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Sandia National Laboratories

Uncertainty and Sensitivity Analysis in the 2008 Performance Assessment for the Proposed Repository for High-Level Radioactive Waste at Yucca Mountain, Nevada

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Outline

- **Description of the proposed Yucca Mountain Repository**
- **Summary of regulatory requirements**
- **Structure of performance assessment**
- **Example uncertainty and sensitivity analysis results from performance assessment**

Waste for Yucca Mountain

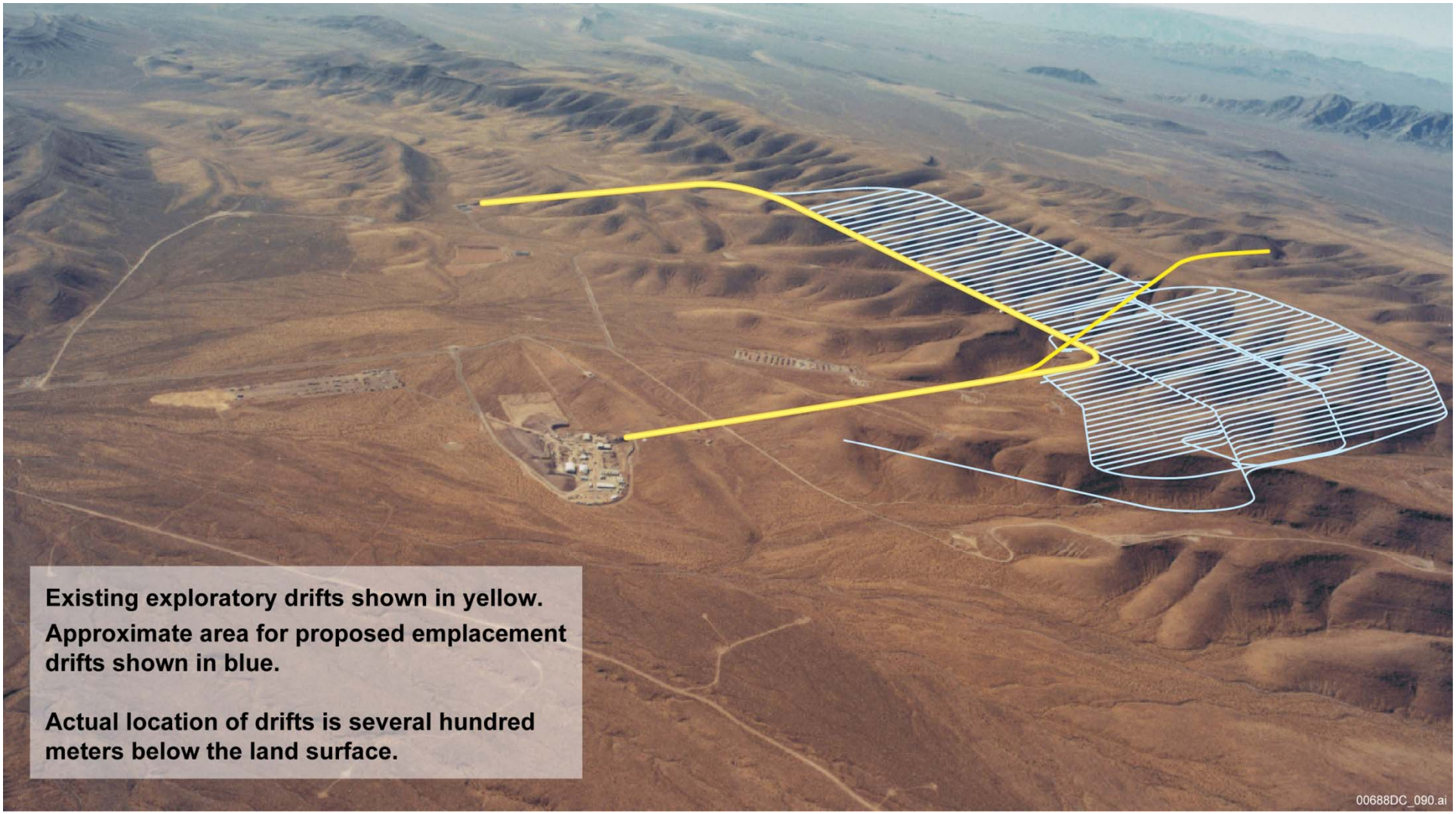
Commercial Spent Nuclear Fuel:
63,000 MTHM (~7500 waste packages)

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

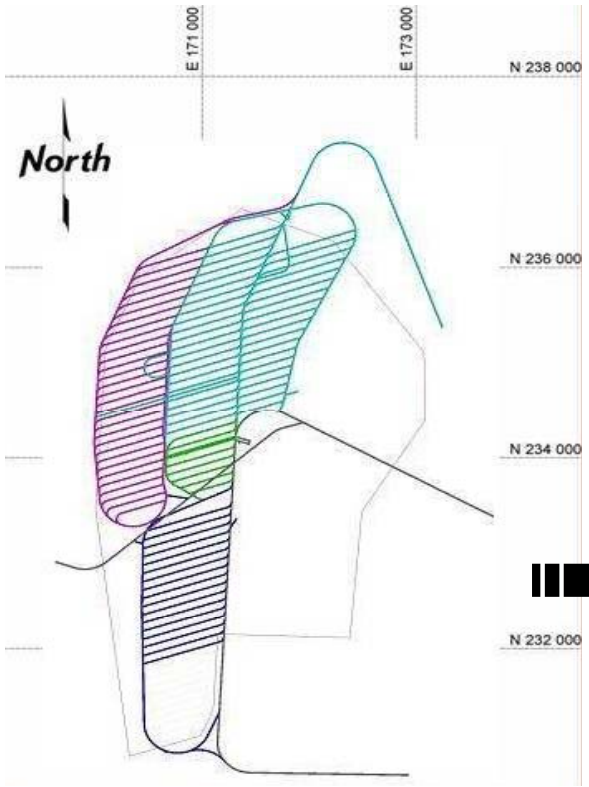
DOE & Commercial High-Level Waste:
4,667 MTHM
(~3000 waste packages of co-disposed DSNF and HLW)

DSNF: Defense Spent Nuclear Fuel
HLW: High Level Radioactive Waste
MTHM: Metric Tons Heavy Metal

Proposed Repository for High-Level Waste and Spent Fuel at Yucca Mountain



Yucca Mountain Subsurface Design



Emplacement drifts

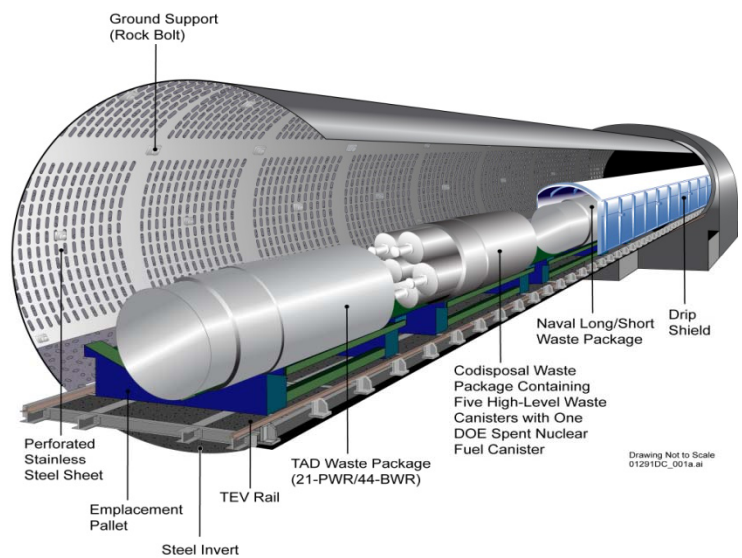
- 5.5 m diameter
- approx. 100 drifts, 600-800 m long

Waste packages

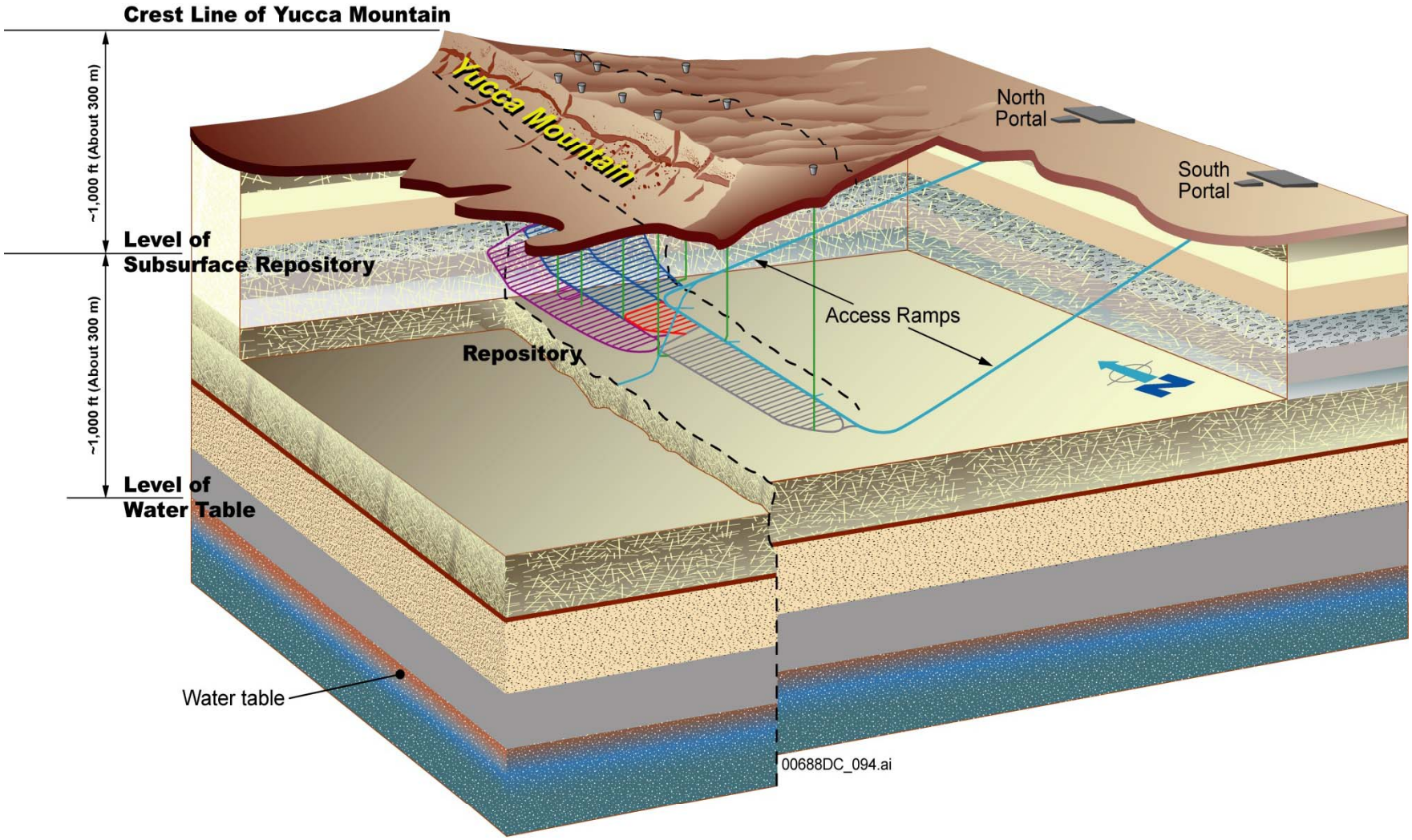
- ~11,000 packages
- ~ 5 m long, 2 m diameter
- outer layer 2.5 cm Alloy 22 (Ni-Cr-Mo-V)
- inner layer 5 cm stainless steel
  - Internal TAD (transportation, aging, and disposal) canisters for commercial spent fuel, 2.5 cm stainless steel

Drip shields

- free-standing 1.5 cm Ti shell



Yucca Mountain Natural Features



10 CFR 63 and 40 CFR Part 197
Core Regulatory Requirements for YM Repository

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

Four Questions Underlying YM TSPA
(Yucca Mountain Total System Performance Assessment)

- **Q1: What can happen?**
- **Q2: How likely is it to happen?**
- **Q3: What are the consequences if it does happen?**
- **Q4: What is the uncertainty in the answers to the first three questions?**

- *Guidance from YMRP*

Risk-Informed Review Process for Performance Assessment—The performance assessment quantifies repository performance, as a means of demonstrating compliance with the postclosure performance objectives at 10 CFR 63.113. The U.S. Department of Energy performance assessment is a systematic analysis that answers the triplet risk questions: what can happen; how likely is it to happen; and what are the consequences. **(YMRP - *Yucca Mountain Review Plan*, p. 2.2-1)**

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*

Example NRC Statements Related to Uncertainty in YM TSPA

Aleatory Uncertainty

The Commission expects that performance assessments conducted by the applicant in support of any potential license application will use probabilistic methods to simulate a wide range of possible future behaviors of the repository system. Each possible future behavior of the repository system is represented by a curve describing the annual dose to the RMEI as a function of time. Generally, but not necessarily, each of the possible curves is assumed to be equally likely. Because none of these possible futures can be demonstrated to describe the actual future behavior of the repository system, the Commission requires that the applicant calculate the mean of these dose versus time curves, properly weighted by their individual probabilities. **(10 CFR Parts 2,19,20, etc., p. 55813)**

Epistemic uncertainty

DOE is expected to conduct uncertainty analyses (i.e., evaluation of how uncertainty in parameter values affects uncertainty in the estimate of dose), including the consideration of disruptive events and associated probability of occurrence. **(10 CFR Parts 2,19,20, etc., p. 55747)**

The approach defined in part 63, which requires DOE to fully address uncertainties in its performance assessment rather than requiring DOE to meet a specific level of uncertainty, is appropriate. The treatment of uncertainty in DOE's performance assessment will be an important part of NRC's review. **(10 CFR Parts 2,19,20, etc., p. 55748)**

Basic Entities Underlying YM TSPA

EN1: Probabilistic characterization of what can happen in the future

- Answers first two questions
- Provides formal characterization of aleatory uncertainty

E.G. Assumption that igneous event occurrence is a Poisson process

EN2: Mathematical models for predicting consequences

- Answers third question

E.G. Models implemented in Goldsim

EN3: Probabilistic characterization of uncertainty in TSPA inputs

- Basis for answering fourth question
- Provides formal characterization of epistemic uncertainty

E.G. Distribution assigned to λ in Poisson process for igneous event

Basic Entities Underlying YM TSPA

EN1: Probabilistic characterization of what can happen in the future

Aleatory uncertainty

- **a** = [a_1,a_2,…] vector characterizing a possible future at YM site
  - *E.G.* $\mathbf{a} = [nSG, t_1, v_1, t_2, v_2, \cdots, t_{nSG}, v_{nSG}]$ *for seismic ground motion events in time interval [0 , 10^4 yr], where nSG= number of seismic events, t_i = time (yr) of ith event, and v_i = PGV for i^{th} event*
- $\mathcal{A}$ = set of all possible values for **a**
- Formally, a probability space ($\mathcal{A}$, A, p_A) with density function d_A(**a**)

TSPA AMR, Sect J4.4

EN3: Probabilistic characterization of uncertainty in TSPA inputs

Epistemic uncertainty

- **e** = [$\mathbf{e}_A$,$\mathbf{e}_M$] = [e_1,e_2,…,e_{nE}] vector of uncertainty in TSPA inputs
  - $\mathbf{e}_A$ *vector of uncertain inputs used in characterizing aleatory uncertainty*
  - $\mathbf{e}_M$ *vector of uncertain model inputs used in calculating consequences*
- $\mathcal{E}$ = set of all possible values for **e**
- Formally, a probability space ($\mathcal{E}$, E, p_E) with density function d_E(**e**)

TSPA AMR, Tables K3-1, K3-2, K3-3

EN2: Mathematical models for predicting consequences

- Sequence of complex linked models
  - *E.G.* $D(\tau \mid \mathbf{a}, \mathbf{e}_M)$ *= dose to RMEI (mrem/yr) at time τ for future* **a** *and conditional on parameter values in* $\mathbf{e}_M$

TSPA AMR, Chapter 6

EN1: Probability Space For Aleatory Uncertainty

- Defining vector for individual future **a** *(Eq. J4.4-1)*

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

where, for the time interval $[0, 2\times10^4 \text{ yrs}]$ or $[0, 10^6 \text{ yrs}]$

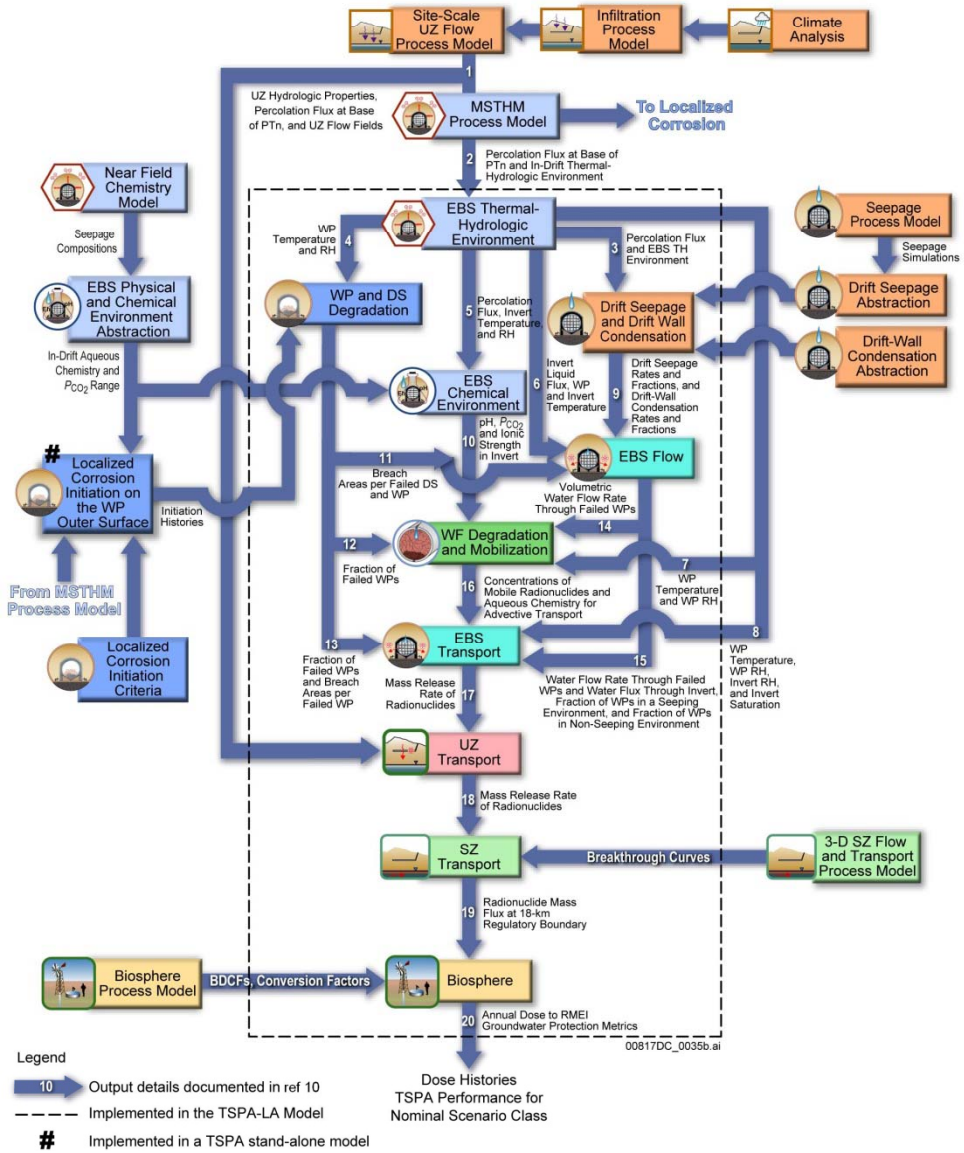
- nEW = number of early WP failures
- nED = number of early DS failures
- nII = number of igneous intrusive events
- nIE = number of igneous eruptive events
- nSG = number of seismic ground motion events
- nSF = number of fault displacement events

- $\mathbf{a}_{EW}$ = vector defining nEW early WP failures *(Eqs. J6.1-12, J6.2-1)*
- $\mathbf{a}_{ED}$ = vector defining nED early DS failures *(Eqs. J6.1-13, J6.3-1)*
- $\mathbf{a}_{II}$ = vector defining nII igneous intrusive events *(Eqs. J7.1-8, J7.2-1)*
- $\mathbf{a}_{IE}$ = vector defining nIE igneous eruptive events *(Eqs. J7.1-9, J7.3-1)*
- $\mathbf{a}_{SG}$ = vector defining nSG seismic ground motion events *(Eqs. J8.1-8, J8.2-1, J8.3-1)*
- $\mathbf{a}_{SF}$ = vector defining nSF fault displacement events *(Eqs. J8.1-9, J8.6-1)*

- Set $\mathcal{A}$ of all futures *(Eq. J4.4-2)*

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

EN2: Models for Nominal Scenario Class



EN3: Probability Space for Epistemic Uncertainty

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

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

Computational Strategy

- **Maintain separation of aleatory and epistemic uncertainty**
  - Epistemic uncertainty in expected dose and other quantities
  - Informative sensitivity analyses
- **Procedures for uncertainty propagation**
  - Sampling-based (LHS) for epistemic uncertainty
  - Integration-based for aleatory uncertainty
- **Seek computational efficiencies in calculation of expected dose**
  - Linearities
  - Interpolations
  - Efficient use of computationally expensive results
- **Produce three types of results for presentation and/or sensitivity analysis**
  - Distributions and expected values over epistemic uncertainty conditional on a specific realization of aleatory uncertainty
  - Distributions and expected values over aleatory uncertainty conditional on a specific realization of epistemic uncertainty
  - Expected values over both aleatory and epistemic uncertainty

Computational Strategy (cont.)

- **Perform extensive sensitivity analysis**
  - ➢ Investigation of sampling-based mapping between uncertain TSPA inputs and TSPA results
  - ➢ Multiple locations: WP, EBS, UZ, SZ, RMEI
  - ➢ Multiple time-dependent and spatially-dependent results: Solubilities, ionic strength, pH, temperature, release rates, integrated releases, dose
  - ➢ Multiple radionuclides
  - ➢ Multiple scenarios: nominal, early WP failure, early DS failure, igneous intrusive, igneous eruptive, seismic ground motion, seismic Fault displacement
  - ➢ Multiple potential sensitivity analysis procedures

    → Examination of scatterplots and cobweb plots
    → Correlation and partial correlation analysis
    → Regression analysis
    → Stepwise regression analysis
    → Rank transforms to linearize monotonic relationships
    → Nonparametric regression: Loess, additive models, projection pursuit, recursive partitioning
    → Tests for patterns based on gridding: nonmonotonic relations, nonlinear relations
    → Tests for patterns based on distance measures
    → Multidimensional Kolmogorov-Smirnov test
    → Tree-based searches
    → Squared differences of ranks
    →Top-down concordance with replicated samples
    →Variance decomposition

- **Employ sensitivity analysis as part of analysis verification**

Expected Dose

- **Formal representation**

$$\overline{D}(\tau|\mathbf{e}_M) = E_A[D(\tau \mid \mathbf{a},\mathbf{e}_M) \mid \mathbf{e}_A] = \int_{\mathcal{A}} D(\tau \mid \mathbf{a},\mathbf{e}_M)\, d_A(\mathbf{a} \mid \mathbf{e}_A)\, dA, \qquad \mathbf{e} = [\mathbf{e}_A, \mathbf{e}_M]$$

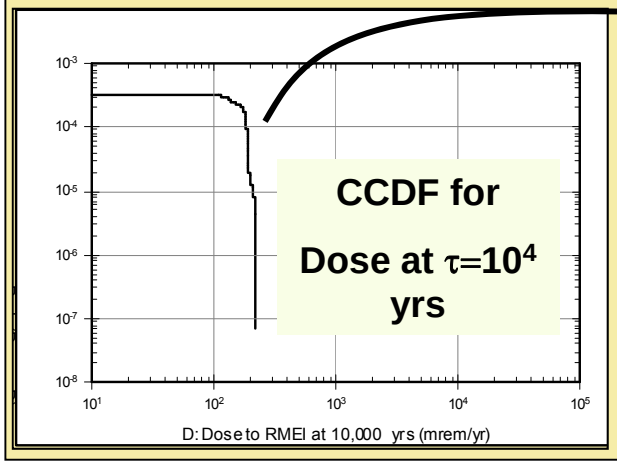
- **Approximation**

$$E_A[D(\tau \mid \mathbf{a},\mathbf{e}_M) \mid \mathbf{e}_A] \cong \begin{cases} \sum_{i=1}^{n} D(\tau|\mathbf{a}_i,\mathbf{e}_M)/n & \text{Monte Carlo: } \mathbf{a}_i\text{'s sampled from } \mathcal{A} \text{ consistent with } d_A(\mathbf{a}|\mathbf{e}_A) \\ \sum_{i=1}^{n} D(\tau|\mathbf{a}_i,\mathbf{e}_M)\, p_A(\mathcal{A}_i|\mathbf{e}_A) & \text{Quadrature: } \mathcal{A} = \cup\, \mathcal{A}_i \;,\; \mathcal{A}_i \cap \mathcal{A}_j = \varnothing \end{cases}$$

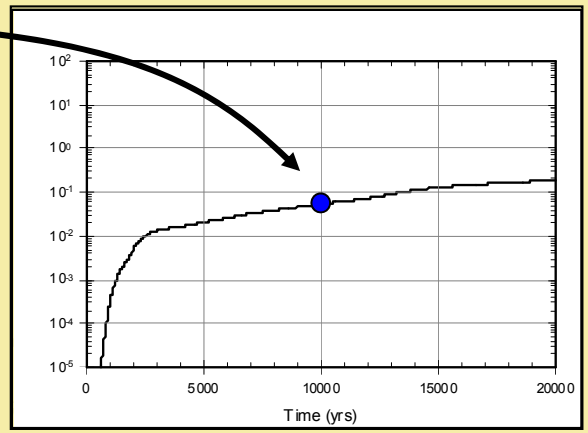
$p_A(\mathcal{A}_i|\mathbf{e}_A)$ = probability for $\mathcal{A}_i$ consistent with $d_A(\mathbf{a}|\mathbf{e}_A)$

Ordered triplet: $\{[\mathcal{A}_i, p_A(\mathcal{A}_i|\mathbf{e}_A), D(\tau|\mathbf{a}_i,\mathbf{e}_M)], i = 1,2,\cdots,n\}$

- **Graphical representation (Ex: Igneous intrusion)**



$$E_A[D(10^4 \mid \mathbf{a},\mathbf{e}_M) \mid \mathbf{e}_A]$$



Uncertainty in Expected Dose over Aleatory Uncertainty

- **Different value for**

$$E_A\left[D(\tau \mid \mathbf{a}, \mathbf{e}_M)\middle|\mathbf{e}_A\right] = \int_{\mathcal{A}} D(\tau \mid \mathbf{a}, \mathbf{e}_M)\, d_A(\mathbf{a} \mid \mathbf{e}_A)\, \mathrm{d}A$$

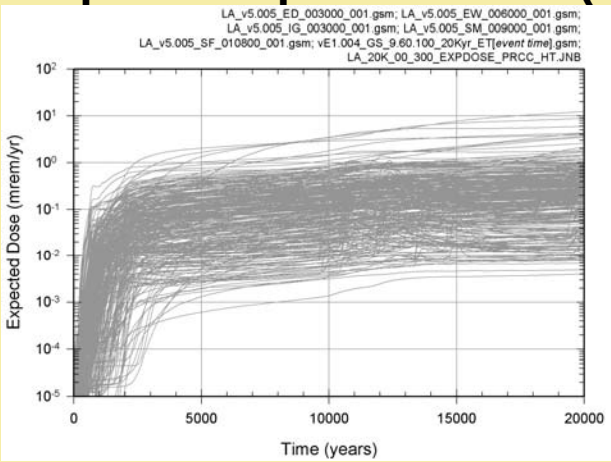
for each $\mathbf{e} = [\mathbf{e}_A, \mathbf{e}_M]$

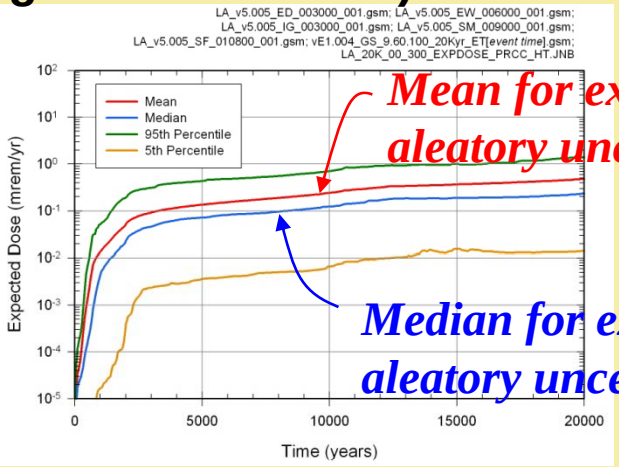
- **Approximation to uncertainty in** $E_A\left[D(\tau \mid \mathbf{a}, \mathbf{e}_M)\middle|\mathbf{e}_A\right]$

$$E_A[D(\tau \mid \mathbf{a}, \mathbf{e}_{Mj})|\mathbf{e}_{Aj}], \quad j = 1, 2, \cdots, n$$

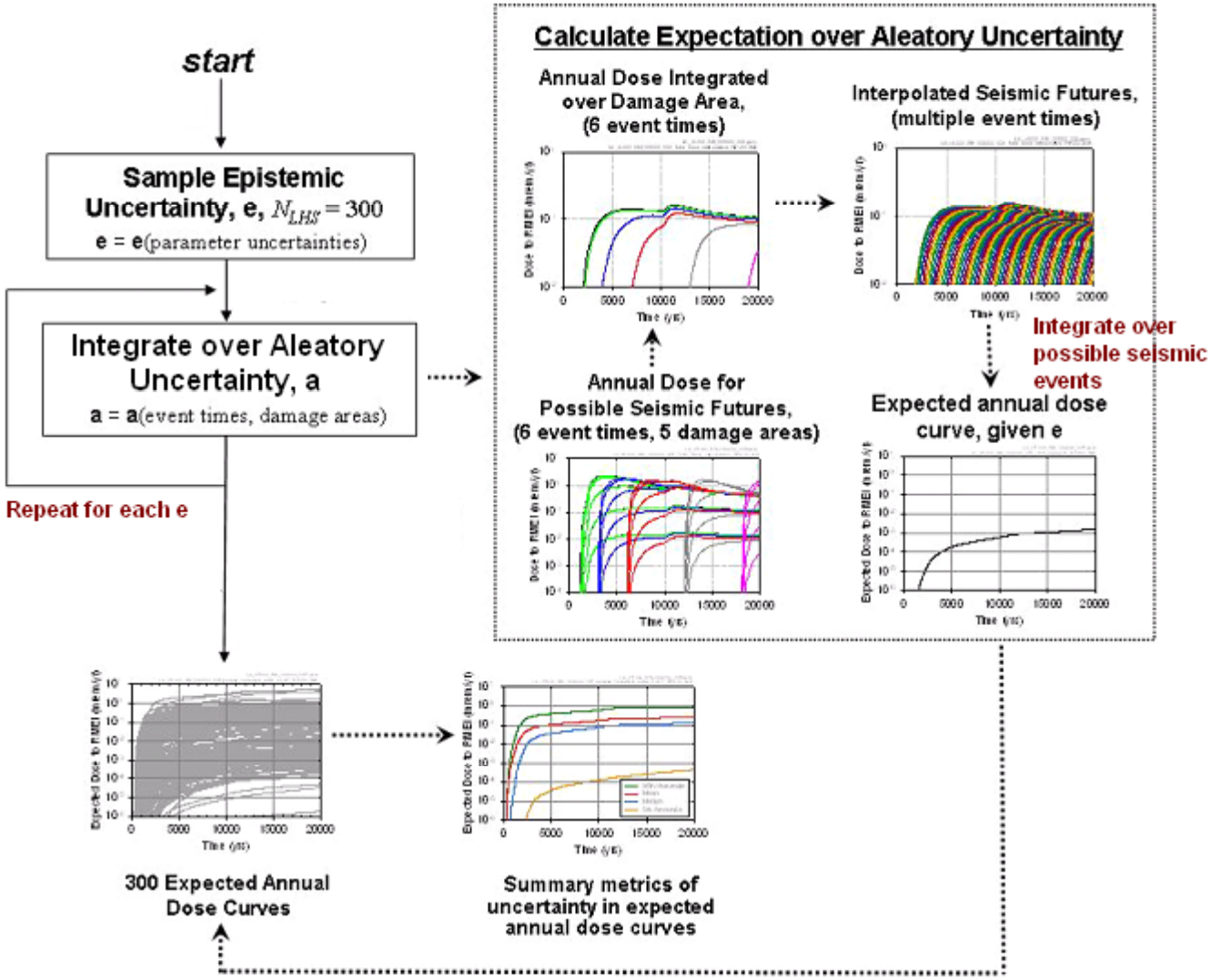
for LHS $\mathbf{e}_1, \mathbf{e}_2, \ldots, \mathbf{e}_n$ **from** $\mathcal{E}$ **consistent with** $d_E(\mathbf{e})$

- **Graphical representation (Ex: Igneous intrusion)**





Calculation of Expected Dose (seismic GM)



Decomposition of Expected Dose $\overline{D}(\tau \mid \mathrm{e})$ Conditional on e=[e_A,e_M]

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

$$= \int_{\mathcal{A}} D(\tau \mid \mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a} \mid \mathbf{e}_A) \mathrm{d}A$$ **(Conservation of probability)**

$$\cong \int_{\mathcal{A}} \sum_{S \in \mathcal{S}} D_S(\tau \mid \mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a} \mid \mathbf{e}_A) \mathrm{d}A, \quad \mathcal{S} = \{N, EW, ED, II, IE, SG, SF\}$$

(No significant synergisms approximation)

$$= \sum_{S \in \mathcal{S}} \int_{\mathcal{A}_S} D_S(\tau \mid \mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a} \mid \mathbf{e}_A) \mathrm{d}A$$

$$= D_N(\tau \mid \mathbf{e}_M) + \overline{D}_{EW}(\tau \mid \mathbf{e}) + \overline{D}_{ED}(\tau \mid \mathbf{e}) + \overline{D}_{II}(\tau \mid \mathbf{e}) + \overline{D}_{IE}(\tau \mid \mathbf{e}) + \overline{D}_{SG}(\tau \mid \mathbf{e}) + \overline{D}_{SF}(\tau \mid \mathbf{e})$$

where

- $D_S(\tau \mid \mathbf{a}, \mathbf{e}_M)$ ~ dose (mrem/yr) at time τ from part of **a** corresponding to event $\mathcal{S}$
- $\mathcal{A}_S$ ~ subset of $\mathcal{A}$ in which event S occurs
- N ~ nominal conditions……...Nominal scenario class
- EW ~ early WP failure events • ED ~ early DS failure events…….Early failure scenario class
- II ~ igneous intrusive events • IE ~ igneous eruptive events……...Igneous scenario class
- SG ~ seismic ground motion events • SF ~ fault displacement events……..……..Seismic scenario class

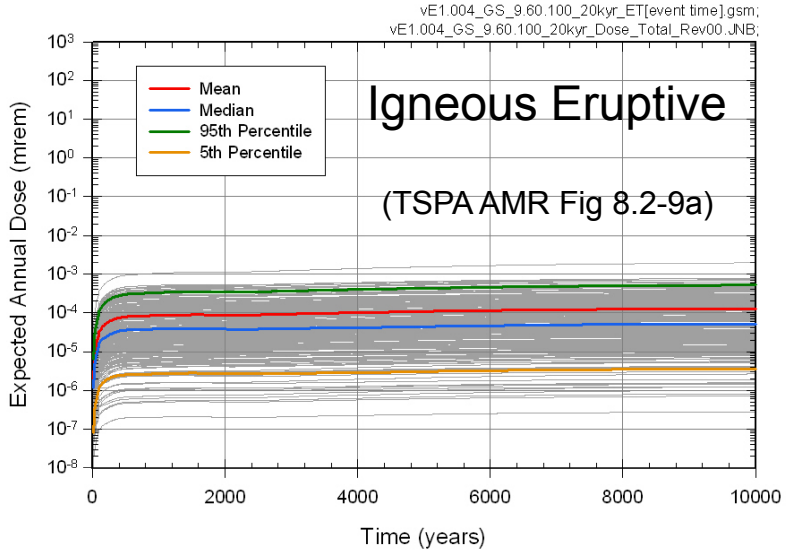
TSPA AMR, Sect J4.6-J4.8

Evaluation of $\overline{D}_S(\tau \mid \mathbf{e}) = \int_{\mathcal{A}_S} D_S(\tau \mid \mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a} \mid \mathbf{e}_A) \mathrm{d}A$

for $S = \{N, EW, ED, II, IE, SG, SF\}$

- N ~ nominal conditions — ***TSPA AMR, Sect. J5***
  - Always zero for $[0, 2\times10^4\ yrs]$
  - Combined with seismic ground motion (SG) for $[0, 10^6\ yrs]$
- EW, ED ~ early WP and DS failures — ***TSPA AMR, Sect. J6***
  - Summation of probabilistically weighted results for individual failures
- II ~ igneous intrusive events — ***TSPA AMR, Sect. J7***
  - Quadrature procedure
- IE ~ igneous eruptive events — ***TSPA AMR, Sect. J7***
  - Combinated quadrature/Monte Carlo procedure
- SG ~ seismic ground motion events — ***TSPA AMR, Sect. J8***
  - Quadrature procedure for $[0, 2\times10^4\ yrs]$
  - Monte Carlo procedure for $[0, 10^6\ yrs]$
- SF ~ fault displacement events — ***TSPA AMR, Sect. J8***
  - Quadrature procedure

Total Expected Dose



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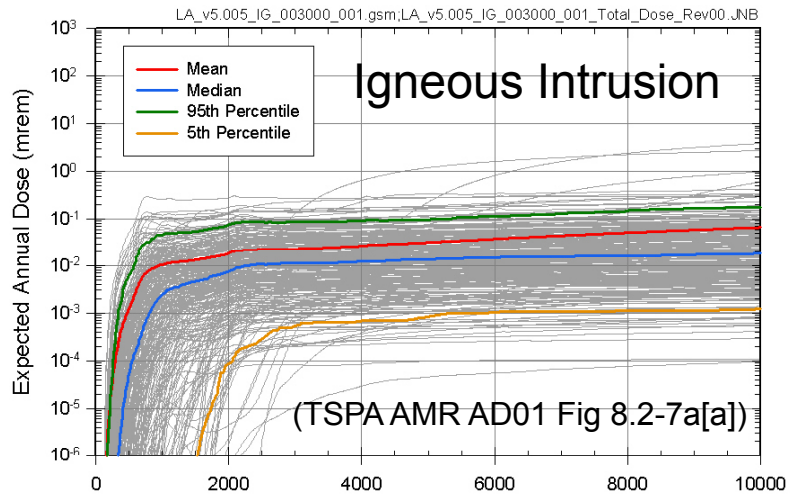

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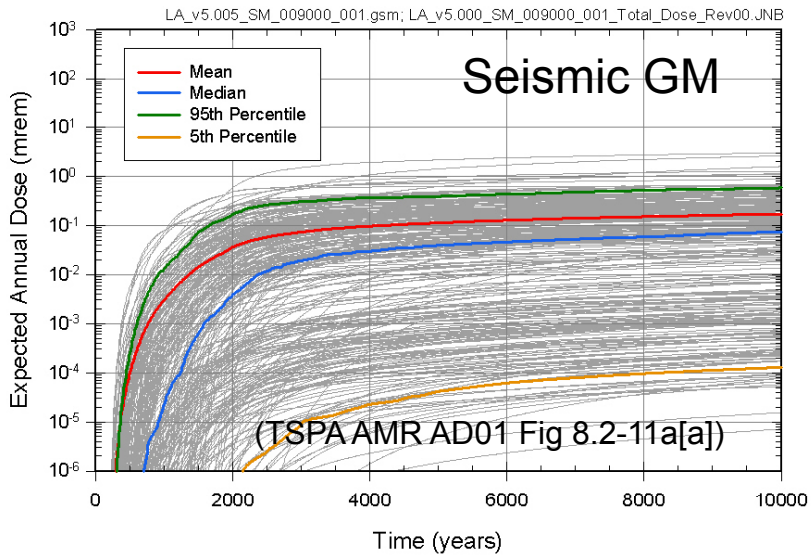

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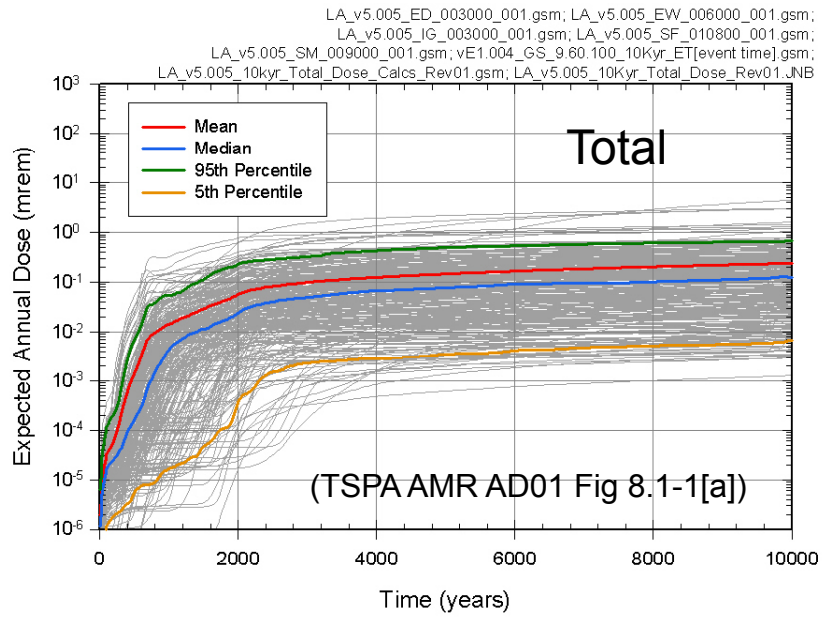
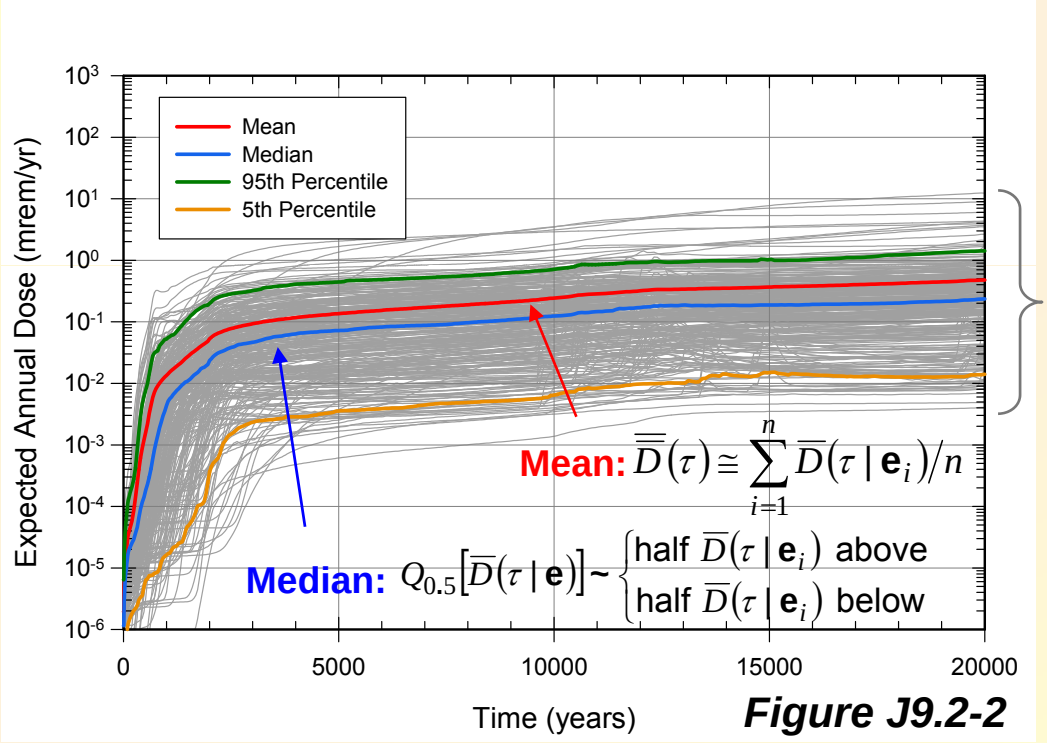


Epistemic Uncertainty in Expected Dose $\overline{D}(\tau \mid \mathbf{e})$

- Derives from probability space $(\mathcal{E}, \mathrm{E}, p_E)$ *(TSPA AMR, Sect. J3.5, Tables K3-1, K3-2, K3-3)*
- Assess with LHS $\mathbf{e}_i$, i=1,2,…,n, from $\mathcal{E}$ *(TSPA AMR, Sect. J3.5, J4.9, J4.10)*



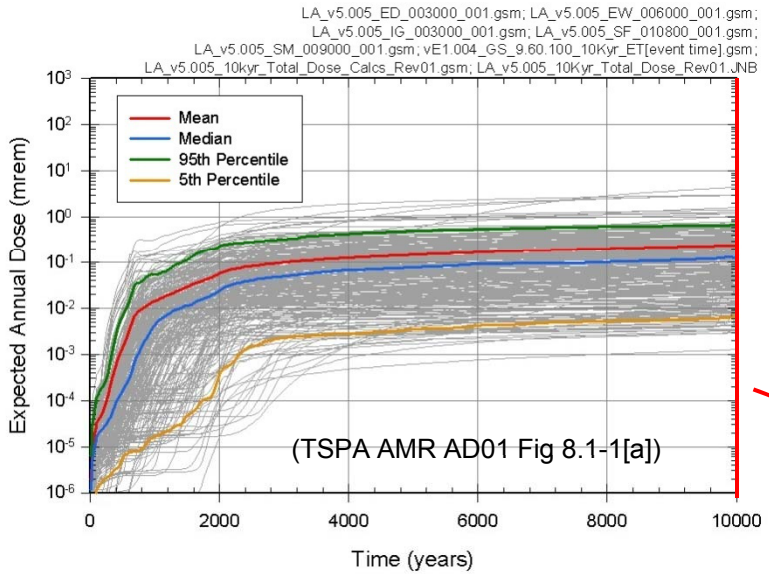
Each grey curve
$$\overline{D}(\tau \mid \mathbf{e}_i) = \sum_{S \in \mathcal{S}} \overline{D}_S(\tau \mid \mathbf{e}_i)$$

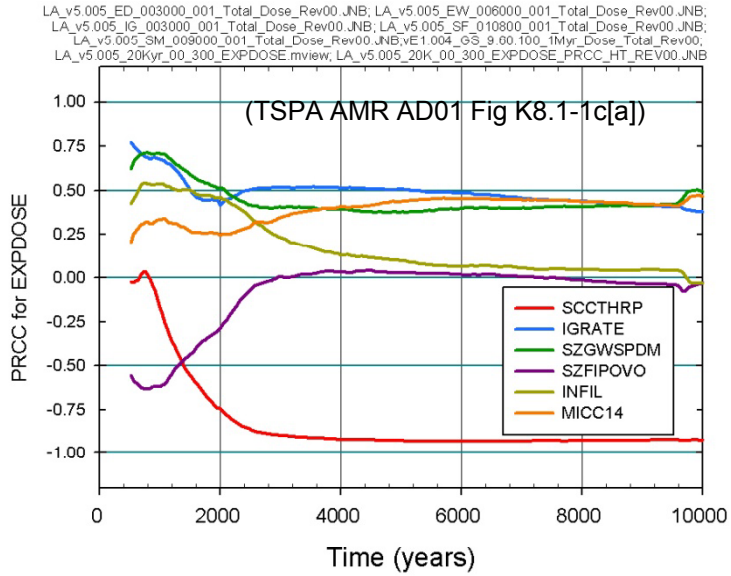
Figure J9.2-2

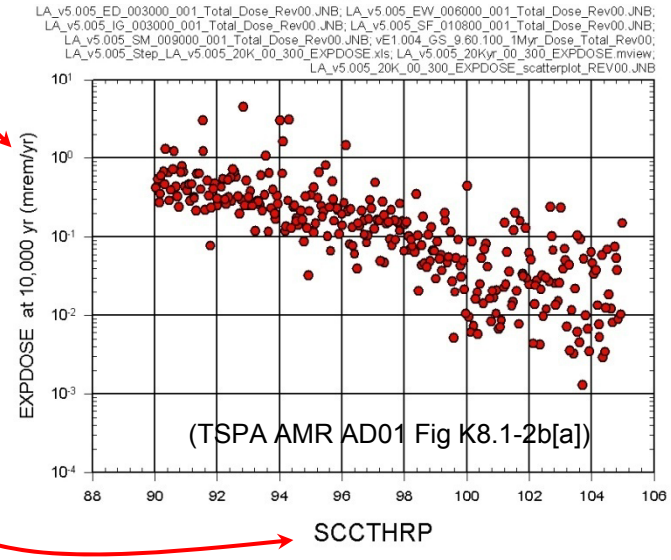
- Perform sensitivity analysis on mapping *(TSPA AMR, App. K)*

$$\left[\mathbf{e}_i, \overline{D}(\tau \mid \mathbf{e}_i), D_N(\tau \mid \mathbf{e}_i), \overline{D}_{EW}(\tau \mid \mathbf{e}_i), \cdots\right], \; i = 1, 2, \cdots, n$$

Uncertainty in Total Expected Dose

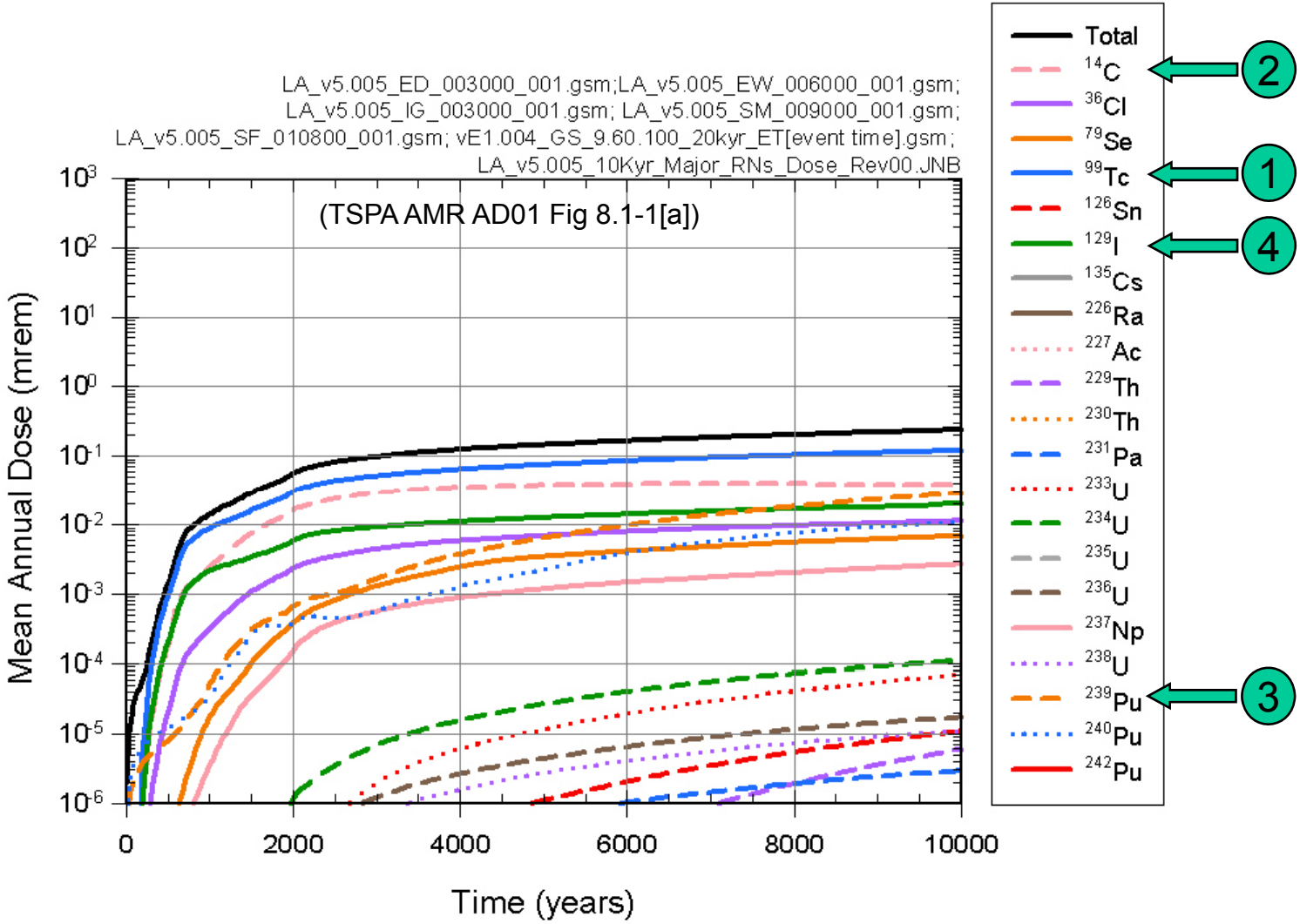




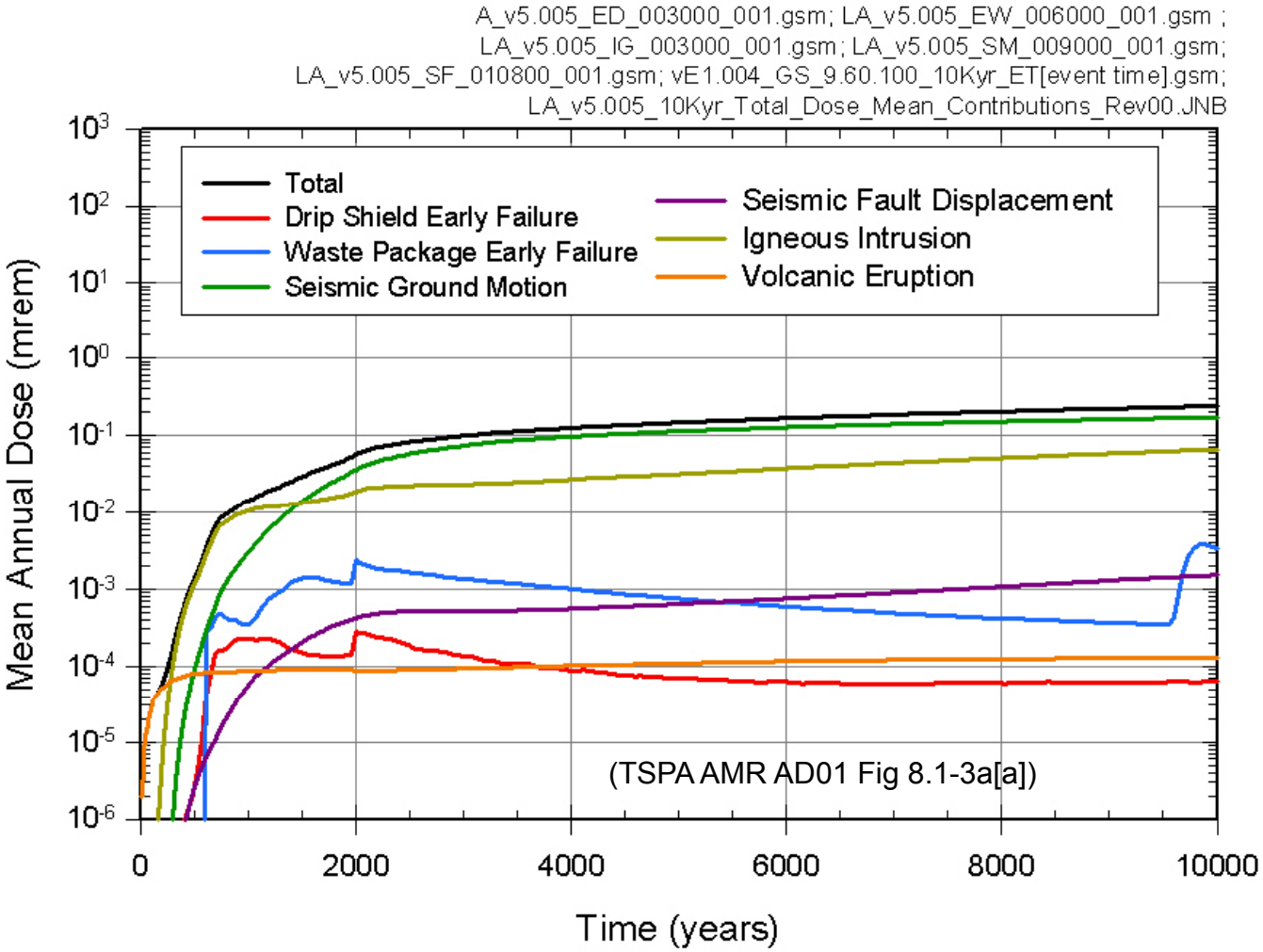


SCCTHRP – stress threshold for SCC initiation (90 to 105% of yield strength)
IGRATE – frequency of igneous events
SZGWSPDM – logarithm of uncertainty factor in groundwater specific discharge
SZFIPOVO – flowing interval porosity in volcanic units
INFIL – infiltration case
MICC14 – biosphere dose conversion factor for C14

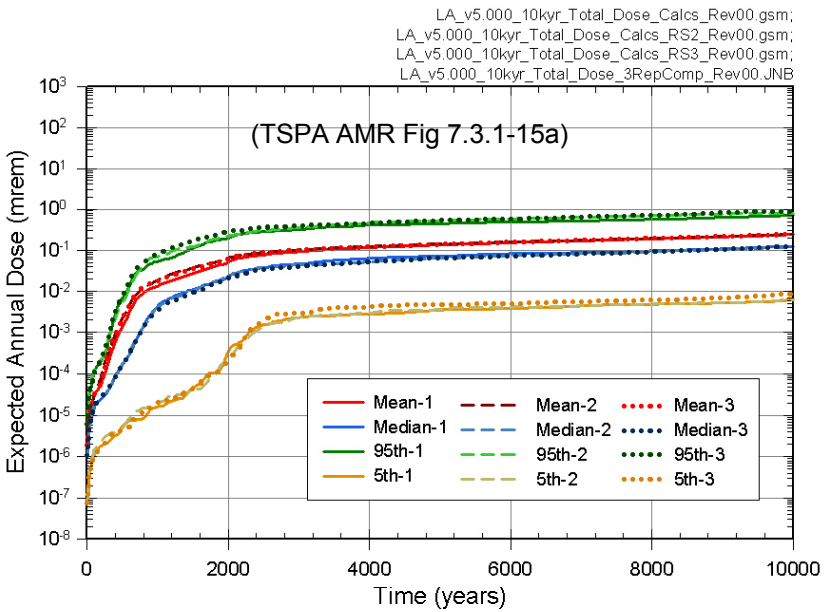
Radionuclides Contributing to Total Mean Dose at 10,000 Years

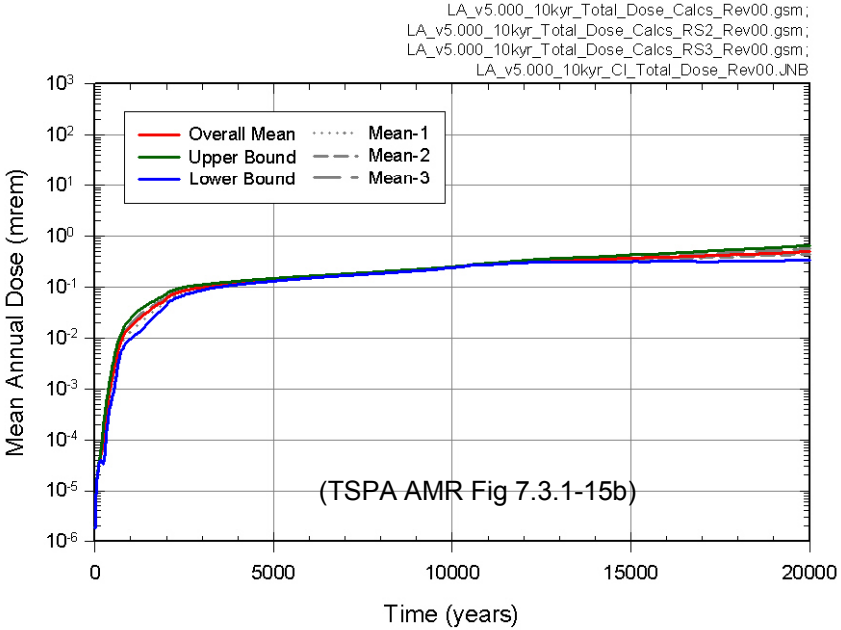


Total Mean Dose Contributions By Modeling Case



Stability of Total Dose

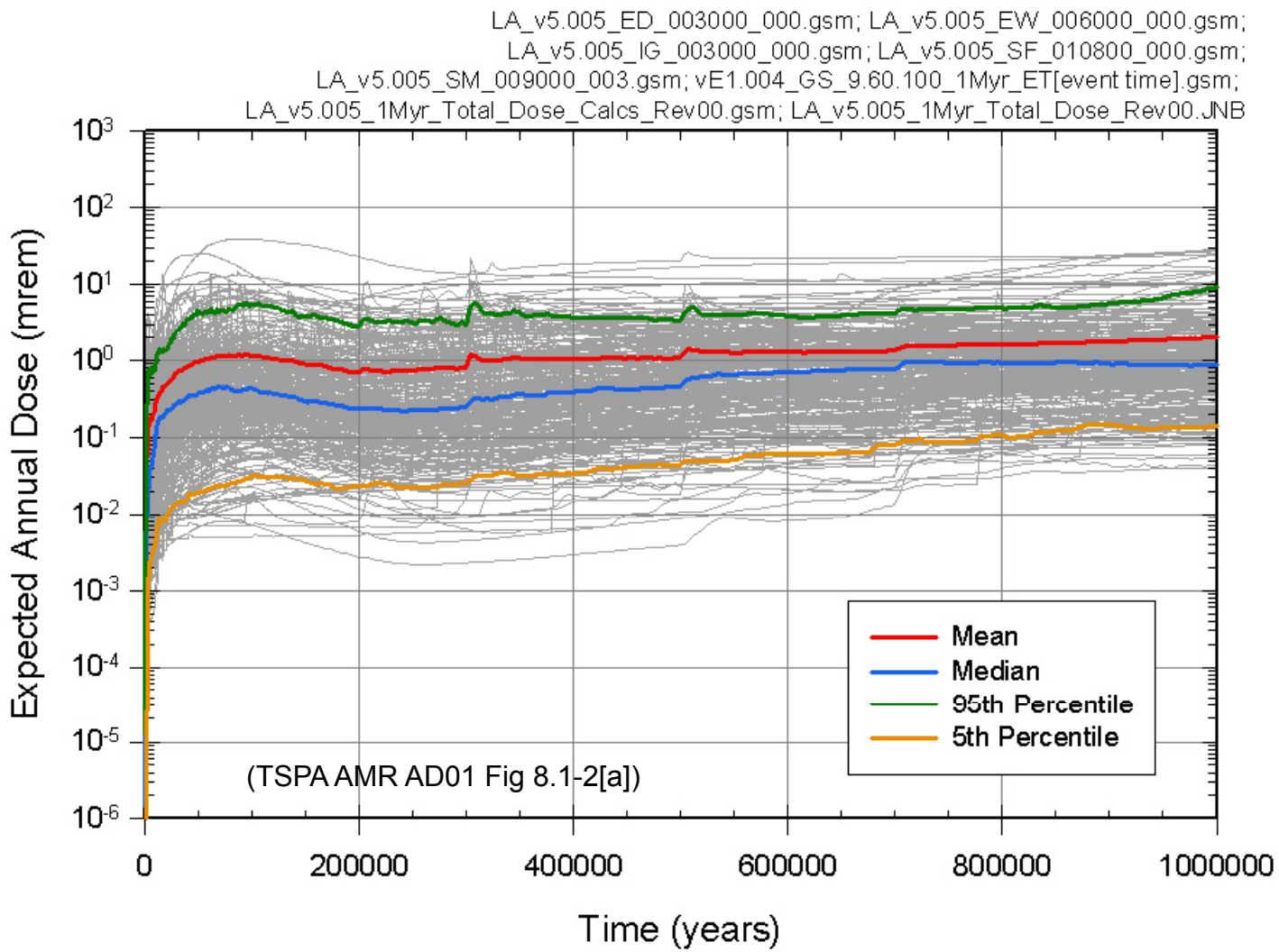




Replicated sampling demonstrates that sample size is sufficient

Confidence interval illustrates precision of estimate of total mean dose

Total System Performance Assessment Results (post-10,000-year period)



BACKUP SLIDES

Basic Parts of Analysis

- Characterization of uncertainty in occurrence of future events (EN1)
  - Probability space ($\mathcal{A}$, A, p_A) for aleatory uncertainty
  - Each element **a** of $\mathcal{A}$ a possible future
- Characterization of uncertainty in analysis inputs (EN3)
  - Probability space ($\mathcal{E}$, E, p_E) for epistemic uncertainty
  - Each element $\mathbf{e}=[\mathbf{e}_A,\mathbf{e}_M]$ of $\mathcal{E}$ uncertain input to analysis
- Models for predicting physical behavior and evolution of repository (EN2)
  - Function $\mathbf{y}(\tau|\mathbf{a},\mathbf{e}_M)$ of time τ, future **a** and uncertain inputs $\mathbf{e}_M$
  - Many different forms depending on future **a**
  - $\mathbf{y}(\tau|\mathbf{a},\mathbf{e}_M)$ has many components: conditions in EBS, releases from EBS, UZ and SZ, dose to RMEI, …

Approach to Uncertainty and Sensitivity Analysis

- Define distributions for uncertain analysis inputs (i.e., define probability space ($\mathcal{E}$, E, p_E) for epistemic uncertainty)

- Select specific futures for analysis (i.e., elements **a** of $\mathcal{A}$)

- Generate Latin Hypercube Sample (LHS) $\mathbf{e}_{Mi}$, i=1,2,….,n, from $\mathcal{E}$ consistent with defining distributions for ($\mathcal{E}$, E, p_E)

- Evaluate $\mathbf{y}(\tau|\mathbf{a},\mathbf{e}_{Mi})$, i=1,2,…,n, for each future **a** selected for consideration

- Present uncertainty results: Cumulative and complementary cumulative distribution functions (CDFs, CCDFs), quantiles, expected values, …

- Perform sensitivity analysis on mapping $[\mathbf{e}_{Mi},\mathbf{y}(\tau|\mathbf{a},\mathbf{e}_{Mi})]$, i=1,2,…,n: scatterplots, partial rank correlation coefficients (PRCCs), stepwise rank regressions, …

Scale of Analysis

- 392 epistemically uncertain analysis inputs (i.e., $\mathbf{e}_M=[e_{M,1},e_{M,2},\ldots,e_{M,392}]$)
- Futures corresponding to a variety of modeling cases considered: *nominal conditions, early WP failure, early DS failure, igneous intrusion, igneous eruption, seismic ground motion, seismic fault displacement*
- LHS of size n=300 used
- $\mathbf{y}(\tau|\mathbf{a},\mathbf{e}_{Mi})$, i=1,2,…,n=300, evaluated for each future **a** under consideration
- Approximately 70 time-dependent results (i.e., elements of $\mathbf{y}(\tau|\mathbf{a},\mathbf{e}_{Mi})$) analyzed (as presented in next slide)
- Analysis replicated 3 times to test for stability
- Example results follow

Nominal Scenario Class: Results for Analysis

- Examples of 11 of 32 Time-Dependent Results (i.e., elements of $\mathbf{y}(\tau|\mathbf{a},\mathbf{e}_i)$) analyzed for nominal scenario class

BACSFLAD : Average breached area (m^2) on failed CSNF WPs under dripping conditions
DOSTOT: Dose to RMEI (mrem/yr) from all radioactive species
DSFLTM : Drip Shield failure time (yr)
ISCSINAD : Ionic strength (molal) in the invert beneath the WP for CSNF WPs under dripping conditions
NCDFL : Number of failed CDSP WPs
NCSFL : Number of failed CSNF WPs
NCSFLAD : Number of failed CSNF WPs under dripping conditions
NCSFLND : Number of failed CSNF WPs under nondripping conditions
PCO2CSIA : Partial pressure of CO_2 (bars) in the invert for CSNF WPs under dripping conditions
PHCSINAD : pH in the invert beneath the WP for CSNF WPs under dripping conditions
RHCDINV : Relative humidity for CDSP WPs in the invert beneath the WP

Nominal Scenario Class: Uncertain Analysis Inputs

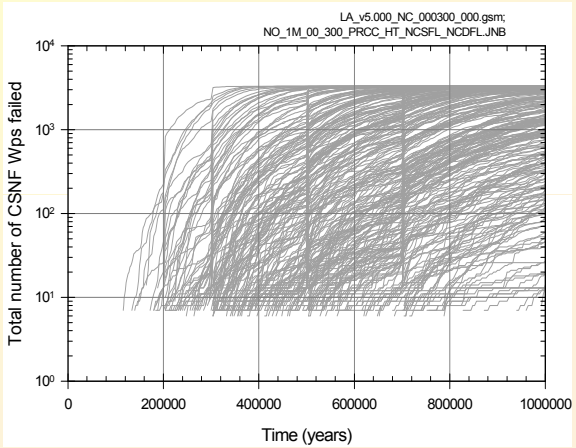
- Examples of variables (i.e., elements of **e**) identified in sensitivity analyses for nominal scenario class

WDGCA22: Temperature dependent slope term of Alloy 22 general corrosion rate (K). *Distribution:* Truncated normal. *Range:* 666 to 7731. *Mean:* 4905. *Standard Deviation:* 1413.
WDZOLID : Deviation from median yield strength range for outer lid (dimensionless). *Distribution:* Truncated normal. *Range:* -3 to 3. *Mean:* 0. *Standard Deviation:* 1.
INFIL : Pointer variable for determining infiltration conditions: 10th, 30th, 50th or 90th percentile infiltration scenario (dimensionless). *Distribution:* Discrete. *Range:* 1 to 4.
THERMCON : Selector variable for one of three host-rock thermal conductivity scenarios (low, mean, and high) (dimensionless). *Distribution:* Discrete. *Range:* 1 to 3.
WDNSCC : Stress corrosion cracking growth rate exponent (repassivation slope) (dimensionless). *Distribution:* Truncated normal. *Range:* 0.935 to 1.395. *Mean:* 1.165. *Standard Deviation:* 0.115.
WDGCUA22: Variable for selecting distribution for general corrosion rate (low, medium, or high) (dimensionless). *Distribution:* Discrete. *Range:* 1 to 3.
SCCTHR : Stress threshold for stress corrosion cracking (MPa). *Distribution:* Uniform. *Range:* 315.9 to 368.55.

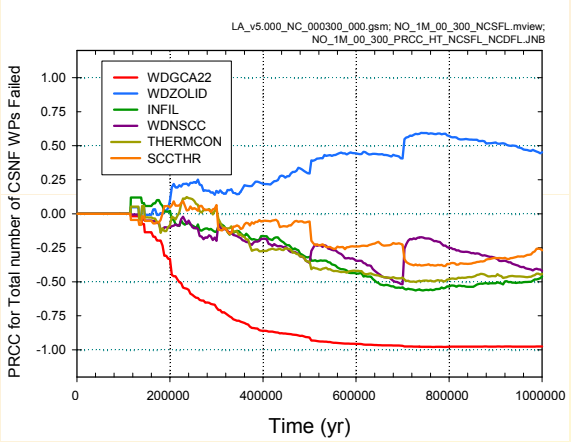
Nominal Scenario Class: Number of Failed CSNF WPs (*NCSFL*)

- Uncertainty and sensitivity analysis results for *NCSFL*: (a) *NCSFL* for all (i.e., 300) sample elements, (b) PRCCs for *NCSFL*, (c) stepwise rank regression analysis for *NCSFL* at 10^6 yr, and (d) scatterplot for (*WDGCA22, NCSFL*) at 10^6 yr

(a)



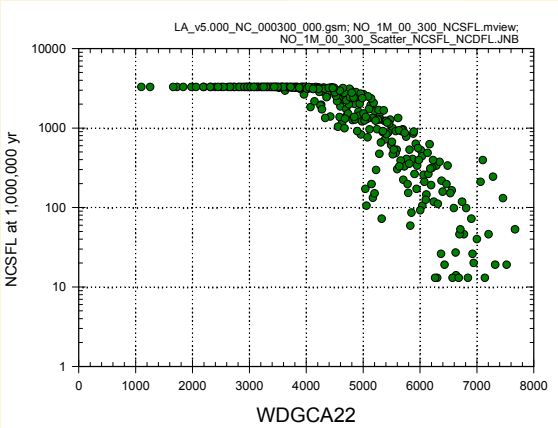
(b)



(c)

NCSFL: 1M yr		
Variable	**R^2**	**SRRC**
WDGCA22	0.91	-0.98
WDZOLID	0.92	0.10
INFIL	0.93	-0.12
THERMCON	0.94	-0.10
WDNSCC	0.95	-0.09
WDGCUA22	0.96	0.09
SCCTHR	0.96	-0.05

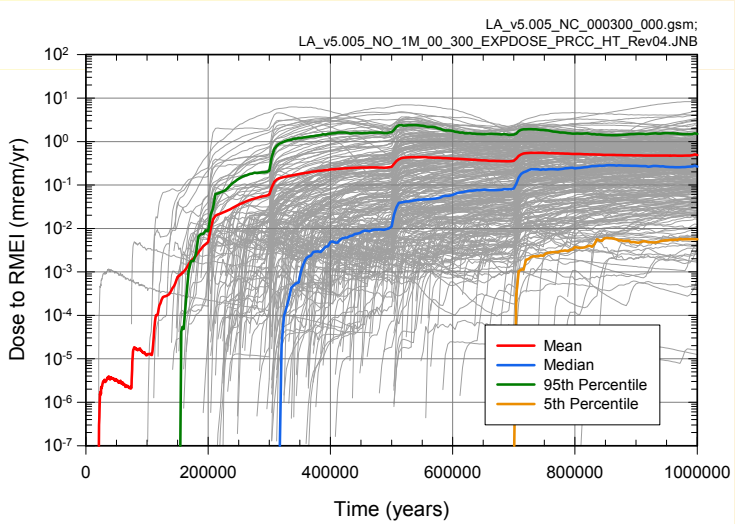
(d)



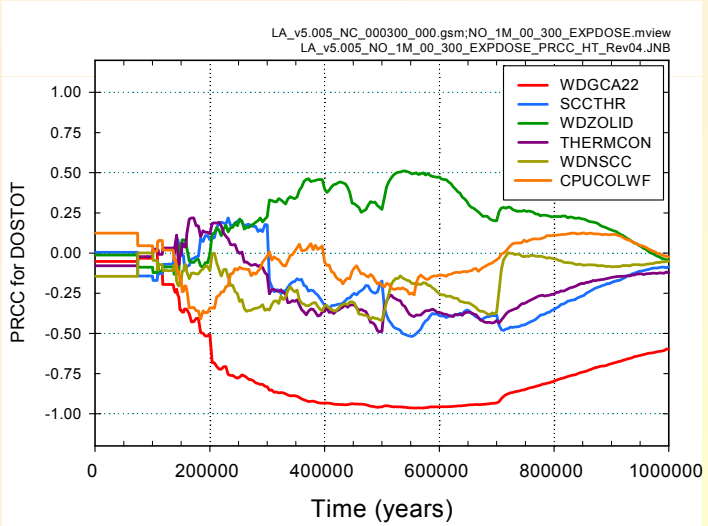
Nominal Scenario Class: Dose to RMEI (*DOSTOT*)

- Uncertainty and sensitivity analysis results for *DOSTOT*: (a) *DOSTOT* for all (i.e., 300) sample elements, and (b) PRCCs for *DOSTOT*

(a)



(b)



Igneous Intrusive Scenario Class (time of event=10yr) Results for Analysis

- Examples of 7 of 49 Time-Dependent Results Analyzed for igneous intrusive scenario class

DONP237: Dose to RMEI (mrem/yr) from dissolved ^{237}Np
ESNP237: Release rate (g/yr) for the movement of dissolved ^{237}Np from the EBS to the UZ
ESNP237C : Cumulative release (g) for the movement of dissolved ^{237}Np from the EBS to the UZ
SZNP237: Release rate (g/yr) for the movement of dissolved ^{237}Np across a subsurface plane at the location of the RMEI
SZNP237C : Cumulative release (g) for the movement of dissolved ^{237}Np across a subsurface plane at the location of the RMEI
UZNP237: Release rate (g/yr) for the movement of dissolved ^{237}Np from the UZ to the SZ
UZNP237C : Cumulative release (g) for the movement of dissolved ^{237}Np from the UZ to the SZ

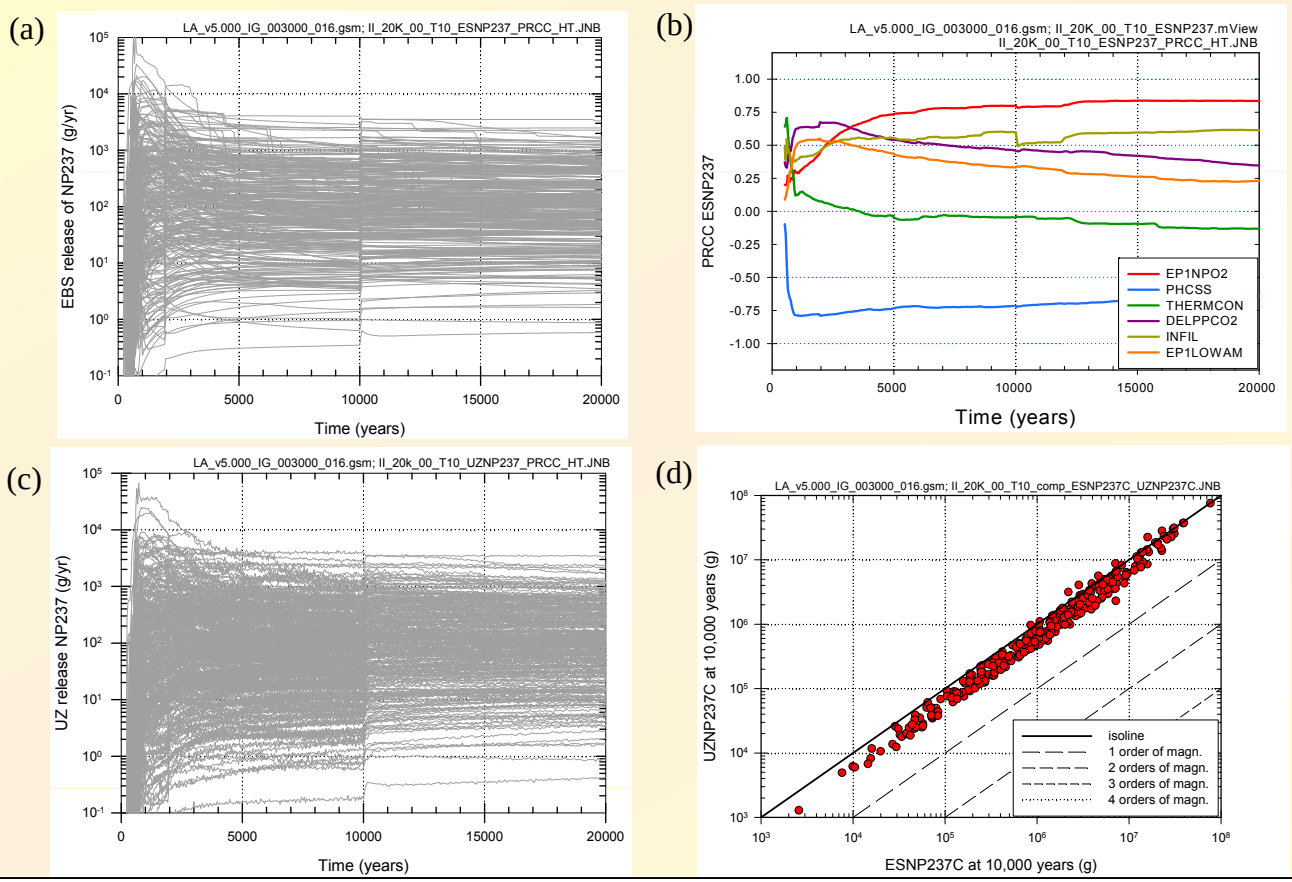
Igneous Intrusive Scenario Class (time of event=10yr) Uncertain Analysis Inputs

- Examples of variables (i.e., elements of **e**) identified in sensitivity analyses for igneous intrusive scenario class

EP1NPO2: Logarithm of the scale factor used to characterize uncertainty in NpO_2 solubility at an ionic strength below 1 molal (dimensionless). *Distribution:* Truncated normal. *Range:* -1.2 to 1.2. *Mean:* 0. *Standard Deviation:* 0.6.
PHCSS: Pointer variable used to determine pH in CSNF Cell1 under liquid influx conditions (dimensionless). *Distribution:* Uniform. *Range:* 0 to 1.
THERMCON: Selector variable for one of three host-rock thermal conductivity scenarios (low, mean, and high) (dimensionless). *Distribution:* Discrete. *Range:* 1 to 3.
DELPPCO2: Selector variable for partial pressure of CO_2 (dimensionless). *Distribution:* Uniform. *Range:* -1 to 1.
INFIL: Pointer variable for determining infiltration conditions: 10th, 30th, 50th or 90th percentile infiltration scenario (dimensionless). *Distribution:* Discrete. *Range:* 1 to 4.
EP1LOWAM: Logarithm of the scale factor used to characterize uncertainty in americium solubility at an ionic strength below 1 molal (dimensionless). *Distribution:* Truncated normal. *Range:* -2 to 2. *Mean:* 0. *Standard Deviation:* 1.
SZGWSPDM: Logarithm of the scale factor used to characterize uncertainty in groundwater specific discharge (dimensionless). *Distribution:* Piecewise uniform. *Range:* -0.951 to 0.951.
SZFIPOVO: Logarithm of flowing interval porosity in volcanic units (dimensionless). *Distribution:* Piecewise uniform. *Range:* -5 to -1.

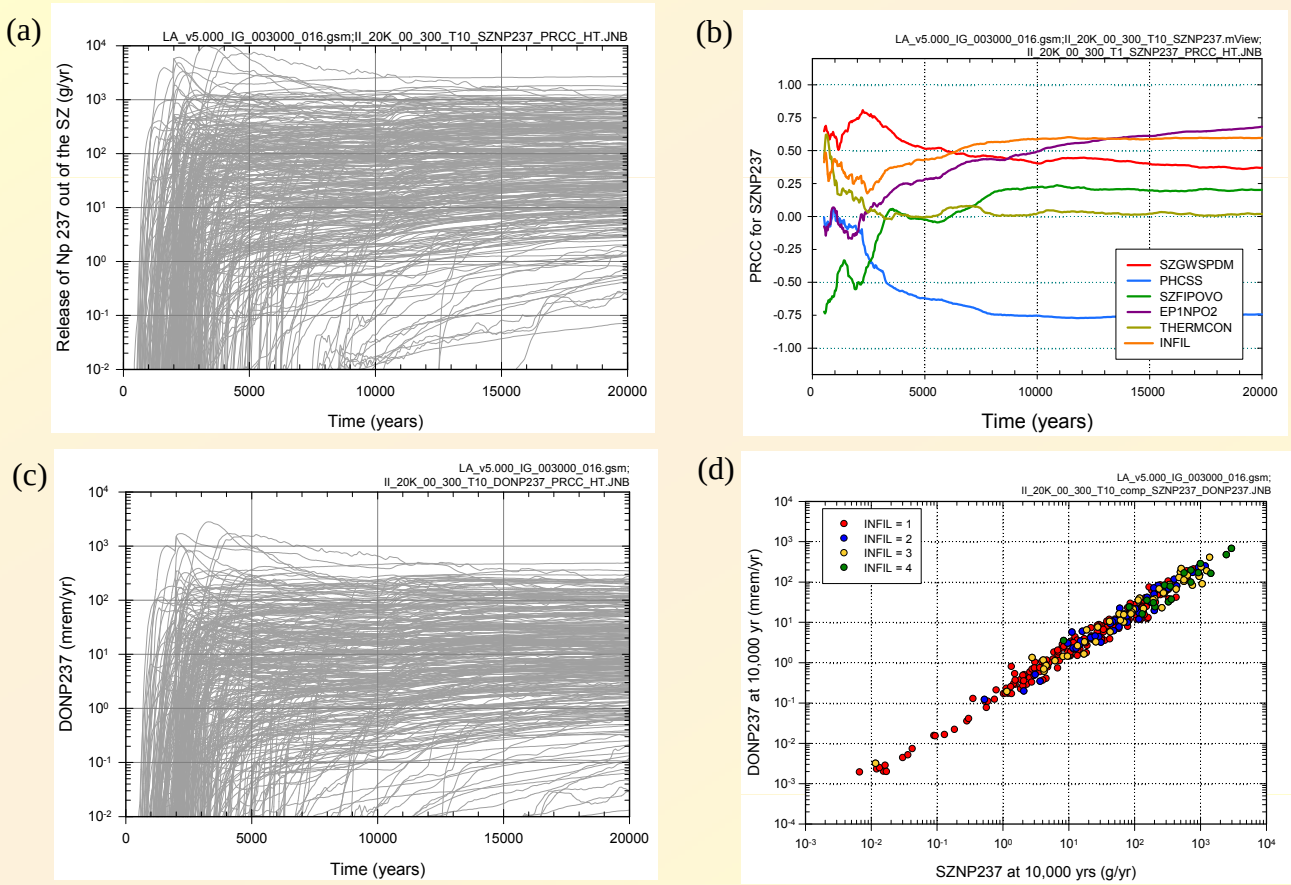
Igneous Intrusive Scenario Class (time of event=10yr)
^{237}Np Releases from EBS (*ESNP237*) and UZ (*UZNP237*)

- Uncertainty and sensitivity analysis results for *ESNP237* and *UZNP237*: (a) *ESNP237* for all (i.e., 300) sample elements, (b) PRCCs for *ESNP237*, (c) *UZNP237*, and (d) scatterplot for (*ESNP237C*, *UZNP237C*) at 10^4 yr



Igneous Intrusive Scenario Class (time of event=10yr)
^{237}Np Releases from SZ (*SZNP237*) and Dose to RMEI (*DONP237*)

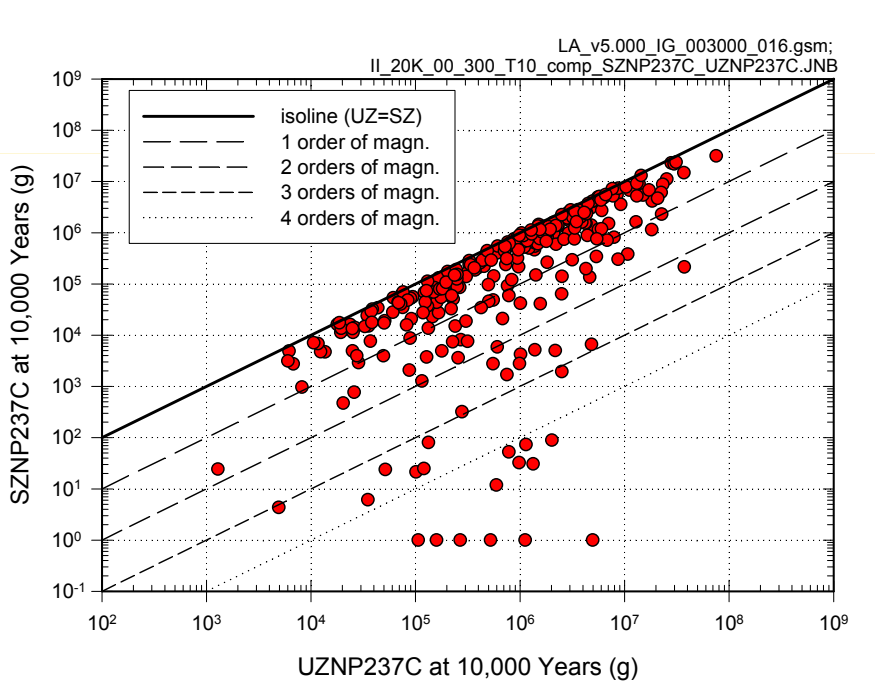
- Uncertainty and sensitivity analysis results for *SZNP237* and *DONP237*: (a) *SZNP237* for all (i.e., 300) sample elements, (b) PRCCs for *SZNP237*, (c) *DONP237*, and (d) scatterplot for (*SZNP237*, *DONP237*) at 10^4 yr



Igneous Intrusive Scenario Class (time of event=10yr)

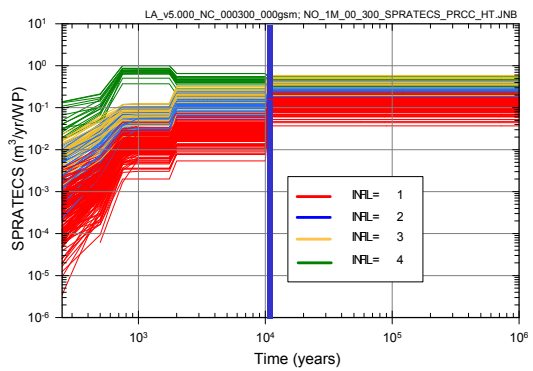
Comparison of Cumulative ^{237}Np Releases from UZ (*UZNP237C*) and SZ (*SZNP237C*)

- Scatterplot for (*UZNP237C*, *SZNP237C*) at 10^4 yr

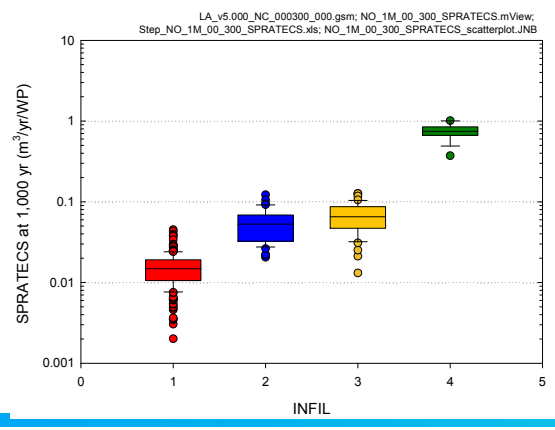


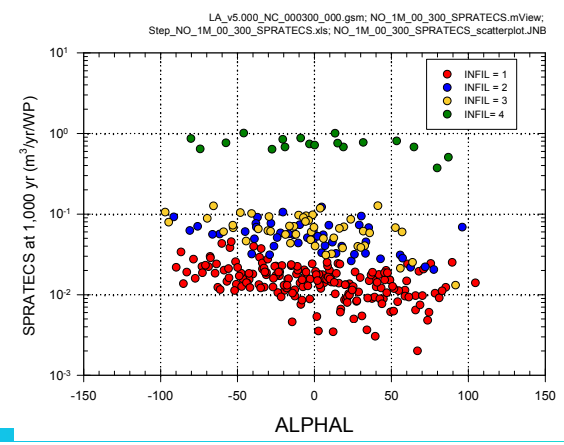
Uncertain Model for Infiltration

- **INFIL** – Pointer variable for four alternative surface infiltration models
- Results in four alternative three dimensional flow fields
- Many effects including: seepage rates (m^3/yr/WP) above CSNF WPs in percolation bin 3 under nominal conditions (TSPA AMR Figs K4.3-1, -2)



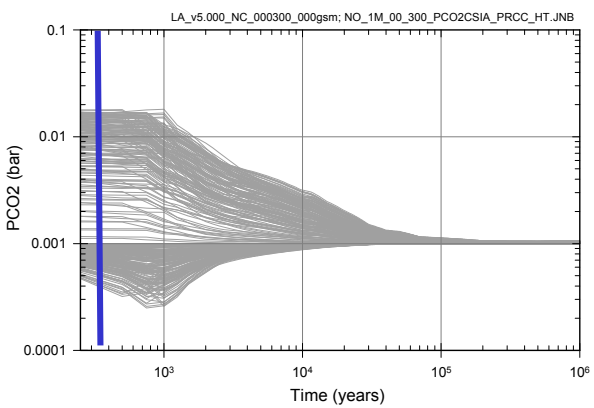
	SPRATECS: 1K yr		
Step	**Variable**	**R^2**	**SRRC[d]**
1	INFIL	0.67	0.83
2	SEEPPRMN	0.76	-0.28
3	ALPHAL	0.82	-0.26
4	SEEPPRM	0.85	-0.19
5	SEEPUNC	0.87	0.15
6	INRFRCTC	0.88	0.06
7	CORRATSS	0.88	-0.05

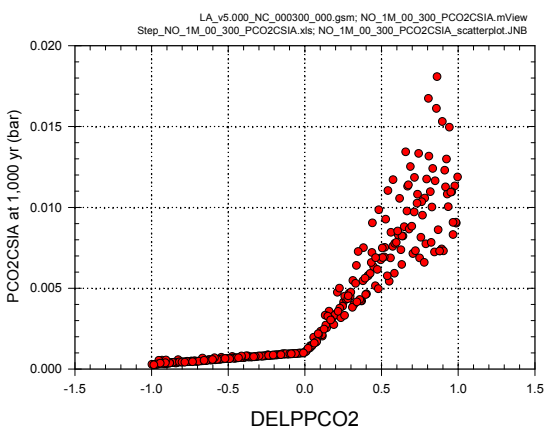




Uncertain Model for CO_2 Partial Pressure

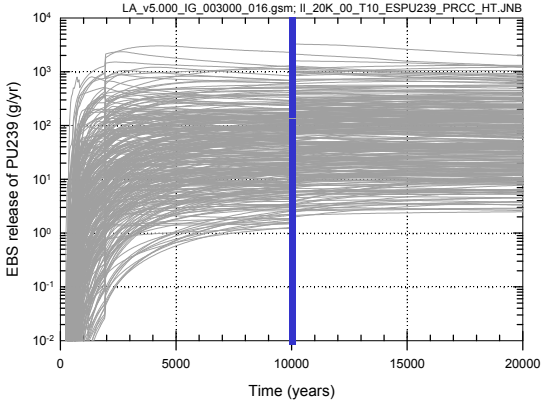
- **DELPPCO2** – Selector variable for CO_2 Partial Pressure model
  - Uniform on [-1,1], with negative and positive values indicating Mode 1 or 2, respectively
  - |DELPPCO2| scales model results
- Example results: Partial pressure for CO_2 (bars) in invert for CSNF WPs experiencing dripping conditions in percolation bin 3 under nominal conditions (TSPA AMR Figs. K.4.3-7,-8)

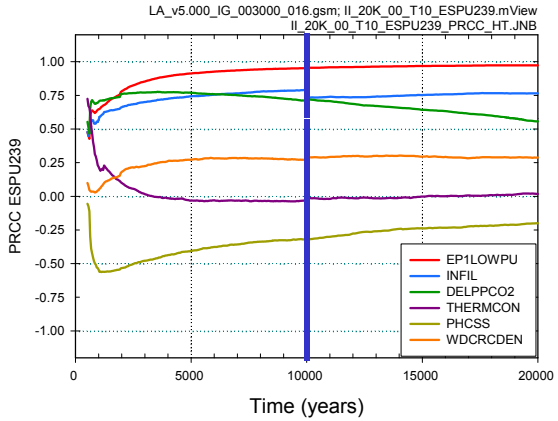


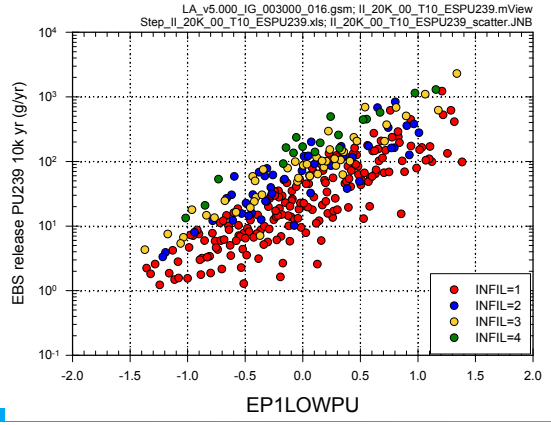


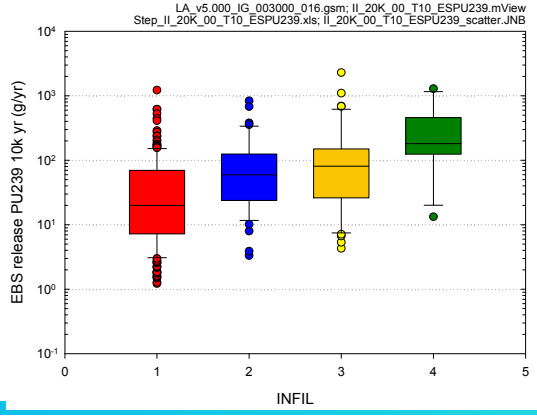
Uncertain Model for Plutonium Solubility

- **EP1LOWPU** – Logarithm of scale factor for plutonium solubility model under low ionic strength conditions. Distribution: truncated normal on [-1.4,1.4] with μ=0.0 ; σ=0.7
- Example results: Release rate (g/yr) of dissolved ^{239}Pu from EBS for igneous event at 10 yr that destroys all WPs (TSPA AMR Figs K6.3.1-7,-8)



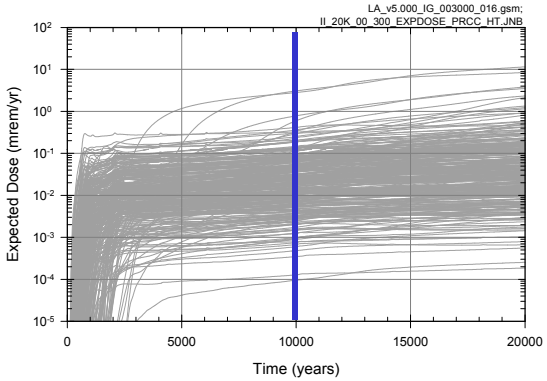


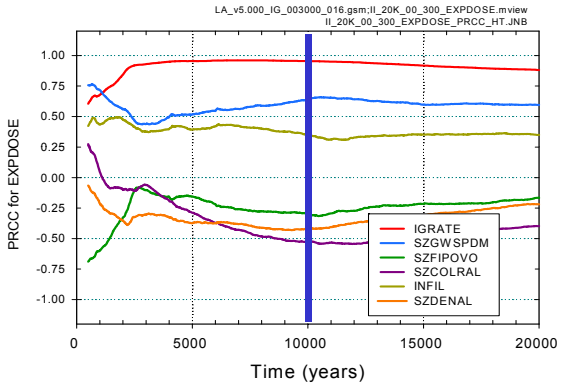


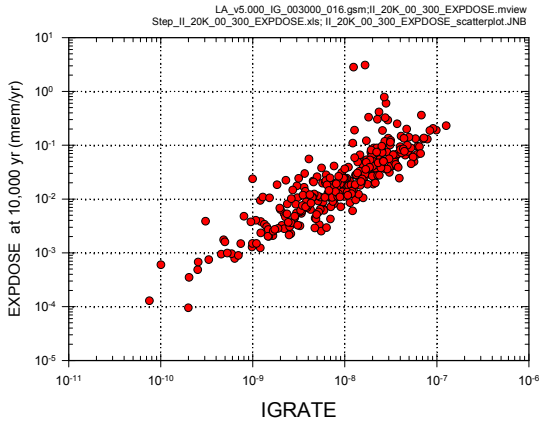


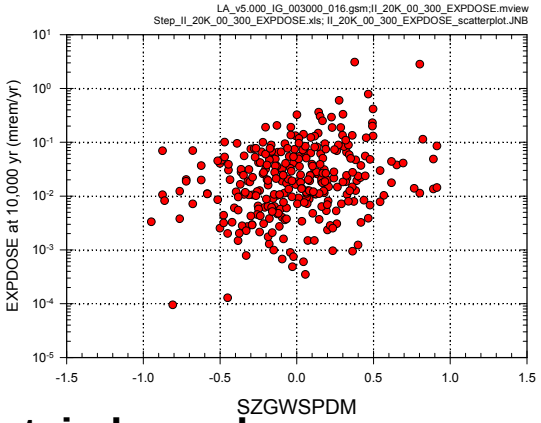
Uncertain Model for Poisson Process

- **IGRATE** – Defining rate (yr^{-1}) for Poisson model for occurrence of igneous events. Piecewise uniform on [0, 7.76×10^{-7} yr^{-1}]
- Example: Expected dose (mrem/yr) to RMEI from igneous intrusion (TSPA AMR Figs K6.7.1-1,-2)





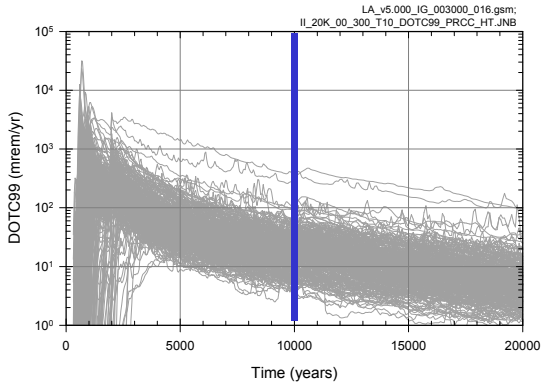
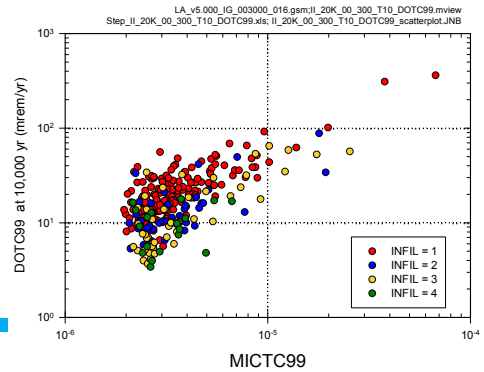
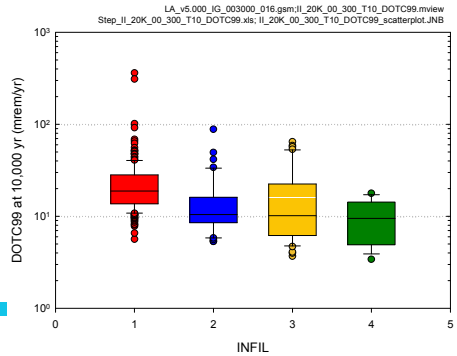




More interesting: Uncertain hazard curves

Uncertain Model for Dose Conversion

- **MICTC99** – Groundwater dose conversion factor ((Sv/yr)/(Bq/l)) for ^{99}Tc. Discrete from [5.28×10^{-6},2.85×10^{-4}]
- Distribution direct result of sampling-based uncertainty analysis for <u>all</u> dose conversion factors
- Example: Dose (mrem/yr) to RMEI from ^{99}Tc for igneous event at 10 yr that destroys all WPs (TSPA AMR Figs K6.6.1-9,-10)



	DOTC99: 10,000 yr		
Step	**Variable**	**R^2**	**SRRC**
1	MICTC99	0.29	0.57
2	INFIL	0.47	-0.43
3	SZGWSPDM	0.59	-0.33
4	SZFISPVO	0.64	-0.30
5	CSNFMASS	0.70	0.24
6	SZDIFCVO	0.72	0.13
7	KDRACOL	0.73	0.09