA 40 CFR 197.12: *"Performance assessment* means an analysis that

(1) *Identifies the features, events, 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 effective 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."

"All significant features, events, and processes, and sequences of events and processes" do not include very unlikely events and events of low consequence on overall performance

From NRC 10 CFR Part 63342(a): "DOE's performance assessments conducted to show compliance with §§ 63.311(a)(1), 63.321(b)(1), and 63.331 *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, DOE's performance assessments *need not evaluate the impacts* resulting from any features, events, and processes or sequences of events and processes with a higher chance of occurring *if the results of the performance assessments would not be changed significantly* in the initial 10,000-year period after disposal."

(Emphasis added)

Goals of FEP Analysis/Screening

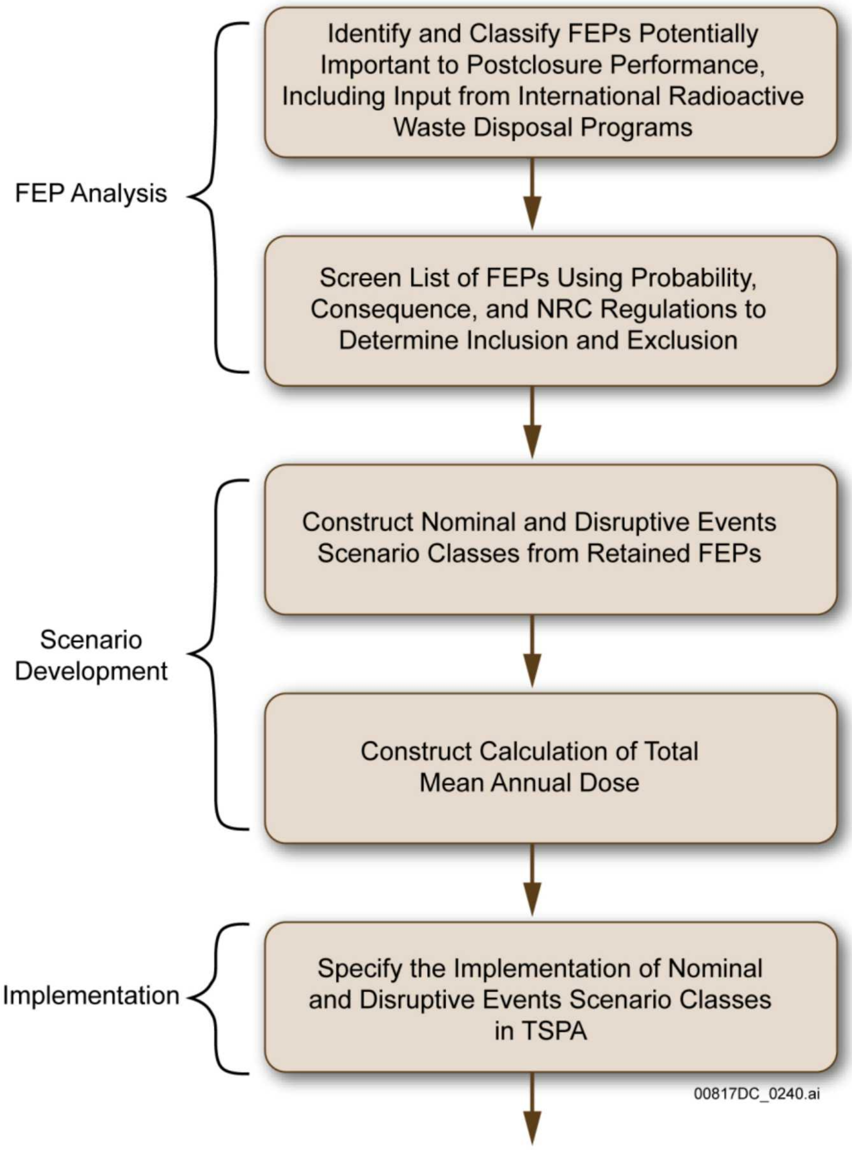
- **Comprehensiveness of repository technical bases**
  - *Have we thought of everything?*
    - Formal FEP analysis provides objective evidence that all potentially relevant events and processes have been considered

- **Completeness of PA**
  - *Are all important phenomena represented in the PA Model?*
    - Formal FEP analysis provides a structure to ensure that all significant FEPs are captured in the PA model (subject to regulatory guidance)

FEP Screening and Scenario Development for Yucca Mountain

- **374 FEPs evaluated for the YM License Application (SNL 2008a,b)**
  - 222 excluded from the TSPA
  - 152 included in the TSPA

- **Four scenario classes defined for TSPA analysis**
  - Nominal Performance
  - Early Failure
  - Igneous Disruption
  - Seismic Disruption



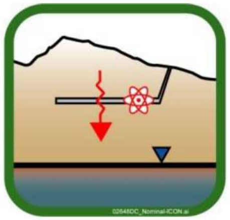
SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Figure 6.1.1-1.

Scenario Classes for Yucca Mountain

- **Definition and division of scenario classes is based on the type of screened-in initiating events**
  - Events grouped by similar effects ("common natural process") to form event/scenario classes – see 10 CFR 63.102(j))
- **Yucca Mtn: <u>Four</u> scenario classes further divided into <u>seven</u> modeling cases to facilitate computational efficiency/feasibility:**

<u>Nominal Scenario Class</u>

- Nominal Modeling Case (expected processes $p = 1$ in time frame)

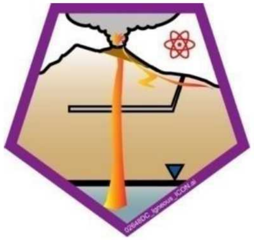


<u>Early Failure Scenario Class</u>

- Waste Package Modeling Case
- Drip Shield Modeling Case

<u>Igneous Scenario Class</u>

- Intrusion Modeling Case
- Eruption Modeling Case

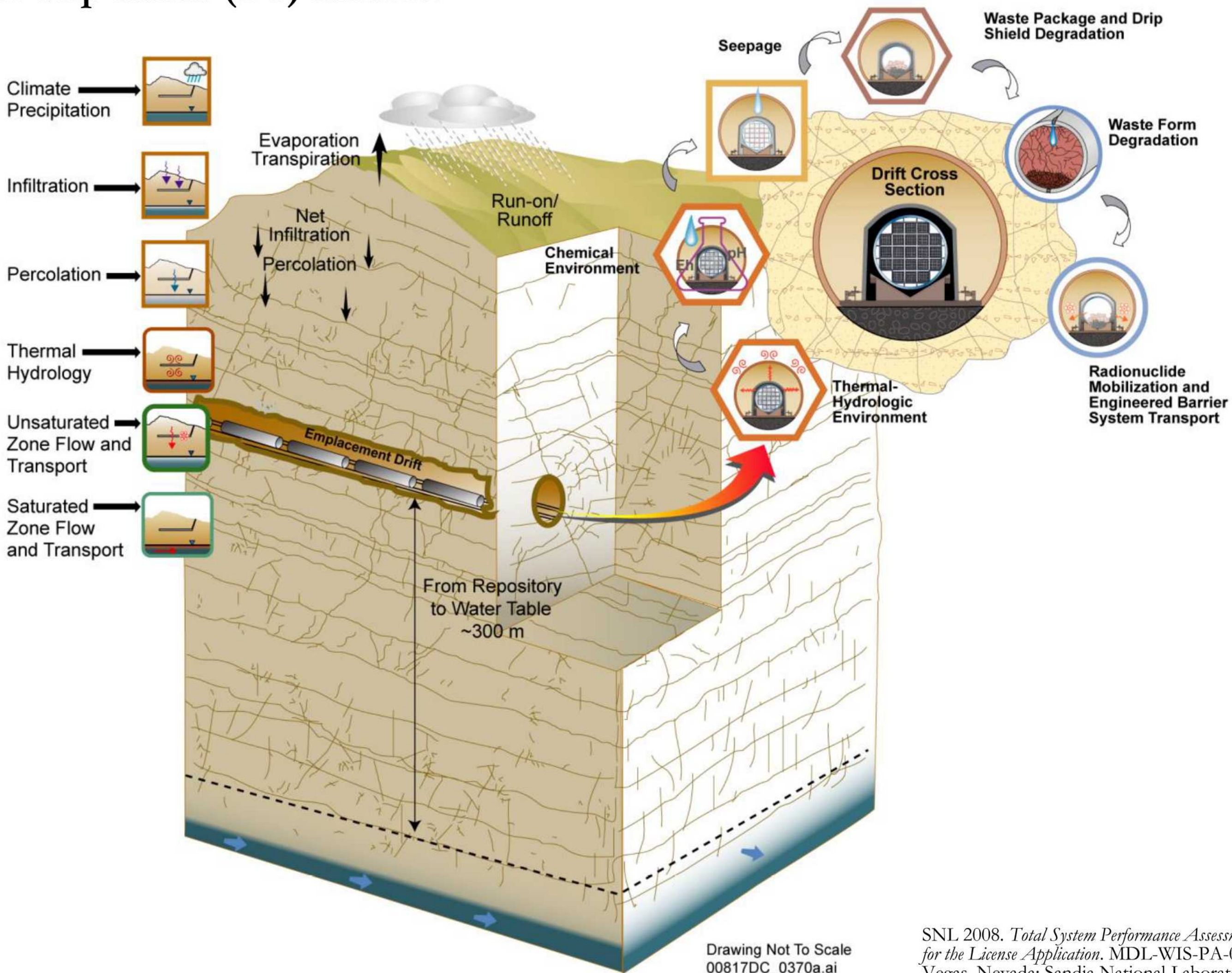


<u>Seismic Scenario Class</u>

- Ground Motion Modeling Case
- Fault Displacement Modeling Case

Expected "Nominal" Processes for the Natural and Engineered Barrier Systems at Yucca Mountain

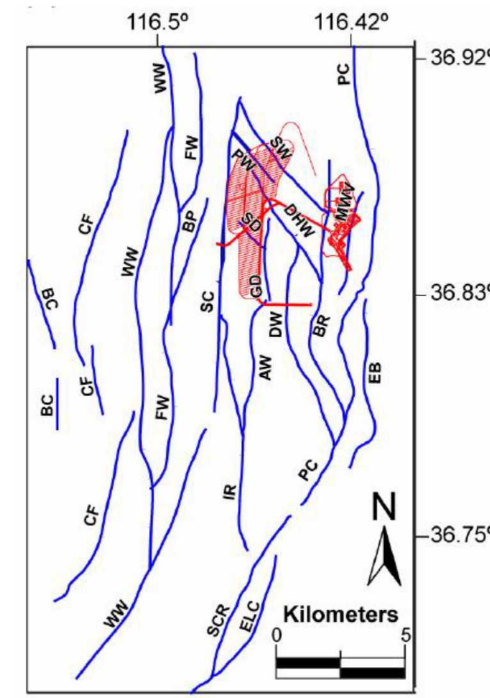
- **The nominal scenario class is defined as the set of possible futures containing no disruptive events (i.e., no igneous or seismic events) and no early waste package (WP) or drip shield (DS) failures:**



SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Figure ES-10.

Potential Disruptive Geologic Events at Yucca Mountain

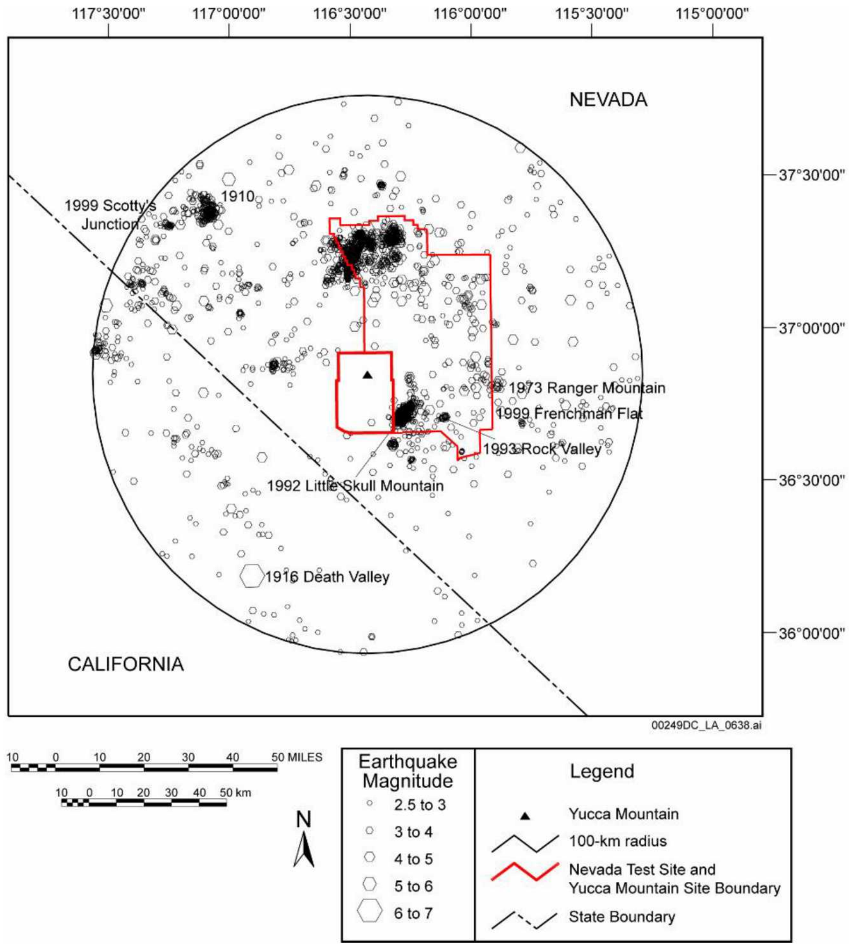
- **Volcanism**
  – Photo taken looking SW from Yucca Mountain crest shows small volcanic cones approximately 1 Myr old.



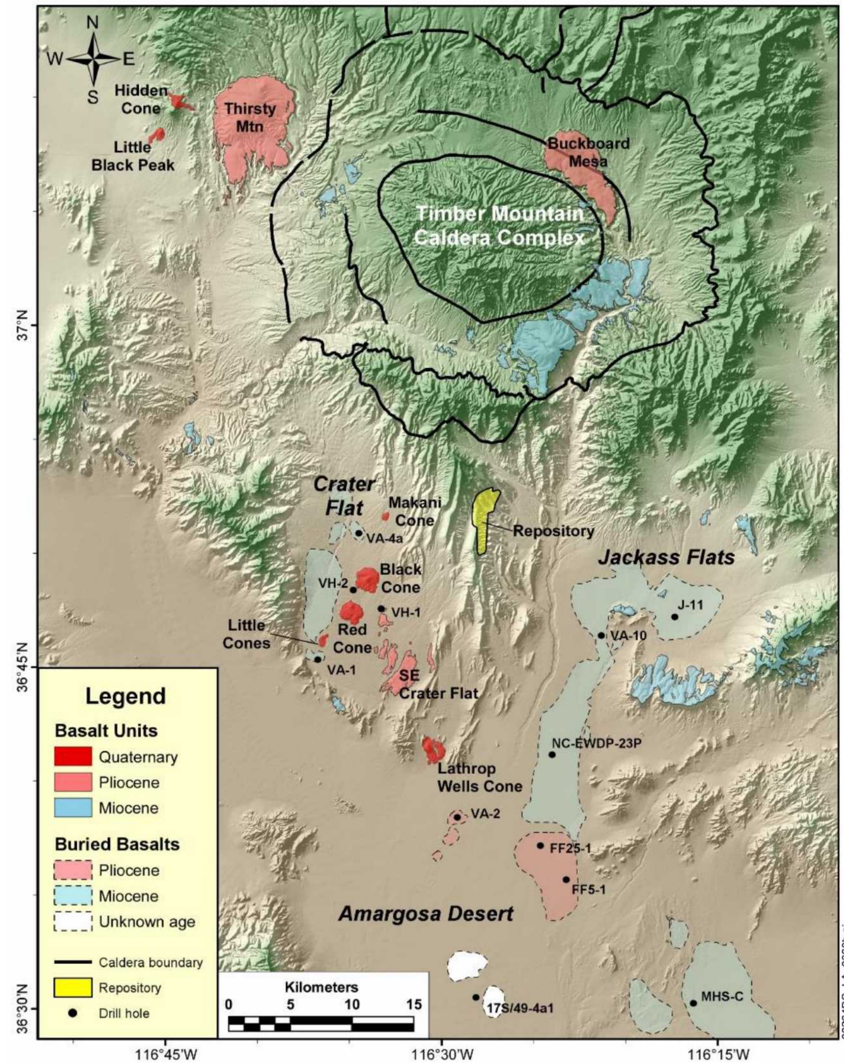
- **Seismicity**
  – Map shows Quaternary age faults (<1.5Myr) in the Yucca Mountain region (from US DOE 2008 GI Figure 5-35)

Seismic and Igneous Activity in the Yucca Mountain Region

Historical Earthquake Epicenters with 100 km of Yucca Mountain (DOE/RW-0573 Rev. 1, Figure GI 5-38)



Distribution of Miocene and younger (< 5.3 Ma) Basaltic Rocks in the Yucca Mountain Region (DOE/RW-0573 Rev. 1, Figure GI 5-39)



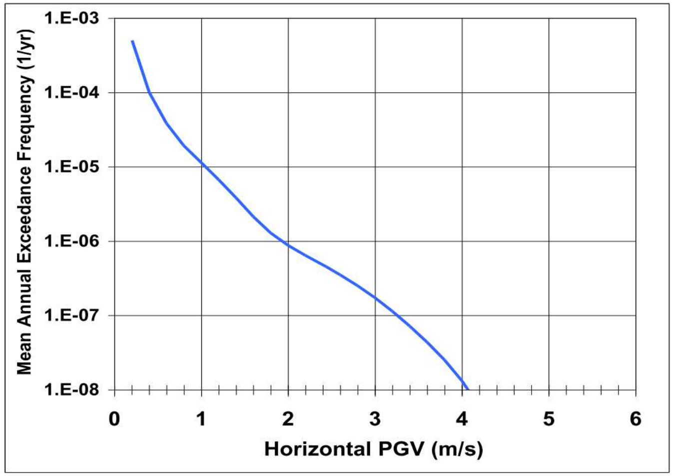
Seismic Events and Processes

- **The seismic scenario class is broadly defined as the set of possible futures that contain one or more seismic events but no igneous events**
- **The seismic scenario class includes all FEPs that are part of the nominal scenario class (all "expected" FEPs), plus FEPs associated with seismicity**
- **Nominal and seismic WP degradation processes are strongly coupled through the state of the Alloy 22 waste-package overpack and the state (intact or degraded) of the stainless steel inner vessel**
  - General corrosion patch and stress corrosion cracking (SCC) failures in the Alloy 22 WPs occur due to nominal corrosion processes
  - Seismic damage to WPs depends on the presence of the DS:
    - For intact DSs, SCC damage to the Alloy 22 WP occurs through package-to-pallet impacts (more important) and package-to-package impacts (less important); there is a small chance of plastic rupture damage
    - For failed DSs (by general corrosion and/or rubble loading), crack damage to the Alloy 22 WP occurs from stresses induced by the surrounding rock rubble during strong ground motions
- **Effect of fault displacement failures expected to be small ($\lambda < 2\times10^{-7}$ per year)**

Probability of Seismic Scenario Class

- **The probability of the seismic scenario class depends on the definition of the maximum annual exceedance frequency, λ, that can result in a "potentially damaging" seismic event**
  - The annual exceedance frequency (λ) of seismic events of varying magnitudes (PGV*) is defined by the (mean) seismic hazard curve
  - Not all events can cause Engineered Barrier System (EBS) damage; small PGVs (i.e., more frequent, but smaller, events) are unlikely to have a consequence
  - For most events of any magnitude, damage to the WP is generally in the form of very small stress corrosion cracks

YM Seismic Hazard Curve (PGV)



*Peak Ground Velocity

- **Example of the effect of event frequency in the seismic scenario class:**
  - For a Poisson process such as seismicity, the probability, *P*, of one or more events with an annual frequency of 1×10^{-4} per year is about 0.63 for $T = 10{,}000$ years and effectively 1.0 for $T = 1{,}000{,}000$ years; therefore:
  - For the 1,000,000-year modeling-case simulations, seismic and nominal effects are combined, but are separated for 10,000-year simulations

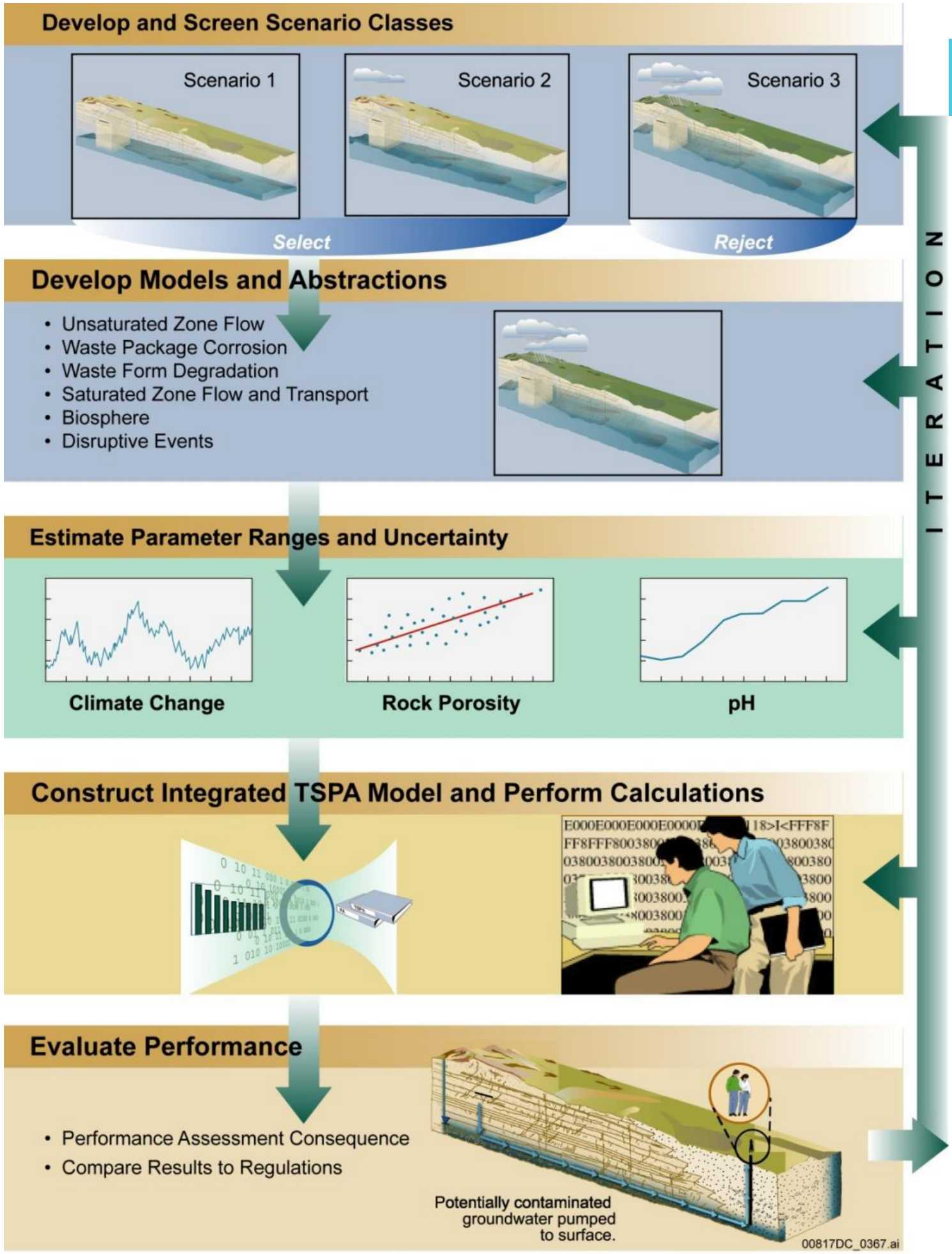
$$P(N(T) \geq 1) = 1 - \exp(-\lambda T)$$

where N(T) = number of events in time T

SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Figure 6.6-6.

Major Steps in a Performance Assessment

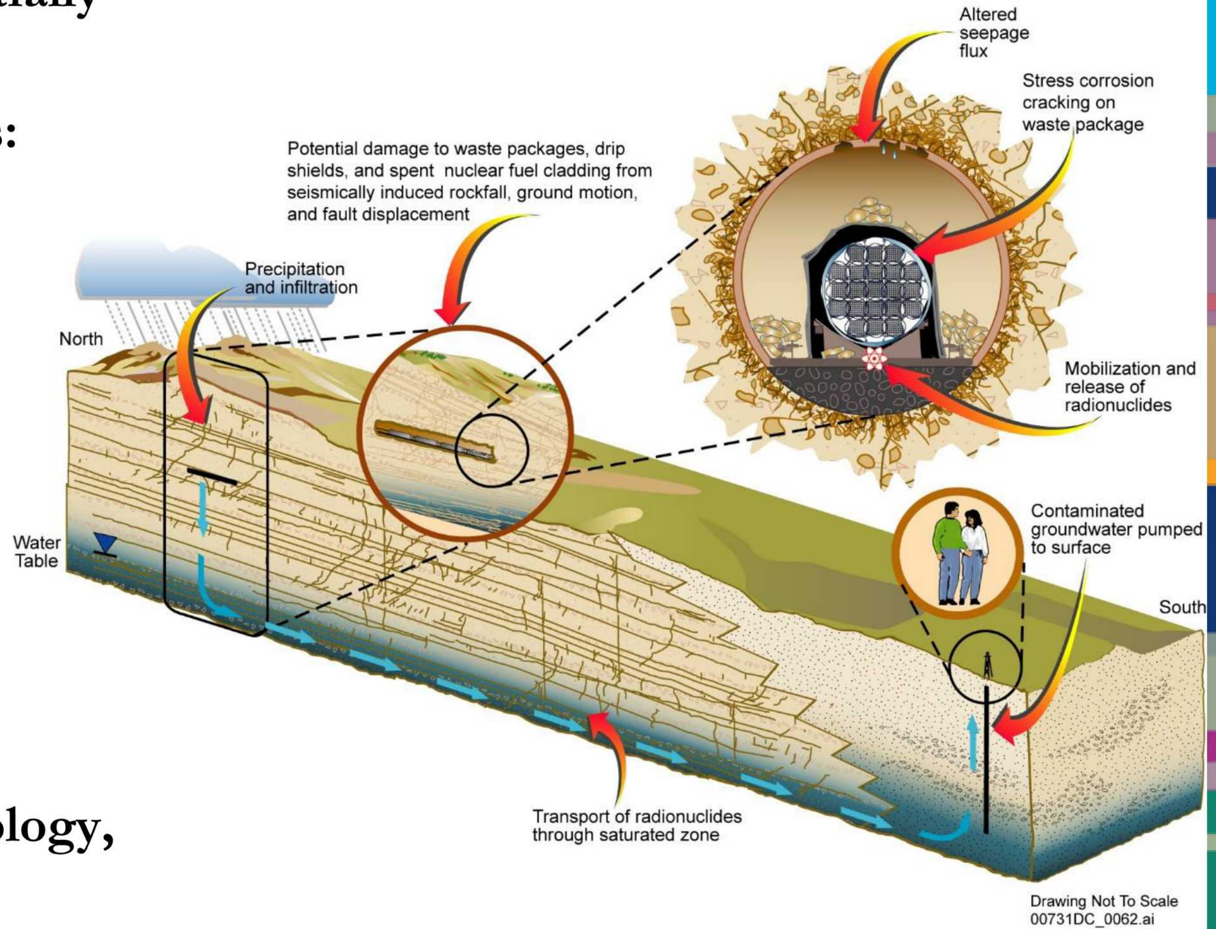
- *Screen Features, Events, and Processes (FEPs)* and develop scenario classes
- *Develop (process) models* and abstractions, along with their scientific basis, for logical groupings of FEPs within scenario classes
- *Estimate uncertainty* in model inputs (UQ)
- *Construct integrated TSPA model* using 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
- Iterate



SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Figure ES-4.

Conceptual Model for Seismic Processes

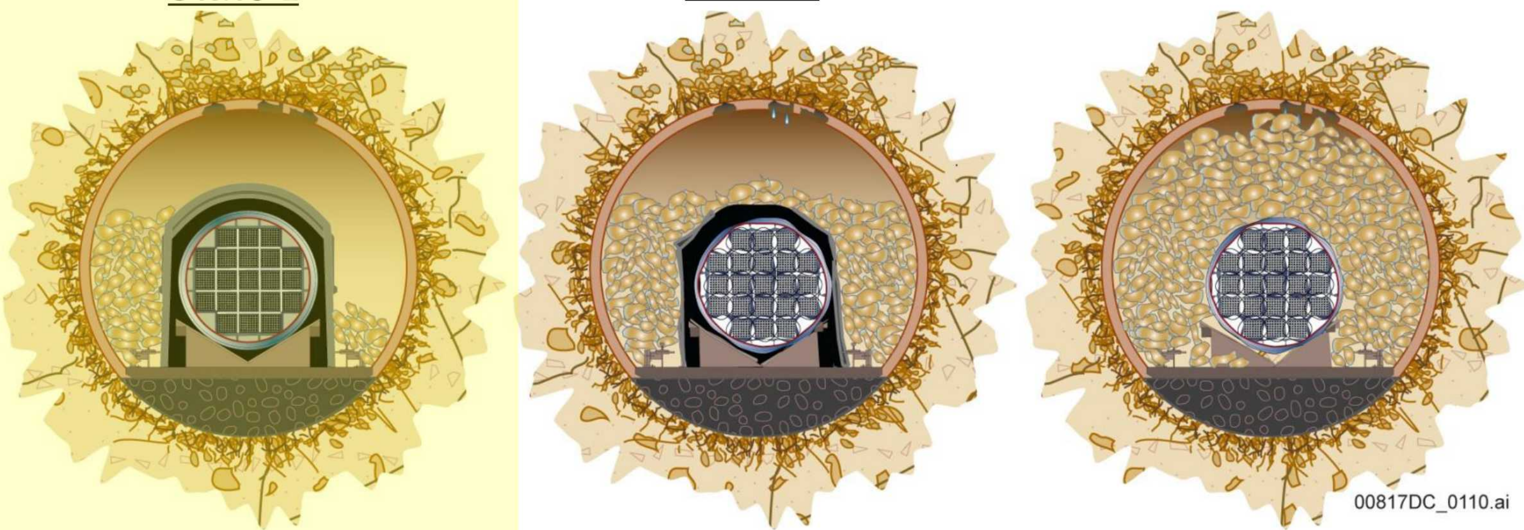
- **"Source term" = ground motion time history from a potentially damaging seismic event**
- **EBS consequence models:**
  - Rubble accumulation and loading in drift
  - DS damage or fragility (static and dynamic loading)
  - WP damage when DS is intact: cracking or rupture
  - WP damage after DS has failed: cracking
- **Changes to thermal hydrology, seepage, and transport**



SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Figure 6.6-4.

Conceptual Model for EBS Evolution

State 1 | **State 2** | **State 3**



(a) Initial Configuration

(b) After Drip Shield Framework Failure

(c) After Drip Shield Plate Failure

Kinematic analyses and damage catalogs define damaged areas for a WP moving freely beneath the DS. WP SCC or rupture may occur, degrading internals

Fragility analysis for buckling of DS framework. Additional WP damage may occur.

Fragility analysis for rupture of DS plates. WP damage defined by 2-D calcs for WP surrounded by rubble

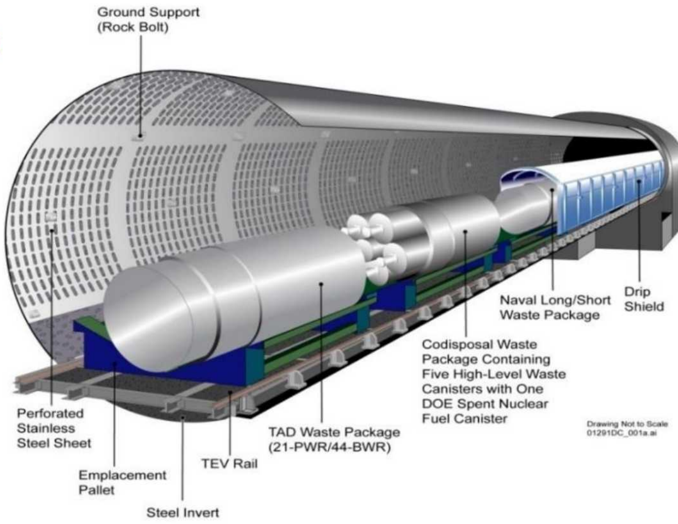
DS Failure

Time

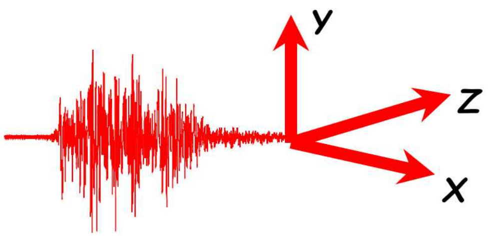
SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Figure 6.6-5.

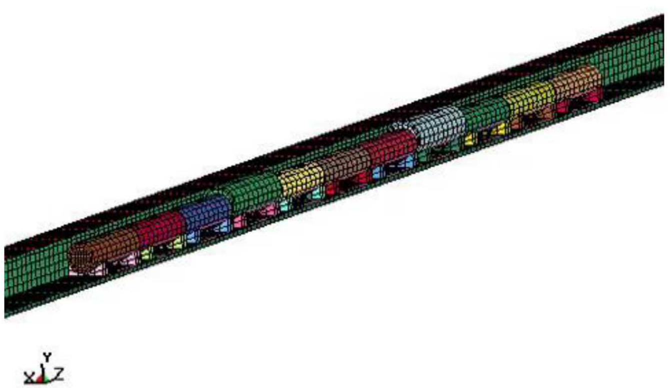
Example Process Model: Seismic Ground Motion

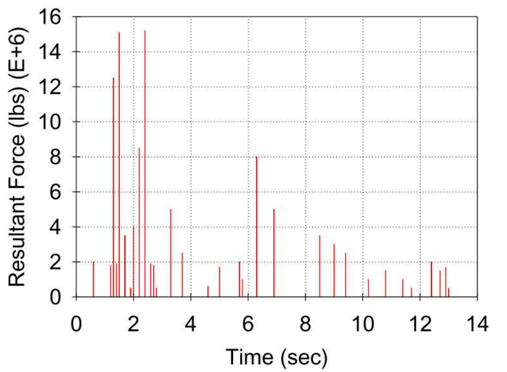
- Non-degraded drifts: 3-D kinematic analyses (using LS-DYNA code) of CSNF* and co-disposal (CDSP) waste packages to produce histories of multiple WP impacts for each of 17 ground motion time histories at four horizontal peak ground velocity (PGV) levels (earthquake magnitude)



Schematic Ground Motion Time History → **Representative Drift Configuration** → **Illustrative Impact Force History (single event)**







Input → **Analysis** → **Output**

*Commercial Spent Nuclear Fuel

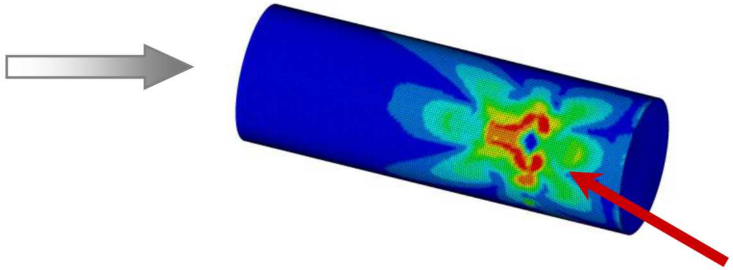
SNL 2007. *Seismic Consequence Abstraction*. MDL-WIS-PA-000003 REV 03, Sandia National Laboratories, September 2007, DOC.20070928.0011.

EBS Evolution State 1

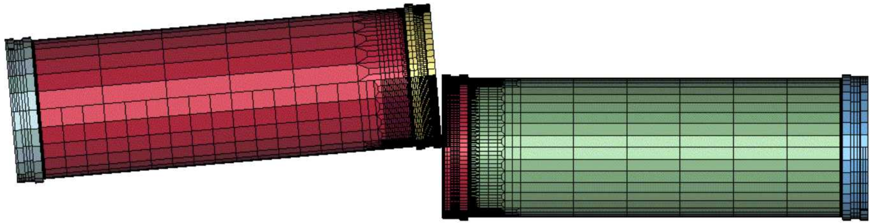
■ Detailed damage analyses (for damage catalogs)

- Develop catalogs for damage area and rupture condition for individual impacts in the impact force history—fine discretization of WP
  - Catalogs consider either intact or degraded states of WP internals
  - Catalogs consider multiple impact locations and impact velocities for three angles for WP-pallet impacts and one angle for WP-WP impacts

- **WP-to-pallet impacts:**



- **WP-to-WP impacts:**

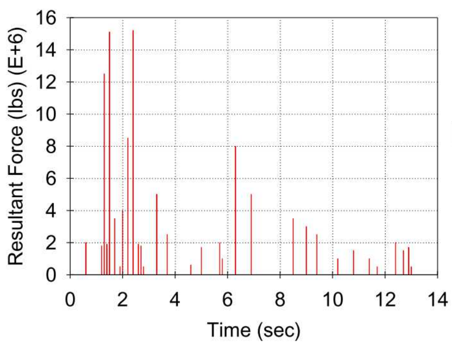


SNL 2007. *Seismic Consequence Abstraction*. MDL-WIS-PA-000003 REV 03, Sandia National Laboratories, September 2007, DOC.20070928.0011.

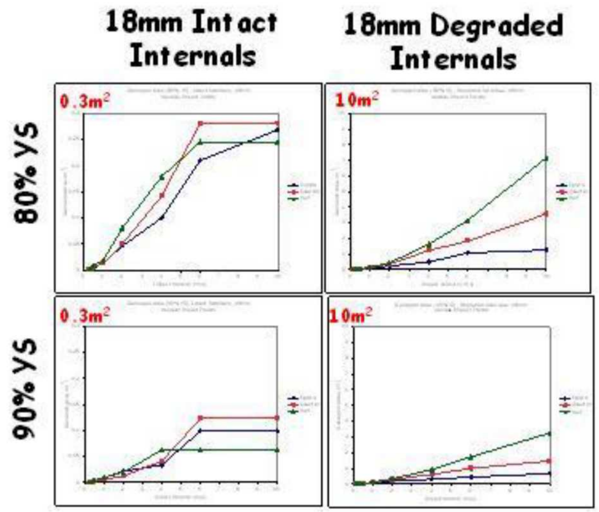
EBS Evolution State 1 (cont.)

- **Kinematic Analyses combined with Detailed Analyses:**
  - Combination of impact force history and damage catalogs generates potential WP damage (residual stress field and/or rupture condition) for a given seismic event

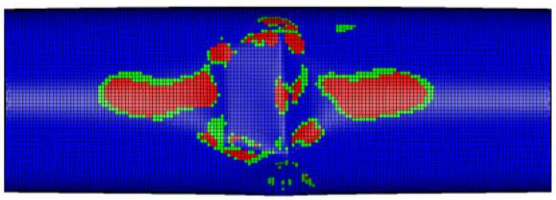
Illustrative Impact Force History (single event)



Damage Catalog
(see previous slide)



Residual Stress Field
("from many impacts")

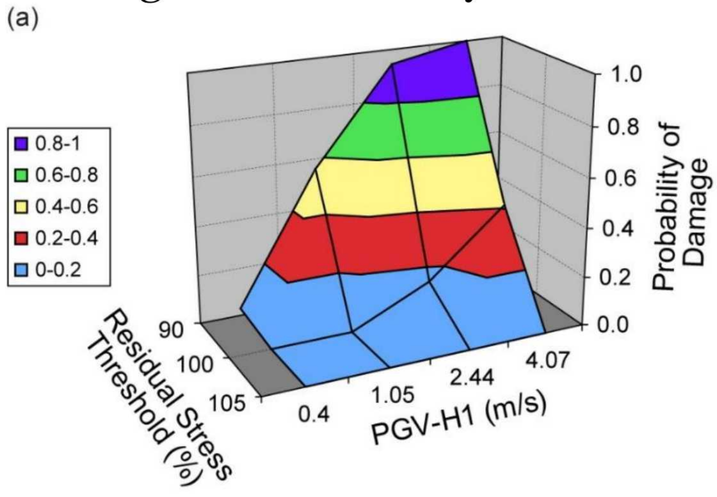


  - Results define both the probability of damage and the amount of damaged area as a function of the WP state and PGV level;
  - Damaged area is the area with residual stress above the threshold for initiation of stress corrosion cracking (SCC) (90% to 105% of yield strength for Alloy 22)

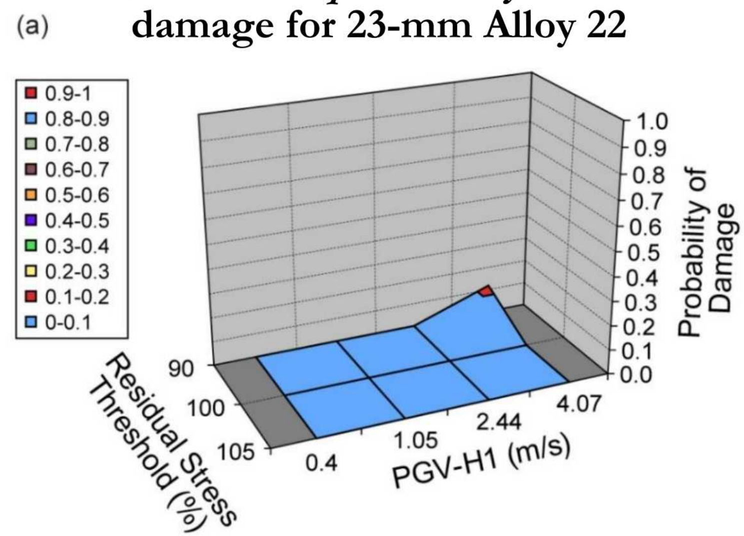
SNL 2007. *Seismic Consequence Abstraction*. MDL-WIS-PA-000003 REV 03, Sandia National Laboratories, September 2007, DOC.20070928.0011.

EBS State 1 SCC Damage to WP:
(Intact DS, Intact Internals)

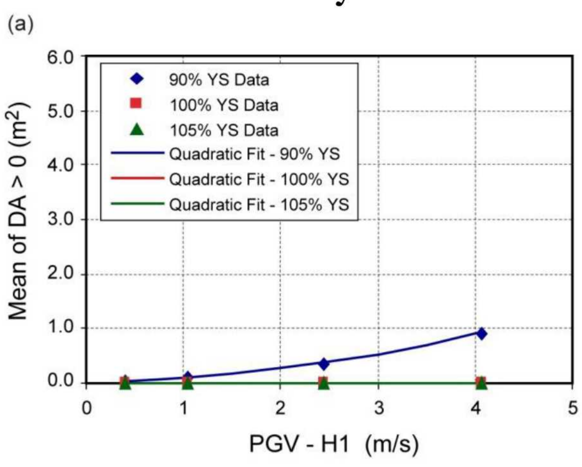
- **Co-disposal WP** ***probability*** **of SCC damage for 23-mm Alloy 22**



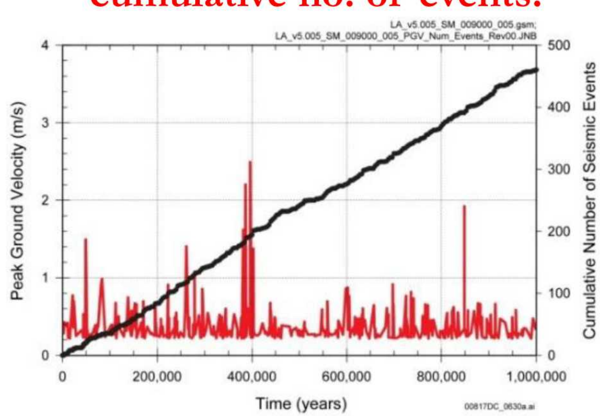
- **CSNF WP** ***probability*** **of SCC damage for 23-mm Alloy 22**



- **Co-disposal WP** ***mean damage area*** **for 23-mm Alloy 22**



Integrate damage area through time over the cumulative no. of events:

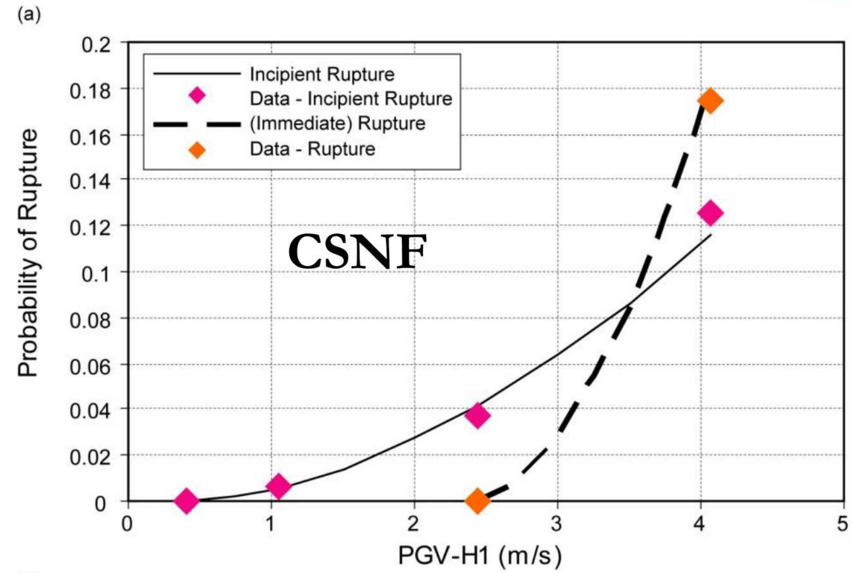


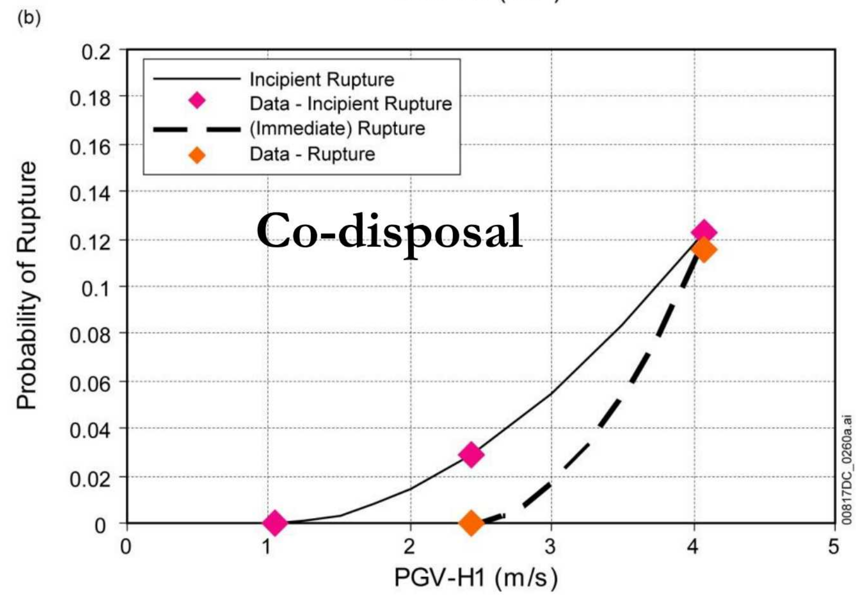
- **CSNF WP** ***mean damage area*** **for 23-mm Alloy 22**
  - 0.00408 m^2 at PGV=4.07 m/s and RST=90% Y.S.
  - 0.0 m^2 for all other data points

SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Figures 6..6-10, 6.6-11, and 6.6-13.

EBS State 1: WP Rupture
(Intact DS, Degraded Internals)

- **Probability of incipient and immediate rupture**
  - incipient rupture requires a subsequent seismic event to cause damage
  - WP rupture allows advective releases
- **Mean damage area is sampled uniformly:**
  - between 0 m^2 and the WP cross-sectional area 2.78 or 3.28 m^2

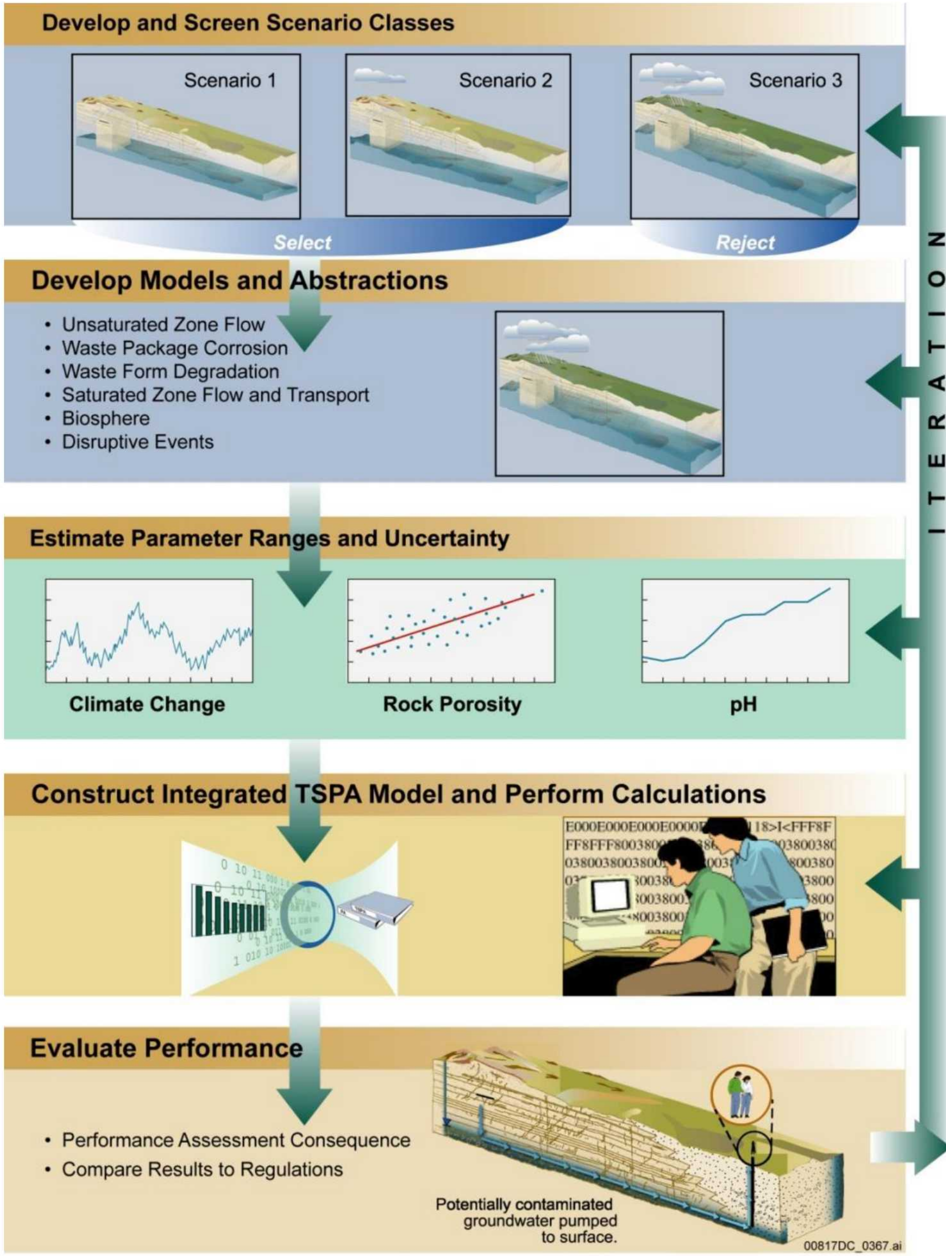




SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Figure 6.6-14.

Major Steps in a 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
- *Estimate uncertainty* in model inputs (UQ)
- *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
- Iterate



SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Figure ES-4.

Evaluate/Characterize Uncertainty (UQ)

- **Sources and types of uncertainty**
  - Parameter uncertainty
  - Model uncertainty
  - Scenario uncertainty
- **Project-wide parameter uncertainty workshop convened to put all technical staff on a common ground with respect to parameter/model uncertainty characterization and the associated review process**
- **Parameter uncertainty review team (PUT) convened**
  - Ensure consistency with applicable regulations and NRC guidance
  - Ensure consistency (across all submodels) and traceability
  - Ensure that sound statistical methods and interpretations are applied when developing probability distributions
  - Reasonable and defensible, as opposed to focusing on extremes which could introduce risk dilution (use principle of reasonable expectation)
- **Risk-informed approach used:**
  - Focused on the subset of uncertain input parameters most important to total dose, based on uncertainty and sensitivity analyses conducted during TSPA model development
  - 15 formal reviews of about 40 key parameters

Major Types of Parameter Uncertainty

Aleatory Uncertainty

- Inherent randomness in events that could occur in the future; cannot be reduced by further measurements
- Alternative descriptors: irreducible, stochastic, intrinsic, type A
- Examples:
  - Time and size of a seismic event (time = hazard curve; size = ground motion time history)
  - Damage caused by seismic event

Epistemic Uncertainty

- Lack of knowledge (or degree of belief) about appropriate value to use for a quantity assumed to have a fixed value; can be reduced by further measurements (feedback for prioritizing experimental program)
- Alternative descriptors: reducible, subjective, state of knowledge, type B
- Examples:
  - Waste-form degradation rates, chemical equilibrium constants, sorption coefficients, inventory masses, corrosion rates, etc.
  - Rates defining Poisson processes

Conceptual Model Uncertainty

- **10 CFR 63.114(c): "Consider alternative conceptual models of feature and processes that are consistent with available data and current scientific understanding and evaluate the effects that alternative conceptual models have on the performance of the geologic repository."**
- **For YM, not generally represented explicitly at the TSPA model level as separate probability-weighted models**
- **Alternative conceptual models (ACMs) are evaluated at the process model level and generally the more conservative one was chosen for inclusion in the TSPA, if more than one was deemed appropriate; also, additional uncertainty may be included in the selected model**
- **A performance margin analysis (PMA) was conducted as part of TSPA model validation and confidence-building to quantify the effect of a set of model conservatisms on system performance**
  - Include less conservative alternative conceptual models
  - Narrower parameter uncertainty distributions in cases where conservative bounding values were assumed
  - Includes additional coupling among different physical and chemical processes

Some Examples of ACMs (>60 total)

Alternative Conceptual Models	Key Assumptions	Assessment and Basis
WP and DS Degradation: Parabolic General Corrosion Rate Law for DS Degradation	Assumes that the increasing oxide layer thickness on diffusion of oxidizing species to the underlying metal will have an inhibiting effect on corrosion.	Model is less conservative than the primary model.
WP and DS Degradation: Decreasing Rate Law for WP Degradation	General corrosion rates of metals and alloys tend to decrease with time	The time-dependent general corrosion behavior of the WP was not included in the TSPA-LA because the constant (time-independent) rate model (for a given temperature) is more conservative and bounds the general corrosion behavior of the WP outer shell over the repository time period.
UZ Transport: Inclusion of Drift Shadow Effects	Inclusion of drift shadow effects would approximate the influence of capillary diversion, which may cause low fracture saturation below the drift	There is insufficient data to support this effect. It is considered conservative to ignore drift shadow effects. Additionally, the increased infiltration associated with future climate states may decrease the effects

From SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Table 6.2-1.

Scenario Uncertainty

- **When disruptive event-driven processes are important (e.g., seismicity), then scenarios are deterministically aggregated into scenario classes, which are defined by the type of initiating event**
  - Uncertainty for a particular scenario class is then represented by the aleatory uncertainty in the annual frequency of the initiating event
- **In probabilistic PAs, scenario uncertainty for the nominal scenario class (i.e., no disruptive events) is not generally treated explicitly**
  - Uncertainty in future evolution is included through parameter and or model uncertainty in probabilistic PAs
  - Scenario uncertainty is more appropriate for deterministic PAs that aggregate sets of futures for nominal evolution (i.e., for the nominal scenario class) into specific scenarios, for example based on thermal evolution – not used in the U.S. program
- **For YMP, scenario classes may be screened out of the performance assessment if their annual event frequency is less 10^{-8} per year, e.g., nuclear criticality**

Major Steps in a Performance Assessment

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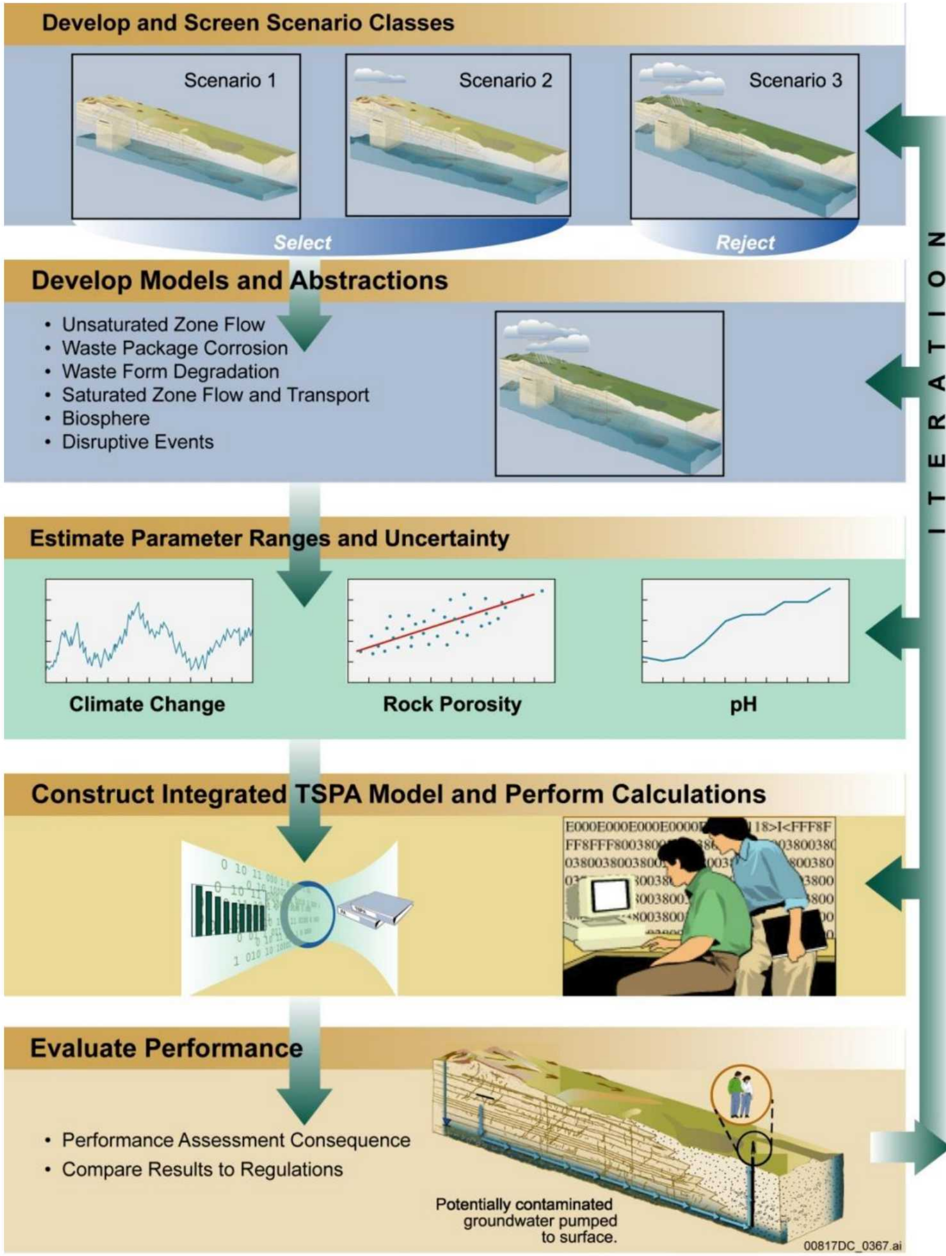
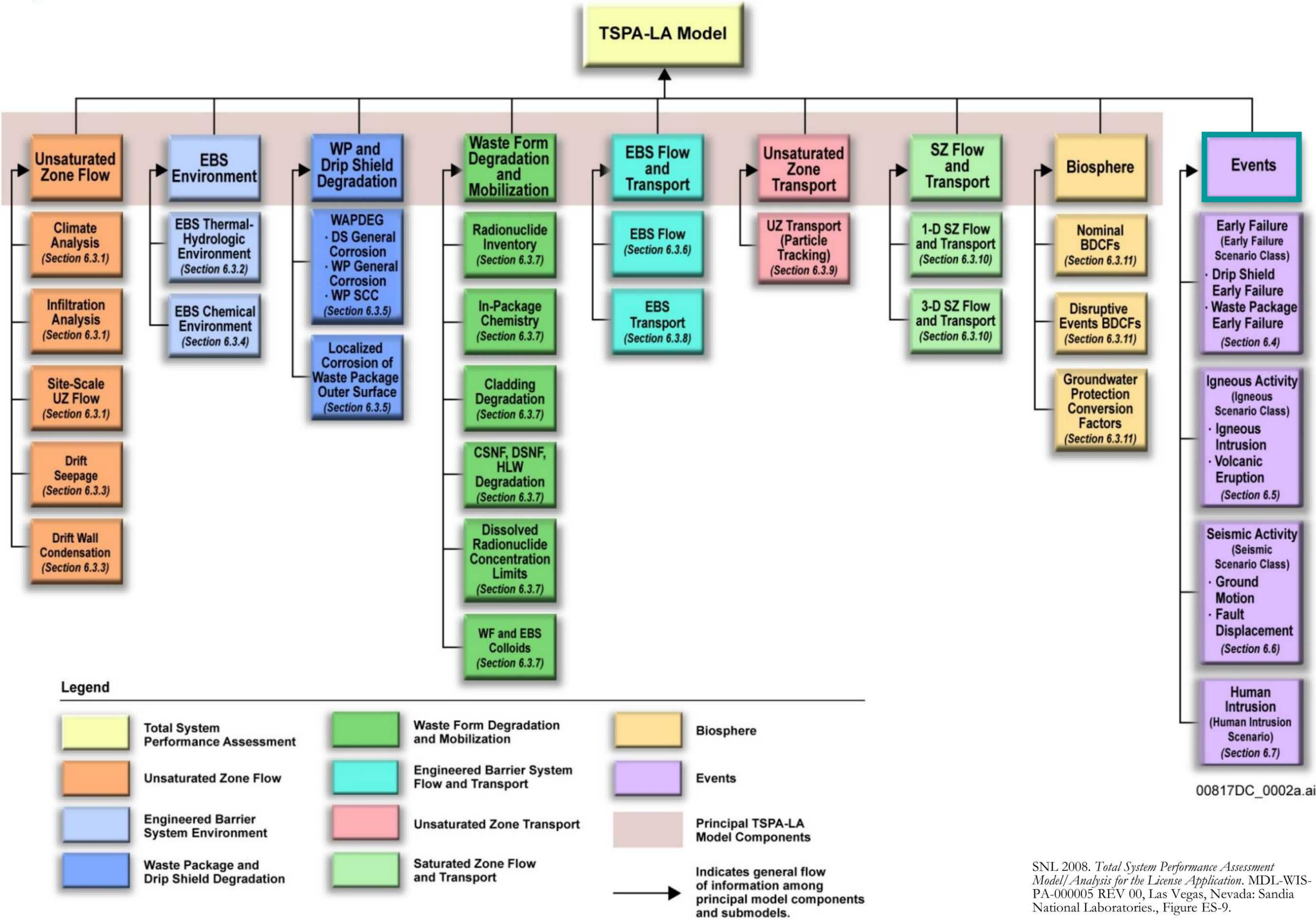
- *Construct integrated TSPA model* using all retained FEPs and *perform calculations* for the scenario classes and "modeling cases" within scenario classes
- *Evaluate total system performance,* incorporating uncertainty through Monte Carlo simulation
- <u>Iterate</u>



SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Figure ES-4.

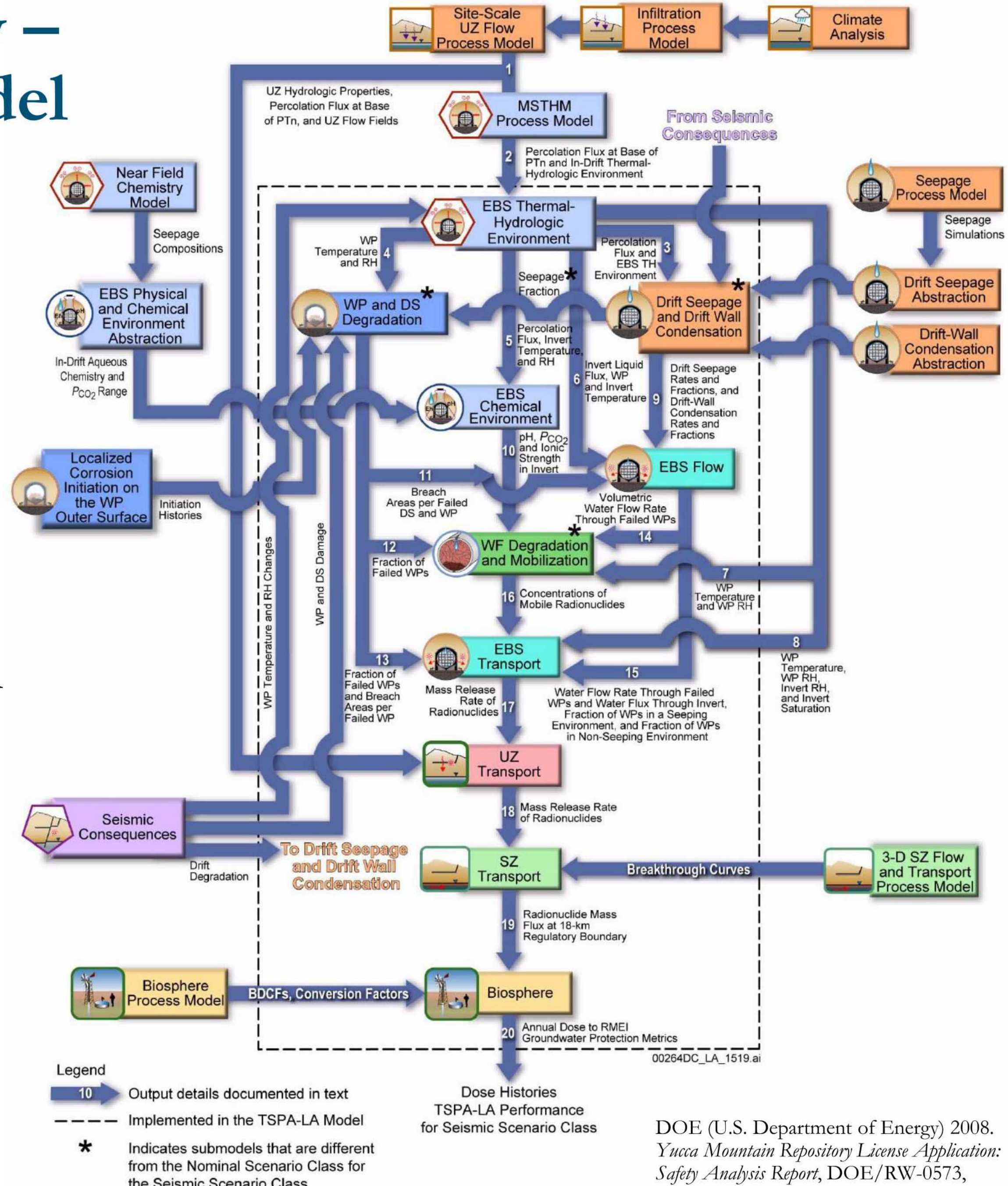
Performance Assessment System Model
(with component models and submodels)



SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories., Figure ES-9.

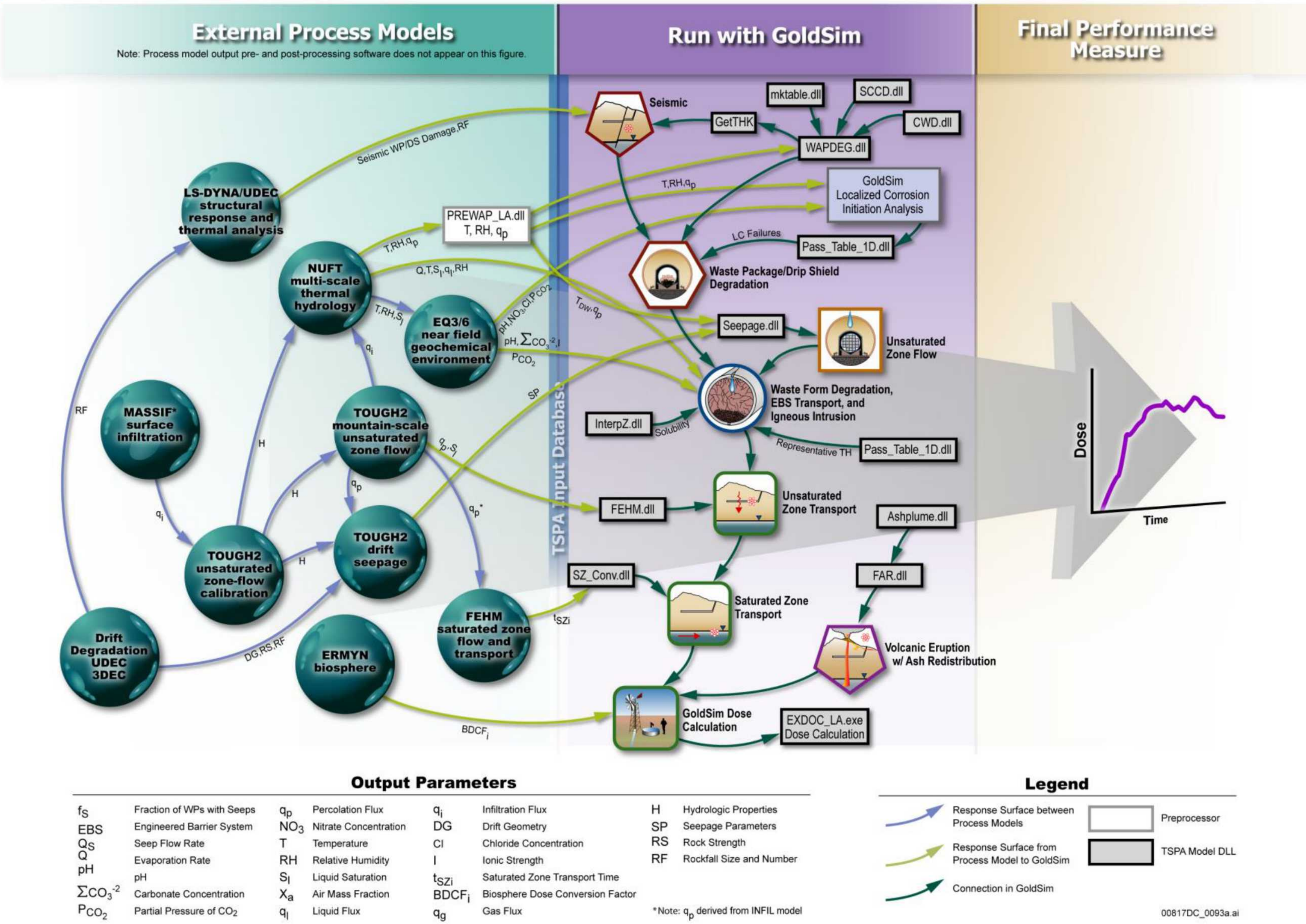
Information Flow – YMP TSPA Model

- Seismic scenario class
- Shows finer division of component models into submodels/abstractions
- Shows primary types of information passed from process models to TSPA abstractions, and among TSPA abstractions and submodels
- *Indicates models that are different from the nominal scenario class models



DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application: Safety Analysis Report*, DOE/RW-0573, Revision 1, Figure 2.4-117

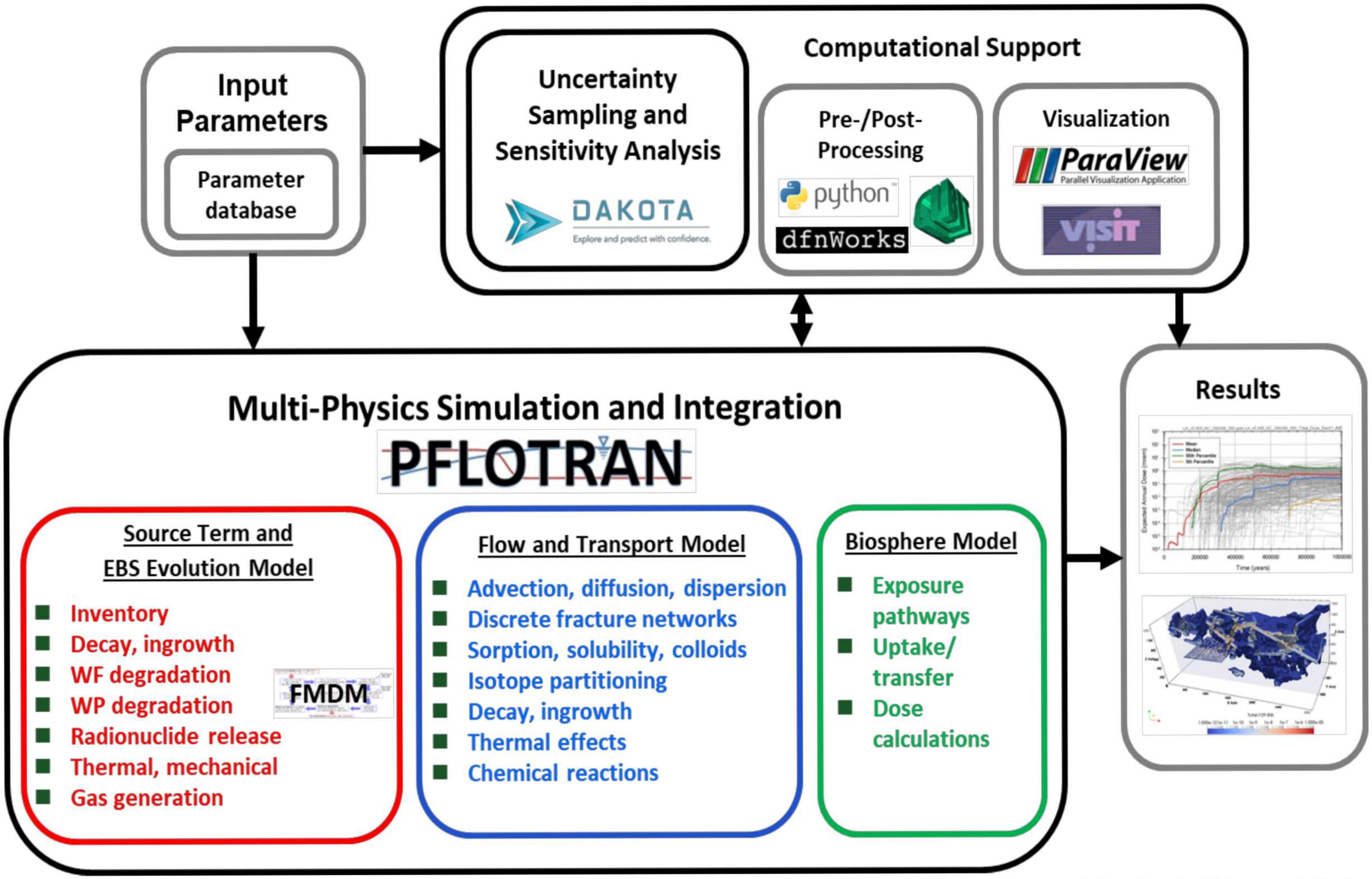
"Then"…. YM Software Architecture



SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Figure 3-2.

"Now"…. GDSA* Software Architecture

- Where's the "beef"?? (i.e., the connections and information flow between process models and PA?)



*Geologic Disposal Safety Assessment

Mathematical Structure for Calculations

- **Two (probability) spaces for inputs**
  - Aleatory uncertainties $\mathcal{A} = \{\mathbf{a} : \mathbf{a} = [nEW, nED, \ldots]\}$
  - Epistemic uncertainties $\mathcal{E} = \{\mathbf{e} : \mathbf{e} = [e_1, e_2, \ldots, e_N]\}$
- **Notionally, a function $D(\tau \mid \mathbf{a}, \mathbf{e})$ (dose as a function of time, τ) to be evaluated**
- **Example: mean value of $D(\tau \mid \mathbf{a}, \mathbf{e})$ over both aleatory and epistemic uncertainties:**

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

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

Approximated by summing over modeling cases (MC):

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

YMP TSPA Dose Terminology

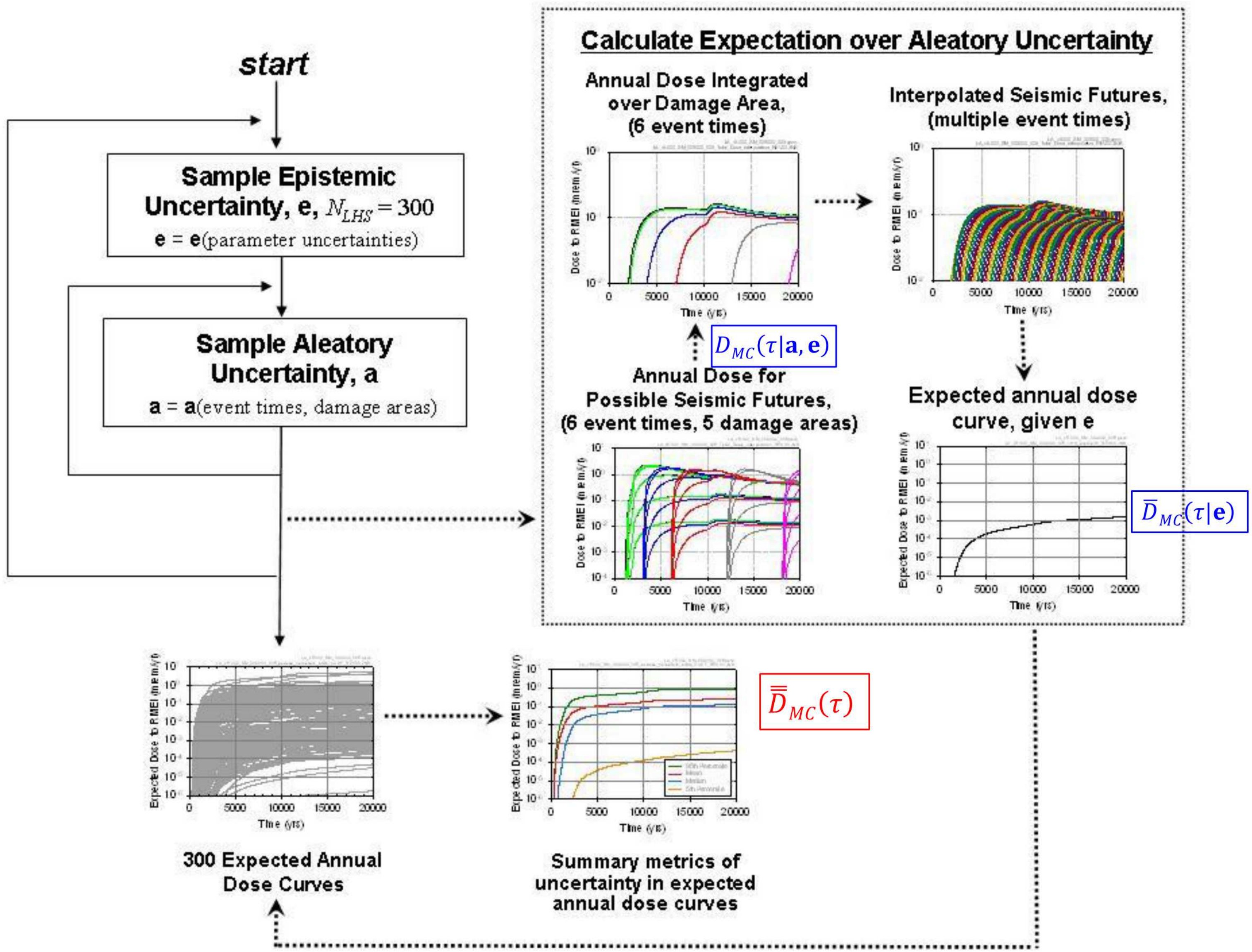
- **"Dose" – annual dose to the RMEI as a function of time (per modeling case)** $D_{MC}(\tau|\mathbf{a},\mathbf{e})$
  - Depends on both aleatory and epistemic uncertainty
  - Summed over all radionuclides
- **"Expected Dose"** $\overline{D}_{MC}(\tau|\mathbf{e})$
  - Expectation is taken over aleatory quantities
  - Conditional on epistemic uncertainty
  - Calculated for each modeling case
- **"Mean Dose"** $\overline{\overline{D}}_{MC}(\tau)$
  - Expectation is taken over both epistemic and aleatory
  - Calculated for each modeling case
- **"Total Expected Dose"**
  - Summed over all modeling cases by epistemic vector

$$\overline{D}(\tau|\mathbf{e}) = \sum_{MC} \overline{D}_{MC}(\tau|\mathbf{e})$$

- **"Total Mean Dose"**
  - Average of Total Expected Dose (i.e., over all N epistemic vectors)

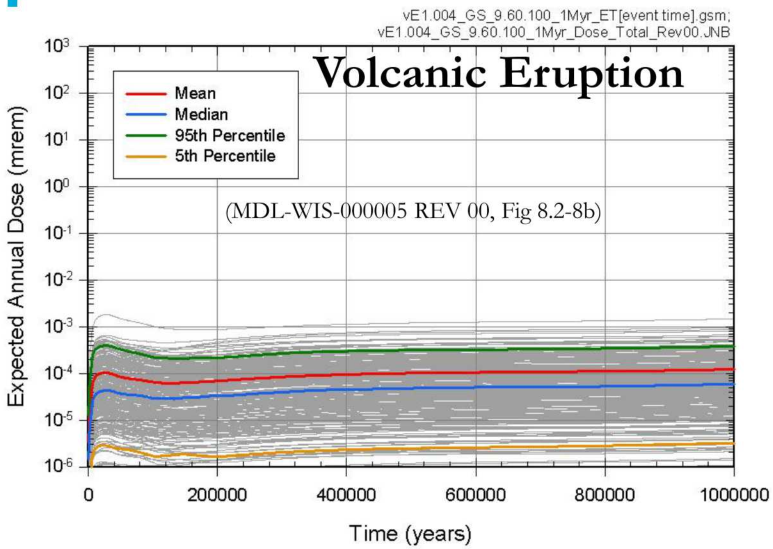
$$\overline{\overline{D}}(\tau) = \frac{1}{N}\sum_{i=1}^{N} \overline{D}(\tau|\mathbf{e}_i)$$

Calculation Methodology for Seismic Expected Dose



DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application: Safety Analysis Report*, DOE/RW-0573, Revision 1, Fig. 2.4-8

Calculation and Construction of Total Dose



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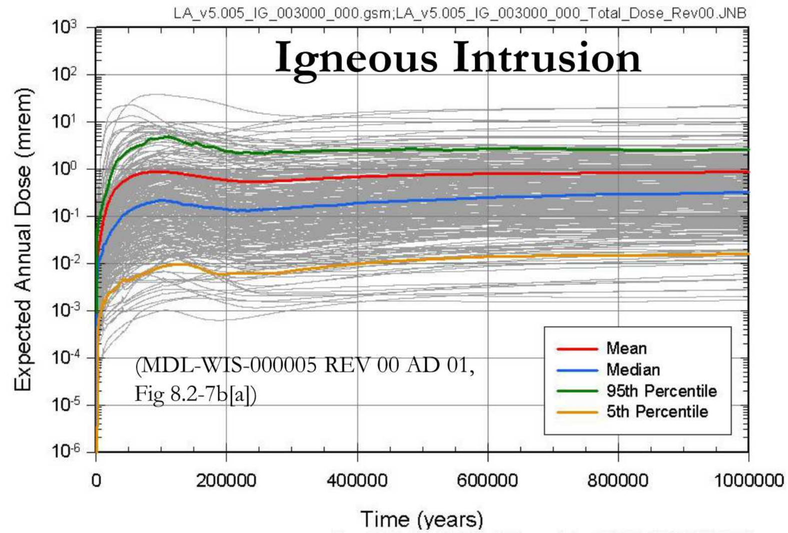

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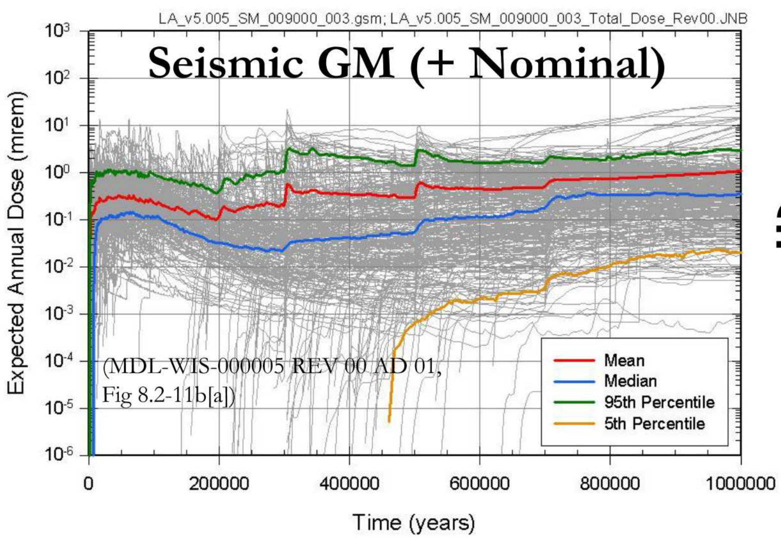

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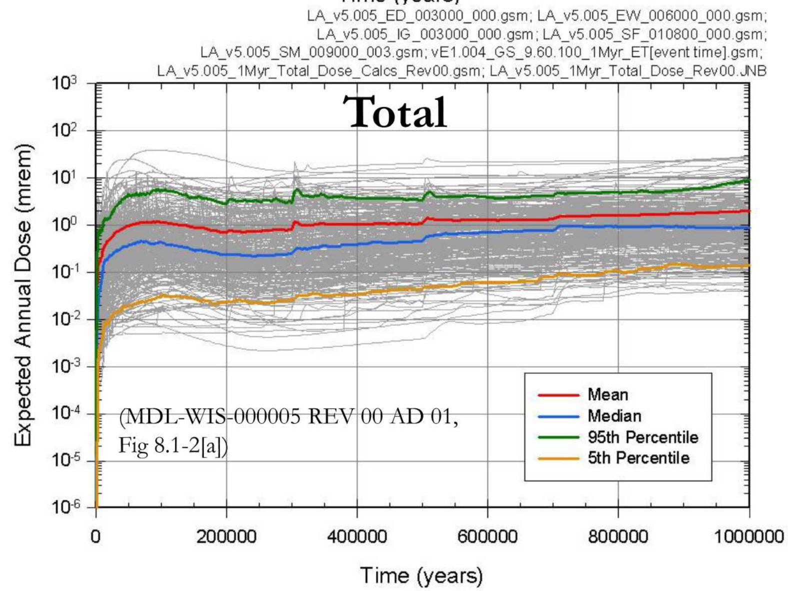
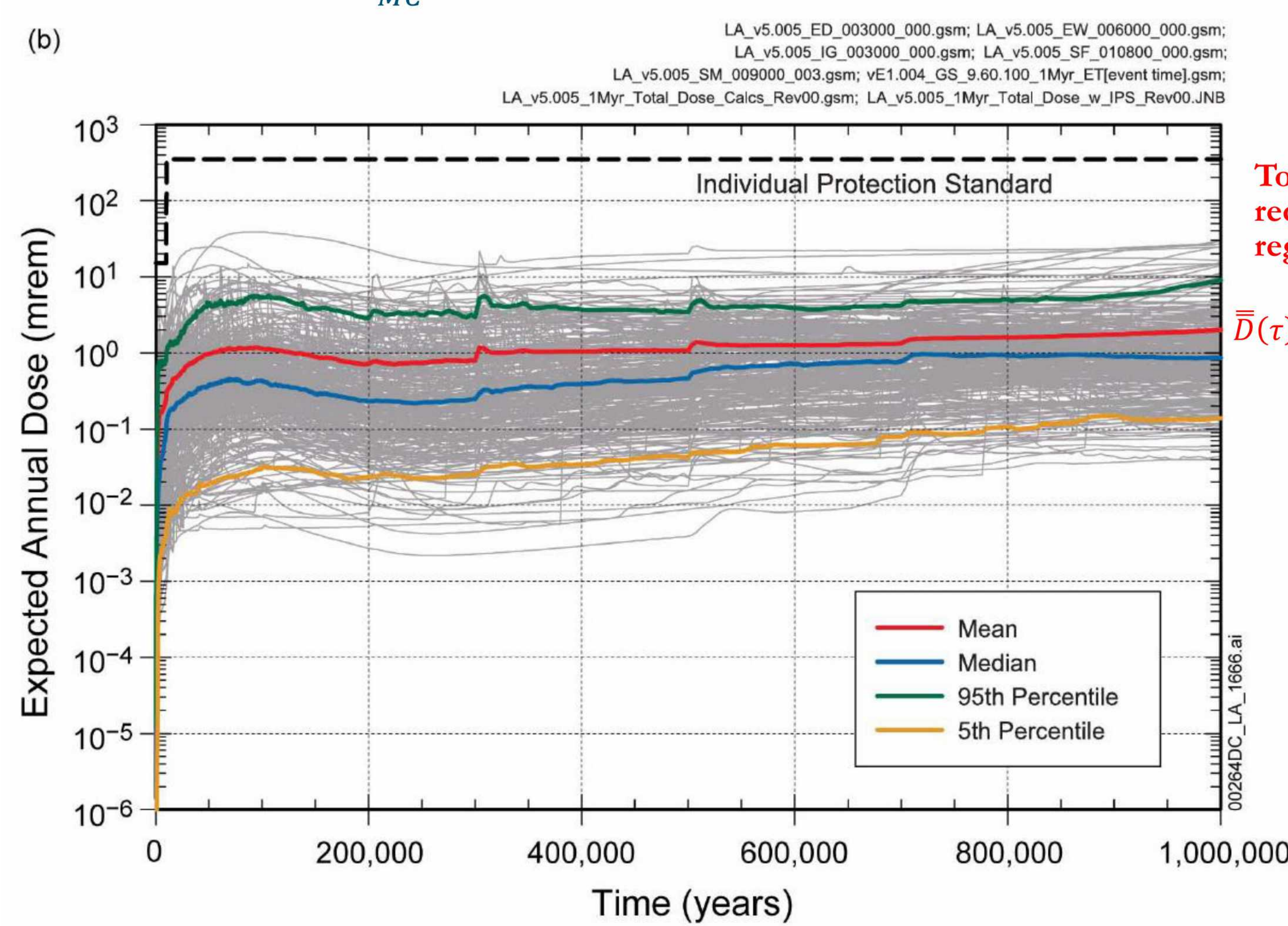


SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00 AD 01. Las Vegas, Nevada: Sandia National Laboratories.

Total Expected Dose (all modeling cases)

$$\bar{D}(\tau|\mathbf{e}) = \sum_{MC} \bar{D}_{MC}(\tau|\mathbf{e})$$ **i.e., by epistemic vector**



Total mean dose, red curve, regulatory metric:

$$\bar{\bar{D}}(\tau) = \frac{1}{N}\sum_{i=1}^{N} \bar{D}(\tau|\mathbf{e}_i)$$

DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application: Safety Analysis Report*, DOE/RW-0573, Revision 1, Fig. 2.4-10

Major Steps in a Performance Assessment

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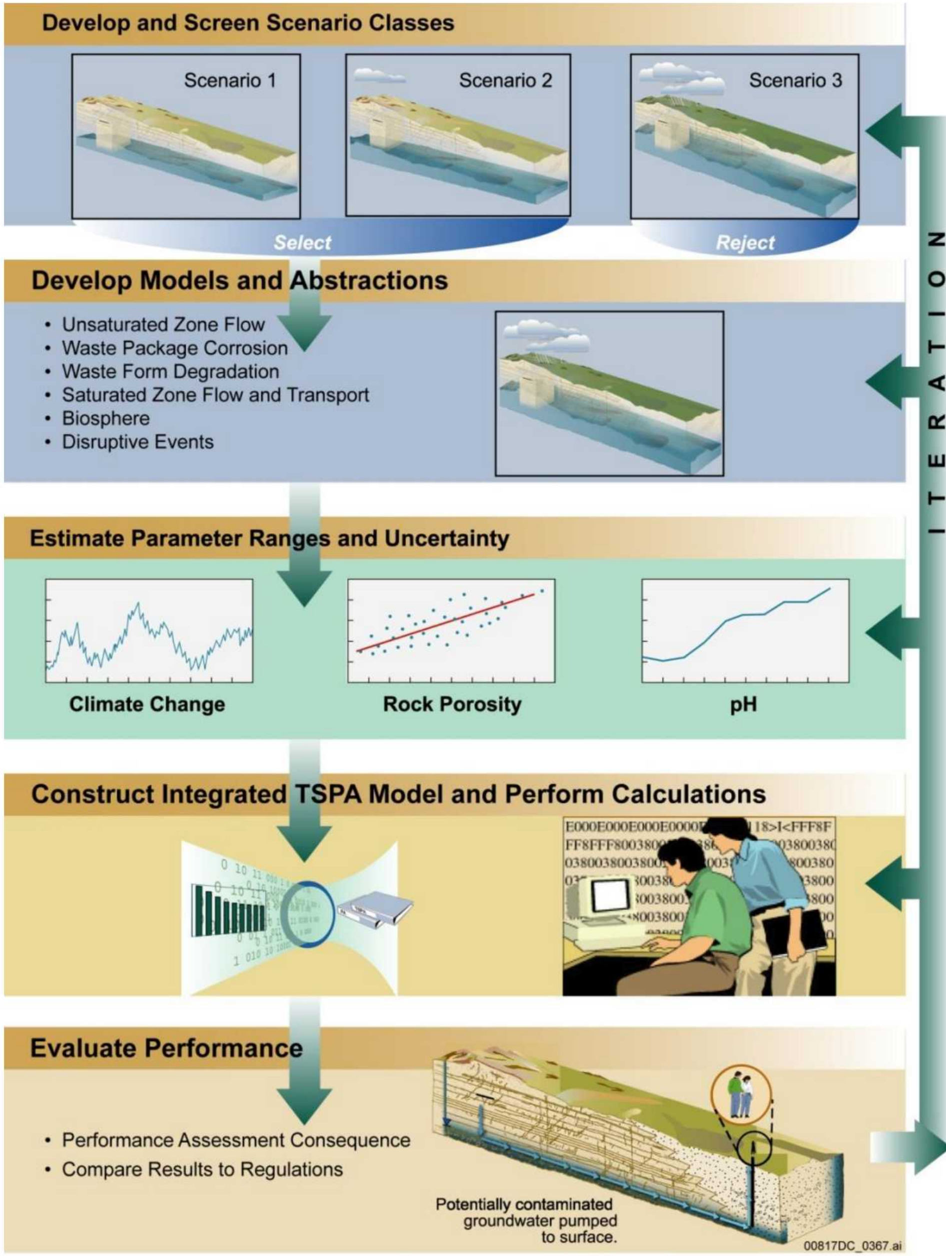
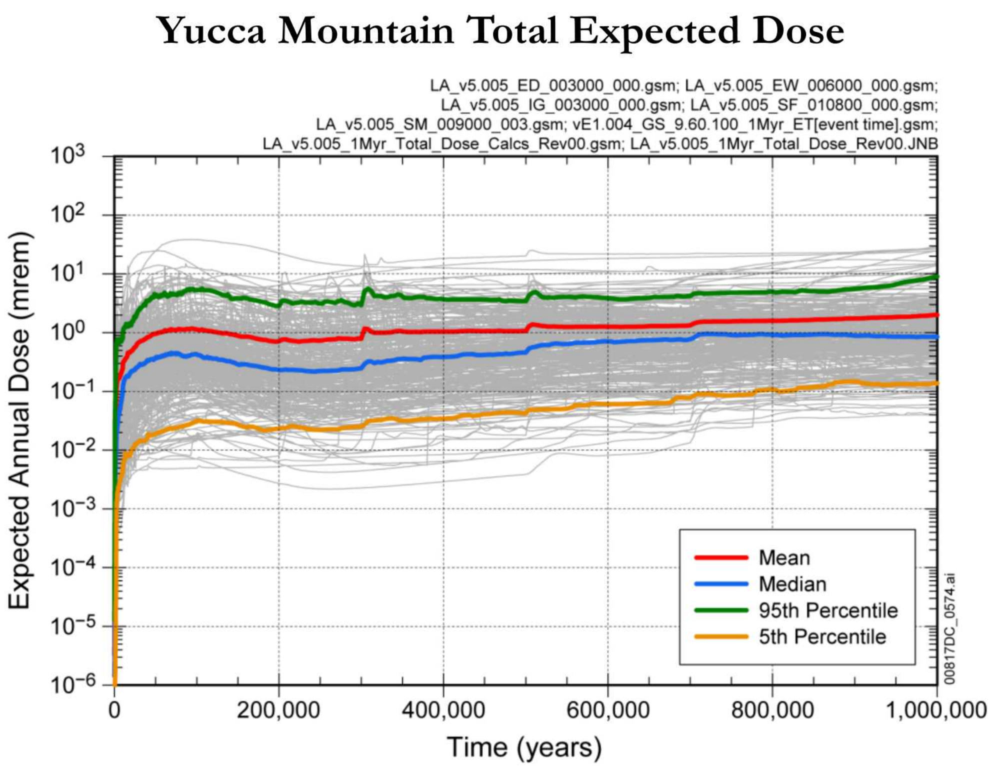
- ***Evaluate total system performance,*** **incorporating uncertainty through Monte Carlo simulation**
- **<u>Iterate</u>**



SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories, Figure ES-4.

Analysis of Results

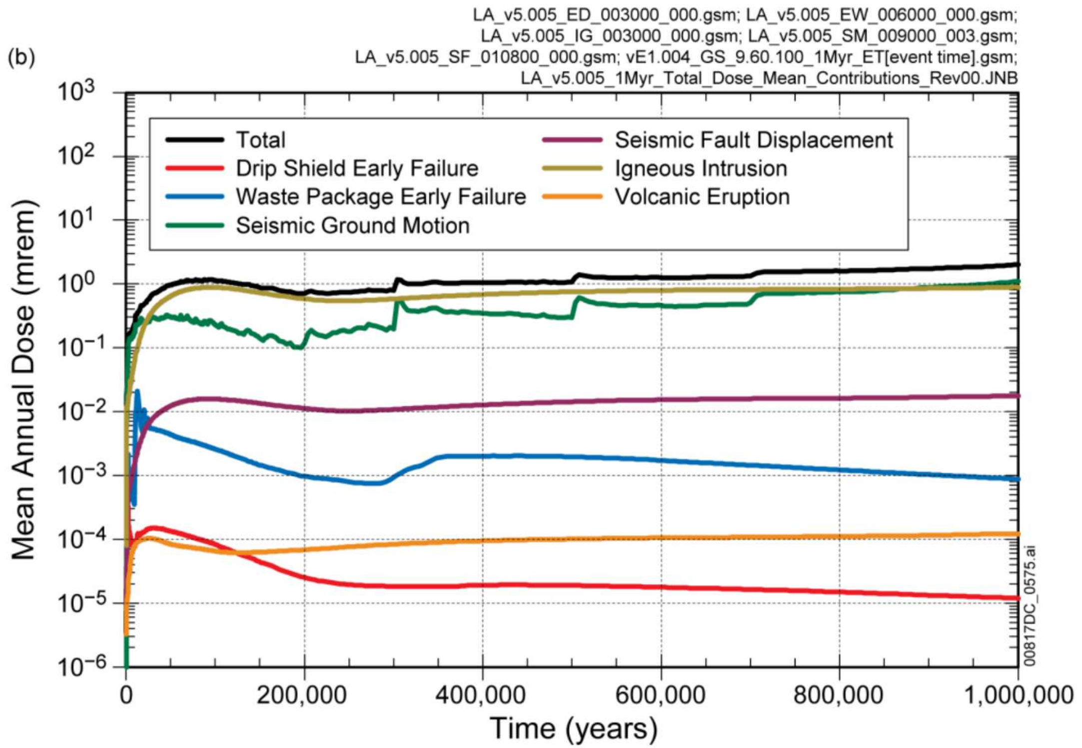


SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00 ADD 01. Las Vegas, Nevada: Sandia National Laboratories, Figure 8.1-2[a].

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?

Modeling Cases Contributing to Total Mean Annual Dose



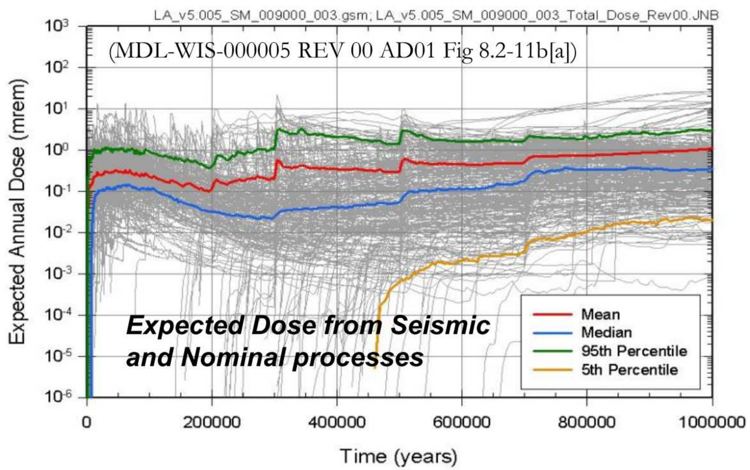
MDL-WIS-PA-000005 REV 00 AD 01, Figure 8.1-3[a]

<u>In order of importance</u>:

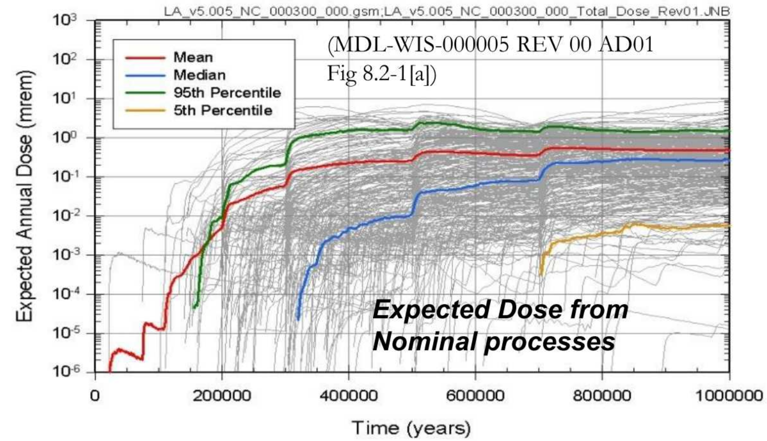
1. **Igneous Intrusion**
2. **Seismic Ground Motion (includes effects of nominal processes)**
3. **Seismic Fault Displacement**
4. **Early Failure, Volcanic Eruption**

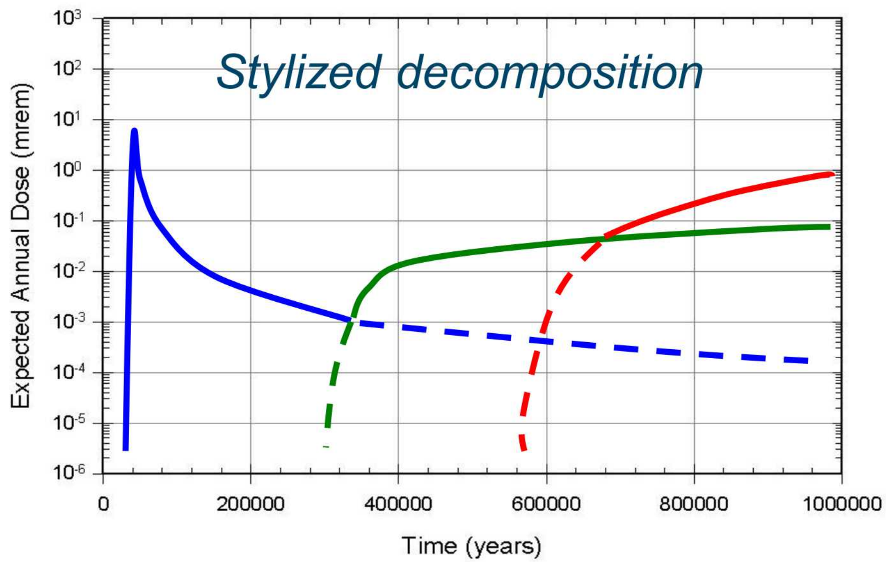
SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00 AD 01. Las Vegas, Nevada: Sandia National Laboratories.

Decomposition of Seismic Ground Motion Case



Included





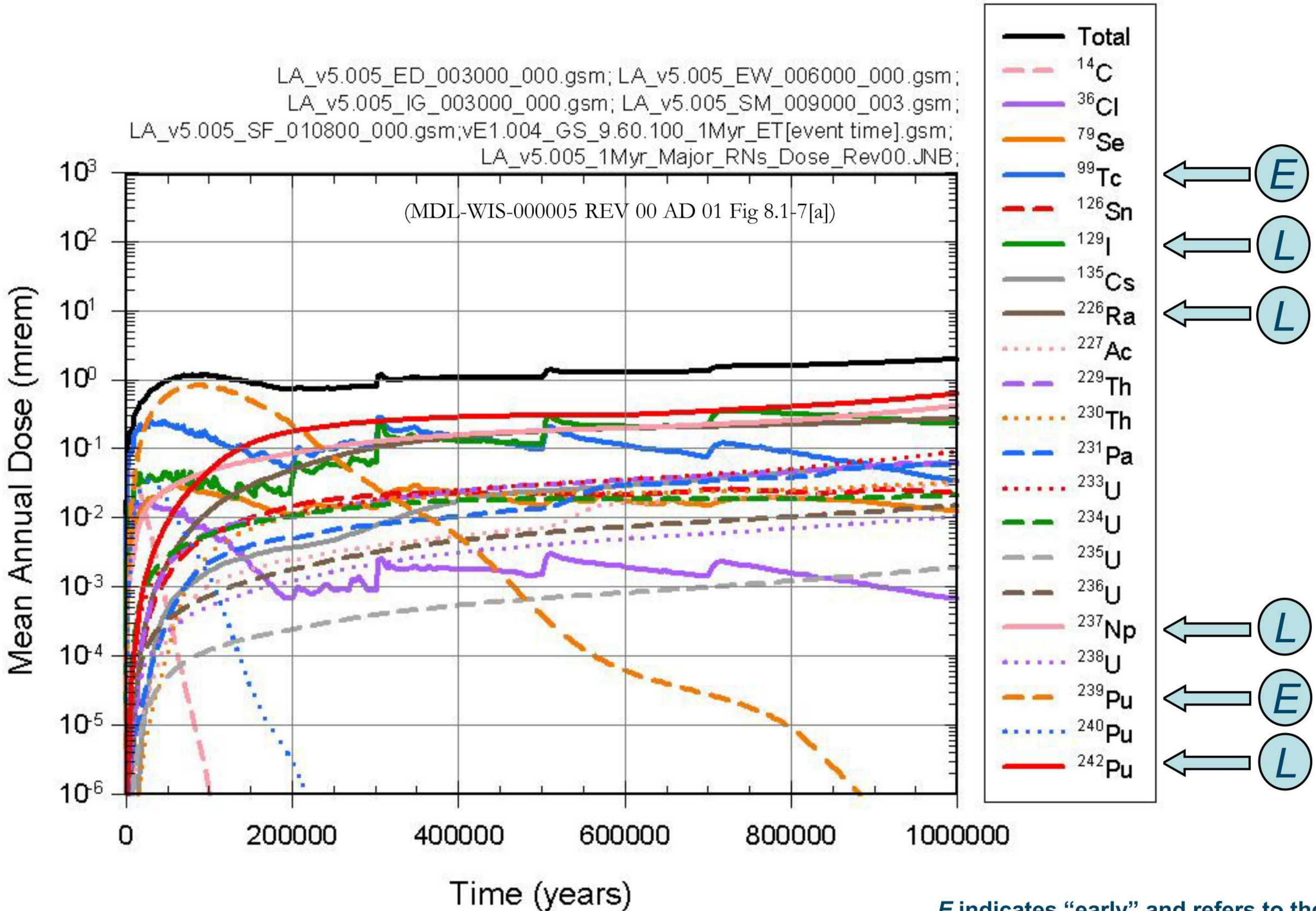
From seismic damage to CDSP WP (diffusion)

From SCC failure of CSNF WP (diffusion)

From general corrosion failure of both WPs (advection)

SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00 AD 01. Las Vegas, Nevada: Sandia National Laboratories.

Radionuclides Important to Total Mean Dose (i.e., over all modeling cases)



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**

SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00 AD 01. Las Vegas, Nevada: Sandia National Laboratories.

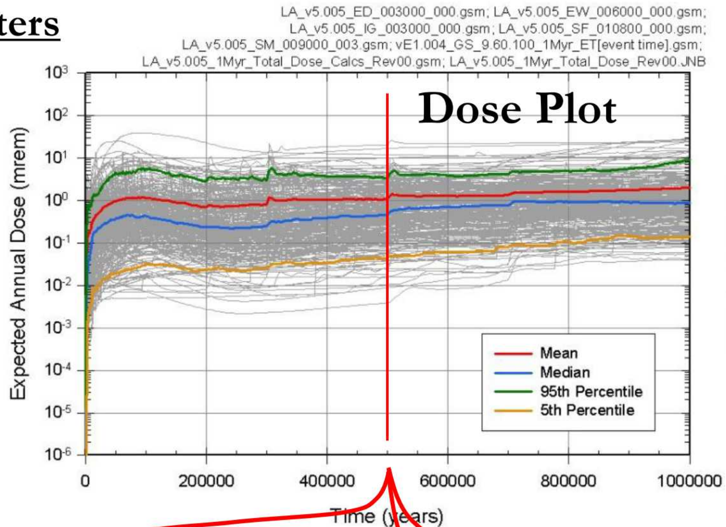
Sensitivity Analyses for Total Expected Dose:
(Sum over All Scenario Classes and RNs)

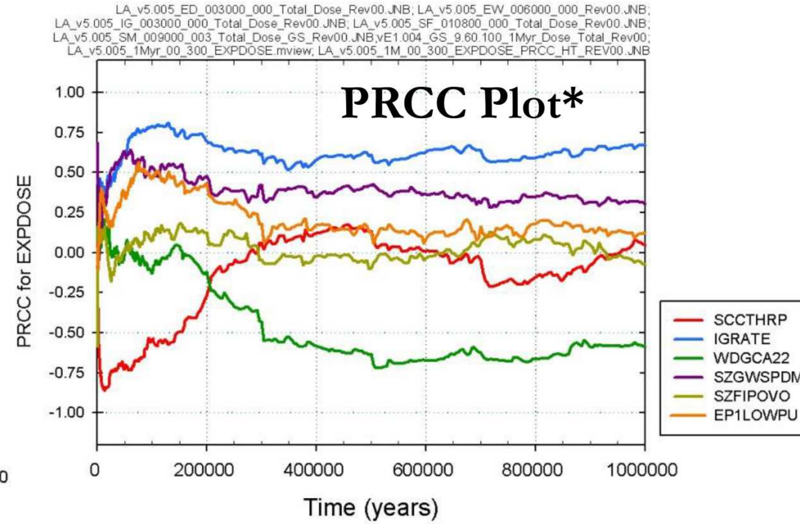
Important Parameters

SCCTHRP – Stress threshold for SCC initiation

IGRATE – Frequency of igneous events

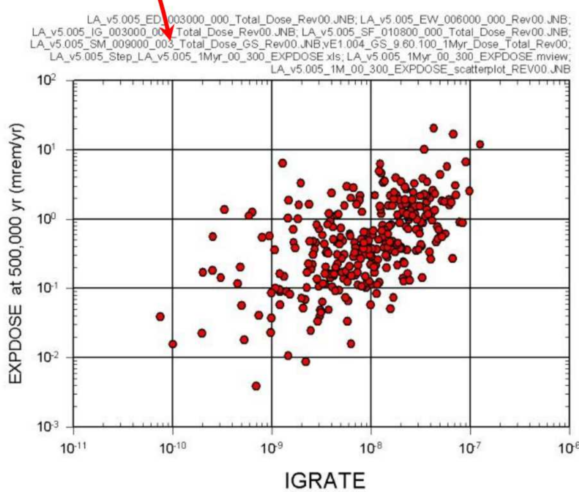
WDGCA22 – Temperature dependence in Alloy 22 corrosion rate

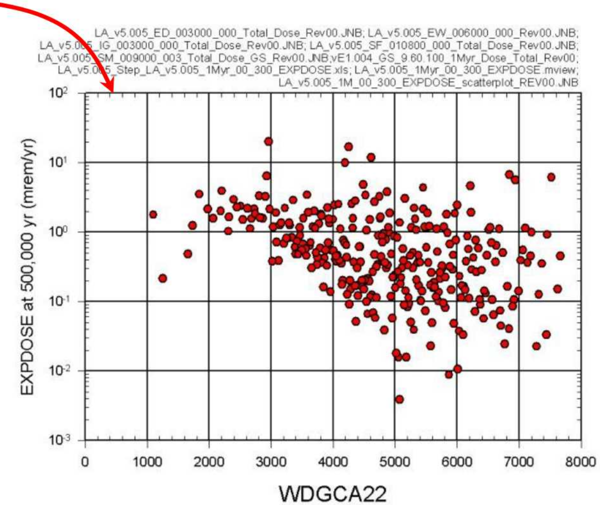




Stepwise Rank Regression

EXPDOSE: 500,000 Years		
Variable	R^2	SRRC
IGRATE	0.29	0.54
WDGCA22	0.46	−0.38
SZGWSPDM	0.53	0.24
EP1LOWNU	0.56	0.19
MICNP237	0.59	0.16
EP1L0WPU	0.61	0.17
SZCONCOL	0.64	0.15
SZFISPVO	0.66	0.15
INFIL	0.67	0.11
GOESITED	0.68	−0.10
SZKDCSVO	0.69	−0.10
HFOSITED	0.69	−0.09
SZDIFCVO	0.70	−0.09



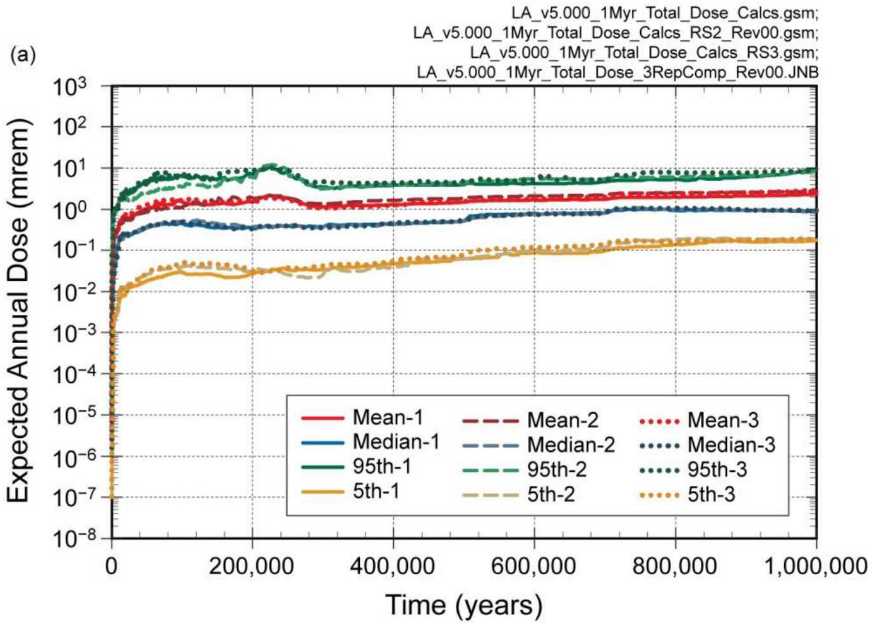


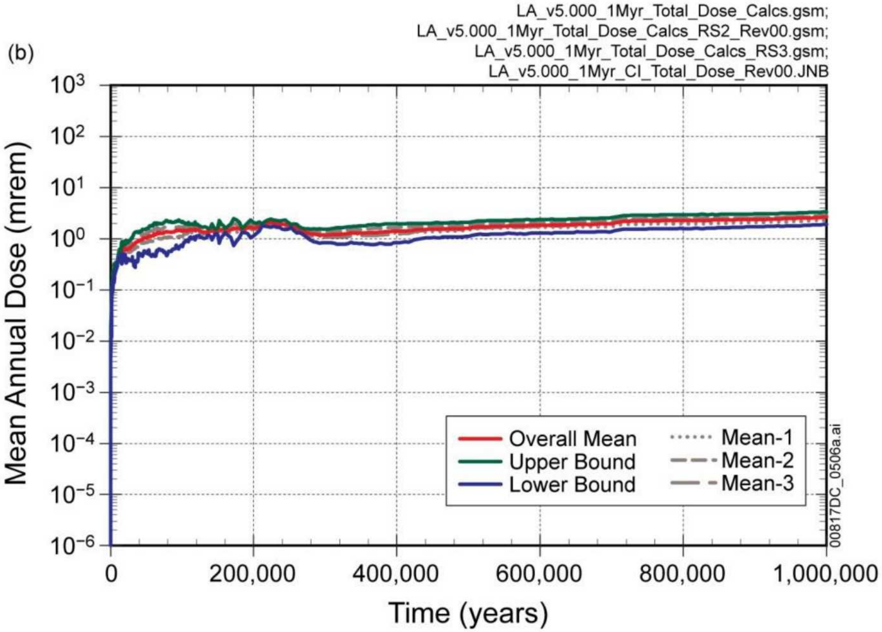
*PRCCs (partial rank correlation coefficients) provide a measure of the strength of the monotonic relationships between an independent variable e_j and a dependent variable y_k) after a correction has been made to remove the monotonic effects of the other independent variables in the analysis.

Statistical Stability for the Epistemic Uncertainty:
1,000,000-Year Total Dose (over all modeling cases)

- **Replicate testing**
  - 3 different random seeds
  - Visual test

- **95% Confidence intervals for mean**
  - Use the 3 replicates
  - Assume a Student-t distribution





Illustrative figures from TSPA AMR (MDL-WIS-PA-000005) Figure 7.3.1-16 (a and b)

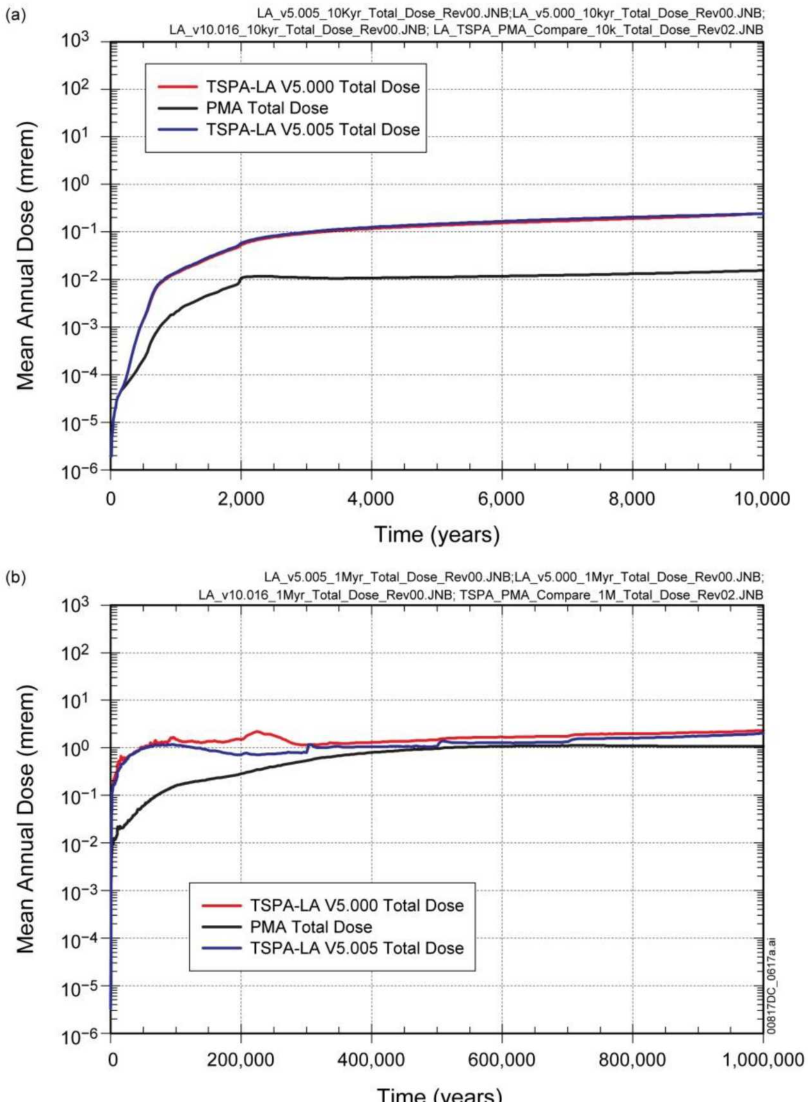
SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories.

TSPA Model "Validation" Approach

- **During-development Confidence-Building Activities**
  - Verification of inputs, software, submodel implementation, and submodel coupling
  - Model stability testing: statistical stability, numerical accuracy, temporal stability, spatial stability
  - Uncertainty characterization reviews
- **Post-development Confidence-Building Activities**
  - Corroboration of abstraction model results with the results of process-level models
  - Corroboration with auxiliary analyses
    - *Deterministic single realization analyses*
    - *Comparison of TSPA Model results to simplified system models*
    - *Comparison of TSPA Model results to TSPA models developed by external organizations*
    - *Performance Margin Analysis (PMA): remove key conservatisms*
  - Corroboration with natural analogue information
  - Technical review

Performance Margin Analyses – to test Alternative Conceptual Models

- **Submodel conservatisms propagated through the total system do not underestimate the total mean annual dose**
- **PMA dose is more than a factor of 10 lower at 10,000 years and a factor of 2 lower at 1,000,000 years**
- **The evaluated conservatisms do not introduce any risk dilution in TSPA results**



Illustrative figure from TSPA AMR (MDL-WIS-PA-000005) Figure 7.7.4-7[a] (a and b)

SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00 AD 01. Las Vegas, Nevada: Sandia National Laboratories.

Independent Technical Review

- **Successive iterations of the TSPA model have been subject to independent reviews by technical staff and various external organizations**
- **During the development of subsequent iterations of the TSPA model, recommendations from the technical review of the preceding iterations were considered**
- **In addition to routine Nuclear Waste Technical Review Board (NWTRB) reviews, three other technical reviews include**
  - TSPA-VA model peer review conducted in 1999
  - TSPA-SR model review by an International Review Team in 2002
  - TSPA-LA draft model review by an Independent Validation Review Team completed in 2006

Yucca Mountain Repository Timeline – Various TSPAs

MDL-WIS-PA-00005 REV 00 FES-5 January 2008

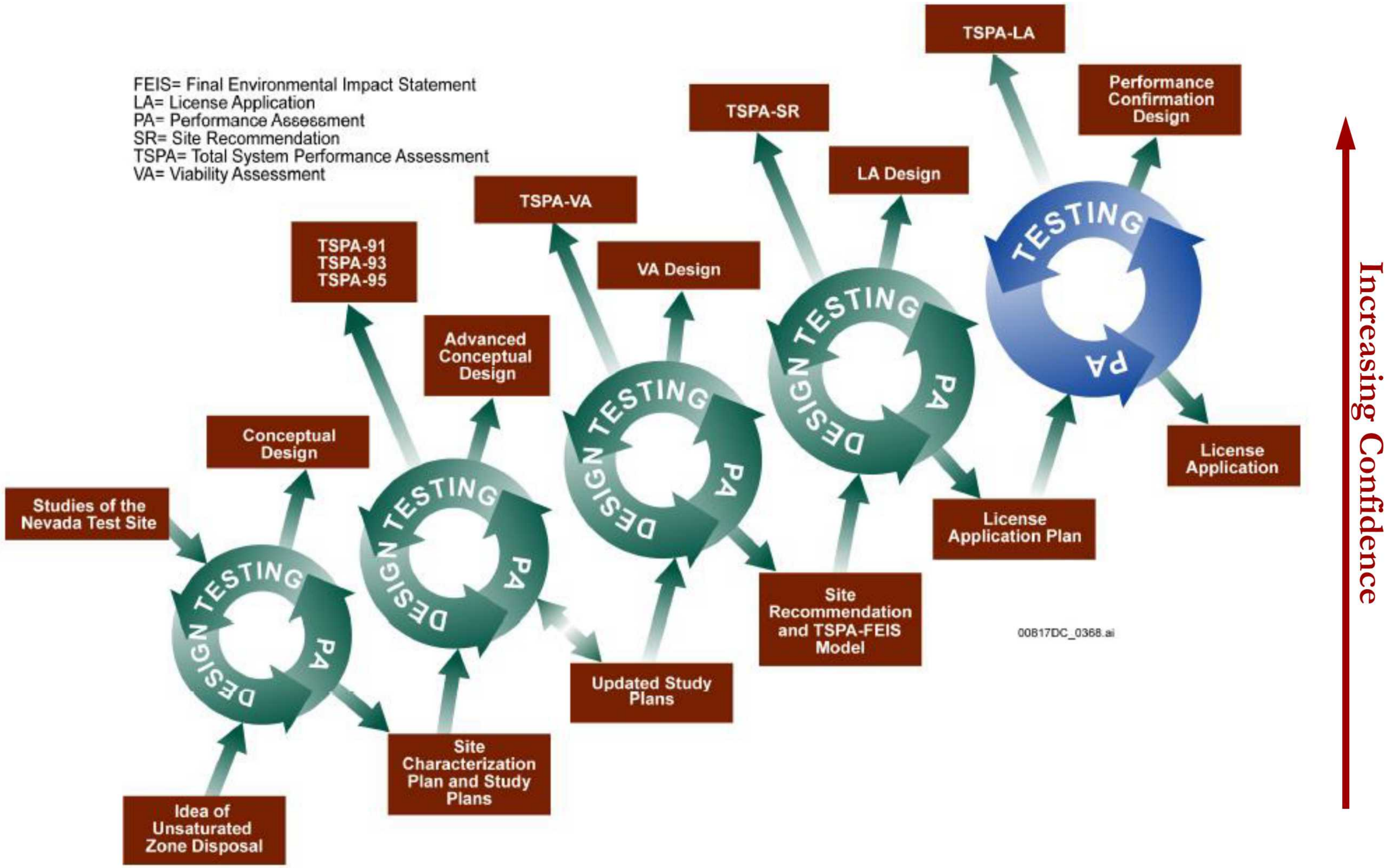


Figure ES-5. Iterative Application of the TSPA Process

SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories.


Discussion?
Questions?

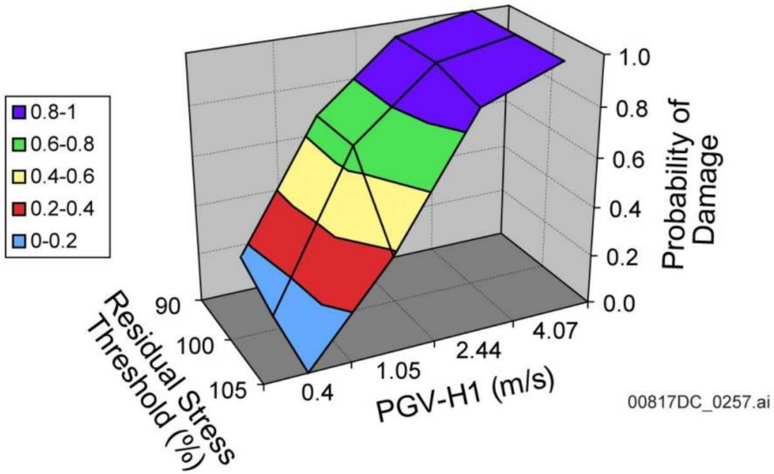
Back-Up Slides

References

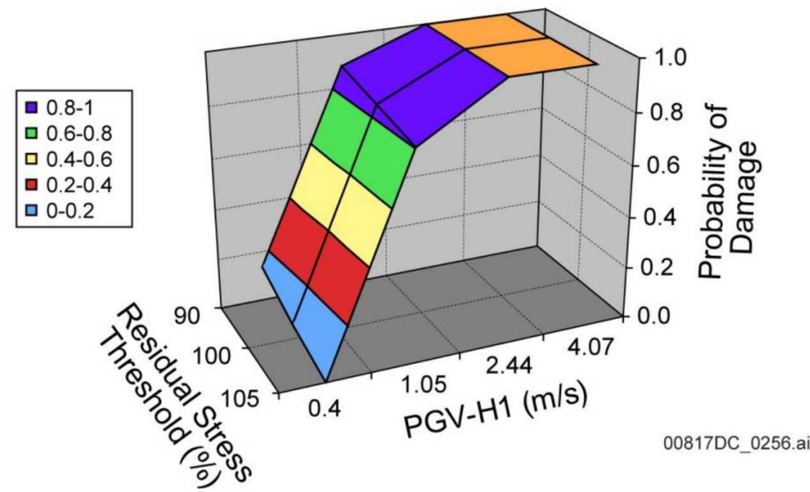
- DOE (U.S. Department of Energy) 2008. *Yucca Mountain Repository License Application: Safety Analysis Report*, DOE/RW-0573, Revision 1. Available at https://www.nrc.gov/waste/hlw-disposal/yucca-lic-app/yucca-lic-app-safety-report.html#1
- Sevougian, S. D. 2010. *Representation of THMC Coupling in Seismic Consequences Models: An Example from the Yucca Mountain Performance Assessment*, IAEA Regional Training Course, June 22, 2010, Albuquerque, New Mexico, SAND2010-3465P, Sandia National Laboratories, Albuquerque, NM.
- Sevougian, S. D. 2010. *Methods for Developing and Validating Total System Models: With Examples from the Yucca Mountain Performance Assessment*, IAEA Regional Training Course, June 25, 2010, Albuquerque, New Mexico, SAND2010-3684P, Sandia National Laboratories, Albuquerque, NM.
- Sevougian, S. D., G. E. Hammond, P. E. Mariner, E. R. Stein, J. M. Frederick, and R. J. MacKinnon 2018. *GDSA Framework: High-Performance Safety Assessment Software to Support the Safety Case*, IGSC Safety Case Symposium 2018, Rotterdam, The Netherlands, October 11, 2018, SAND2018-10064C, Sandia National Laboratories, Albuquerque, NM.
- SNL 2007. *Seismic Consequence Abstraction*. MDL-WIS-PA-000003 REV 03, Sandia National Laboratories, September 2007, DOC.20070928.0011.
- SNL (Sandia National Laboratories) 2010. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 Rev00, AD 01, Sandia National Laboratories, Albuquerque, NM.

EBS State 1 SCC Damage to WP: (Intact DS, Degraded Internals)

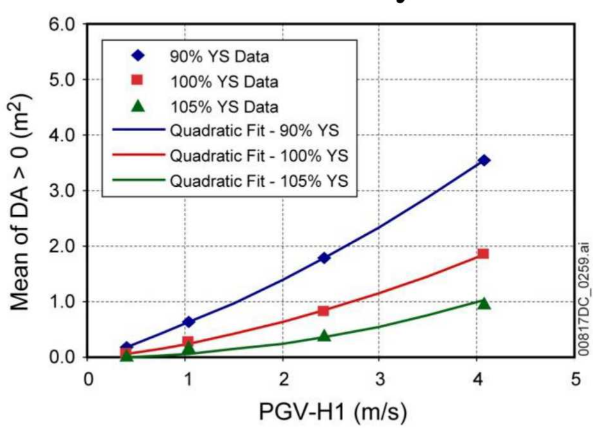
- **Co-disposal WP probability of SCC damage for 17-mm Alloy 22**



- **CSNF WP probability of SCC damage for 17-mm Alloy 22**

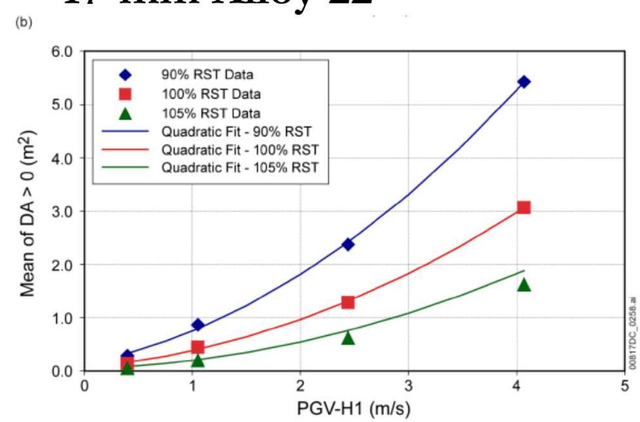


- **Co-disposal WP mean damage area for 17-mm Alloy 22**



MDL-WIS-PA-000005, Figures 6.6-11 and 6.6-13

- **CSNF WP mean damage area for 17-mm Alloy 22**

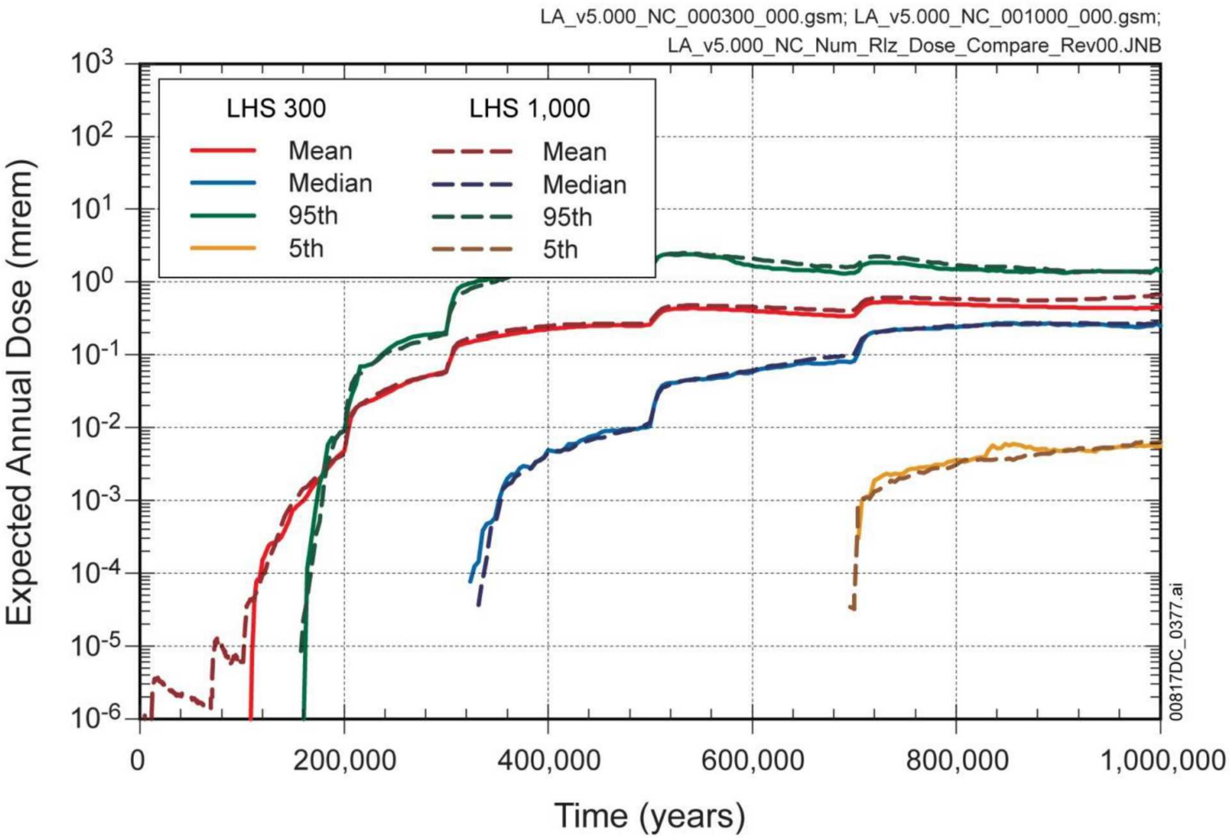


MDL-WIS-PA-000005, Figures 6.6-10 and 6.6-12

SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories.

Numerical Accuracy
1,000,000-Year Nominal Modeling Case

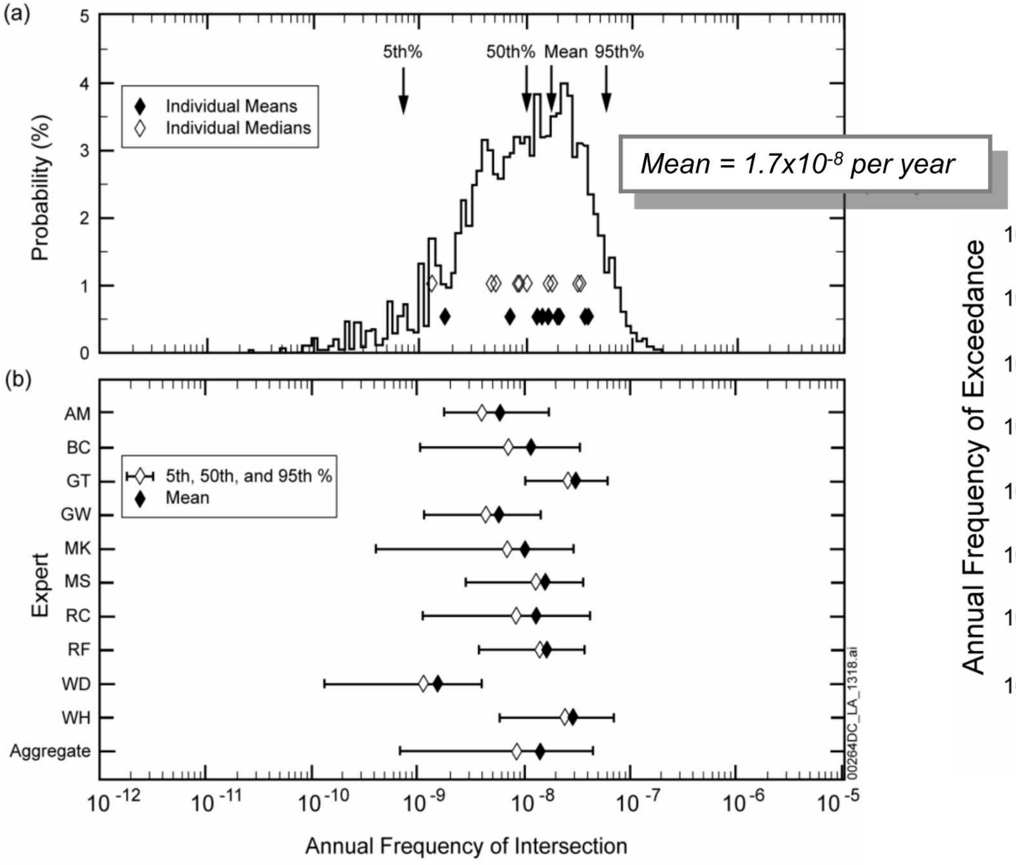
- Effect of number of realizations



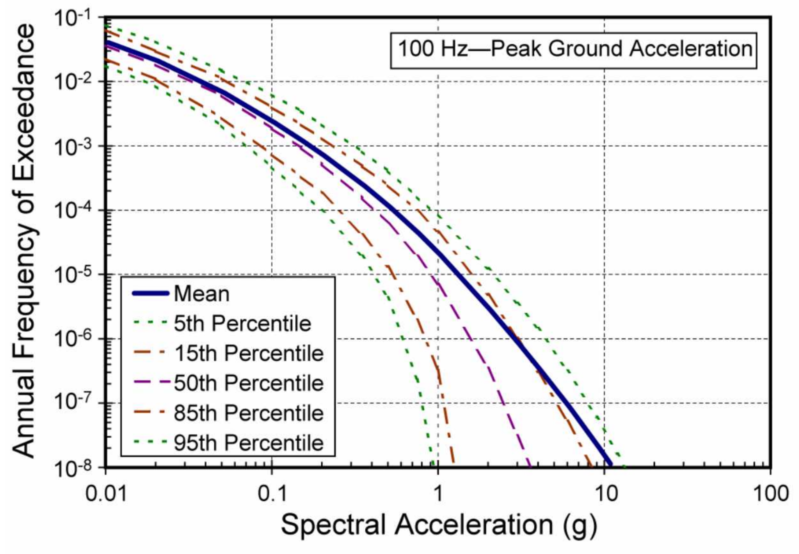
Illustrative figure from TSPA AMR (MDL-WIS-PA-000005) Figure 7.3.2-2

SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*. MDL-WIS-PA-000005 REV 00, Las Vegas, Nevada: Sandia National Laboratories.

Yucca Mountain Event Probabilities Estimated by Formal Expert Elicitation

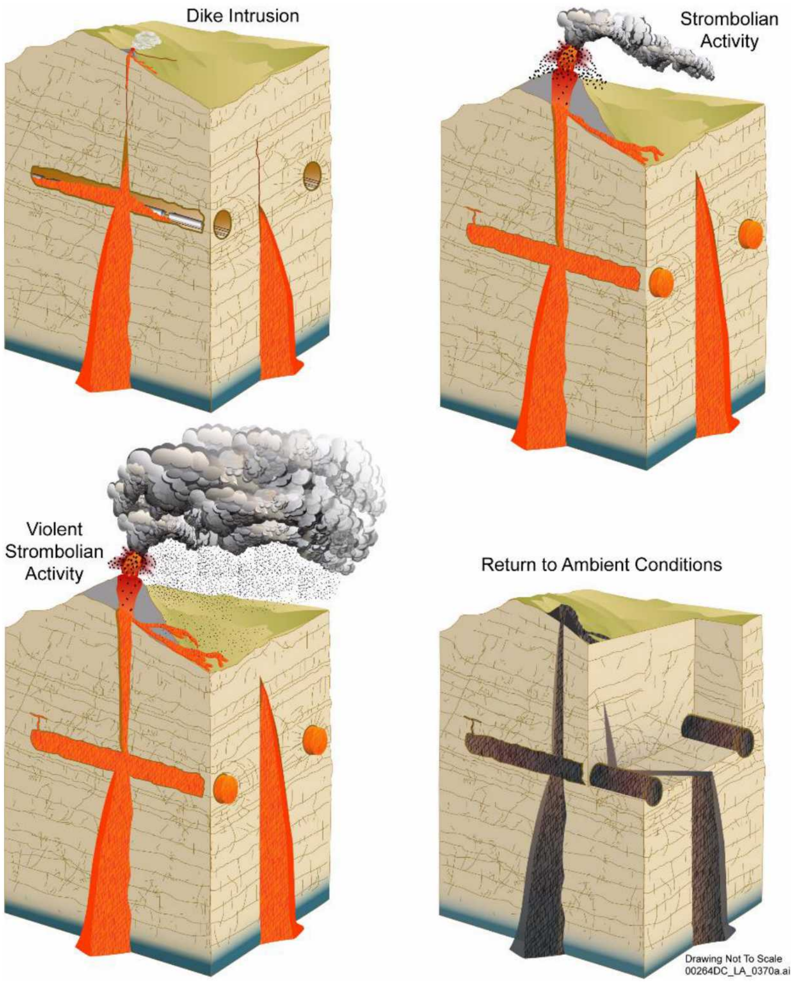


Estimated annual frequency of an igneous intrusion intersecting the repository footprint (DOE/RW-0573 Rev. 1, Figure 2.3.11-8)



Estimated annual frequency of peak ground acceleration, 100 Hz (DOE/RW-0573 Rev. 1, Figure 2.3.4-7)

Consequence Models for Igneous Disruption at Yucca Mountain

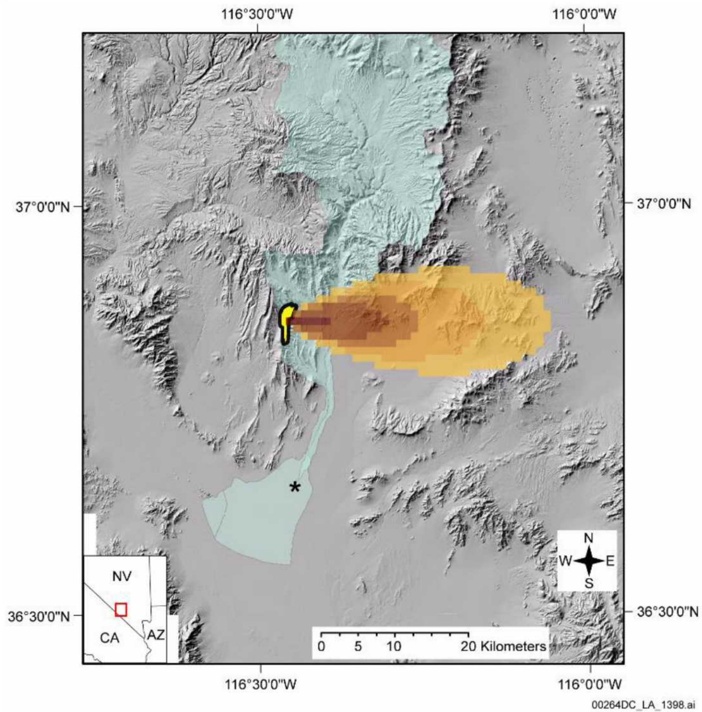


Schematic Drawing of an Igneous Event at Yucca Mountain (DOE/RW-0573 Rev. 1, Figure 2.3.11-5)

Two Release Scenarios:

- **Volcanic eruption of contaminated ash**
  - Releases limited to waste packages intersected by the volcanic conduit
    - Mean number of waste packages intersected = 3.8
    - Mean fraction of waste package content ejected = 0.3
    - Ash redistribution by fluvial processes after deposition
- **Groundwater transport from damaged packages that remain in the repository**
  - All waste packages in the repository assumed to be sufficiently damaged to provide no barrier to flow and transport
  - Groundwater flow and radionuclide transport assumed to occur as in nominal scenario

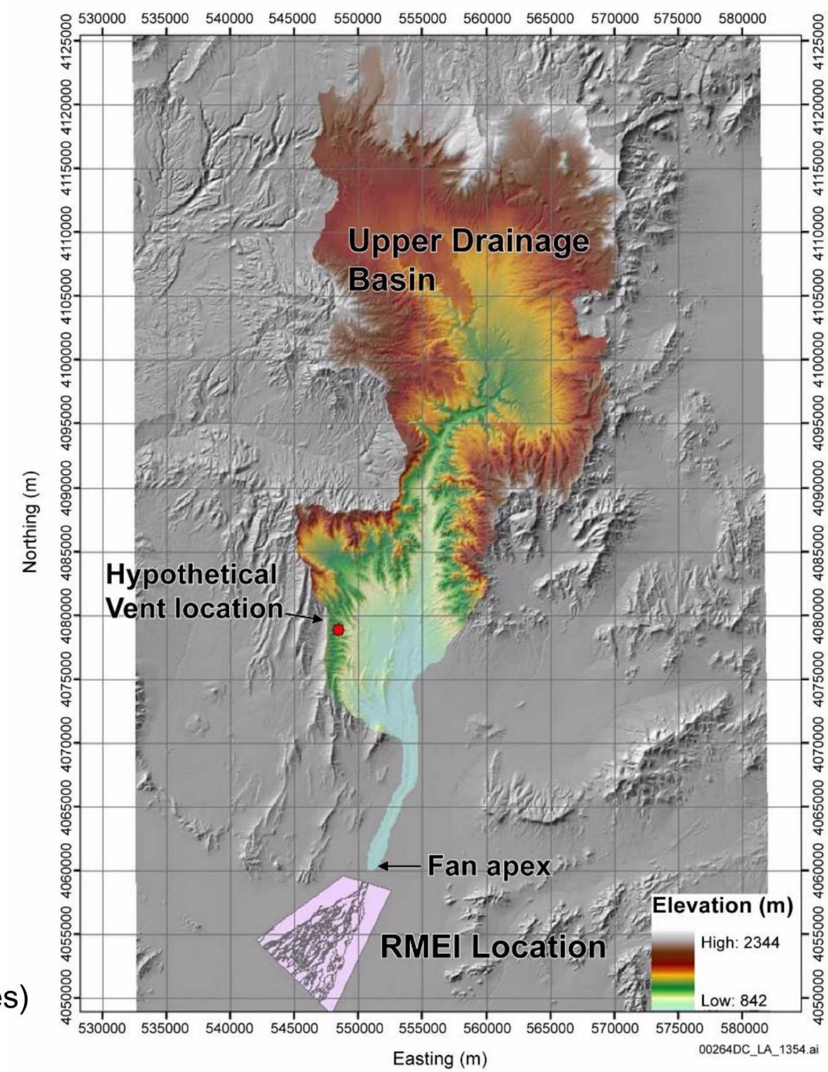
Modeling Consequences of Volcanic Eruption



Model results showing representative ash deposition following an eruption at Yucca Mountain (wind from west) (DOE/RW-0573 Rev. 1, Figure 2.3.11-16)

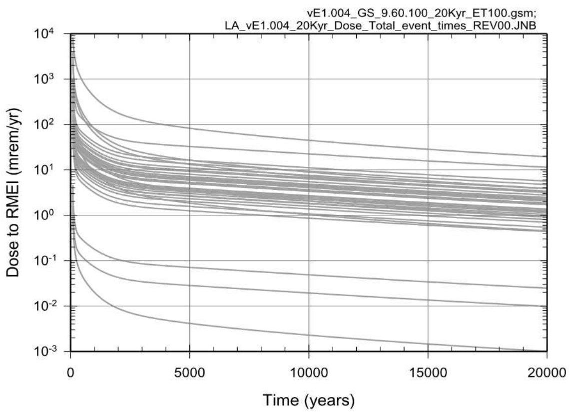
Uncertain variables include:

- Eruption properties, including power and duration
- Conduit diameter (controls number of waste packages)
- Wind speed and direction
- Ash particle size
- Fraction of waste entrained in ash (vs. lava)

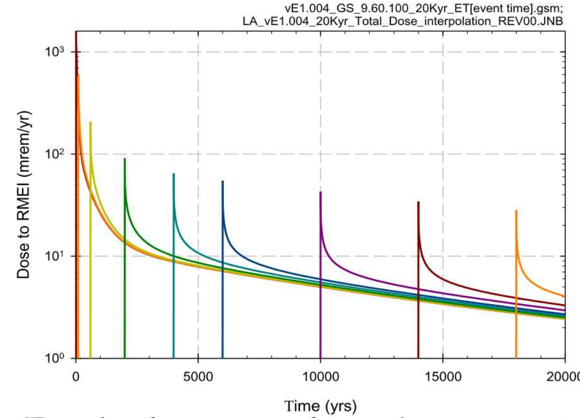


Model domain for surface redistribution of ash (DOE/RW-0573 Rev. 1, Figure 2.3.11-5)

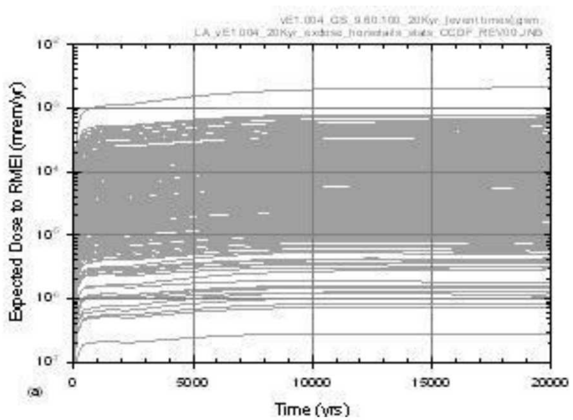
Estimating Mean Annual Dose from Unlikely Events: Eruptive Dose



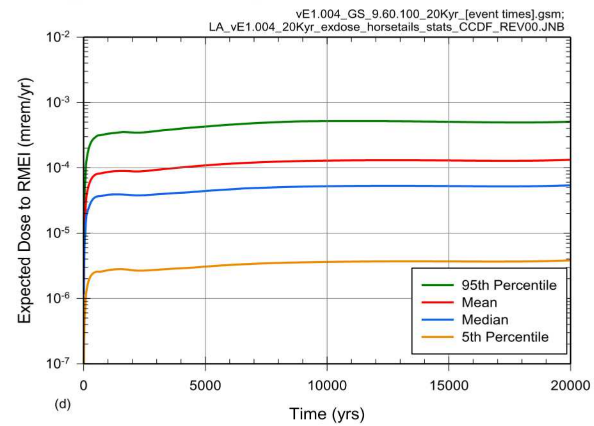
Eruptive dose: 40 realizations of aleatory uncertainty conditional on a single eruption of 1 WP at time zero



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, 3.2,& 3.4, http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app/references.html