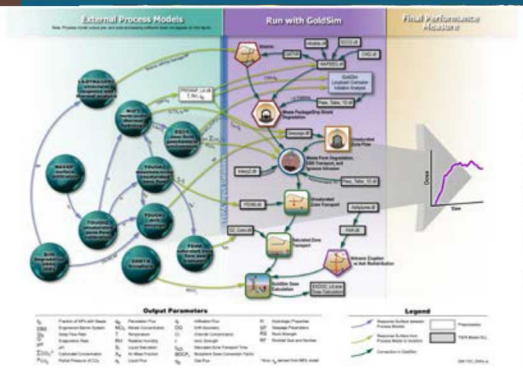
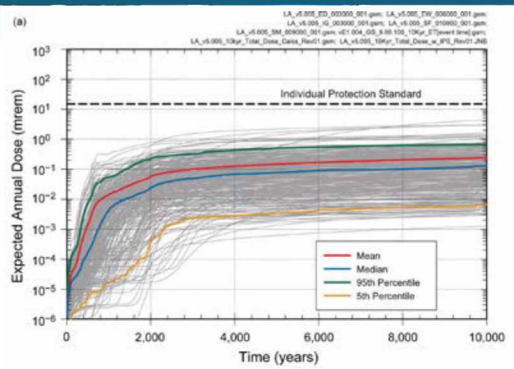
Sandia National Laboratories

SAND2019-14977PE

Evaluating Compliance with Long-Term Regulatory Standards





PRESENTED BY

Peter Swift

Nuclear Energy Fuel Cycle Knowledge Management Workshop

December 17-19, 2019; Albuquerque, New Mexico

EVALUATING COMPLIANCE WITH LONG-TERM REGULATORY STANDARDS
NEFC KNOWLEDGE MANAGEMENT WORKSHOP DECEMBER 17-19 2019
SAND2019-XXXX

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outline

What does a license application for a repository look like?

Legislative Basis for Regulatory Roles and Responsibilities for the Environmental Protection Agency (EPA), the Nuclear Regulatory Commission (NRC), and the Department of Energy (DOE)

Separate Regulations for the Waste Isolation Pilot Plant (WIPP) and the proposed Yucca Mountain repository

Regulatory requirements define the scope of the postclosure performance assessment

- Note that the Yucca Mountain performance assessment model has been identified for decades as the "Total System Performance Assessment" (TSPA)

Examples from performance assessments for Yucca Mountain and WIPP

What does a Repository License Application Look Like?

The 2008 Yucca Mountain License Application (LA) included

- 17 volumes; 8,646 pages
- 198 supporting documents (~38,000 pages) submitted with the application

Nuclear Regulatory Commission (NRC) staff issued approximately 673 formal requests for additional information

Approximately 305 contentions admitted for adjudication by the NRC Atomic Licensing and Safety Board

(nearly all remain unresolved)

NRC Licensing process originally anticipated to take 3-4 years for a decision on construction authorization

Michael Weber (on left), Director, NRC Office of Nuclear Material Safety and Safeguards and Ward Sproat, Director, DOE Office of Civilian Radioactive Waste Management (June 2008)

The DOE's 1996 Compliance Certification Application to the Environmental Protection Agency (EPA) for the Waste Isolation Pilot Plant (WIPP) was ~72,000 pages, including appendices and supporting references

Margaret Chu, Deputy WIPP Project Manager, Sandia National Laboratories (October 1996)

What is in a License Application?

- **General Information**
  - General Description
  - Proposed Schedules for Construction, Receipt and Emplacement of Waste
  - Physical Protection Plan
  - Material Control and Accounting Program
  - Site Characterization
- **Safety Analysis Report**
  - Repository Safety Before Permanent Closure
  - Repository Safety After Permanent Closure
  - Research and Development Program to Resolve Safety Questions
  - Performance Confirmation Program
  - Management Systems

Repository Safety after Permanent Closure is addressed in 3,456 of the 8,646 pages in the 2008 Yucca Mountain License Application

Legislative Basis for Regulatory Roles and Responsibilities

The Nuclear Waste Policy Act of 1982 (section 121) defines responsibilities for regulating disposal of spent nuclear fuel and high-level radioactive waste

- The EPA "shall, by rule, promulgate generally applicable standards for protection of the general environment from offsite release from radioactive material in repositories"
- The NRC "shall, by rule, promulgate technical requirements and criteria that it will apply, under [applicable laws] in approving or disapproving—

  (i) applications for authorization to construct repositories;

  (ii) applications for licenses to receive and possess spent nuclear fuel and high-level radioactive waste in such repositories; and

  (iii) applications for authorization for closure and decommissioning of such repositories."

The Energy Policy Act of 1992 directs the EPA to "promulgate, by rule, public health and safety standards for protection of the public from releases from radioactive materials stored or disposed of in the repository at the Yucca Mountain site"

- Standards shall be "based upon and consistent with the findings and recommendations of the National Academy of Sciences"
- "Such standards shall prescribe the maximum annual effective dose equivalent to individual members of the public…"

The Waste Isolation Pilot Plant Land Withdrawal Act of 1992 (amended 1996) defines roles and responsibilities for regulating disposal of transuranic waste at WIPP

- The EPA "shall … issue final criteria for the Administrator's certification of compliance with the final disposal regulations" at 40 CFR 191
- The EPA "shall certify, by rule… whether the WIPP facility will comply with the final disposal regulations" at 40 CFR 191
- Recertifications required every five years throughout operations

Separate Regulations for WIPP and Yucca Mountain

WIPP

EPA 40 CFR Part 191 (1985, 1993)

- 10,000-year regulatory period
- Normalized cumulative release standard
  - limit set on total allowable release during regulatory period, normalized to initial inventory
  - Dose limits apply only to "undisturbed performance" and have a secondary role in determining compliance
- Human intrusion scenarios included in the analysis of releases due to "all significant processes and events"

EPA 40 CFR 194 (1996)

- Specifies criteria for EPA's certification and recertification of compliance with 40 CFR Part 191
- Establishes expectations for the consideration of future human activities including
  - Oil and gas drilling
  - Potash mining

Yucca Mountain

EPA 40 CFR Part 197 (2001, 2008)

- 1,000,000-year regulatory period
- Dose standard
  - Limit set on maximum mean annual dose to an individual during the regulatory period
  - Diet and lifestyle of "reasonably maximally exposed individual" "representative of the people who now reside" in the region.
- Human intrusion considered in a separate stylized scenario

NRC 10 CFR Part 63 (2001, 2009)

- Implementing criteria define the licensing process
- Postclosure requirements are in almost all cases verbatim from EPA 40 CFR Part 197

What the Two Sets of Regulations Have in Common

Absolute proof is not possible; the standard is met by a "reasonable expectation" of compliance

- From EPA 40 CFR 191.13(b): "Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with § 191.13(a) will be achieved."

Reasonable expectation will be informed by "performance assessment"

- EPA From 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."

What the Two Sets of Regulations Have in Common (cont.)

Performance assessment is a probabilistic uncertainty analysis

- Focused on "the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values" (EPA 40 CFR 197.14)
- "The NRC will determine compliance, based upon the arithmetic mean of the projected doses from DOE's performance assessments…" (EPA 40 CFR 197.14(a))

"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 63: "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."

How the Regulations Drive What We Do
Example from a 1995 WIPP presentation

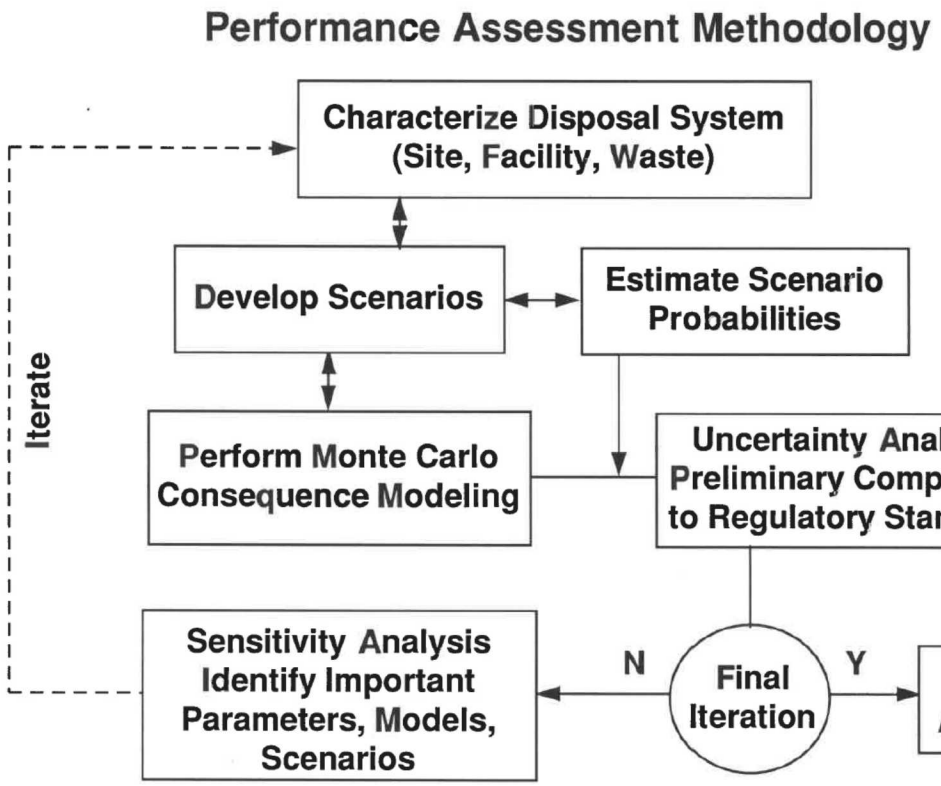


Figure from Swift, 1995, "Integration of Site Characterization and Performance Assessment for the Waste Isolation Pilot Plant," 6th International High-Level Radioactive Waste Management Conference, Las Vegas, Nevada, May 4, 1995

Characterization of the disposal system meets multiple regulatory requirements

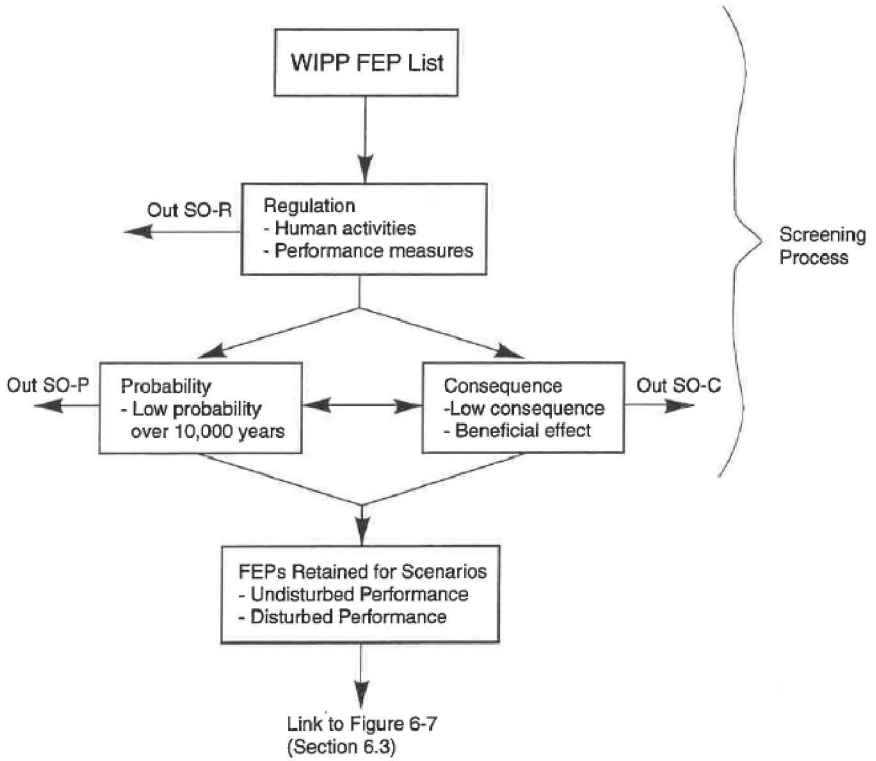
Features, events and processes (FEPs) evaluation and scenario analysis required by the regulatory definition of Performance Assessment

Consequence modeling and uncertainty analysis required by the regulatory definition of Performance Assessment

Sensitivity analysis guides program, identifies the "significant" FEPs and scenarios, and supports requirements to identify important aspects of the disposal system.

Results of final performance assessments are required by regulations

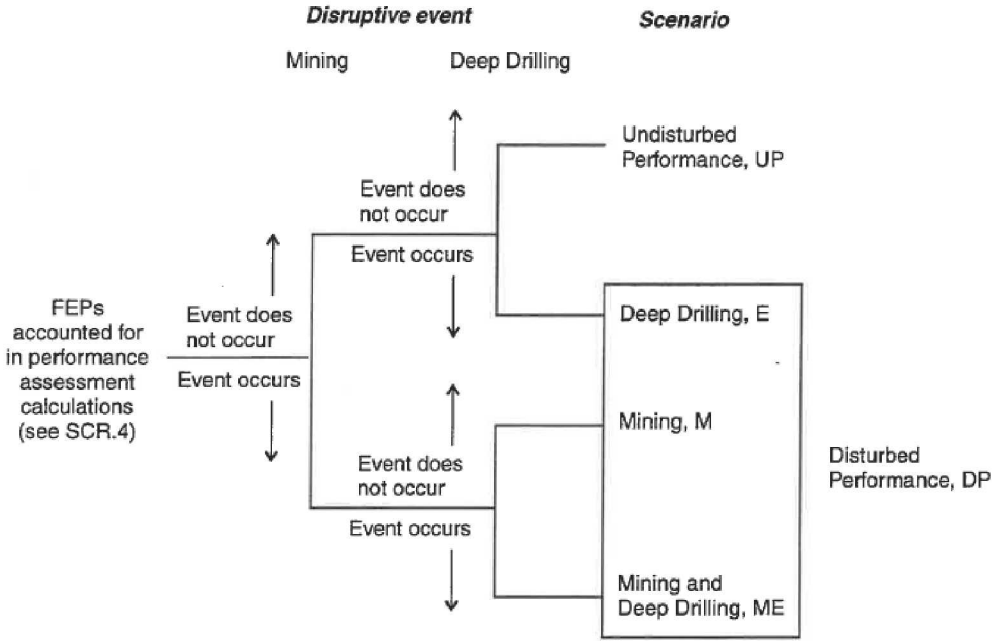
FEP Screening and Scenario Development for WIPP



DOE 1996 Figures 6-6 (above) and 6-7 (right)

Approximately 240 FEPs evaluated, 89 included in the performance assessment

Occurrence or nonoccurrence of two disruptive events (mining and drilling) used to construct scenarios for analysis (below)



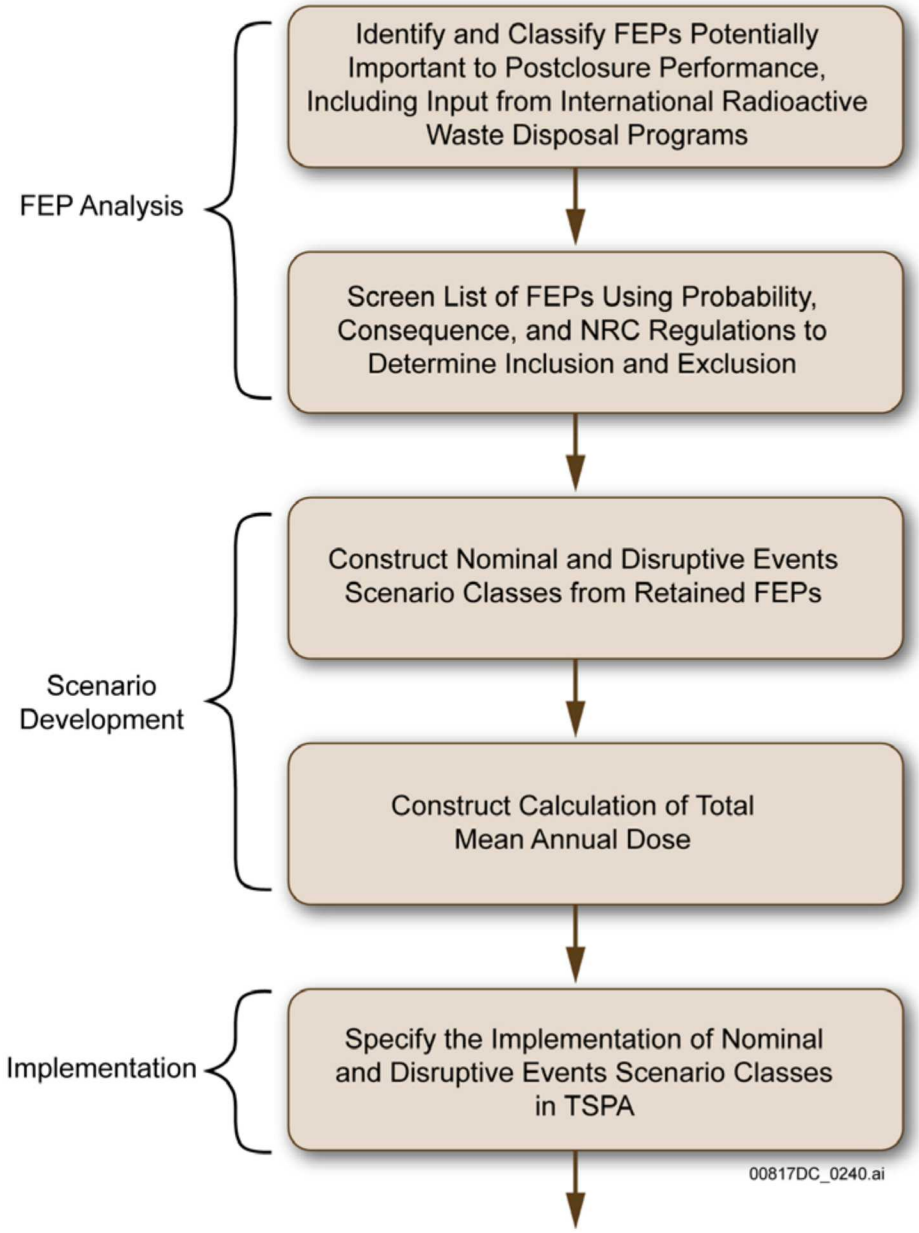
FEP Screening and Scenario Development for Yucca Mountain

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

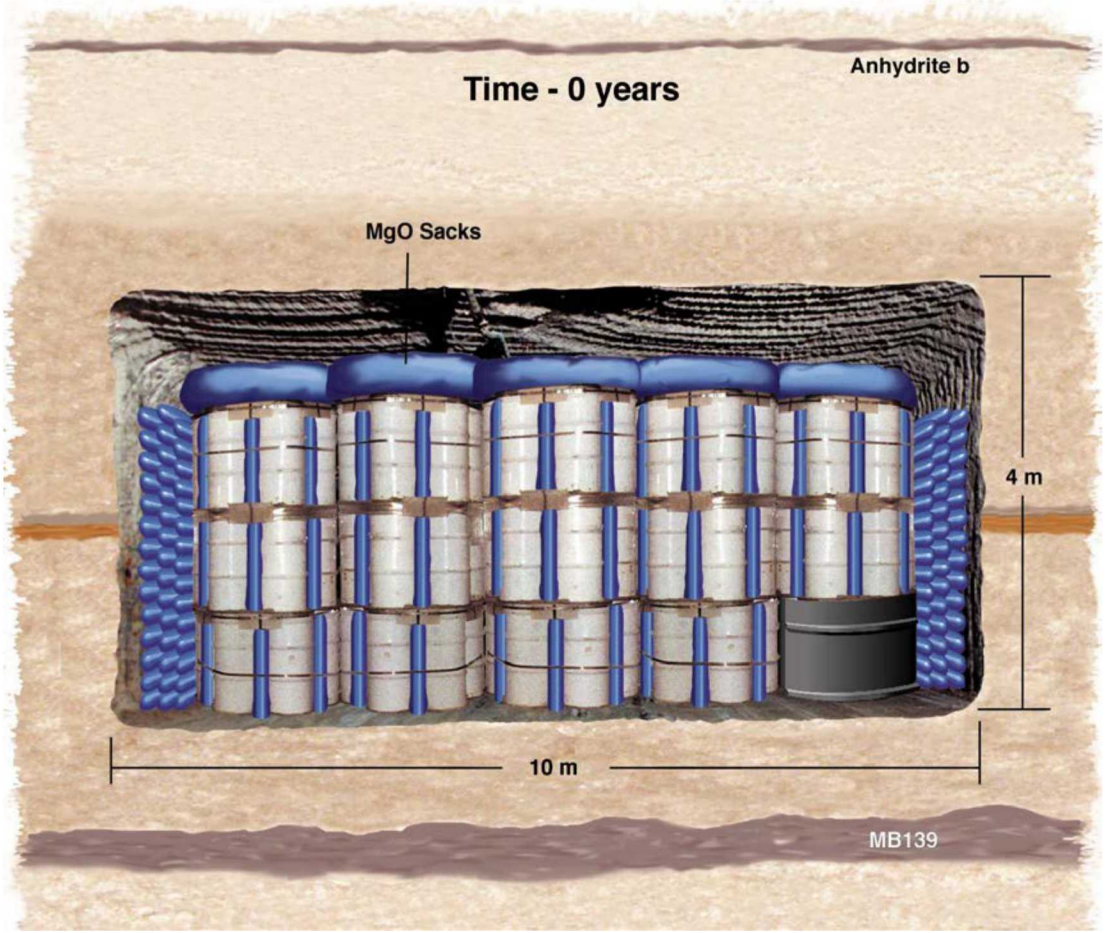
- Nominal Performance
- Early Failure
- Igneous Disruption
- Seismic Disruption



Conceptual Model for Long-term Performance of WIPP: Initial Conditions

Sealed Waste and Dry Backfill

- Introduced components
  - Iron waste drums, boxes
  - MgO backfill
  - Cellulosic, plastic, rubber waste
  - Metallic waste
  - Solidified waste
  - Actinide solids
- Geologic components
  - Salado salt
  - Argillaceous anhydrite interbeds ("marker beds")
- Processes
  - Ground support
  - Ventilation



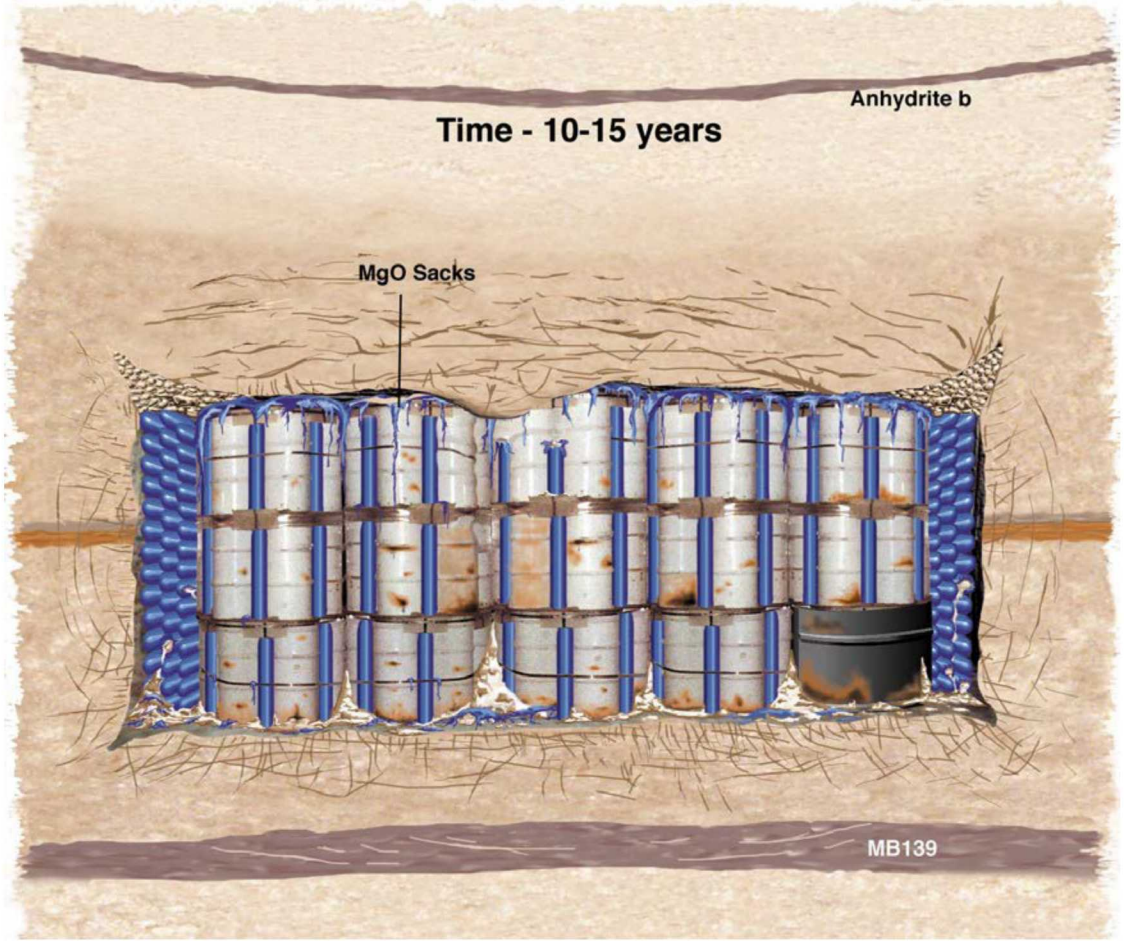
Source: Hansen 2010, WM2010, SAND2010-0535C

Conceptual Model for Long-term Performance of WIPP: The Near Future

Rapid Salt Creep Partially Encapsulates Waste

Processes

- Salt creep
- Floor heave
- Roof fall
- Collapse of salt into waste
- Disturbed-rock-zone dewatering
- Drum crushing
- Porosity, permeability reduction
- Breaching of MgO sacks
- Minor corrosion
- Degradation of organic waste

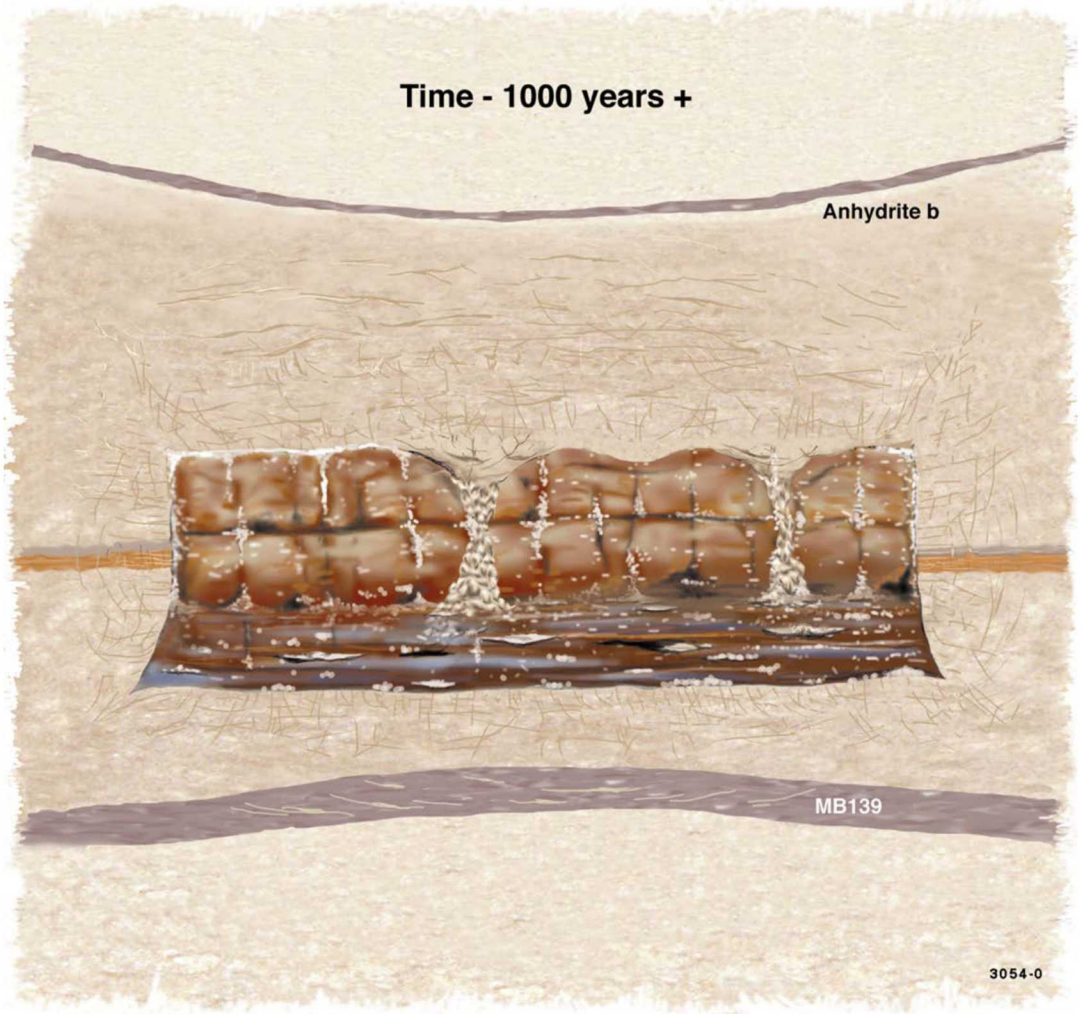


Source: Hansen 2010, WM2010, SAND2010-0535C

Conceptual Model for Long-term Performance of WIPP: Final State?

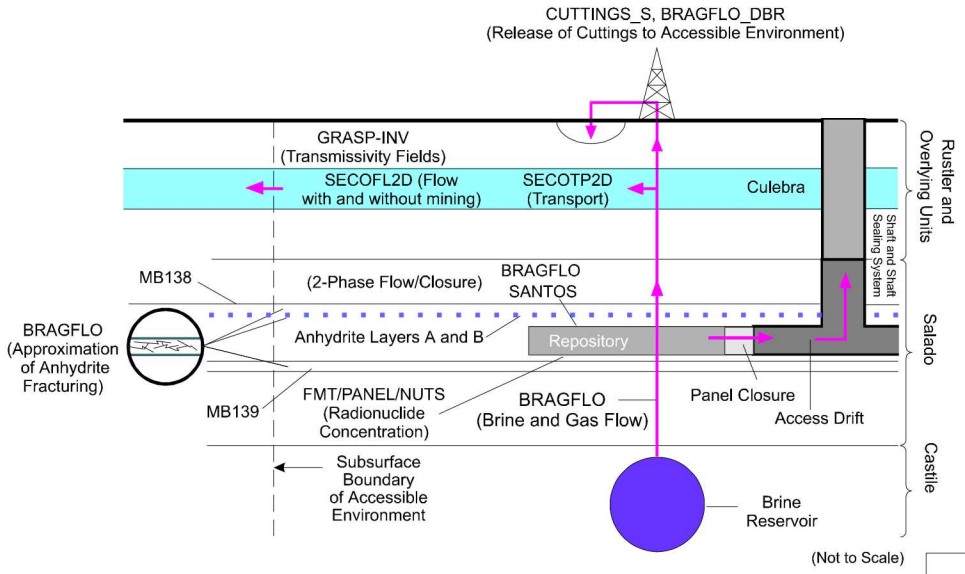
Salt Creep Encapsulates Waste

- Processes
  - Salt creep
  - Consolidation and healing of fractures
  - Porosity, permeability reduction
  - Extensive corrosion of drums and degradation of waste
- Processes of gas generation, brine inflow, and salt creep are highly coupled
- Uncertainty remains about final extent of consolidation and brine saturation



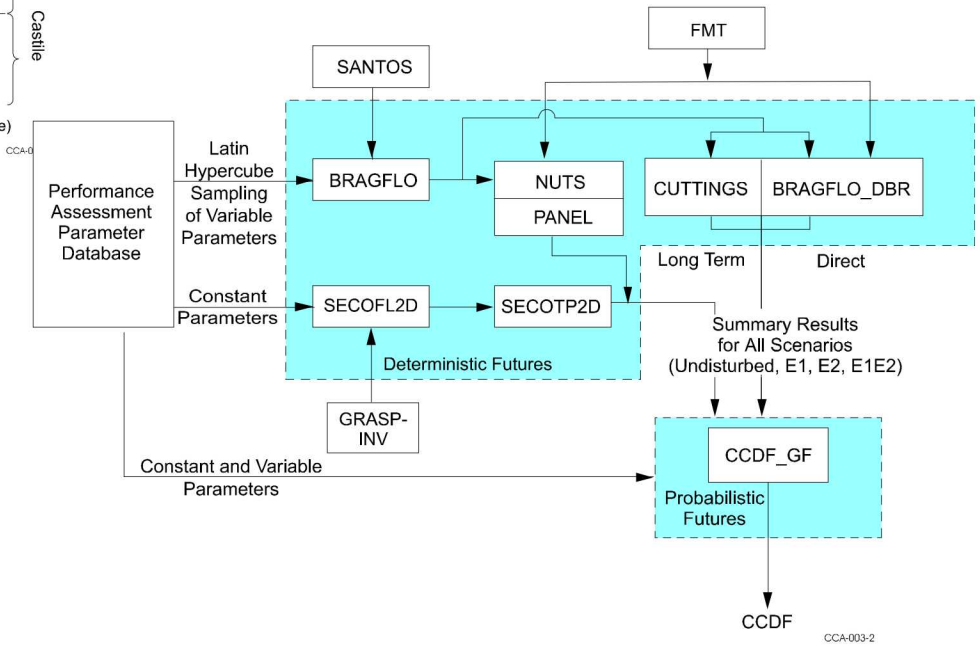
Source: Hansen 2010, WM2010, SAND2010-0535C

WIPP Performance Assessment Models



Models simulate major processes for each scenario

Models are linked to perform Monte Carlo simulations of normalized cumulative release



DOE 1996 Figures 6-25 (right) and 6-26 (above)

Perform Uncertainty Analysis Using Monte Carlo Simulations

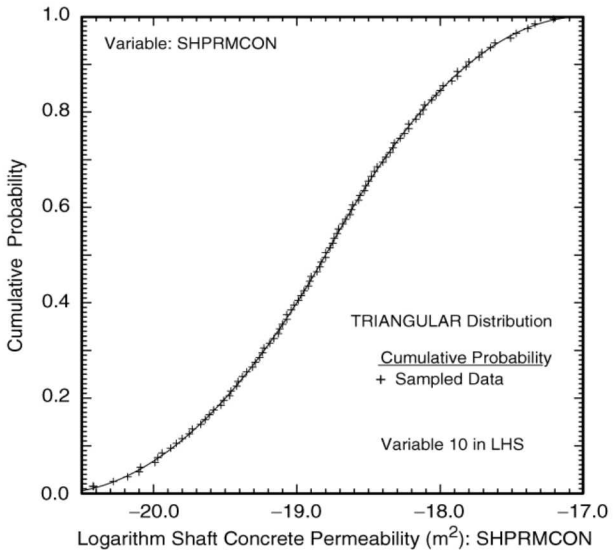
Estimate the number of simulations needed (n)

Draw n samples from each parameter distribution characterizing uncertainty in input parameters (see example at right)

Perform n complete system simulations

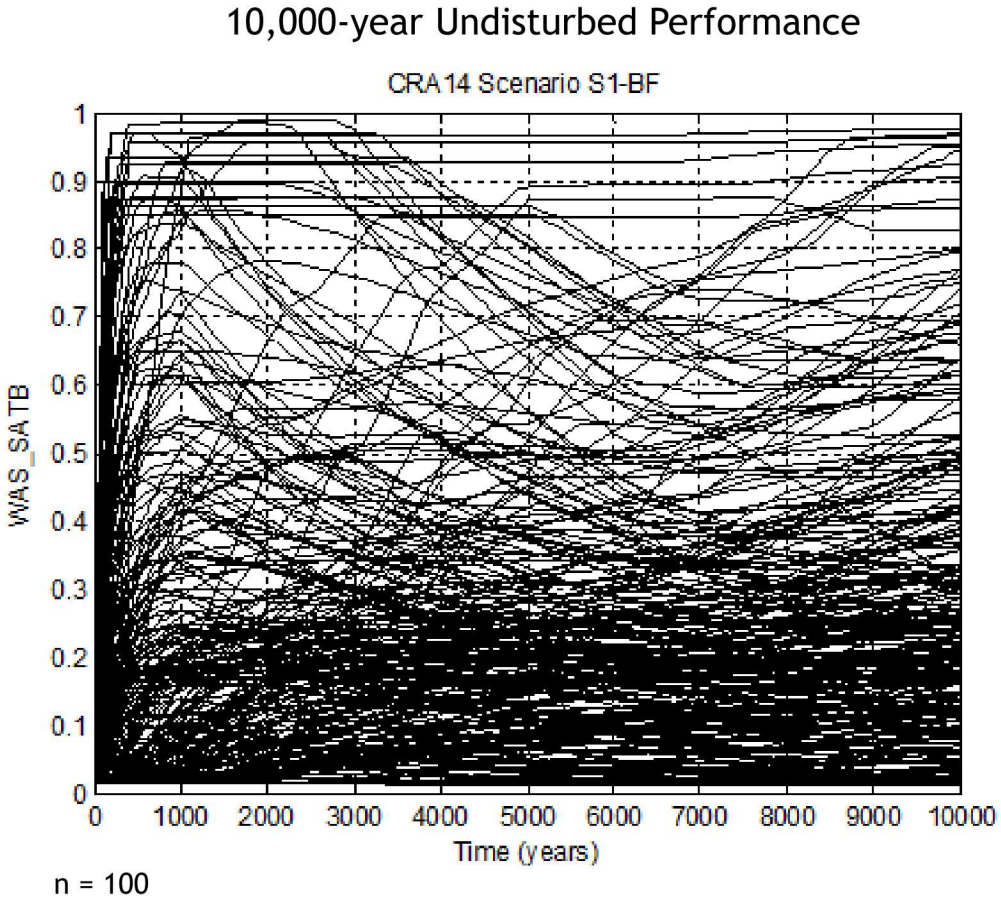
- Each has a different set of sampled input values
- Each has the same fixed-value parameters (constants)
- Each gives a single estimate of system performance, conditional on the chosen input values

Uncertainty in system performance is given by the distribution of results from the individual simulations



Example Cumulative Distribution Function, showing 100 sampled values (from DOE 1996, Appendix PAR, Parameter 10)

Example of Uncertainty in WIPP Performance: Brine Saturation in the Waste

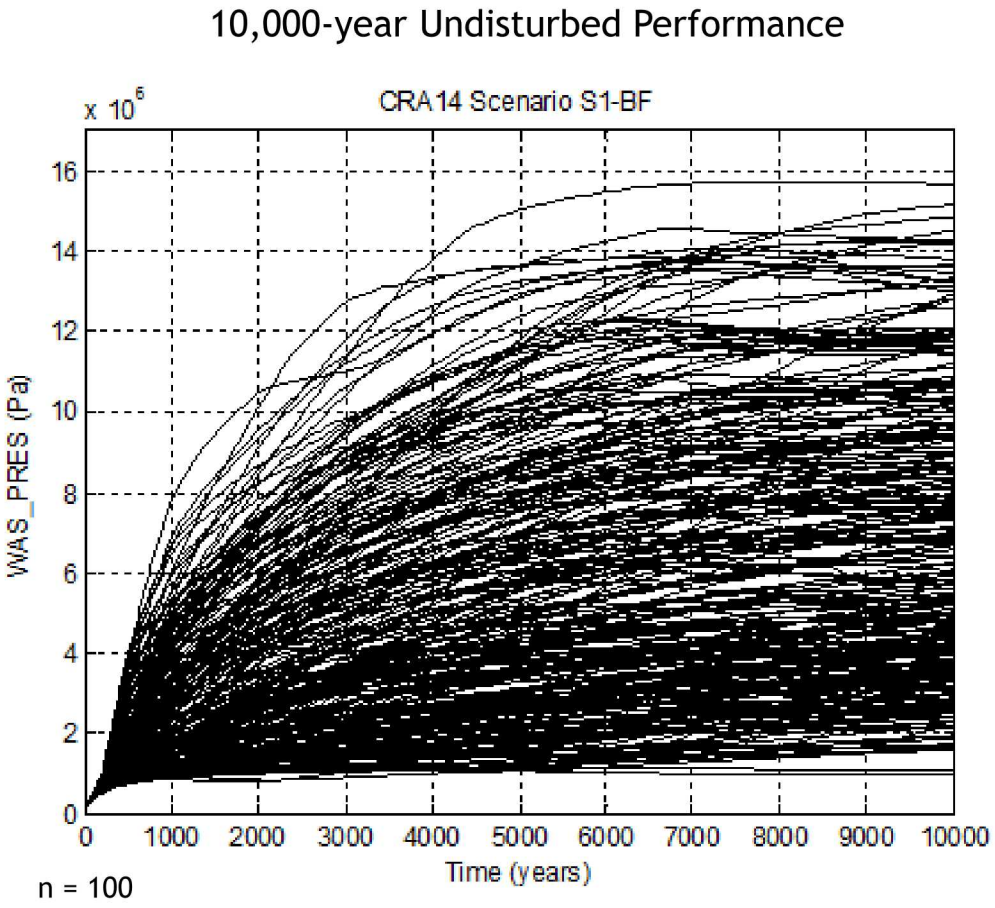


DOE 2014, Appendix PA, Figure PA-41

Saturation in the waste depends on multiple coupled processes

- Brine inflow and outflow
  - Function of permeability and pressure
- Gas generation
  - Function of brine availability and degradation rates
  - Influences pressure
- Brine consumption
  - Function of degradation rates and inventory
- Salt creep
  - Function of pressure

Example of Uncertainty in WIPP Performance: Fluid Pressure in the Waste



DOE 2014, Appendix PA, Figure PA-35

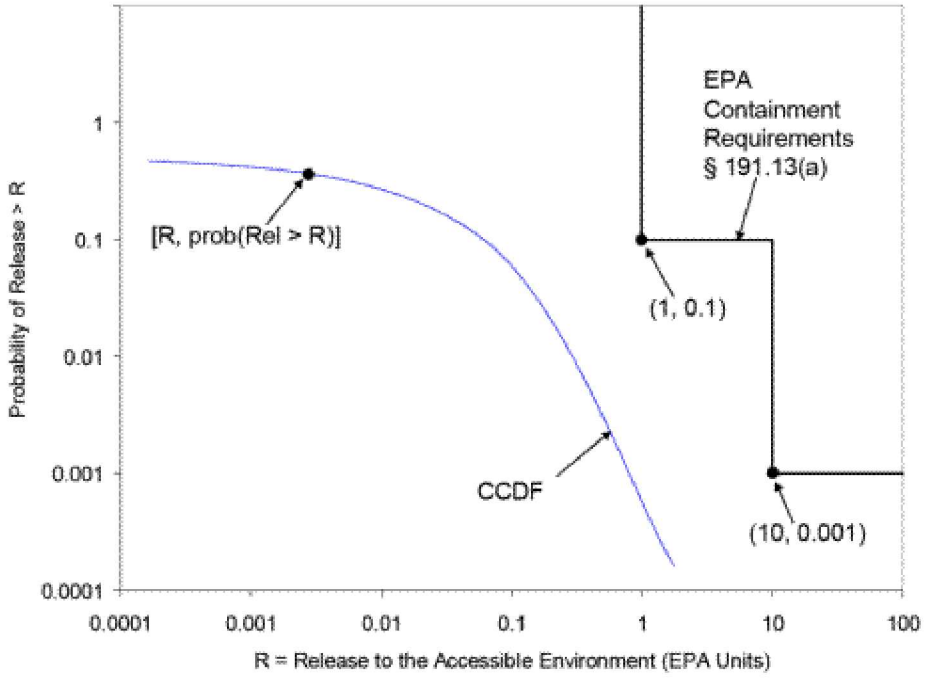
Pressure in the waste depends on multiple coupled processes

- Gas generation
  - Function of brine availability and degradation rates
- Salt creep
  - Function of pressure
- Brine inflow and outflow
  - Function of permeability and pressure
- Brine consumption
  - Function of degradation rates and inventory

Quantitative Compliance Estimates for WIPP

The EPA Containment Requirements at 40 CFR 191.13(a) define a complementary cumulative distribution function (CCDF) of allowable releases

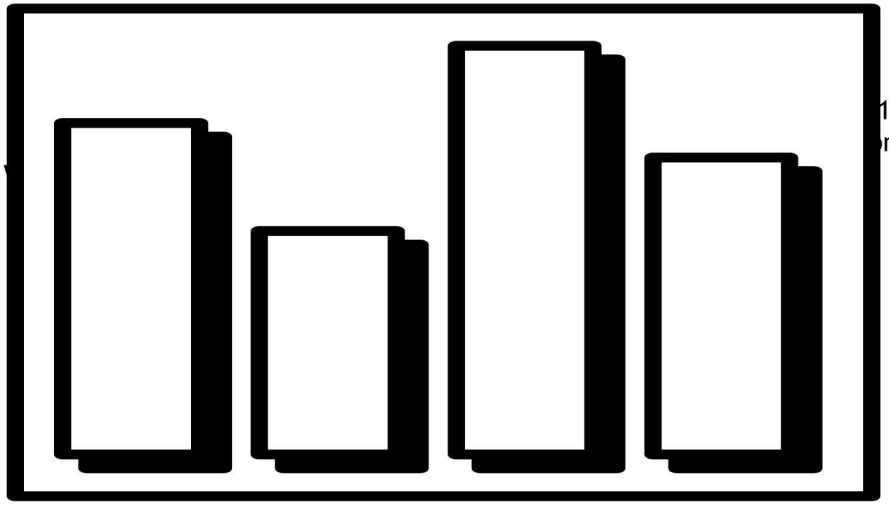
> "… cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:
>
> - (1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (appendix A); and
> - (2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (appendix A)."



DOE 2014, Appendix PA Figure PA-2

The EPA Normalized Release

The "quantity calculated according to Table 1" specified in 40 CFR 191.13 is the "EPA normalized release," calculated as:



14, Appendix PA
n PA-1

Table 1 of 40 CFR 191 Appendix A specifies the release limit for specific radionuclides

Radionuclide	Release limit L_i per 1000 MTHM* or other unit of waste (10^6 curies of TRU for WIPP)
Americium-241 or –243	100
Carbon-14	100
Cesium-135 or –137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium-238, -239,-240, or –242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium-230 or –232	10
Tin-126	1,000
Uranium-233, -234, -235, -236, or -238	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-live greater than 20 years that does not emit alpha particles	1,000

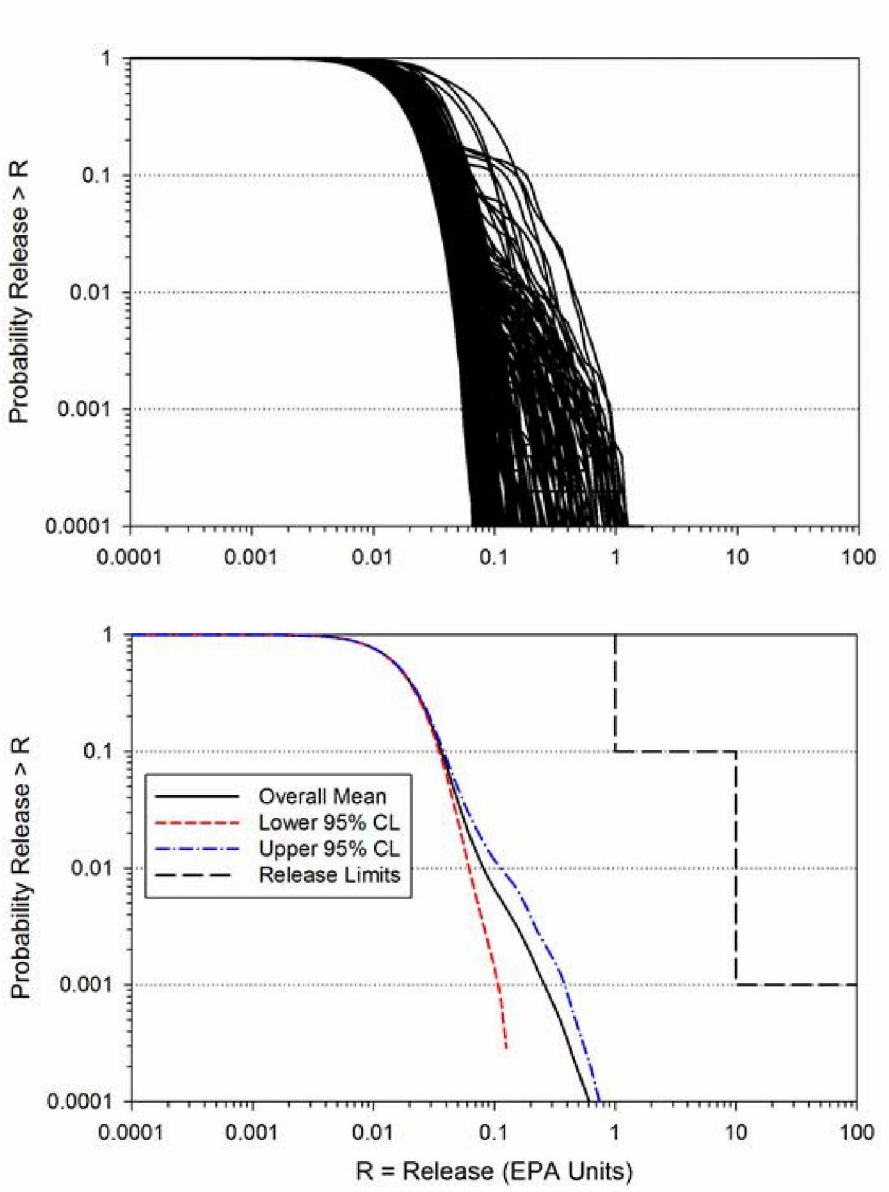
* Metric tons of heavy metal exposed to a burnup between 25,000 megawatt-days per metric ton of heavy metal (MWd/MTHM) and 40,000 MWd/MTHM.

CCDF of Total Normalized Releases From All Scenarios (WIPP)

Upper figure shows 300 individual realizations (calculated in three replicates of 100 realizations each)

Lower figure shows regulatory limits and the overall mean CCDF, with 95% confidence intervals (derived from the Student's T distribution of the mean CCDFs from each of the three replicates)

DOE 2014, Appendix PA
Figures PA-80 and PA-81



Release Mechanisms Contributing to the Overall Mean CCDF

Undisturbed performance results in zero release

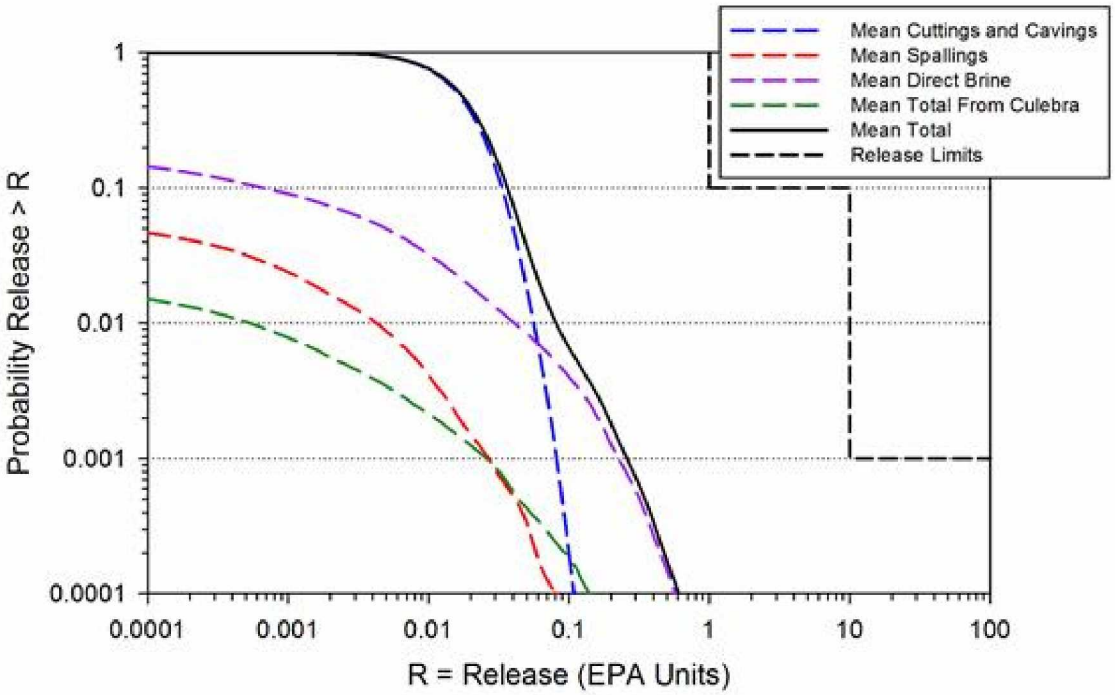
All releases are due to drilling intrusions

"**Cuttings and Cavings**" are the material brought to the surface during drilling

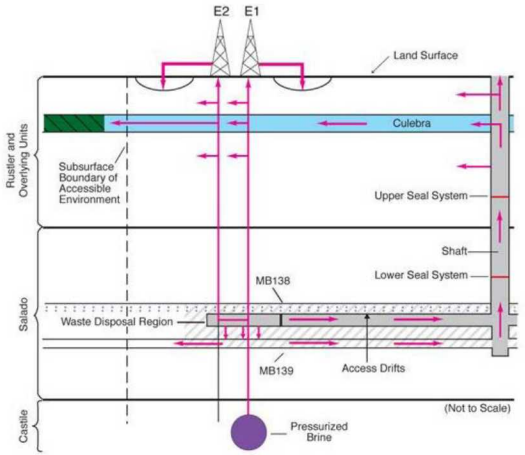
"**Spallings**" are solid material that is transported into the hole during depressurization and brought to the surface during drilling

"**Direct Brine**" is contaminated brine that flows to the surface during the intrusion

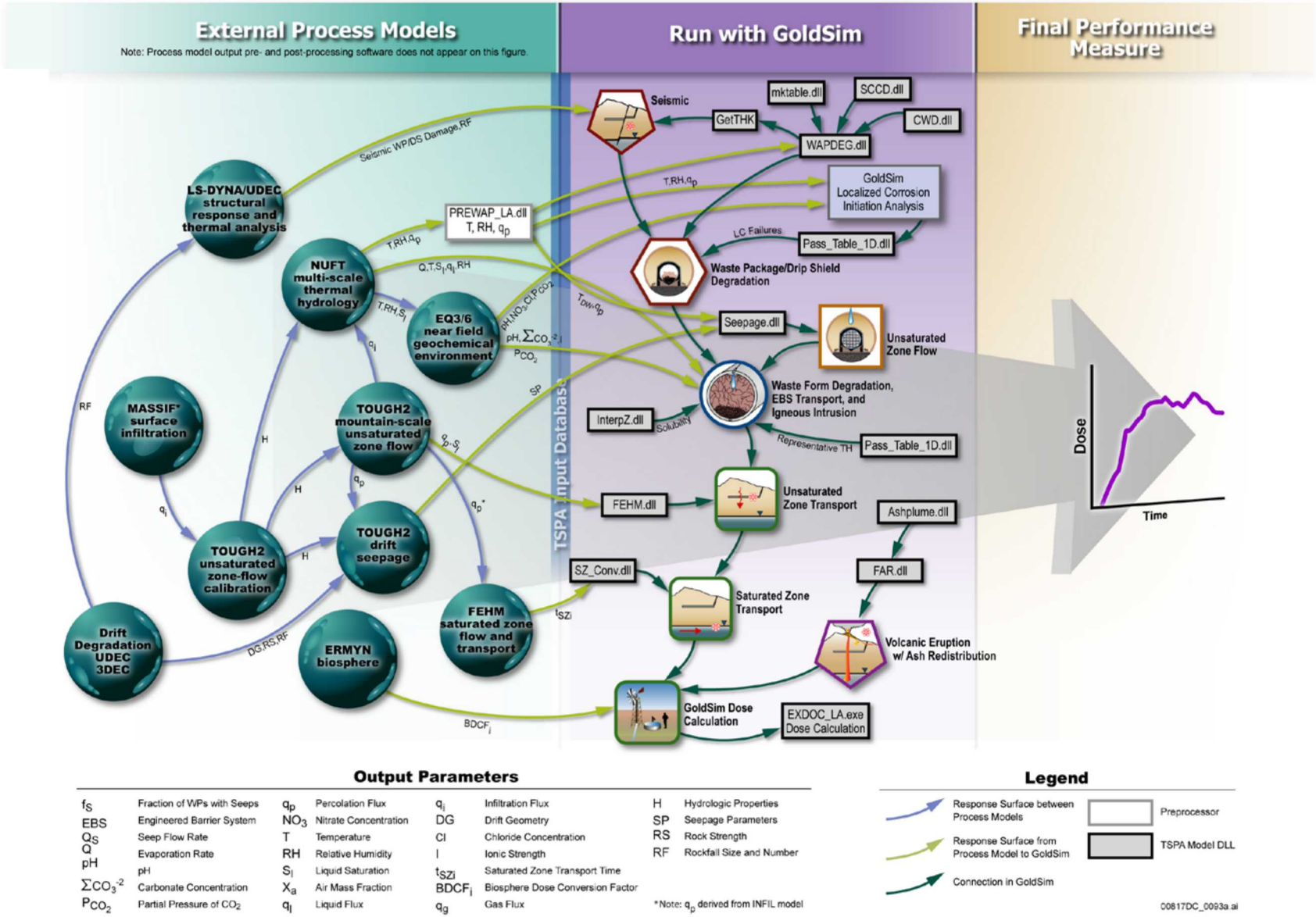
"**Culebra**" is the 10,000-year sum of radionuclides that are transported up the abandoned borehole after the intrusion event is over, and then transported laterally to the site boundary through the Culebra unit



DOE 2014, Appendix PA Figures PA-82 (above) and PA-9 (right)



Total System Performance Assessment Architecture (Yucca Mtn.)



Output Parameters

f_S	Fraction of WPs with Seeps	q_p	Percolation Flux	q_i	Infiltration Flux	H	Hydrologic Properties
EBS	Engineered Barrier System	NO_3	Nitrate Concentration	DG	Drift Geometry	SP	Seepage Parameters
Q_S	Seep Flow Rate	T	Temperature	Cl	Chloride Concentration	RS	Rock Strength
Q	Evaporation Rate	RH	Relative Humidity	I	Ionic Strength	RF	Rockfall Size and Number
pH	pH	S_l	Liquid Saturation	t_{SZi}	Saturated Zone Transport Time		
ΣCO_3^{-2}	Carbonate Concentration	X_a	Air Mass Fraction	$BDCF_i$	Biosphere Dose Conversion Factor		
P_{CO_2}	Partial Pressure of CO_2	q_l	Liquid Flux	q_g	Gas Flux		

*Note: q_p derived from INFIL model

Legend

Response Surface between Process Models
Response Surface from Process Model to GoldSim
Connection in GoldSim
Preprocessor
TSPA Model DLL

00817DC_0093a.ai

SNL 2008c Figure 3-2

Uncertainty in Yucca Mountain TSPA

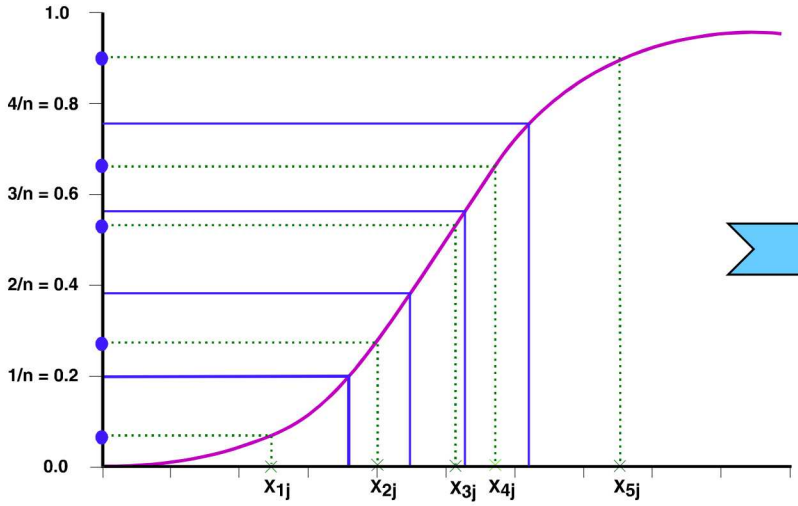
Aleatory Uncertainty
− Inherent randomness in events that could occur in the future − Alternative descriptors: irreducible, stochastic, intrinsic, type A − Examples: ➢ *Time and size of an igneous event* ➢ *Time and size of a seismic event*

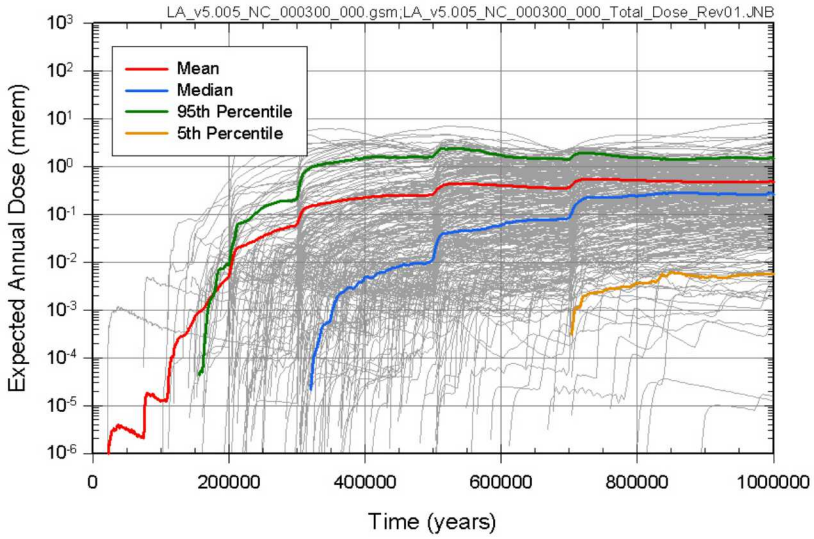
Epistemic uncertainty
− Lack of knowledge about appropriate value to use for a quantity assumed to have a fixed value − Alternative descriptors: reducible, subjective, state of knowledge, type B − Examples: ➢ *Spatially averaged permeabilities, porosities, sorption coefficients, …* ➢ *Rates defining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

Uncertainty in YM TSPA (cont.)

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

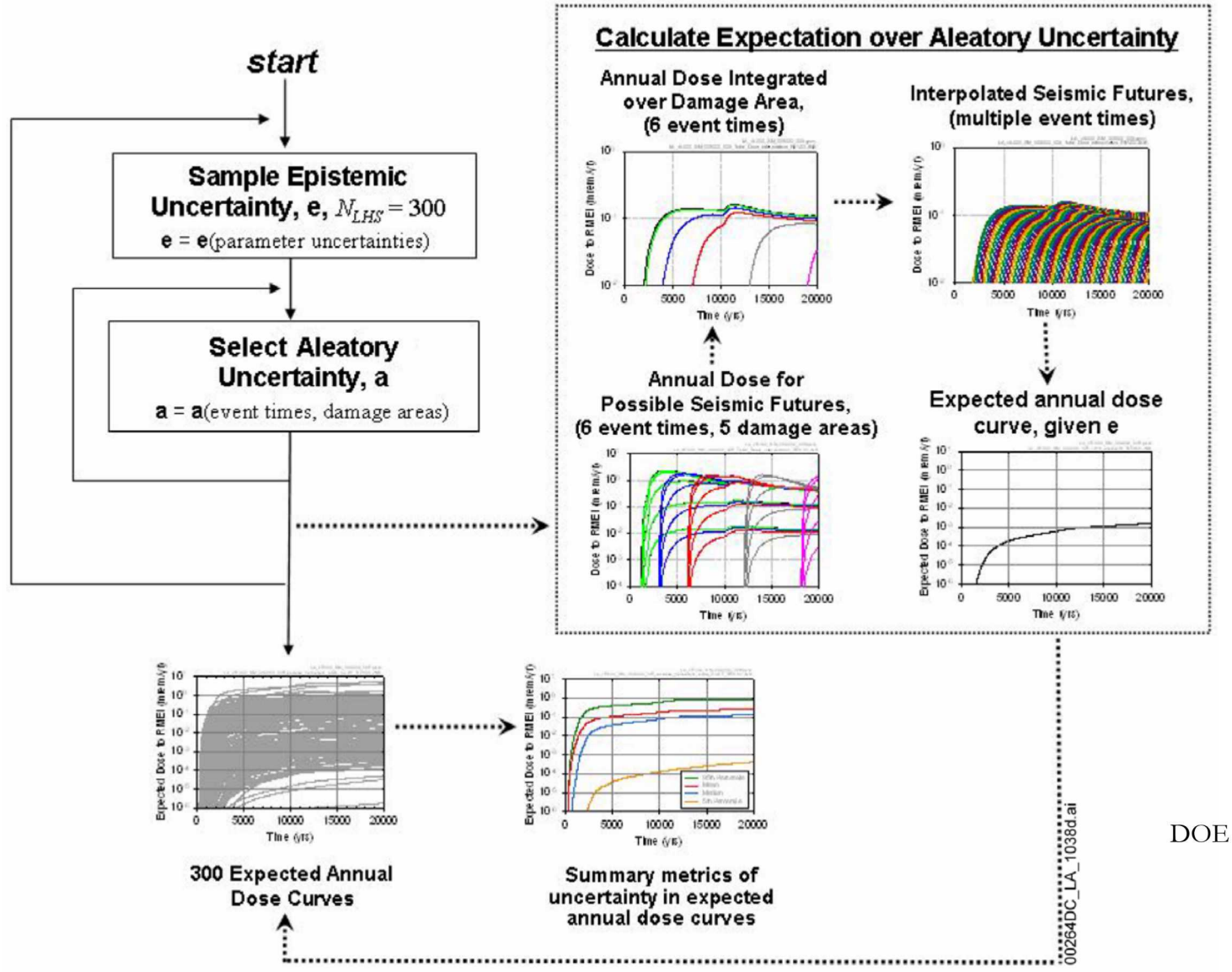
(approx. 400 uncertain epistemic parameters in TSPA-LA)





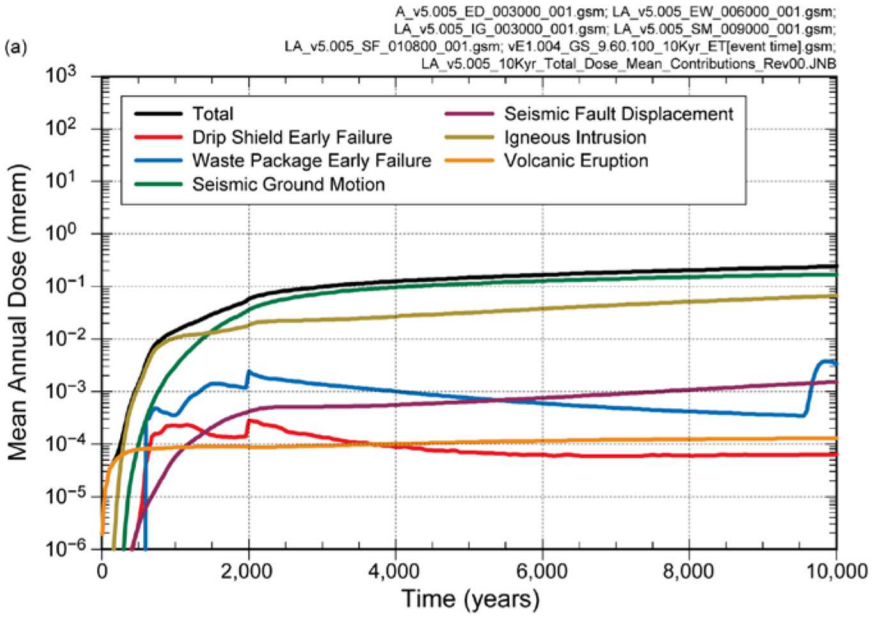
Aleatory uncertainty incorporated through the design of the analysis

Example: Calculation of Expected Seismic Dose

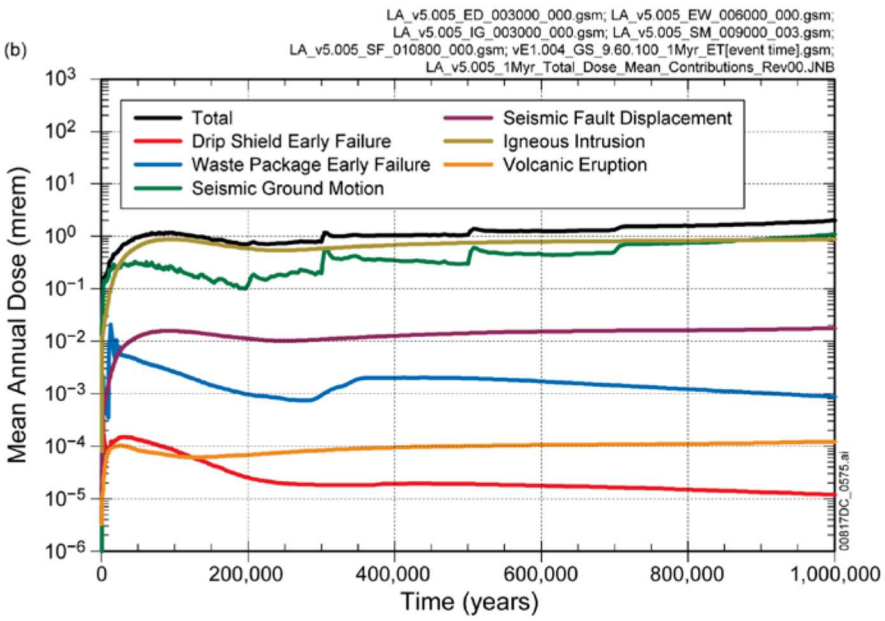


DOE 2008 Figure 2.4-8

Modeling Cases Contributing to Total Mean Annual Dose for Yucca Mountain



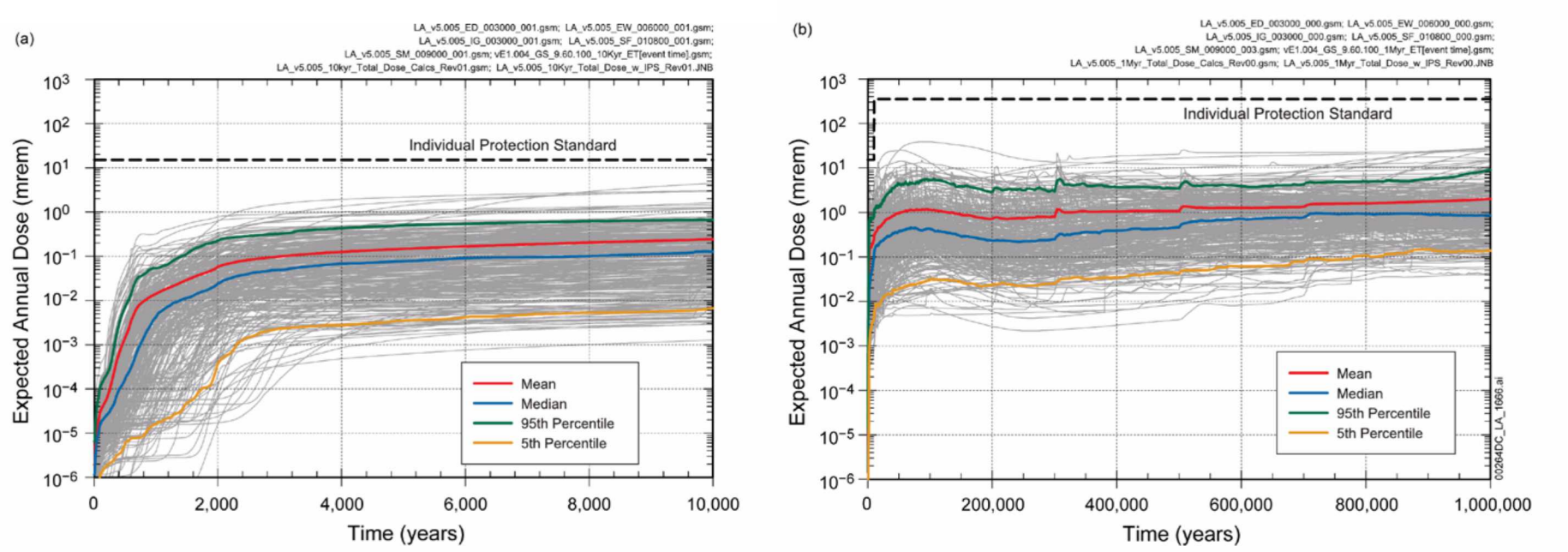
10,000 years



1,000,000 years

MDL-WIS-PA-000005 REV 00 AD 01, Figure 8.1-3[a] (SNL 2008c)

Long-Term Performance of Yucca Mountain



DOE/RW-0573 Rev 1 Figure 2.4-10
(DOE 2008)

10,000 years

10,000-year Standard:
Mean annual dose no more than 0.15 mSv (15 mrem)

TSPA-LA estimated 10,000 yr maximum mean annual dose: 0.0024 mSv (0.24 mrem)

1,000,000 years

1,000,000-year Standard:
Mean annual dose no more than 1 mSv (100 mrem)

TSPA-LA estimated 1,000,000- yr maximum mean annual dose: 0.02 mSv (2.0 mrem)

Closing thoughts

40 CFR 191 (EPA 1985)

"Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with §191.13 (a) will be achieved." (40 CFR 191.13(b)) *[emphasis added]*

"Substantial uncertainties are likely to be encountered in making these predictions. In fact, sole reliance on these numerical predictions to determine compliance may not be appropriate; the implementing agencies may choose to supplement such predictions with qualitative judgments as well." (40 CFR 191 Appendix B (now Appendix C))

There is much more to licensing a repository than the quantitative postclosure safety assessment

References

SNL (Sandia National Laboratories), 2008a. Features, Events, and Processes for the Total System Performance Assessment: Methods. ANL-WIS-MD-000026, Rev 00. Las Vegas, NV: U.S. Department of Energy Office of Civilian Radioactive Waste Management

SNL (Sandia National Laboratories), 2008b. Features, Events, and Processes for the Total System Performance Assessment: Analyses. ANL-WIS-MD-000026, Rev 00. Las Vegas, NV: U.S. Department of Energy Office of Civilian Radioactive Waste Management

SNL (Sandia National Laboratories), 2008c. Total system performance assessment model/analysis for the license application. MDL-WIS-PA-000005 Rev00, AD 01. Las Vegas, NV: U.S. Department of Energy Office of Civilian Radioactive Waste Management

U.S. DOE (U.S. Department of Energy), 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolati on Pilot Plant, DOE/CAO-1996-2184, Carlsbad, NM, U.S. Department of Energy Carlsbad Area Office

U.S. DOE (U.S. Department of Energy), 2008. Yucca Mountain repository license application safety analysis report. DOE/RW-0573, Update no. 1. Las Vegas, NV: U.S. Department of Energy

U.S. DOE (US Department of Energy), 2014. Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2014 for the Waste Isolation Pilot Plant

U.S. Nuclear Regulatory Commission (NRC), 2014. Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 3, Repository Safety after Permanent Closure. NUREG-1949, Vol. 3

U.S. Nuclear Regulatory Commission (NRC), 2015. Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 2, Repository Safety Before Permanent Closure, and Volume 5, Proposed Conditions on the Construction Authorization and Probable Subjects of License Specifications. NUREG-1949, Vol. 2 and Vol. 5

Key Websites: http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app.html; http://www.wipp.energy.gov/library/caolib.htm