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The Yucca Mountain Performance Assessment and Treatment of Uncertainty

Presented to:

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Presentation Outline

- Overview of the proposed Yucca Mountain (YM) repository
- Purpose of YM Total System Performance Assessment (TSPA)
- Uncertainty in YM TSPA
- Development of defensible bases underlying YM TSPA
- Calculation of expected dose and sensitivity analyses
- Computational Strategy
- Summary

Location of Yucca Mountain

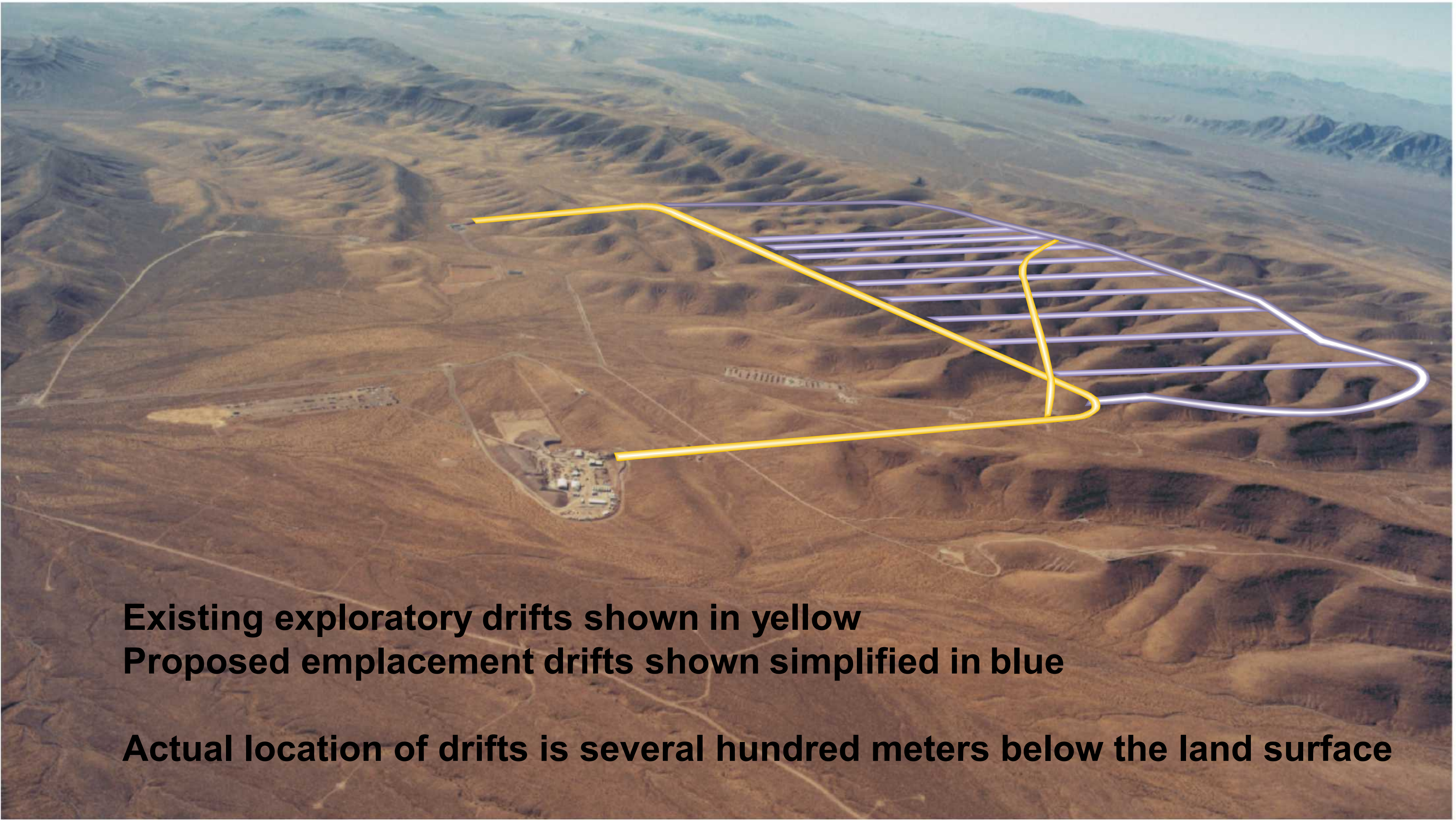
Waste for Yucca Mountain
39 States, 125 Sites

Commercial Spent Nuclear Fuel:
63,000 MTHM

DOE & Naval Spent Nuclear Fuel:
2,333 MTHM

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

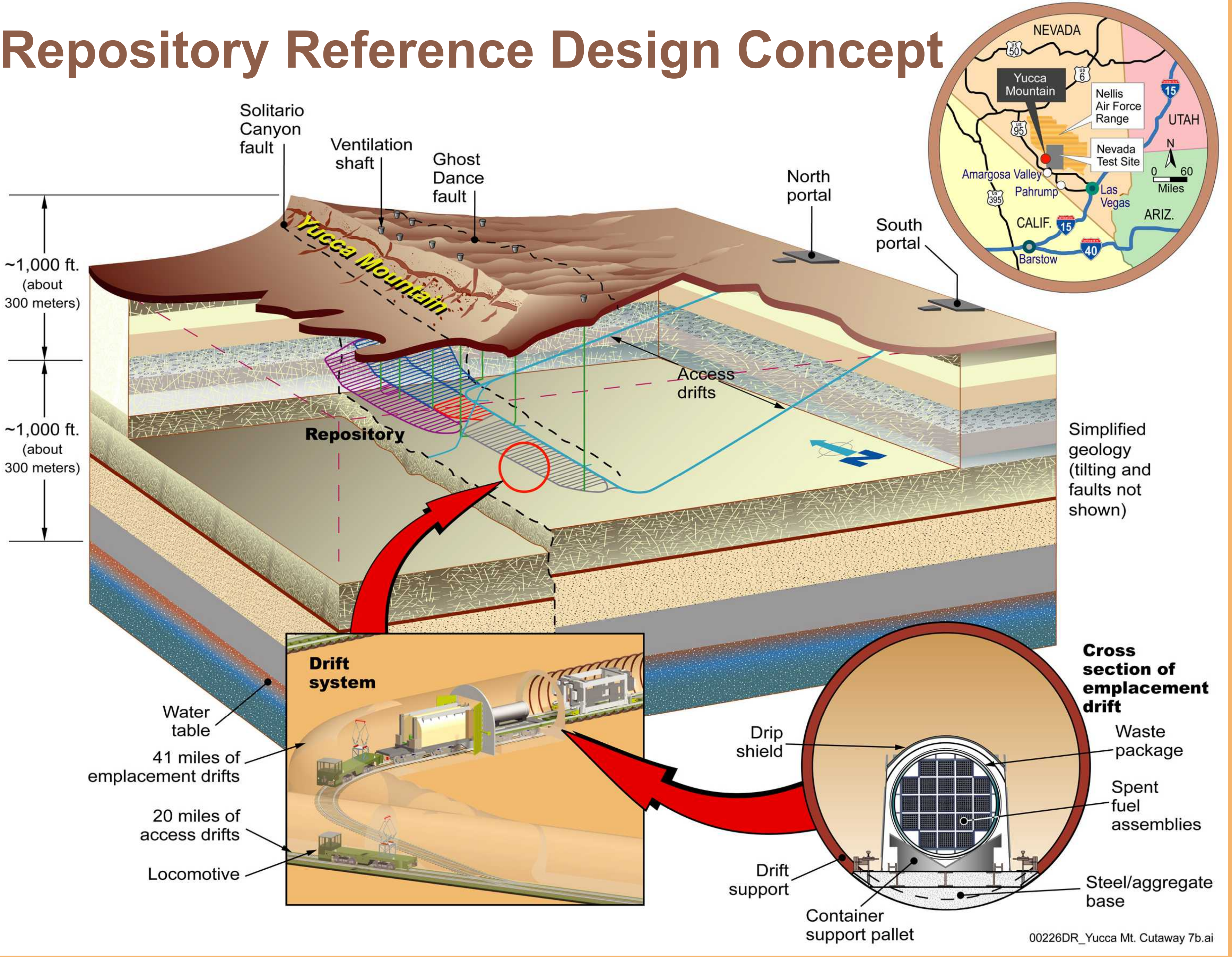
Proposed Repository at Yucca Mountain



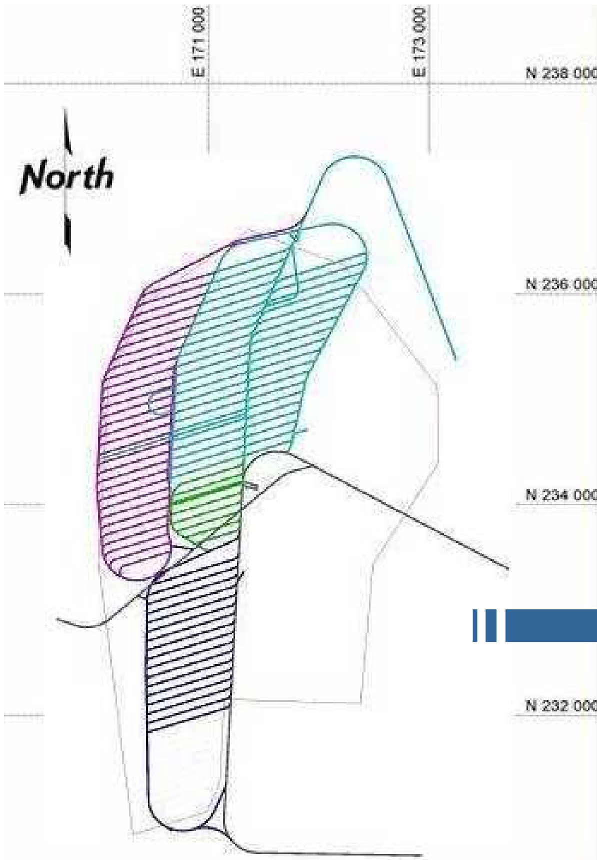
Existing exploratory drifts shown in yellow
Proposed emplacement drifts shown simplified in blue

Actual location of drifts is several hundred meters below the land surface

Repository Reference Design Concept



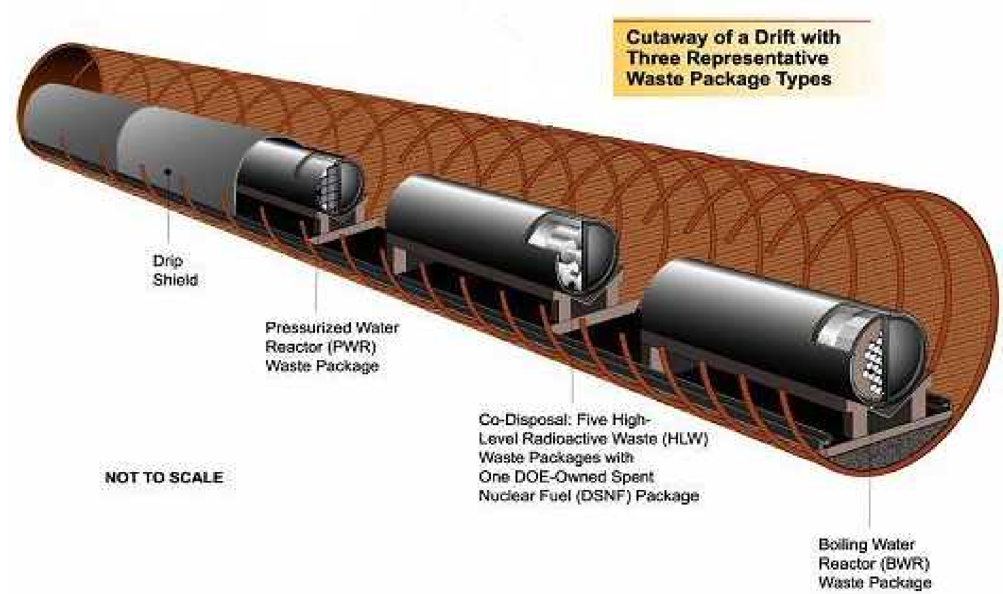
Yucca Mountain Subsurface Design



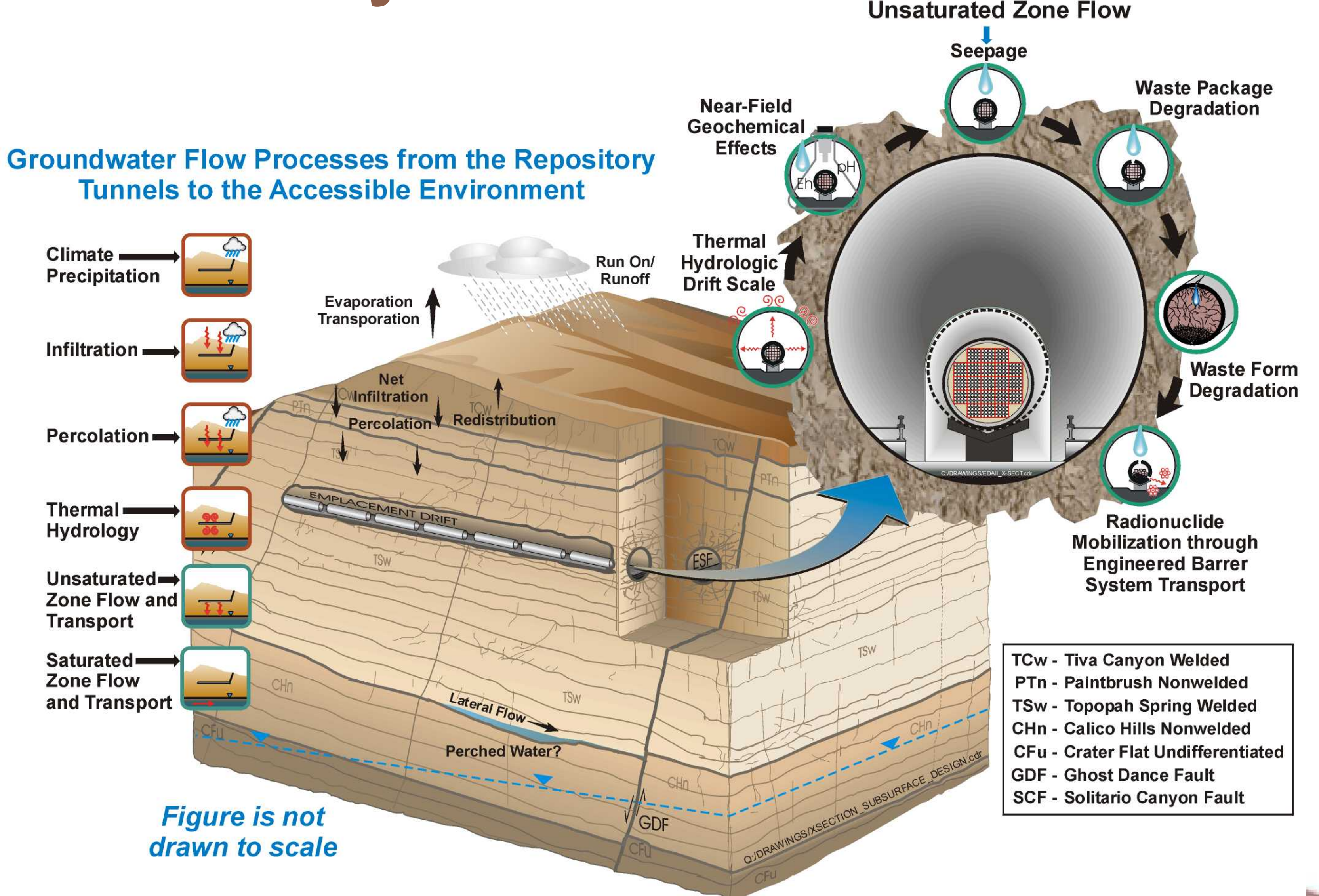
Emplacement drifts
- 5.5 m diameter
- 50-90 drifts, each ~ 1 km long

Waste packages
- ~12,000 packages
- ~ 5 m long, 2 m diameter
- outer layer 2 cm Alloy 22 (Ni-Cr-Mo-V)
- inner layer 5 cm stainless steel

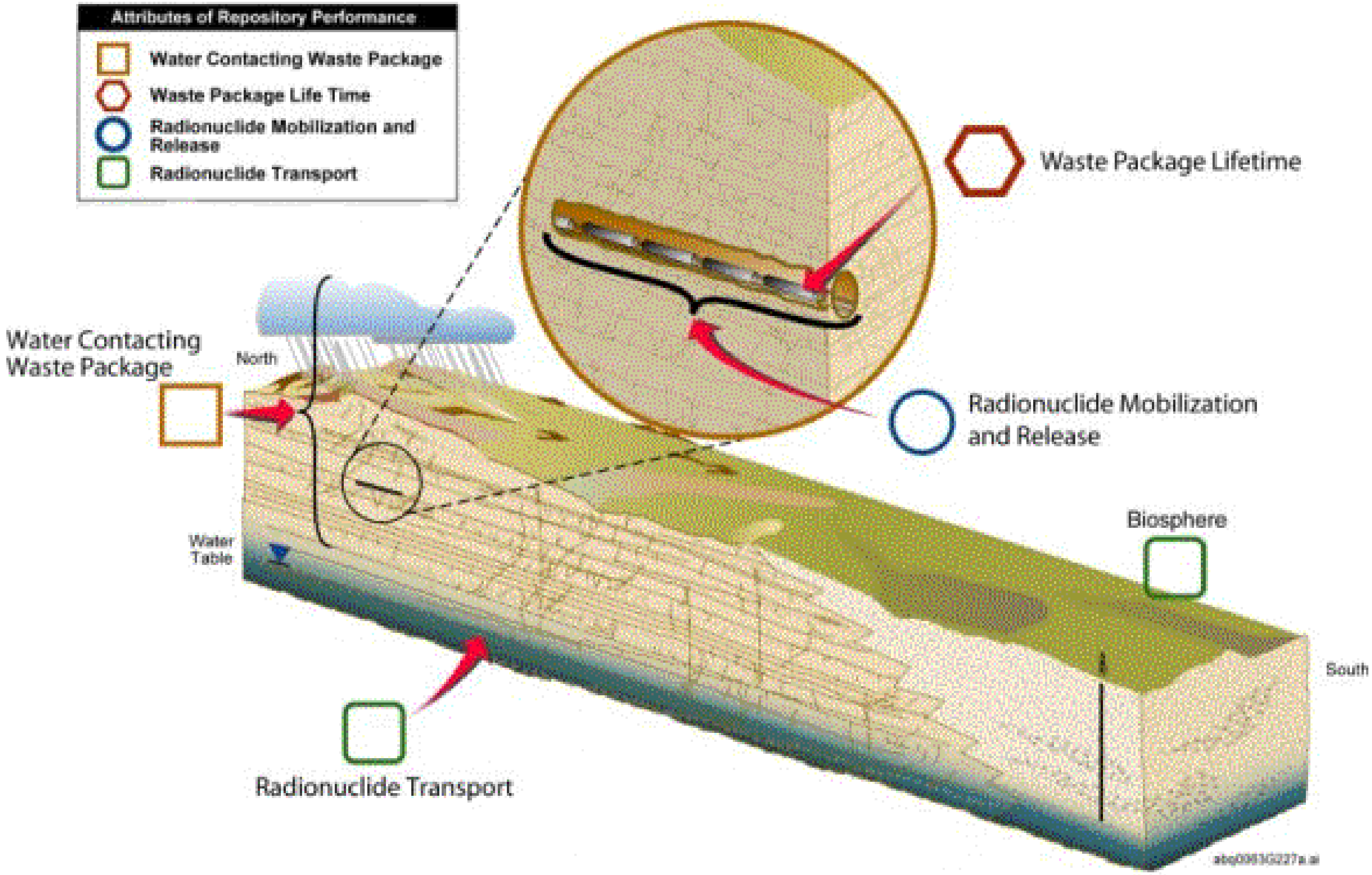
Drip shields
- free-standing 1.5 cm Ti shell



Components of Natural and Engineered Barrier Systems at Yucca Mountain

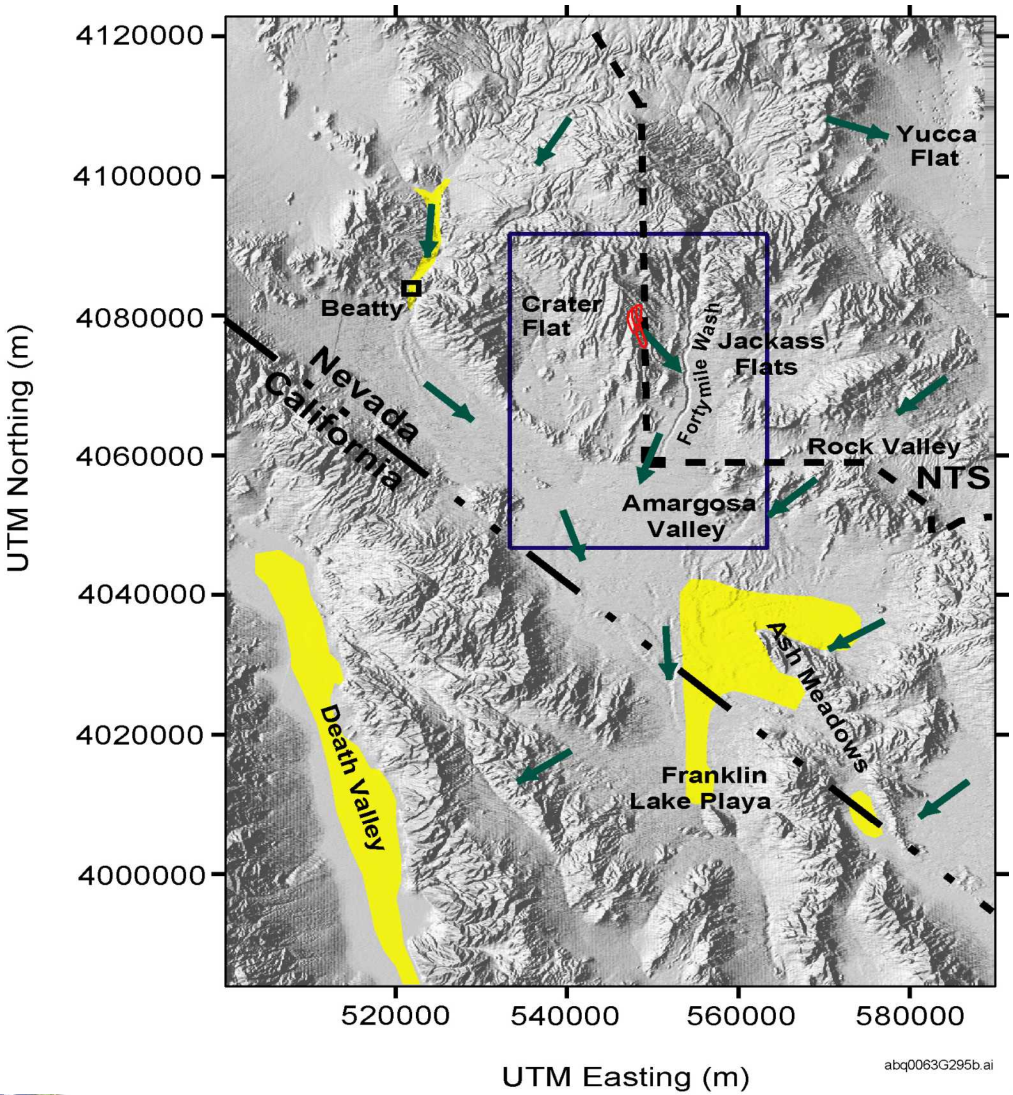


Nominal Performance Scenario Class



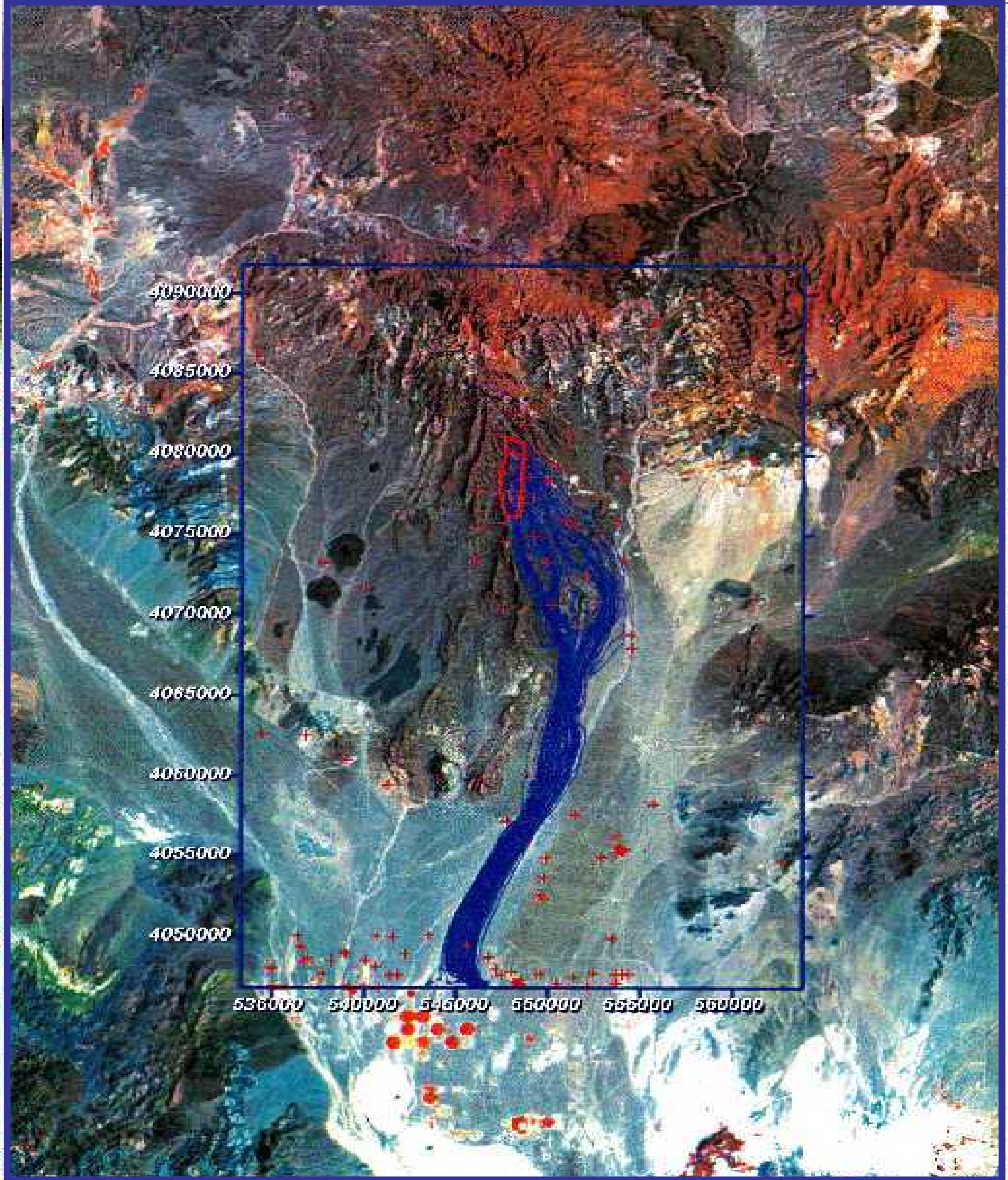
Yucca Mountain Hydrology

Water is the primary means by which radioactive elements could be transported from a repository



Groundwater Flow

- In general, flow is southward
- Compliance point is 18 km (approximately at Nevada Test Site fence line or Lathrop Wells)
- Natural discharge of groundwater from beneath Yucca Mountain probably occurs farther south at Franklin Lake Playa

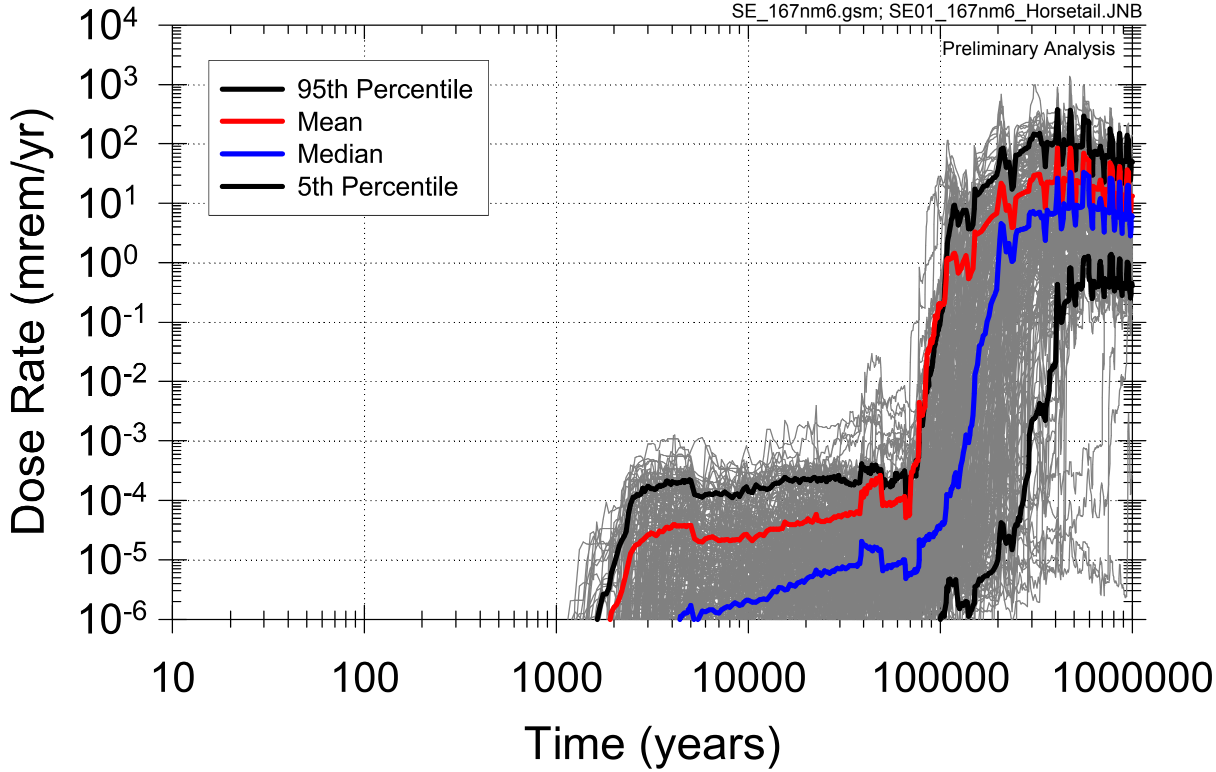


Groundwater Transport Pathways in the Saturated Zone

(Preliminary saturated zone groundwater flow paths as modeled in TSPA-SR Rev. 00, ICN01, 2000)

Overall Performance (2002 Model Results) Nominal Scenario Class

- Total System Performance Assessment - Final Environmental Impact Statement model, modified to include Sr-90 and Cs-137 transport, updated long-term climate states, one early waste package failure per realization, and regulatory specification for 3,000 acre-ft annual groundwater usage
- Results from ANL-WIS-PA-000004 Rev. 00 ICN 00 ("one-on analysis" Case 12)



Mean annual dose based on 300 realizations of high-temperature operating mode nominal performance. Models and input values are preliminary. Results are for information only, and are not suitable for comparison to regulatory standards.

Purpose of TSPA

- Provide a defensible basis for evaluation of compliance with postclosure regulatory standards for the total repository system that meets postclosure performance objectives as defined in 10 CFR 63.113
  - Estimation of mean annual dose to the reasonably maximally exposed individual (RMEI) and groundwater concentrations for a period of 10,000 yrs
  - Estimation of median annual dose to the RMEI after 10,000 years, but within the period of geologic stability (proposed rule)
- Basis includes an evaluation of the extent to which uncertainty in present understanding of the repository system affects these estimates (10 CFR 63.114, 10 CFR 63.115)

Uncertainty in YM TSPA

- Completeness uncertainty
  - Has everything of significance been considered?
  - Addressed through FEPs process
- Aleatory uncertainty
  - Inherent randomness in events that could occur in the future
  - Alternative descriptors: irreducible, stochastic, intrinsic, type A
- Epistemic uncertainty
  - Lack of knowledge about quantities with fixed values
  - Alternative descriptors: reducible, subjective, state of knowledge, type B
- Numerical uncertainty
  - Numerical deviations due to nonconvergence, errors, …
  - Addressed through testing, QA, …
- Aleatory and epistemic uncertainty focus of this presentation

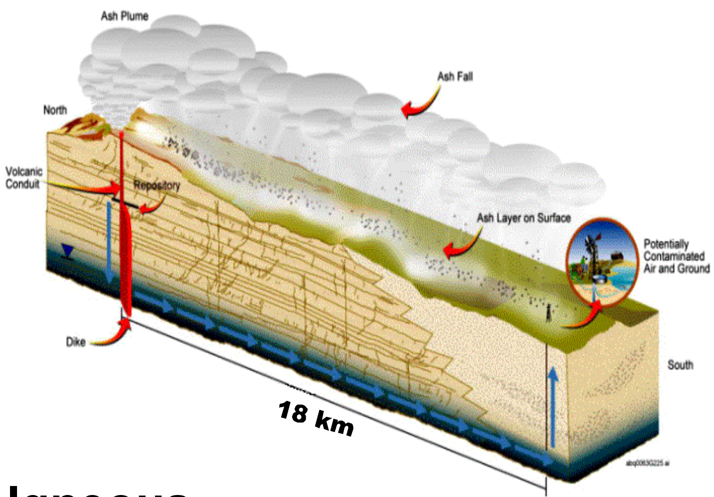
Four Questions Underlying YM TSPA

- **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?**

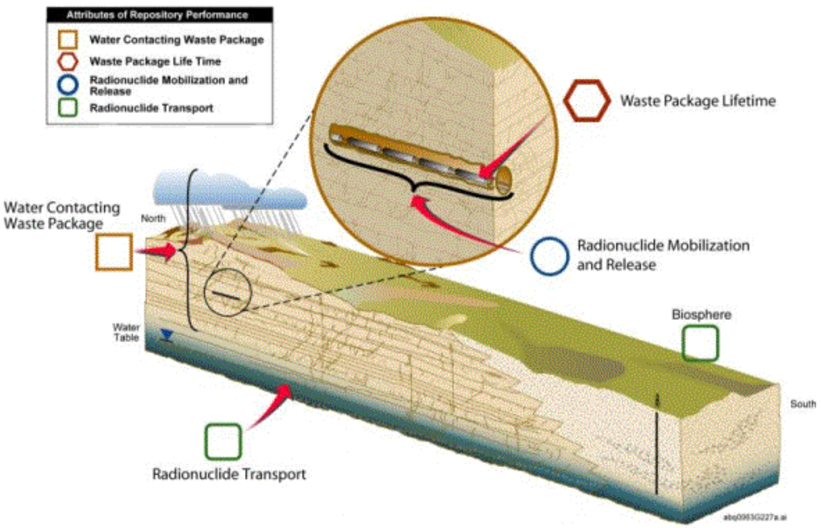
Basic Entities Underlying YM TSPA

1. **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*
2. **Mathematical models for predicting consequences**
   - Answers third question
   - *E.g. Transport models implemented in the TSPA Model*
3. **Basis for answering fourth question**
   - Provides formal characterization of epistemic uncertainty
   - *E.g. Distributions assigned to radionuclide sorption coefficients*

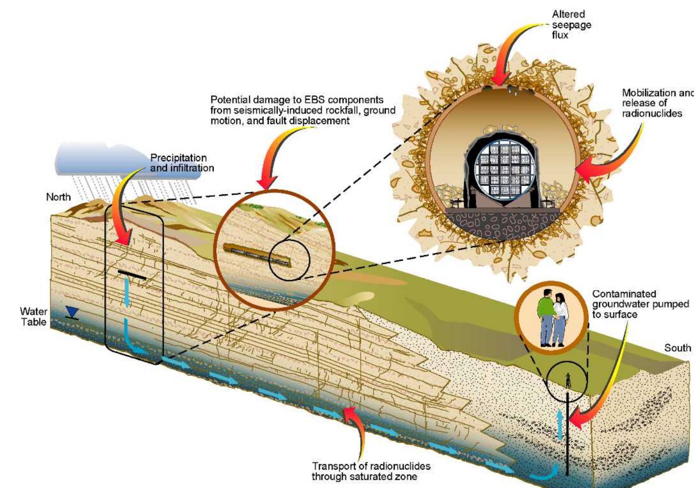
Scenario Classes for Yucca Mountain Total System Performance Assessment



Igneous



Nominal



Seismic

Basic Entities Underlying YM TSPA: More Detail

EN1: Probabilistic characterization of what can happen in the future

- **a** = [a_1,a_2,…] vector characterizing a possible future at YM site
  - *E.G.* **a** = [$nS, t_1, v_1, t_2, v_2, \ldots, t_{nS}, v_{nS}$] *for seismic events in time interval* [*0 yr, 10^4 yr*], *where nS= number of seismic events, t_i = time (yr) of i^{th} event, and v_i = PGV for i^{th} event*
- $\mathcal{A}$ = set of all possible futures for **a**
- d_A(**a**) = density function for **a** defined on $\mathcal{A}$

EN3: Probabilistic characterization of uncertainty in TSPA inputs

- **e** = [$\mathbf{e}_A$,$\mathbf{e}_D$] = [$e_1, e_2, \ldots, e_{nE}$] vector of uncertainty in TSPA inputs
  - $\mathbf{e}_A$ *vector of uncertain inputs used in characterizing aleatory uncertainty*
  - $\mathbf{e}_D$ *vector of uncertain inputs used in calculating consequences*
- $\mathcal{E}$ = set of all possible values for **e**
- d_E(**e**) = density function for **e** defined on $\mathcal{E}$

EN2: Mathematical models for predicting consequences

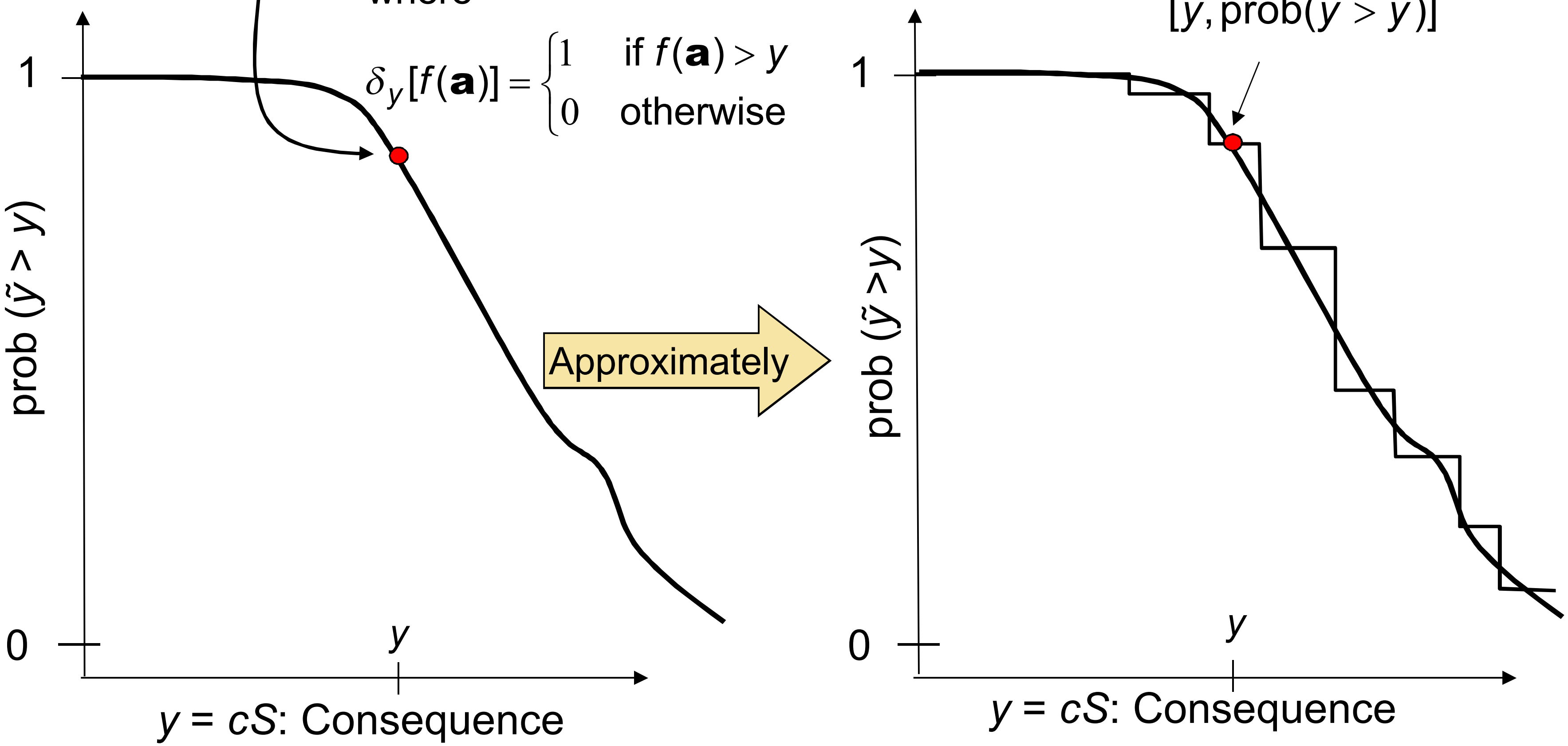
- Usually sequence of complex linked models
  - *E.G.* $D(\tau \mid \mathbf{a}, \mathbf{e}_D)$ *= dose to RMEI at time* τ *for future* **a** *and conditional on parameter values in* $\mathbf{e}_D$

Genesis of Results: Presentation of Risk

$$[y, \text{prob}(\tilde{y} > y)] = \left[y, \int_{\mathcal{A}} \delta_y[f(\mathbf{a})] d_A(\mathbf{a}) \, \mathrm{d}A \right]$$

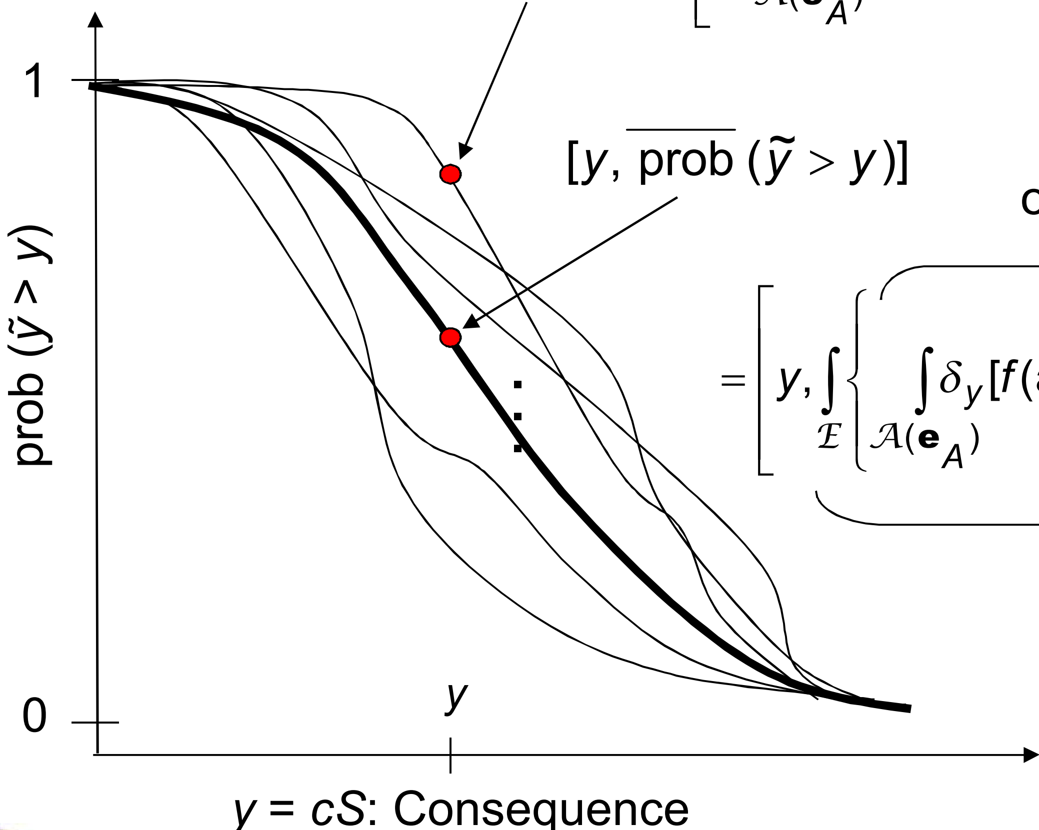
where

$$\delta_y[f(\mathbf{a})] = \begin{cases} 1 & \text{if } f(\mathbf{a}) > y \\ 0 & \text{otherwise} \end{cases}$$



Genesis of Results: Risk with Epistemic Uncertainty

$$[y, \text{prob}\,(\tilde{y} > y \,|\, \mathbf{e})] = \left[y, \int_{\mathcal{A}(\mathbf{e}_A)} \delta_y[f(\mathbf{a} \,|\, \mathbf{e}_M)] d_A(\mathbf{a} \,|\, \mathbf{e}_A)\, \mathrm{d}A \right]$$



$$= \left[y, \int_{\mathcal{E}} \underbrace{\left\{ \overbrace{\int_{\mathcal{A}(\mathbf{e}_A)} \delta_y[f(\mathbf{a} \,|\, \mathbf{e}_M)] d_A(\mathbf{a} \,|\, \mathbf{e}_A)\, \mathrm{d}A}^{\text{over aleatory}} \right\} d_E(\mathbf{e})\, \mathrm{d}E}_{\text{over epistemic}} \right]$$

Expected Dose

- **Formal representation**

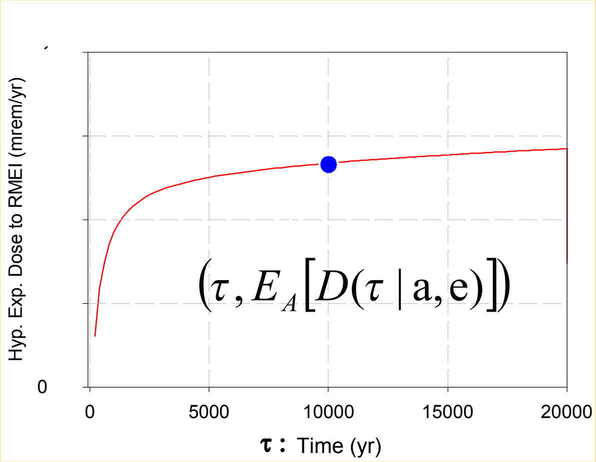
$$E_A[D(\tau \mid \mathbf{a},\mathbf{e})] = \int_{\mathcal{A}} D(\tau \mid \mathbf{a},\mathbf{e}_D) d_A(\mathbf{a} \mid \mathbf{e}_A) \mathrm{d}A, \qquad \mathbf{e} = [\mathbf{e}_A, \mathbf{e}_D]$$

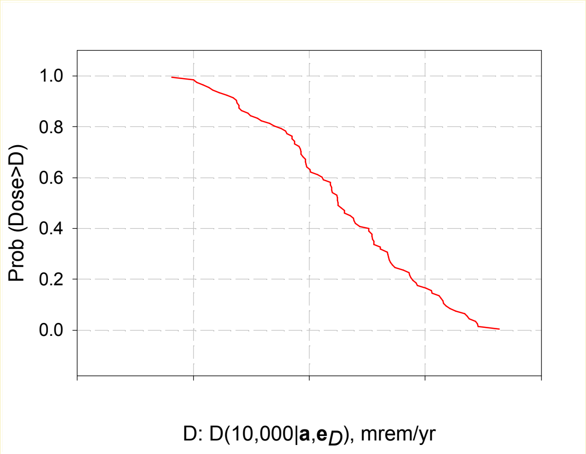
- **Approximation**

$$E_A[D(\tau \mid \mathbf{a},\mathbf{e})] \cong \sum_{i=1}^{m} \frac{D(\tau \mid \mathbf{a}_i, \mathbf{e}_D)}{m}$$

for $\mathbf{a}_1$, $\mathbf{a}_2$, …, $\mathbf{a}_m$ sample from $\mathcal{A}$ consistent with $d_A(\mathbf{a}|\mathbf{e}_A)$

- **Graphical representation – Hypothetical Example**





Uncertainty in Expected Dose

- **Different value for**

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

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

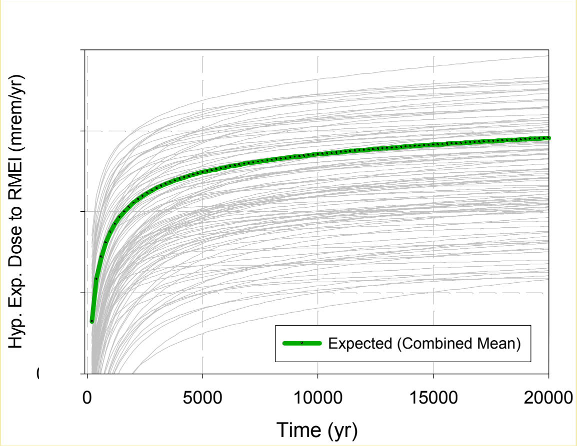
- **Approximation to uncertainty in** $E_A\left[D(\tau\,|\,\mathbf{a},\mathbf{e})\right]$

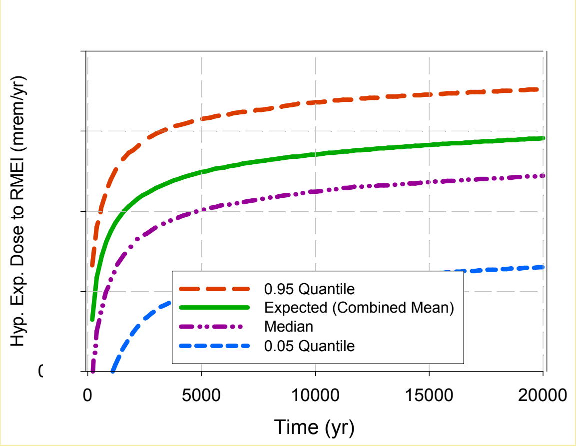
$$E_A[D(\tau\,|\,\mathbf{a},\mathbf{e}_j)],\quad j=1,2,\cdots,n$$

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

- **Graphical representation – Hypothetical Example**

D





Sensitivity Analysis

- **Exploration of mapping**

$$\left(\mathbf{e}_j, E_A[D(\tau \mid \mathbf{a}, \mathbf{e}_j)]\right), \quad j = 1, 2, \cdots, n$$

from (epistemically) uncertain analysis inputs to analysis results

- **Variety of available techniques**
  - Examination of scatterplots
  - Correlation and partial correlation analysis
  - Regression analysis
  - Stepwise regression analysis

Details in J. C. Helton et al. (2006). "Survey of Sampling-based Methods for Uncertainty and Sensitivity Analysis" *Reliability Engineering and System Safety*, Vol 91, pp. 1175-1209

Computational Strategy

- **Maintain separation of aleatory and epistemic uncertainty**
  - ➢ Epistemic uncertainty in expected dose and other quantities
  - ➢ Informative sensitivity analysis
- **Procedures for uncertainty propagation**
  - ➢ Sampling-based (LHS) for epistemic uncertainty
  - ➢ Integration-based and sampling-based (LHS) 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.

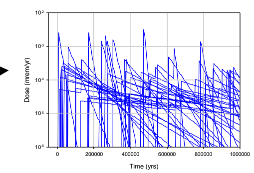
start

Sample Epistemic

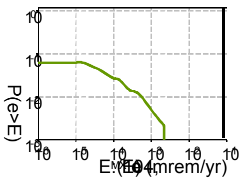
$$\mathbf{e} = [\mathbf{e}_A, \mathbf{e}_D] = [e_1, e_2, \ldots, e_{nE}],$$

Sample Aleatory

$$\mathbf{a} = [nEV, t_1, \lambda_{R1}, t_2, \lambda_{R2}, \ldots, t_{nEV}, \lambda_{R,nEV}],$$



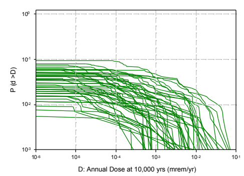
Futures



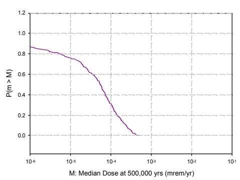
CCDF at *t*

Hypothetical results for illustration purposes

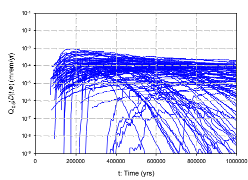
Summary of epistemic Uncertainty



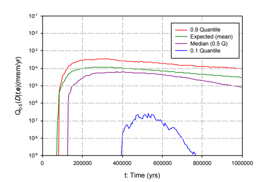
CCDFs at *t*



Performance metric at *t*



Performance metric as f(*t*)



Summary measures of uncertainty in performance metric

Sensitivity Analysis

- **Exploration of mapping**

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from (epistemically) uncertain analysis inputs to analysis results

- **Variety of available techniques**
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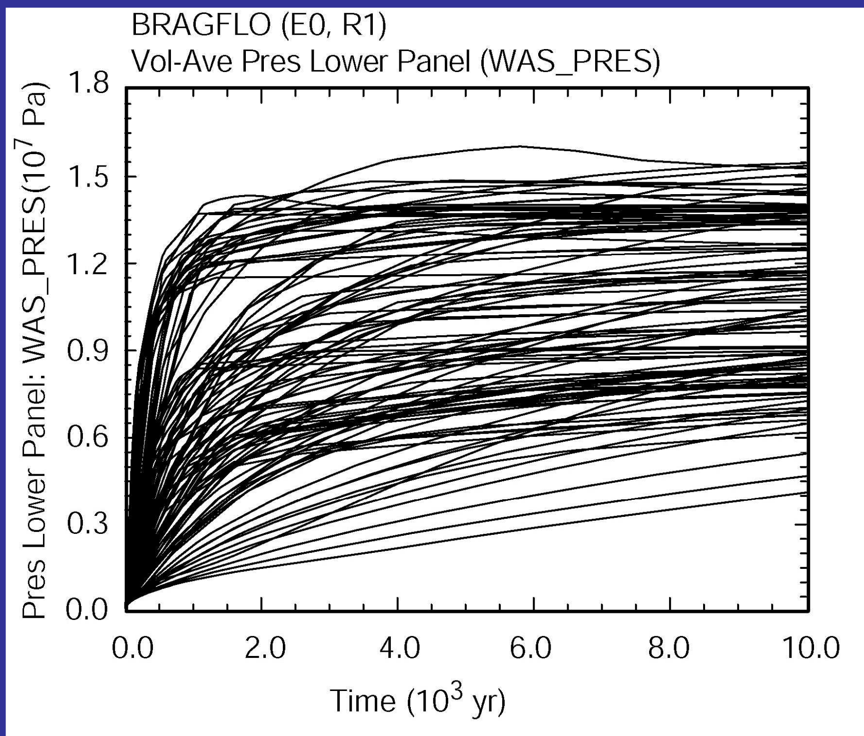
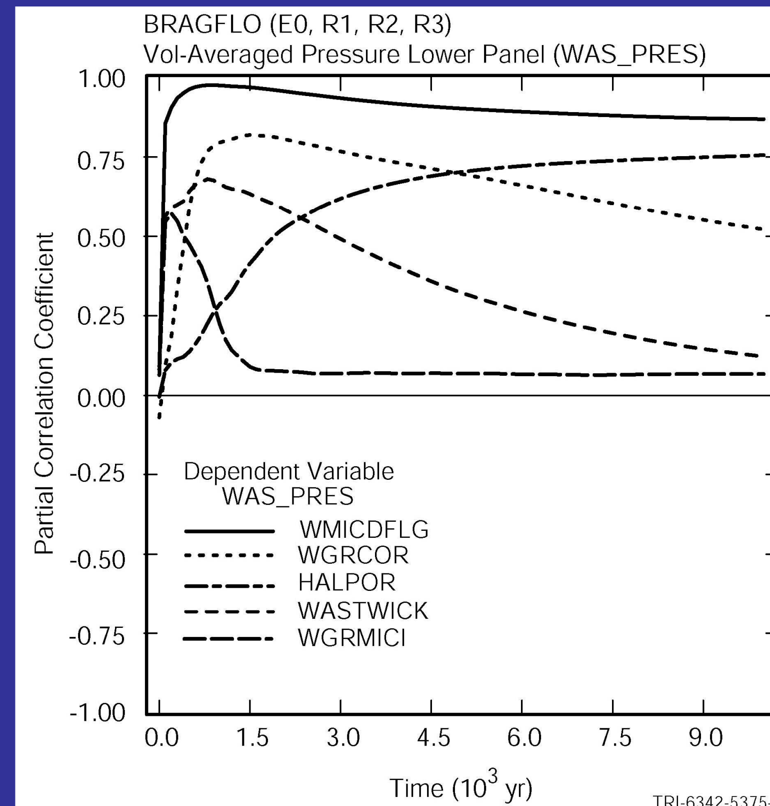
Example from WIPP
Sensitivity Analysis: Time-Dependent PCCs





Summary

- Clear conceptual structure necessary
  - Probabilistic characterization of aleatory uncertainty
  - Function that predicts consequences
  - Probabilistic characterization of epistemic uncertainty
- Analysis proceeds from conceptual structure to computational structure
  - Appropriate separation of aleatory and epistemic uncertainty
  - Uncertainty analysis
  - Sensitivity analysis