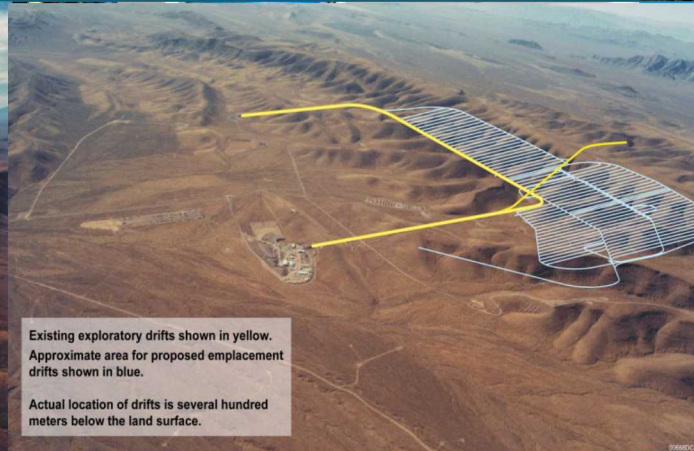


Case Study of the Proposed Yucca Mountain Geologic Repository



PRESENTED BY

David Sassani, Distinguished Member Tech Staff

Nuclear Engineering 290E, Special Topics in Environmental
Aspects of Nuclear Energy

University of California, Berkeley, CA, April 3, 2019

Outline



Project history

Major elements of the disposal concept

- Waste
- Repository Design
- Site geology

Long-term performance

- Undisturbed performance
- Disruptive events

Quantitative estimates of annual dose

Conclusions

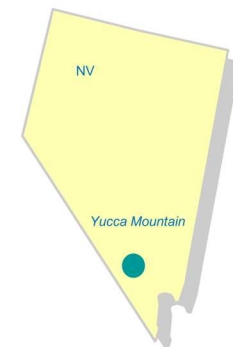
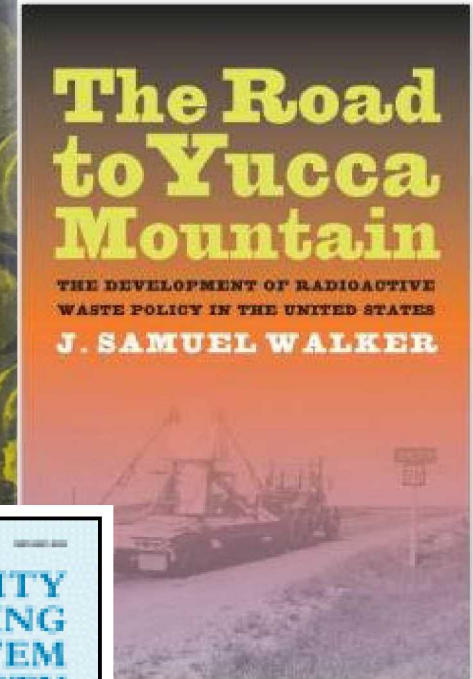
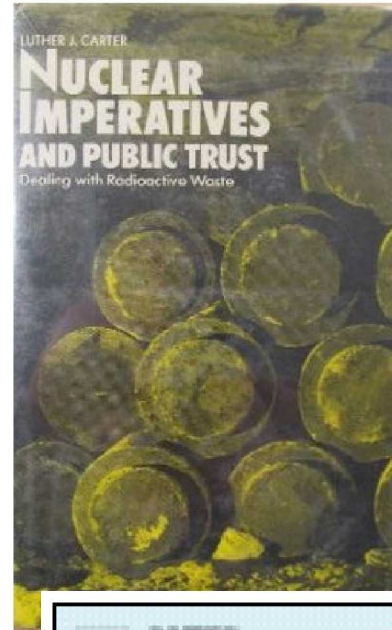
Key References for the History of Yucca Mountain



Luther Carter, 1987, *Nuclear Imperatives and Public Trust: Dealing with Radioactive Waste*, Resources for the Future, Inc. Baltimore, MD: John Hopkins University Press; 1987

J. Samuel Walker, 2009, *The Road to Yucca Mountain*. Berkeley, CA: University of California Press.

R. P. Rechard, T.A. Cotton, and M.D. Voegelé, 2014, “Site Selection and Regulatory Basis for the Yucca Mountain Disposal System for Spent Nuclear Fuel and High-Level Radioactive Waste”, *Reliability Engineering and System Safety* v. 122, p. 7-31 [see also other papers in the same volume]



Background



1940s: Manhattan Project generates first significant volumes of spent nuclear fuel (SNF) and high-level radioactive waste (HLW)

- Waste managed on-site

1955: National Academy of Sciences convenes “Committee on Waste Disposal” at the request of the Atomic Energy Commission (AEC)

- 1957 NAS report “*The Disposal of Radioactive Waste on Land*,” focus on disposal of liquid HLW

1960s-1970s: AEC focus on disposal of solidified HLW and SNF in salt mines (Lyons, Kansas followed by Carlsbad, NM)

- 1969 fire at Rocky Flats focuses attention on transuranic waste

Early 1970s: recognition of potential suitability of multiple rock types, including granitic and crystalline rocks, salt, shale, and tuff (Schneider and Platt, 1974; Ekren et al., 1974)

1976: National policy moves away from reprocessing of commercial SNF

1980: Department of Energy (DOE) completes “Final Environmental Impact Statement: Management of Commercially Generated Radioactive Wastes” (DOE/EIS-0046F)

1982: Congress passes the Nuclear Waste Policy Act (NWPA)

- Tasks Environmental Protection Agency (EPA) with promulgating regulatory standards for disposal
- Tasks Nuclear Regulatory Agency (NRC) with regulating repositories containing HLW and SNF, consistent with EPA standards
- Tasks DOE with managing storage and disposal of HLW and SNF

Early Yucca Mountain Chronology



Early 1970s: Recognition of potential for disposal on the Nevada Test Site (NTS), including in unsaturated rocks, by Winograd and others at United States Geological Survey (USGS) (Ekrens et al., 1974)

1975: Nevada Legislature asks the federal government to consider the NTS

Resolved by the Assembly and the Senate of the State of Nevada, jointly, That the legislature of the State of Nevada strongly urges the Energy Research and Development Administration to choose the Nevada Test Site for the disposal of nuclear wastes;

(Nevada Assembly Joint Resolution 15, May 17, 1975)

1976: USGS formally proposes NTS for disposal (McKelvey, 1976)

- Closed hydrologic basins
- Aridity
- Multiple rock types (clay/shale, granite, tuff)
- Remoteness and nuclear history

1978: First hole drilled at Yucca Mountain for potential repository characterization (Spengler et al., 1979)

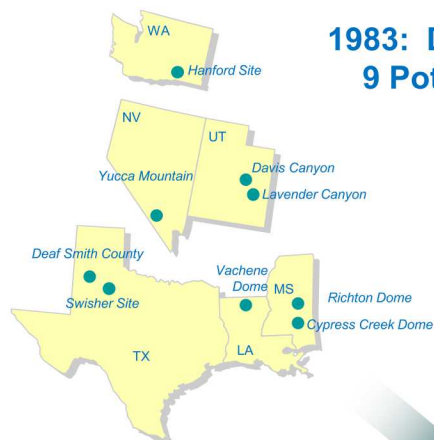
1982: USGS recommends unsaturated rocks at Yucca Mountain (Roseboom, 1983)



1982-1987: The Siting Process under the NWPA

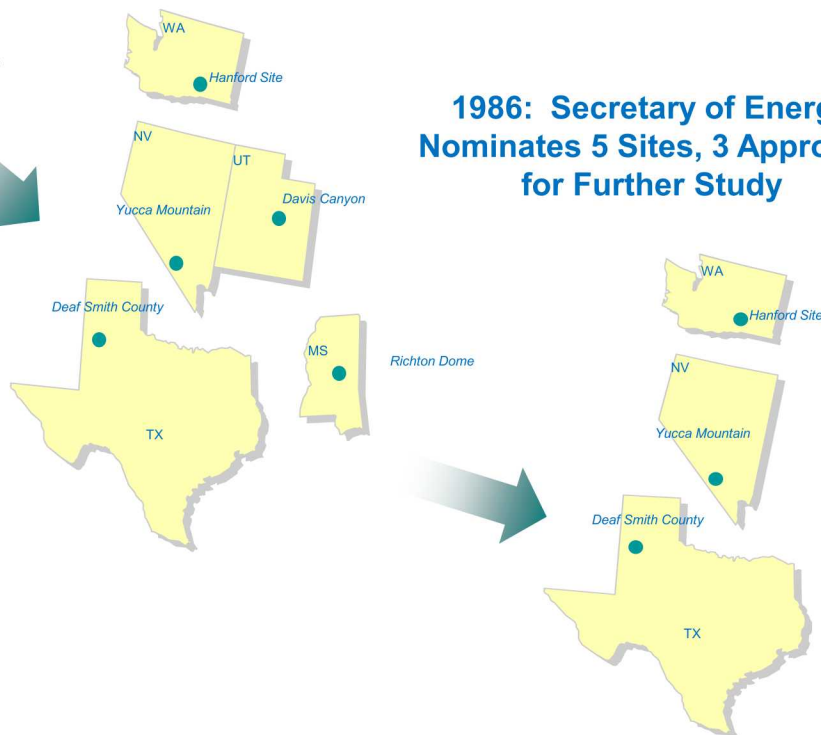


**1983: DOE identifies
9 Potential Sites**

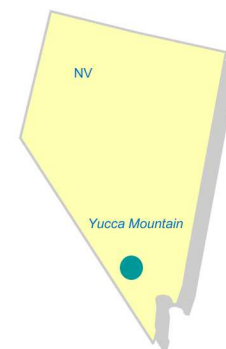


*The NWPA of 1982 (sec. 112) requires
DOE to consult with affected governors and
issue siting guidelines
The Secretary to nominate at least five sites
The Secretary to recommend 3 sites for
characterization*

**1986: Secretary of Energy
Nominates 5 Sites, 3 Approved
for Further Study**



**1987: NWPA Amended to Mandate
One Site for Characterization**



Yucca Mountain from 1987 to 2008



1988: DOE completes the Yucca Mountain Site Characterization Plan (SCP)

- (required by NRC regulation 10 CFR part 60)

1989-2002: DOE conducts extensive site characterization activities in accordance with the SCP and in response to extensive review from the NRC and Nuclear Waste Technical Review Board

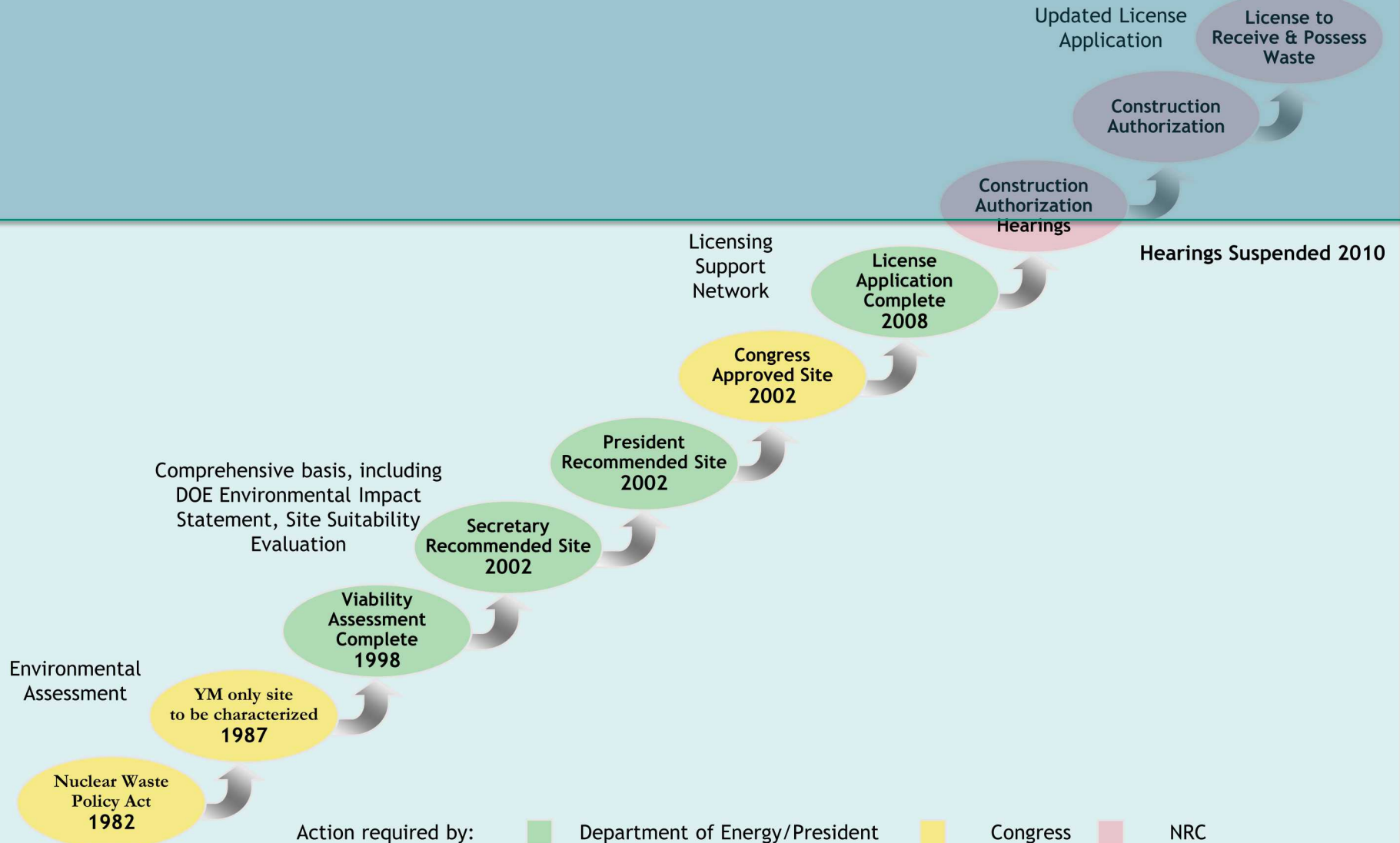
1998: DOE completes the *Viability Assessment* mandated by the NWPA

2002: DOE completes the *Environmental Impact Statement (EIS)* mandated by the National Environmental Policy Act (NEPA) and the *Site Recommendation* mandated by the NWPA

2002: President G.W. Bush approves DOE's recommendation of Yucca Mountain and Congress votes to override the Nevada veto, consistent with requirements of the NWPA

2008: DOE completes a *Final Supplement to the EIS* and submits a *License Application* to the NRC seeking authorization to construct a repository

Yucca Mountain under the NWPA



The Yucca Mountain Program since 2008

“Yucca Mountain is not a workable option” (DOE licensing motion, March 3, 2010)

- “the Secretary’s judgment here is not that Yucca Mountain is unsafe or that there are flaws in the LA [license application], but rather that it is not a workable option and that alternatives will better serve the public interest.” (DOE filing to Nuclear Regulatory Commission Licensing Board, May 27, 2010, footnote 102)

Congress has not appropriated funds for Yucca Mountain or the DOE Office of Radioactive Waste Management since 2010

The Nuclear Waste Policy Act remains in effect and precludes site-specific work at sites other than Yucca Mountain without Congressional authorization and appropriation (NWPA Sec. 161)

Yucca Mountain license hearings remain suspended

- The NRC staff has completed its *Safety Evaluation Report* (NRC 2014, NRC 2015)

All DOE activities related to disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) have moved to the DOE Office of Nuclear Energy

- SNF and HLW remain in storage at multiple sites across the nation, and future plans are uncertain (Bonano et al., 2018)

Major Elements of the Yucca Mountain Repository Concept



The waste:

- HLW and SNF from defense and commercial activities

The repository design

- Waste packages emplaced in open tunnels in unsaturated rock

The site

- Arid climate, topography, and geology limit water flow reaching the engineered barriers and provide a long transport path before radionuclides can reach the human environment

Long-term performance of the repository relies on natural and engineered barriers working together to isolate the waste

The Yucca Mountain Mission

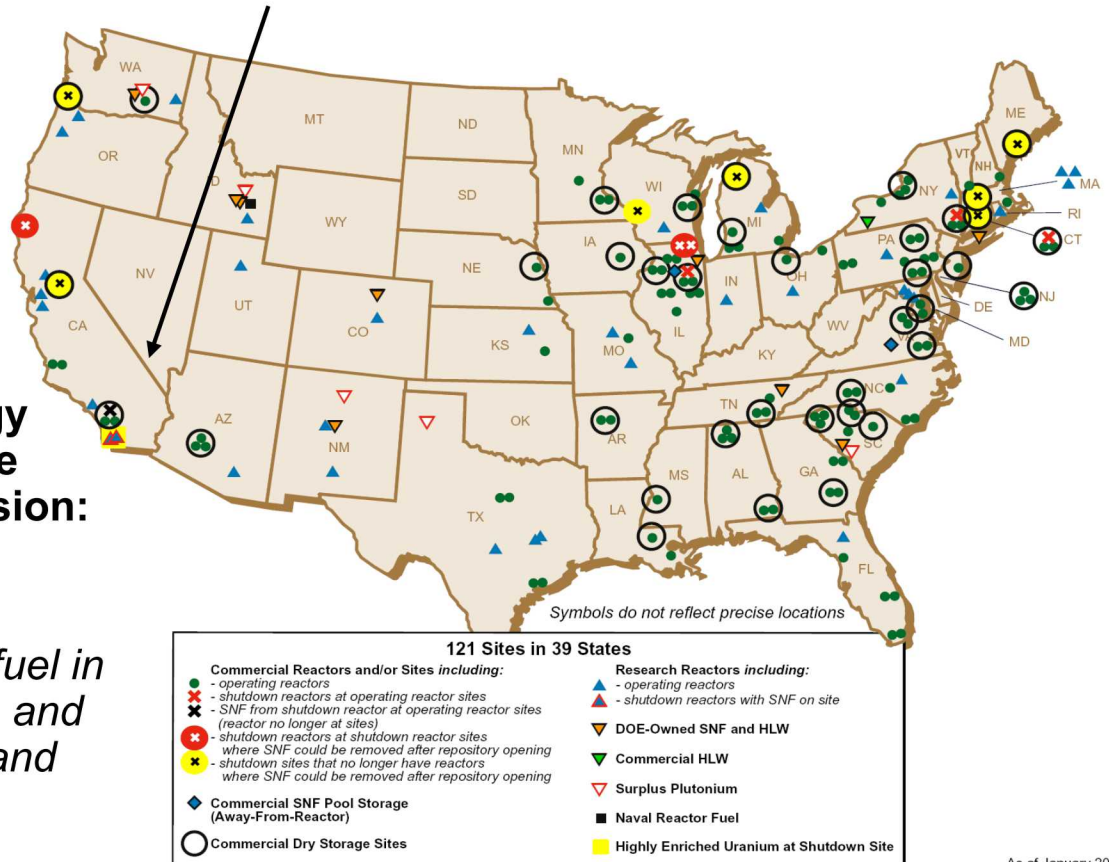
Current locations of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) destined for geologic disposal:

121 sites in 39 states

United States Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM) Mission:

To manage and dispose of high-level radioactive waste and spent nuclear fuel in a manner that protects health, safety, and the environment; enhances national and energy security; and merits public confidence.

Proposed Yucca Mountain Repository



As of January 2008

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)



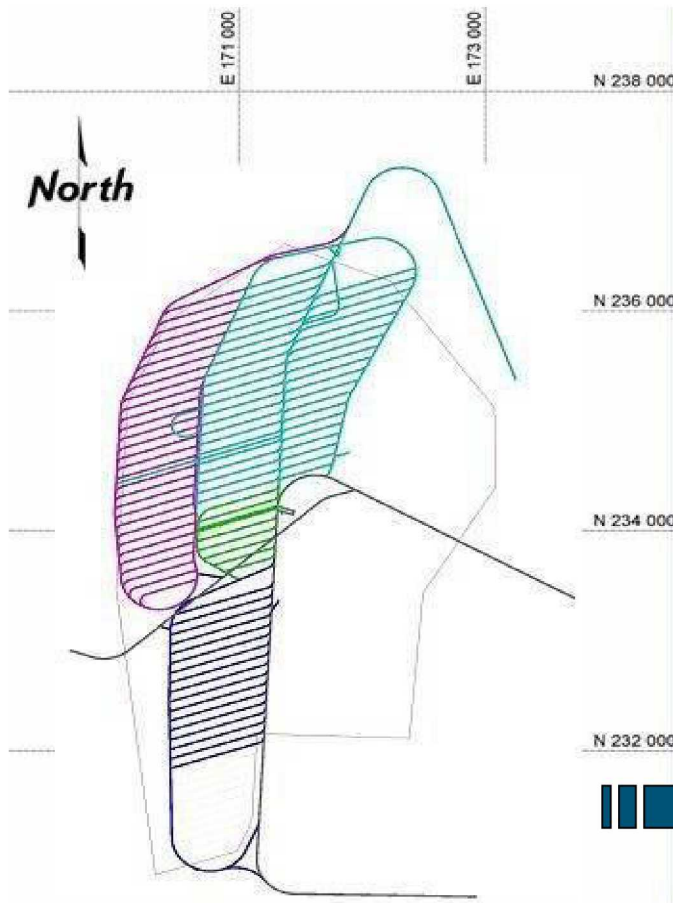
DOE & Commercial High-Level Waste:
4,667 MTHM
(~3000 waste packages of co-disposed DSNF and HLW)



Yucca Mountain
Total 70,000 MTHM

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

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

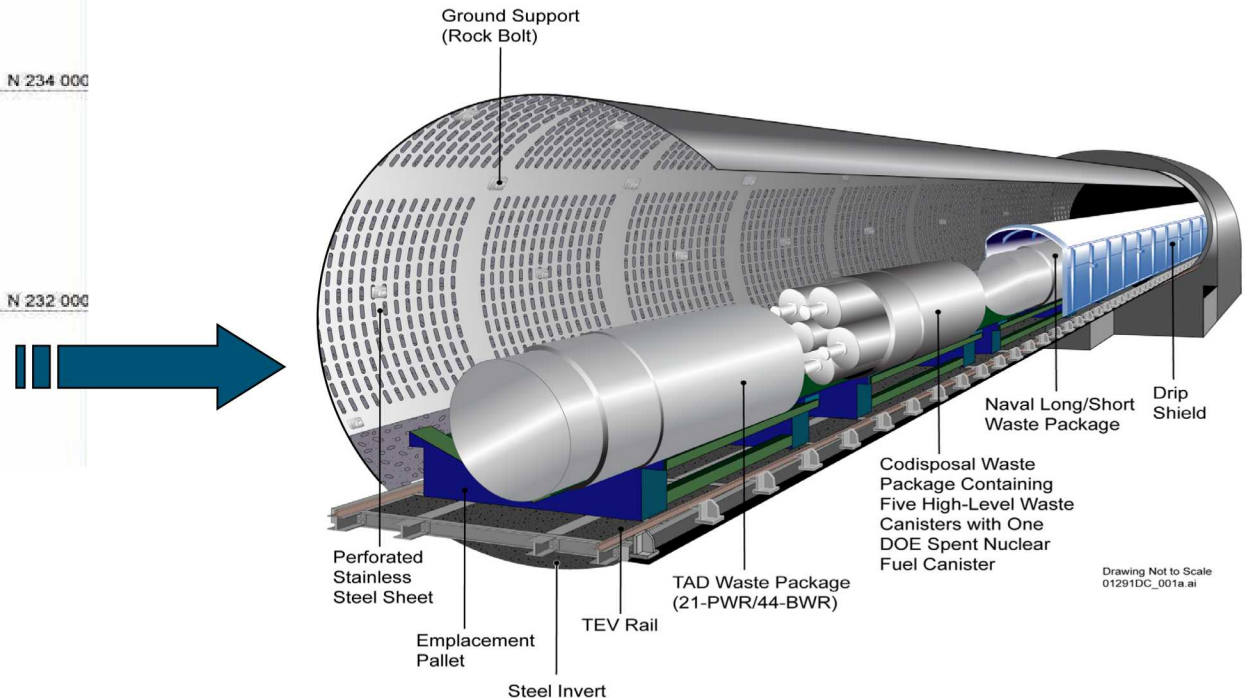
outer layer 2.5 cm Alloy 22 (Ni-Cr-Mo-V)

inner layer 5 cm stainless steel

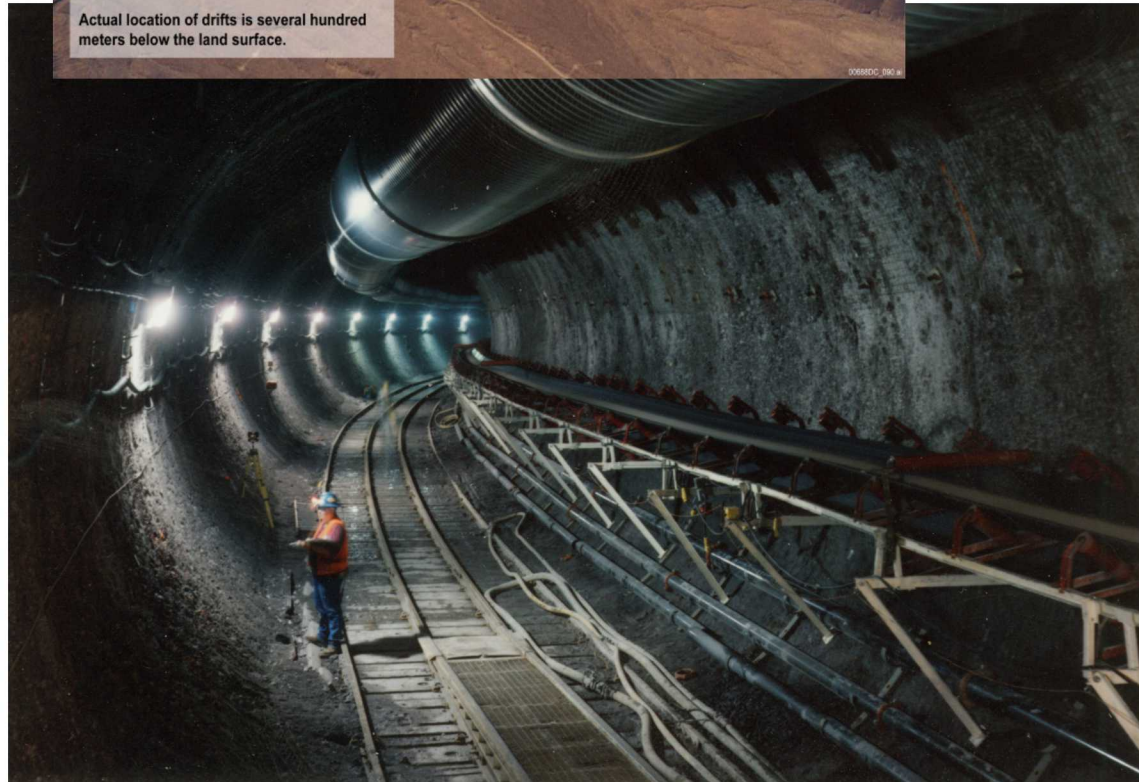
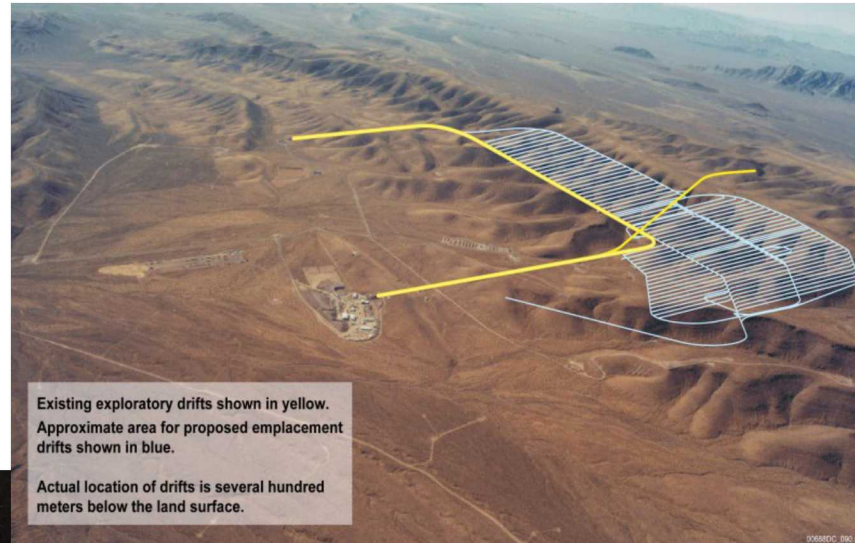
Internal TAD (transportation, aging, and disposal) canisters
for commercial spent fuel, 2.5 cm stainless steel

Drip shields

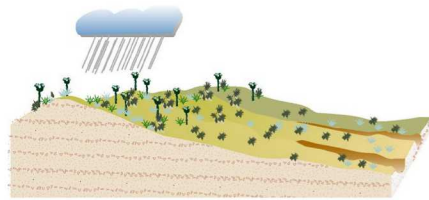
free-standing 1.5 cm Ti shell



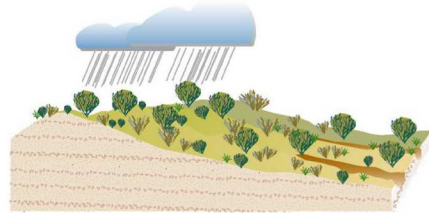
Yucca Mountain Exploratory Studies Facility



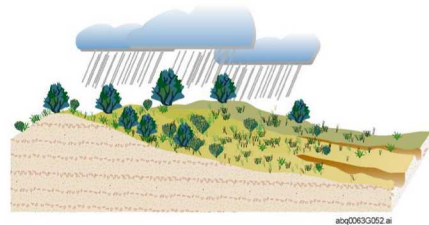
Groundwater Flow at Yucca Mountain



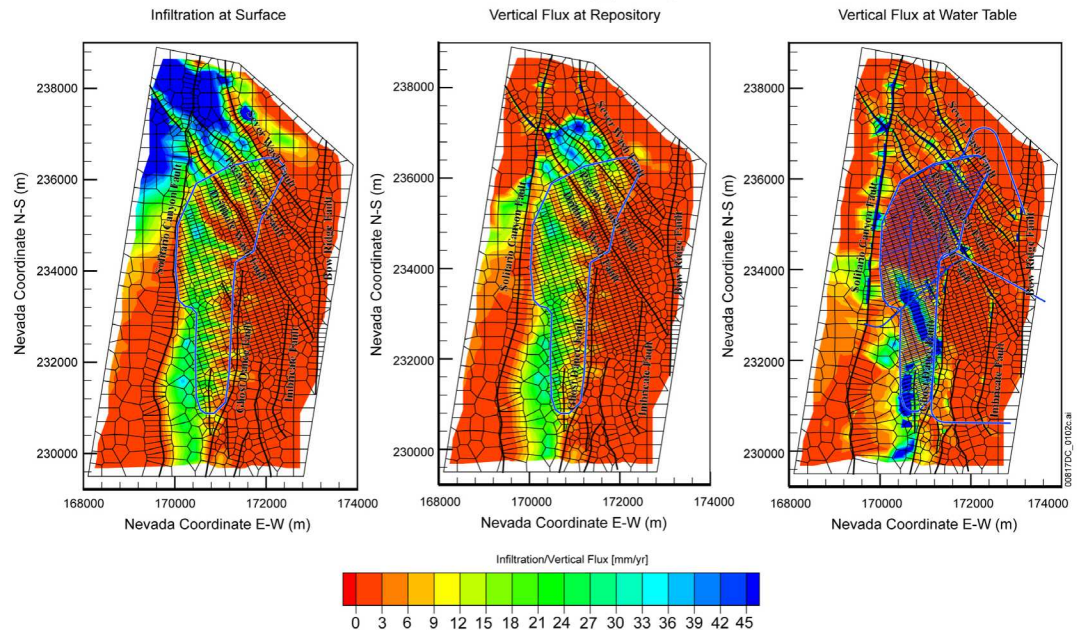
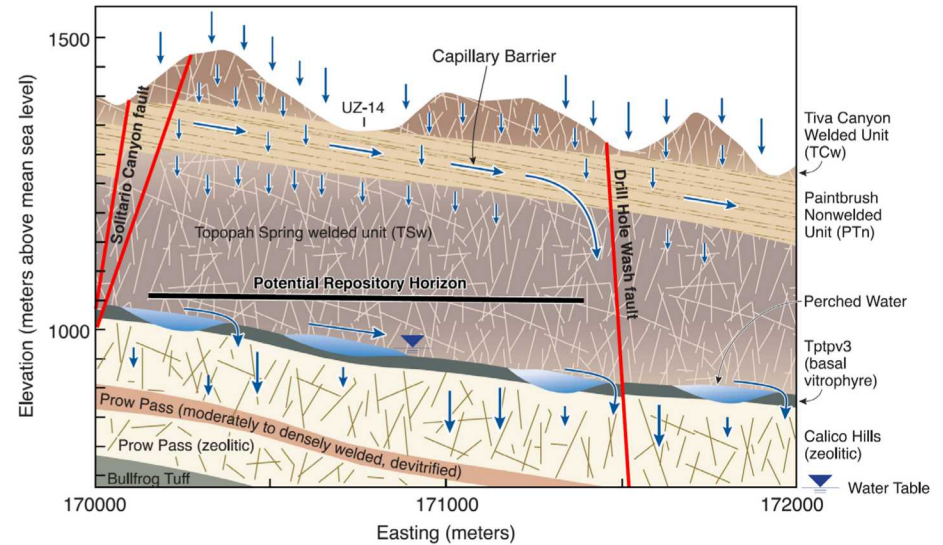
Present Day
Yucca Mountain



Monsoon
Lower-bound analog: Yucca Mountain
Upper-bound analog: Nogales, AZ
Higher precipitation and temperature than present-day

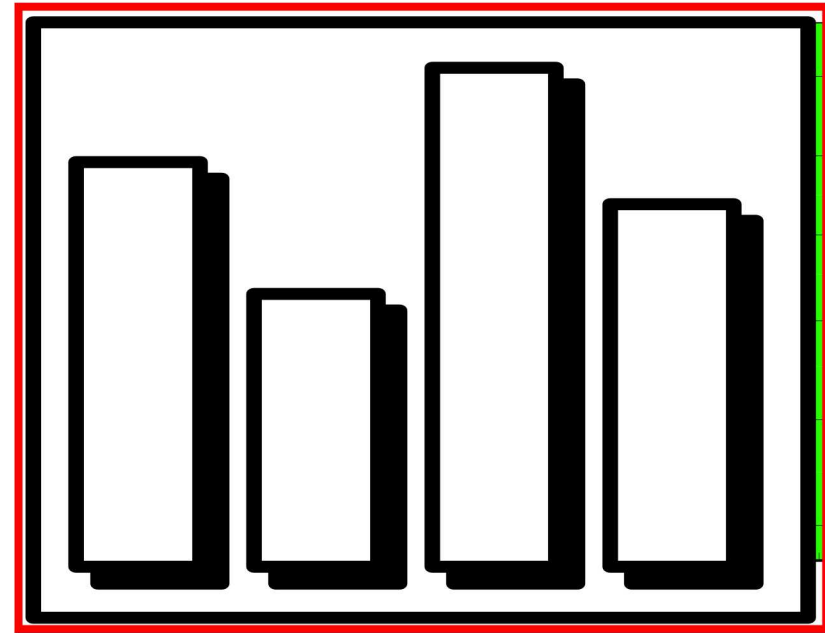
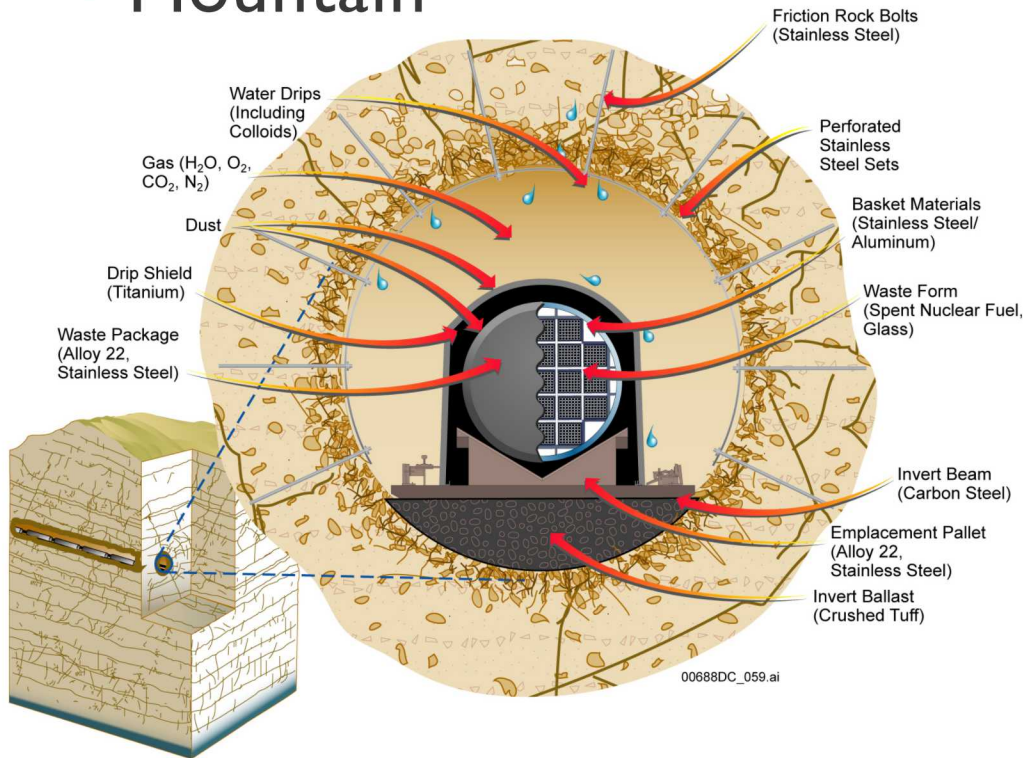


Glacial Transition
Lower-bound analog: Delta, UT
Upper-bound analog: Spokane, WA
Higher precipitation and lower temperature than present-day

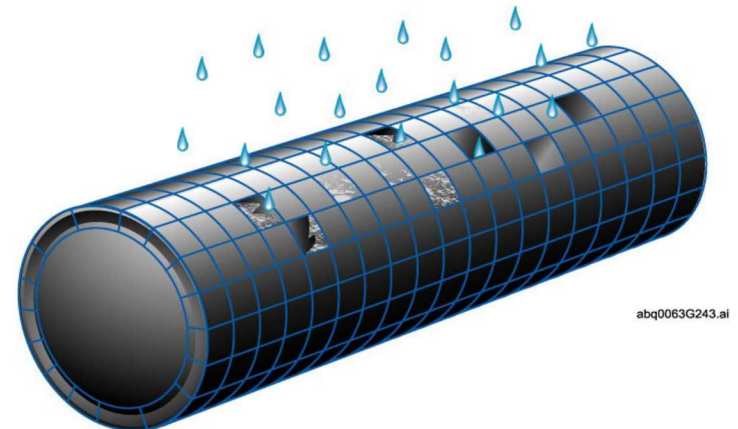
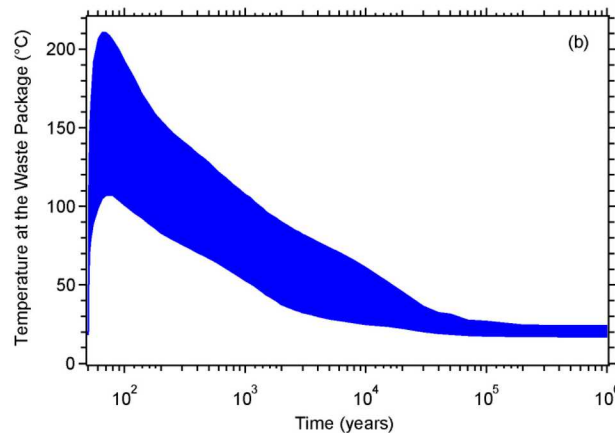


Field tests and models provide basis for understanding infiltration and flow in unsaturated rocks at Yucca Mountain

The Emplacement Environment at Yucca Mountain



Material testing and models characterize performance of the engineered barriers



Regulatory Basis for Estimating Dose



U.S. Environmental Protection Agency defines the form of the post-closure safety assessment

“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.”**

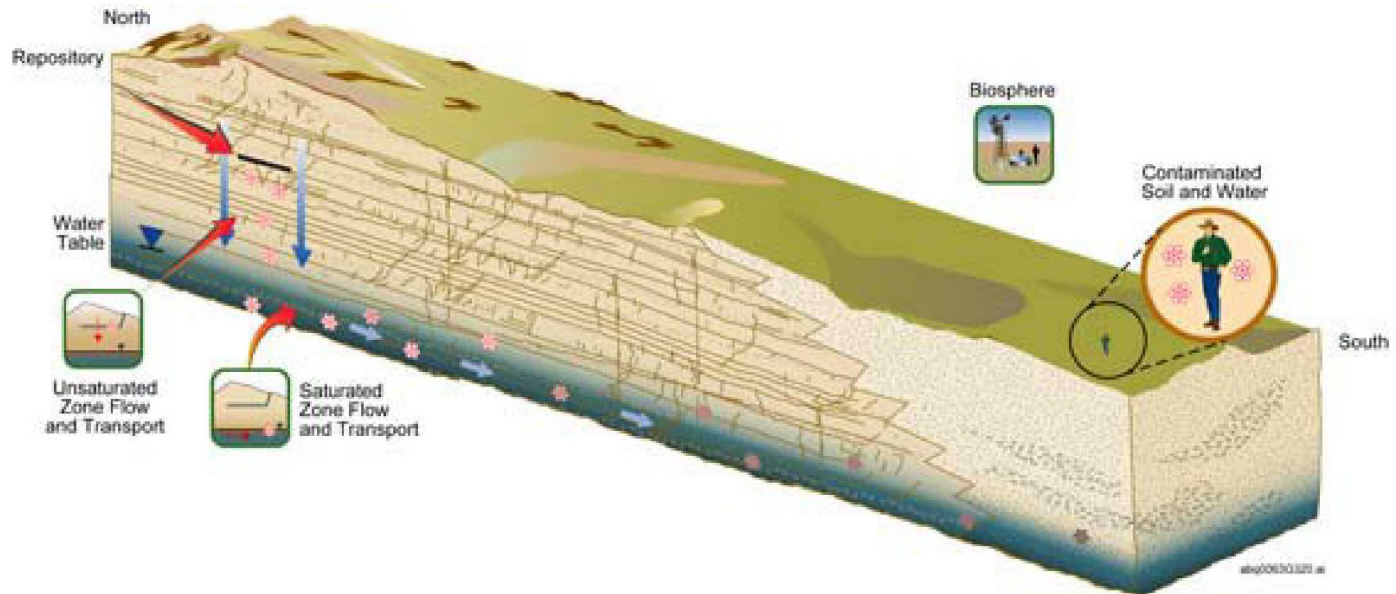
(40 CFR part 197.12, emphasis added. This definition is specific to the proposed Yucca Mountain repository, but concept is analogous in generic standards)

Long-term Performance of the Proposed Yucca Mountain Repository



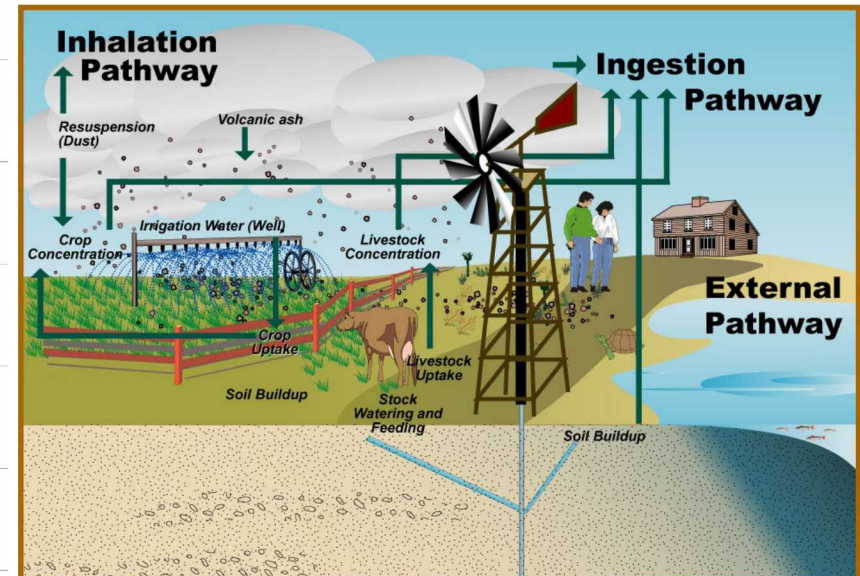
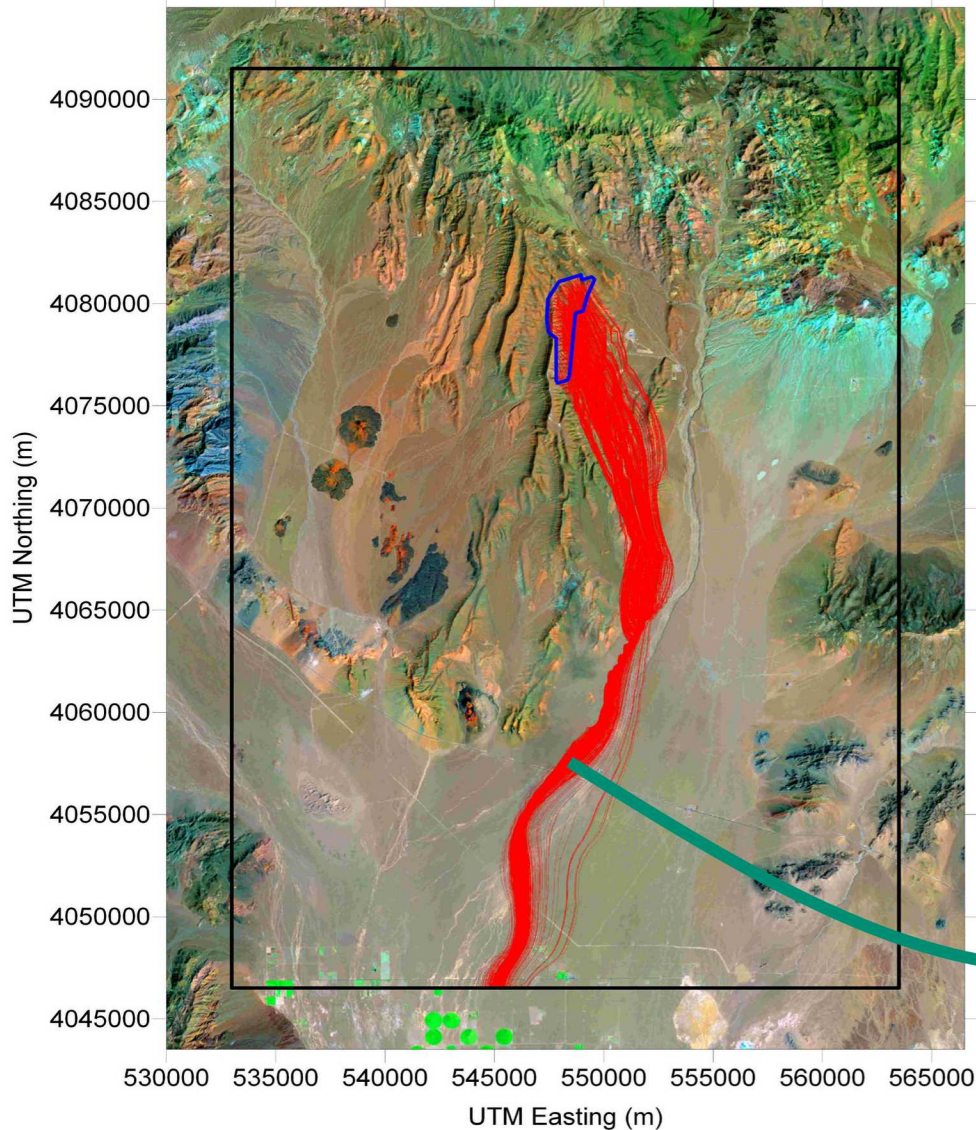
Water provides the primary release mechanism

- Precipitation infiltrates and percolates downward through the unsaturated zone
- Corrosion processes degrade engineered barriers, including the waste form



- Radionuclides are mobilized by seepage water and percolate downward to the water table
- Lateral transport in the saturated zone leads to biosphere exposure at springs or withdrawal wells

Estimating Dose to Hypothetical Future Humans



Modeled groundwater flow paths and hypothetical exposure pathways

Yucca Mountain Total System Performance Assessment

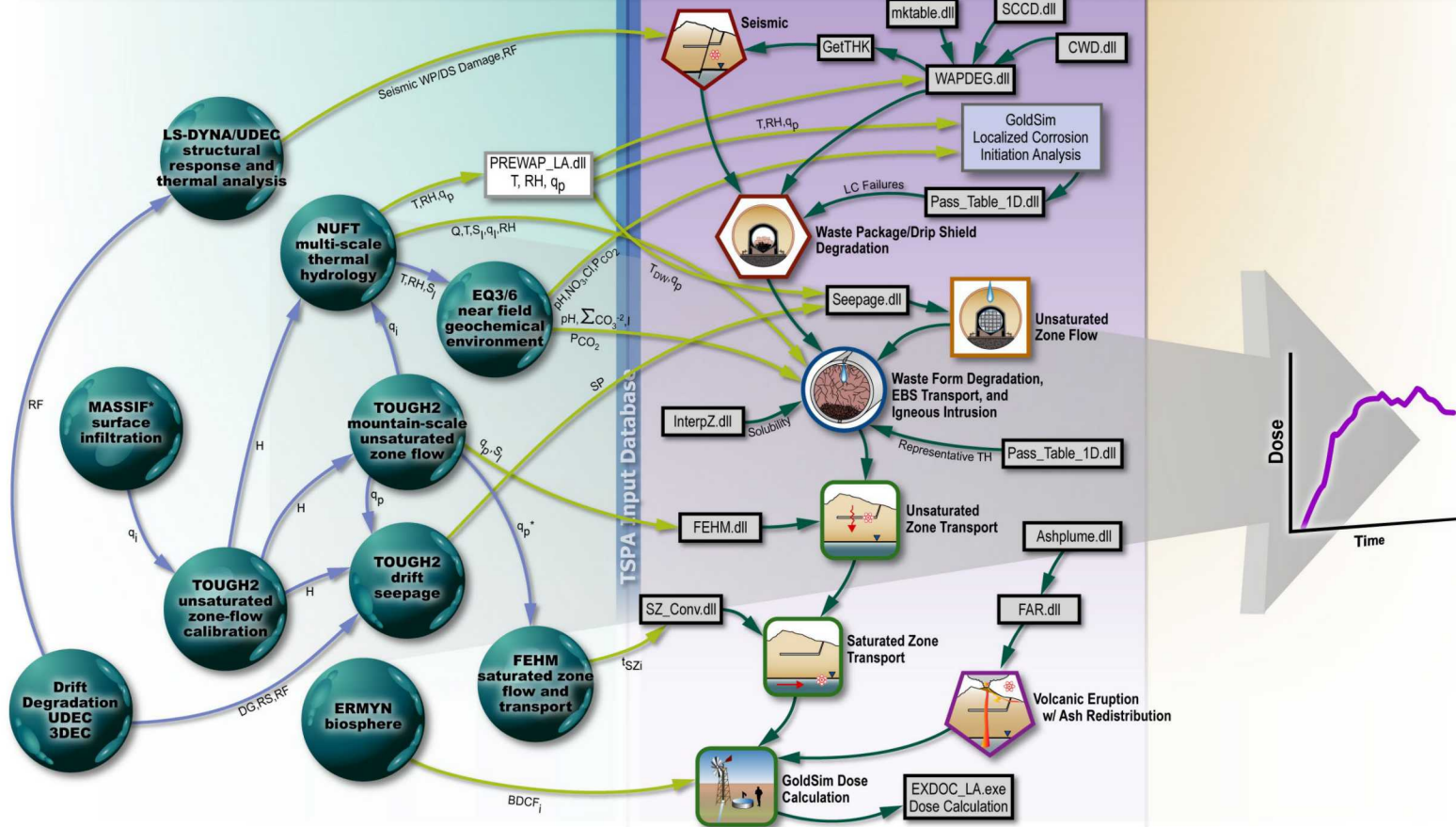


External Process Models

Note: Process model output pre- and post-processing software does not appear on this figure.

Run with GoldSim

Final Performance Measure

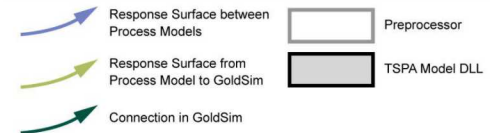


Output Parameters

| | | | | | | | |
|--------------------|----------------------------|--------|-----------------------|----------|----------------------------------|----|--------------------------|
| 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_i | Liquid Saturation | t_{SZ} | 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_i | Liquid Flux | q_g | Gas Flux | | |

*Note: q_p derived from INFIL model

Legend



00817DC_0093a.ai

Regulatory Basis for the Consideration of Unlikely Events



U.S. Environmental Protection Agency establishes criteria for identifying and screening the features, events, and processes that must be included in a safety assessment

“The DOE’s performance assessments conducted to show compliance with [the long term standards] **shall not include consideration of very unlikely features, events, or processes**, i.e., those that are estimated to have less than one chance in 100,000,000 per year of occurring.

...

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

(40 CFR part 197.36(a)(1), emphasis added)

Potential Disruptive Geologic Events at Yucca Mountain

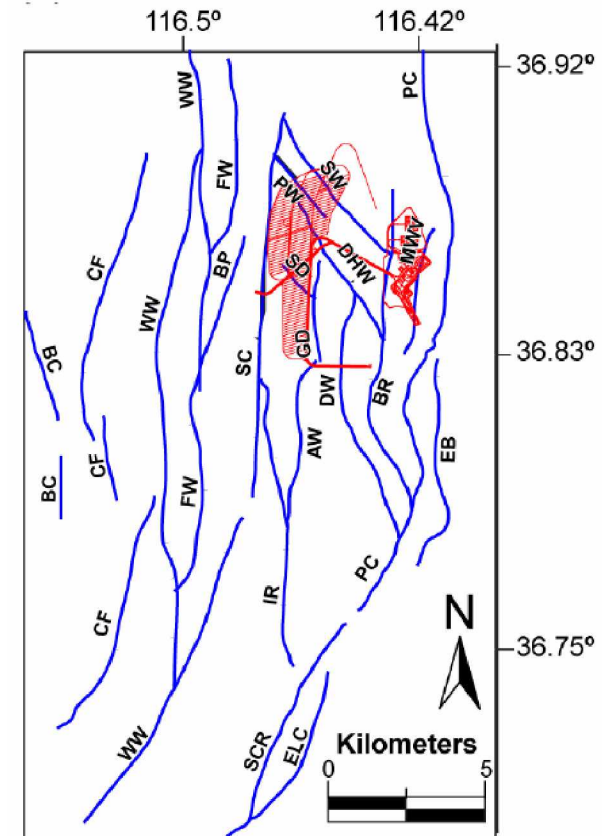


■ Volcanism

- 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)



Uncertainty in the 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*

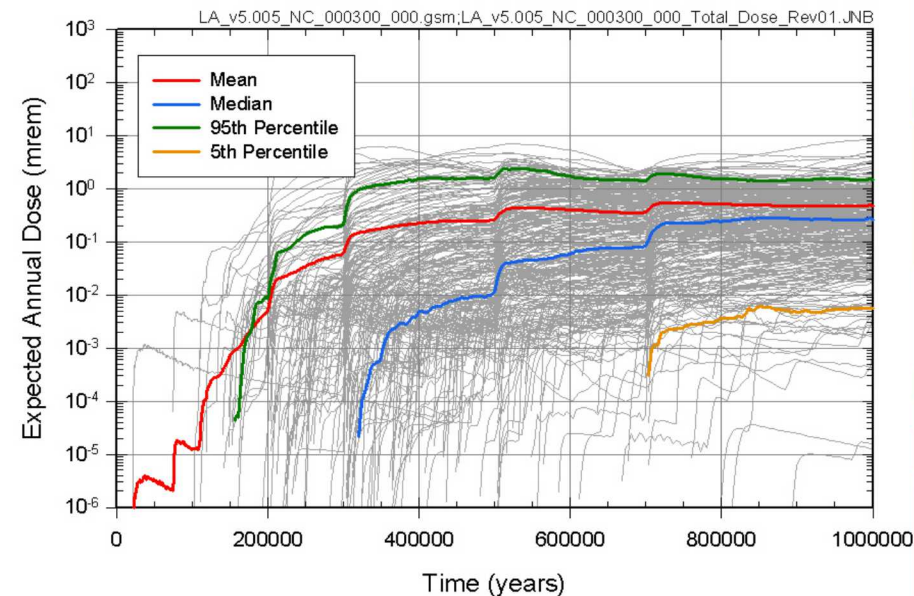
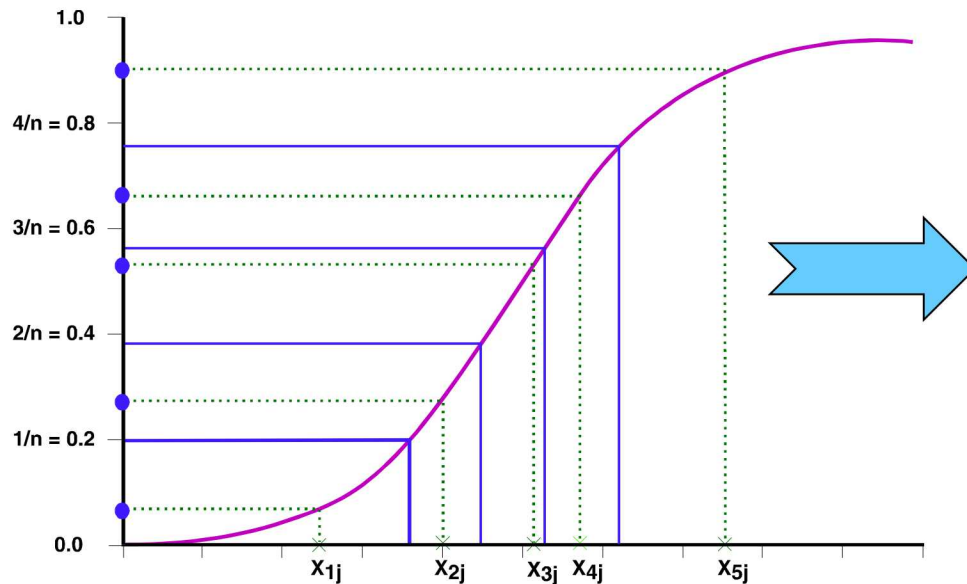
Treatment of Epistemic Uncertainty



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

Uncertainty in external process models incorporated through multiple realizations (e.g., multiple infiltration maps for different climate states lead to multiple maps of seepage entering the repository drifts)

Approx. 400 uncertain epistemic parameters incorporated directly in TSPA-LA

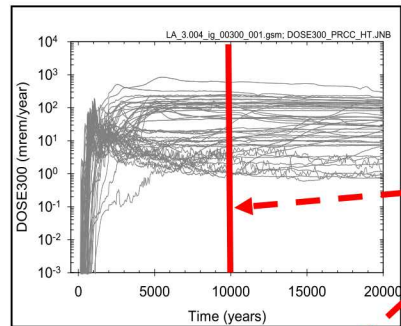


Interpreting the Importance of Epistemic Uncertainty on Performance Assessment Results



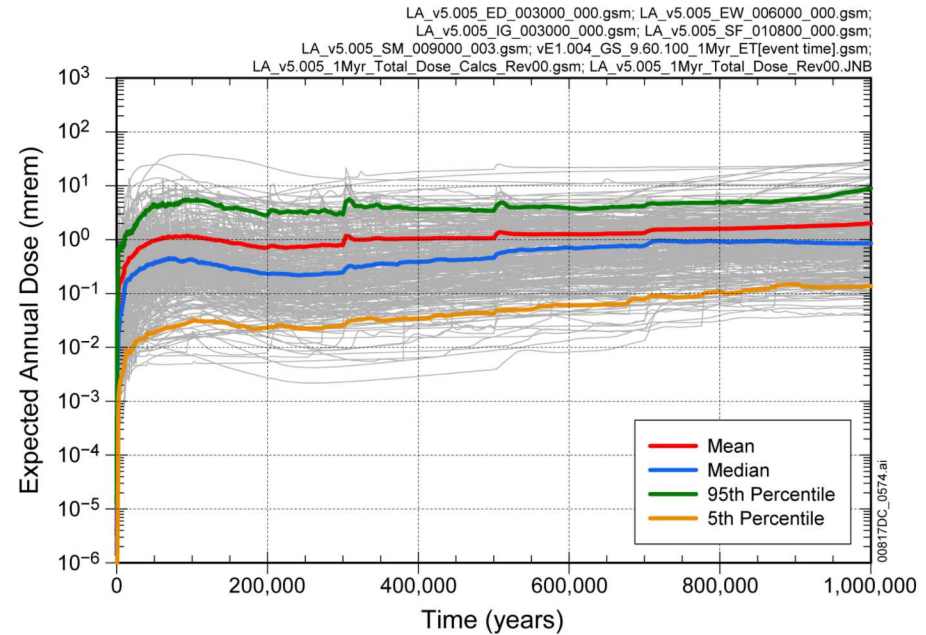
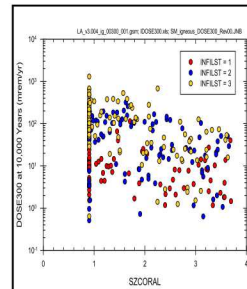
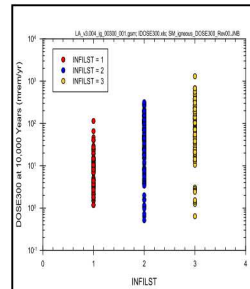
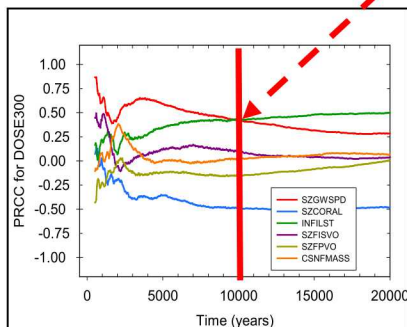
Monte Carlo estimates of overall performance

(Example dose histories from Yucca Mountain Total System Performance Assessment for the License Application, total expected dose from all scenarios)



DOSE300: 10,000 yr

| Variable | R ² | SRRC |
|----------|----------------|-------|
| INFILST | 0.28 | 0.53 |
| SZCORAL | 0.40 | -0.36 |
| SZGWSPD | 0.53 | 0.36 |
| GTCPU239 | 0.61 | 0.27 |
| IGPH | 0.63 | 0.15 |
| SZHAVO | 0.64 | 0.09 |
| EP1LOWU | 0.65 | 0.10 |
| EPSLOWPU | 0.66 | 0.09 |
| SZNVF7 | 0.66 | 0.08 |



Sensitivity and Uncertainty Analyses
Identify model inputs important to uncertainty in performance estimates

Defining Scenarios Based on Unlikely Events



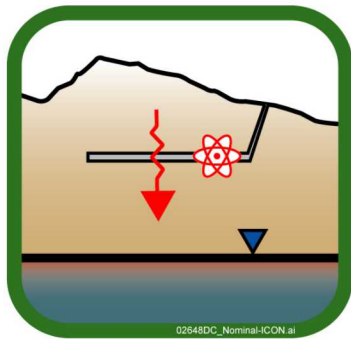
Four scenario classes divided into seven modeling cases

Nominal Scenario Class

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

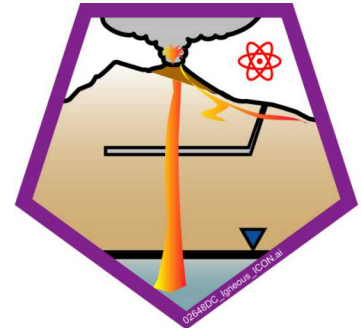
Early Failure Scenario Class

- Waste Package Modeling Case
- Drip Shield Modeling Case



Igneous Scenario Class

- Intrusion Modeling Case
- Eruption Modeling Case

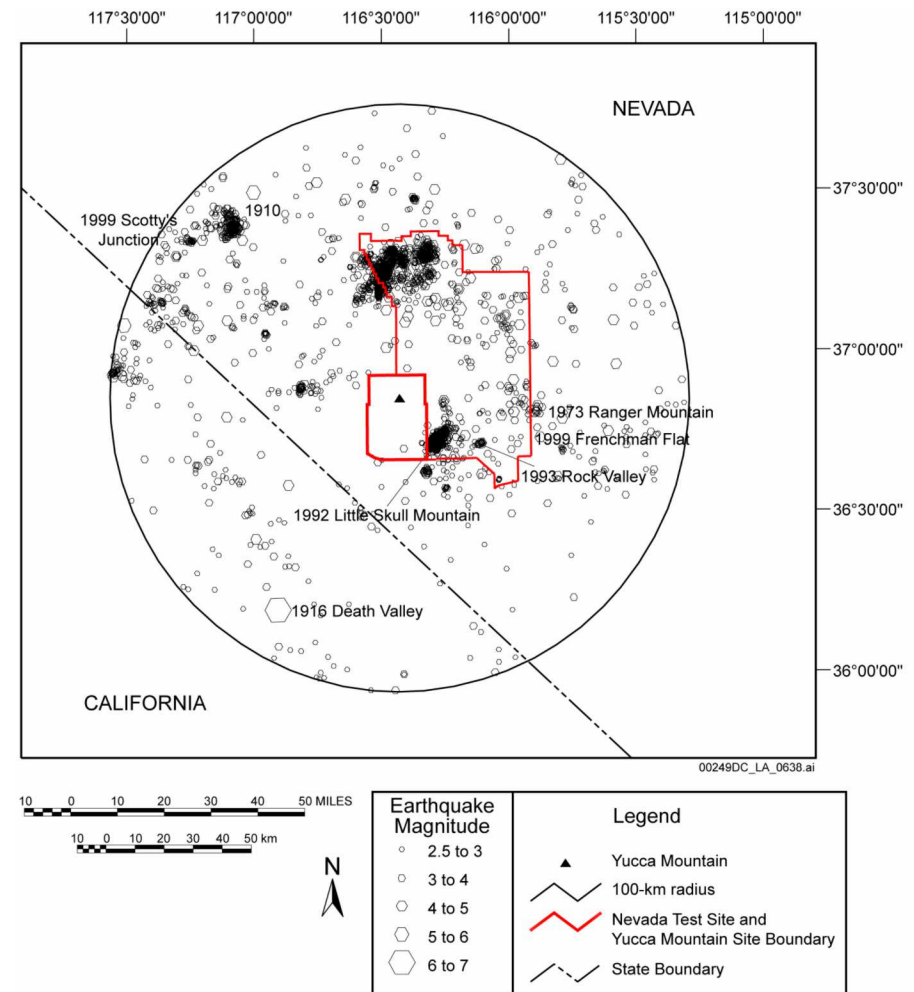
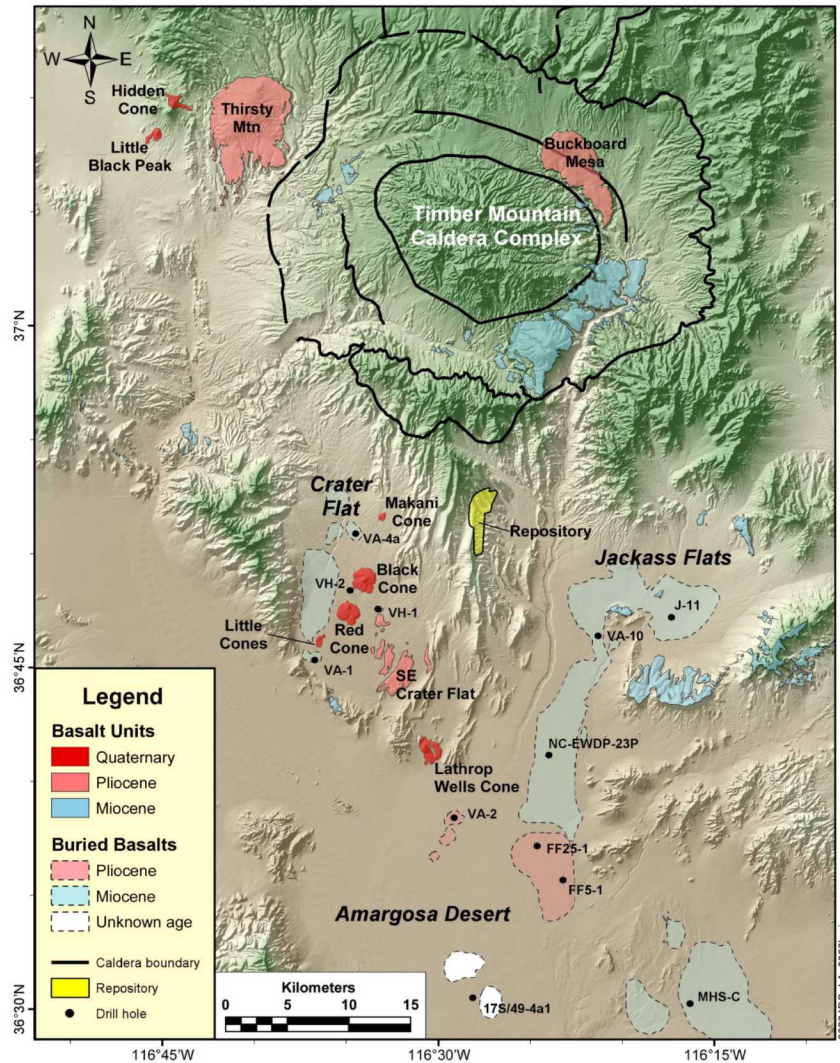


Seismic Scenario Class

- Ground Motion Modeling Case
- Fault Displacement Modeling Case



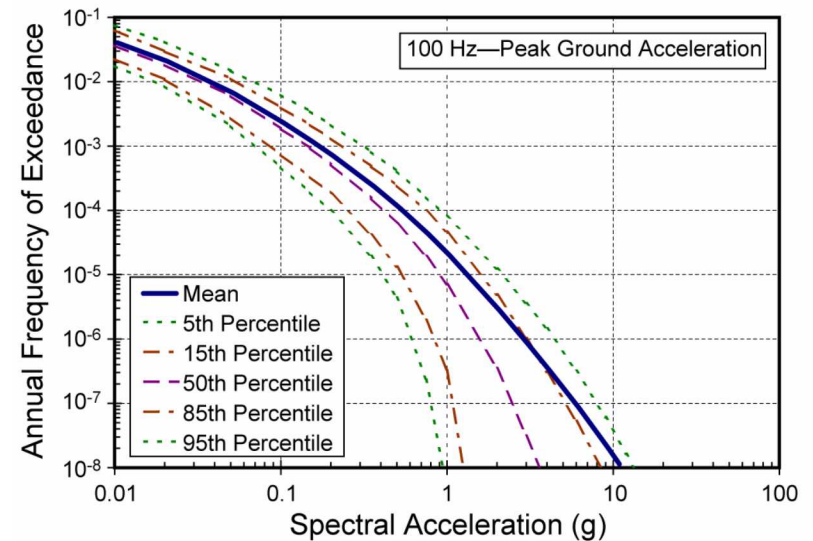
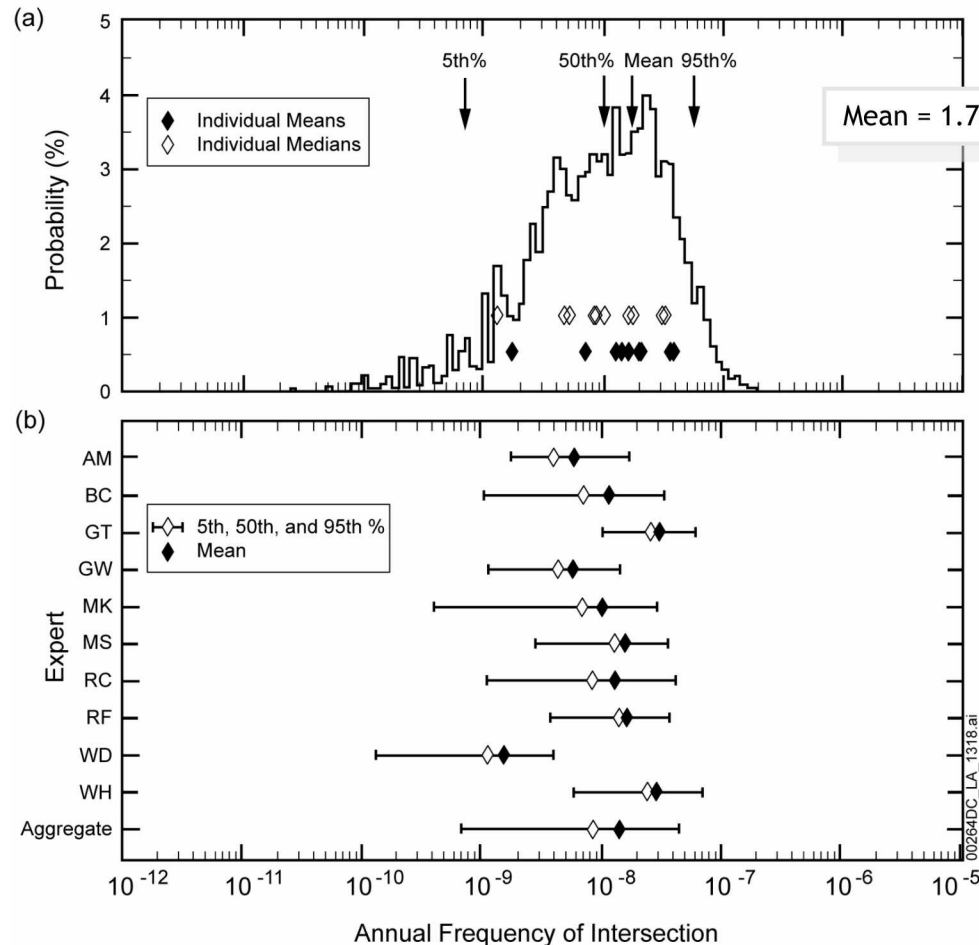
Igneous and Seismic Activity in the Yucca Mountain Region



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)

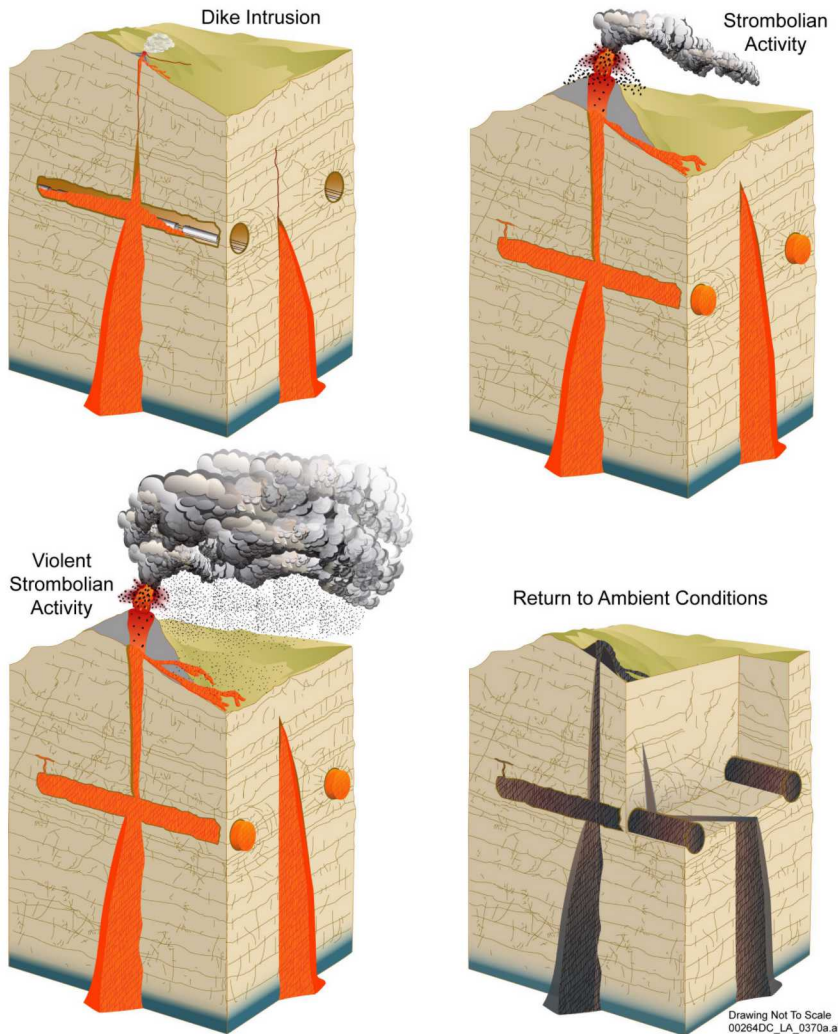
Yucca Mountain Event Probabilities Estimated by Formal Expert Elicitation



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

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

Consequence Models for Igneous Disruption at Yucca Mountain



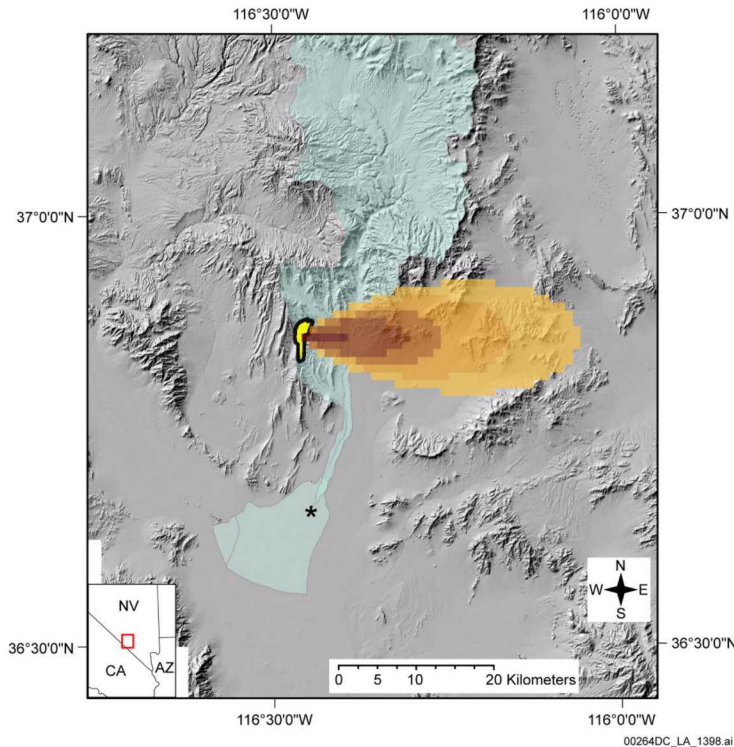
Schematic Drawing of an Igneous Event at Yucca Mountain (DOE/RW-0573 Rev. 1, Figure 2.3.11-5)

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

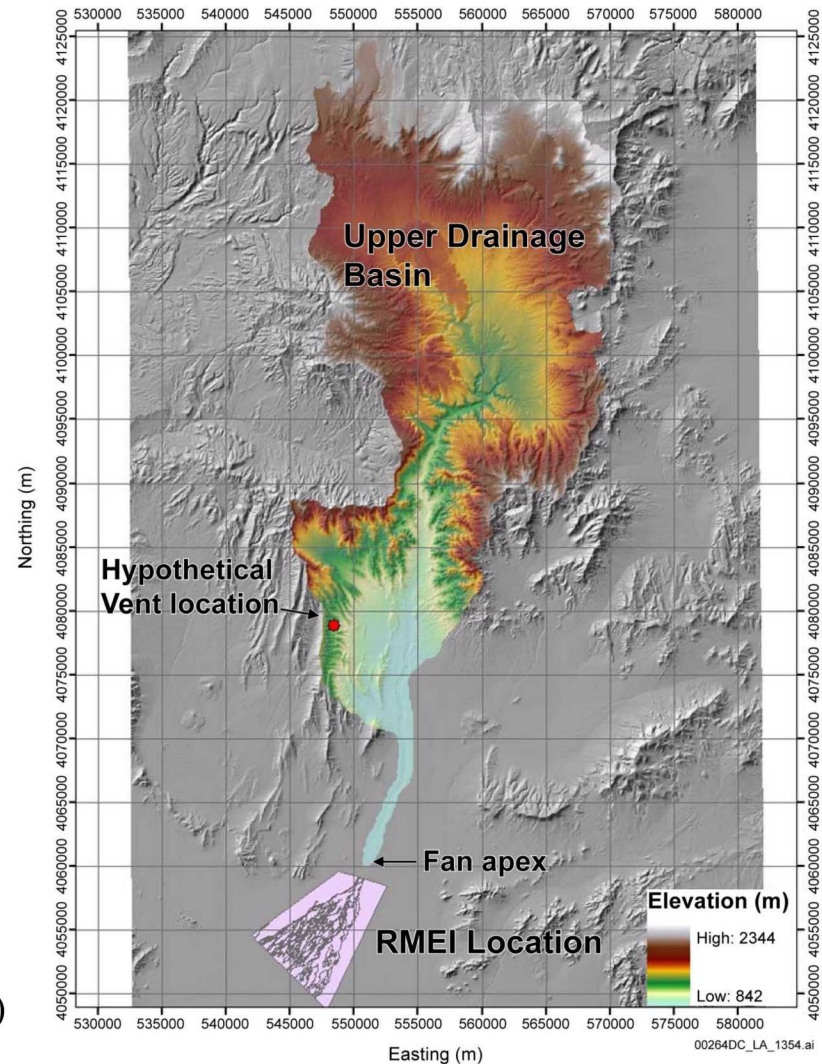
30



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)

Consequence Models for Seismic Disruption at Yucca Mountain

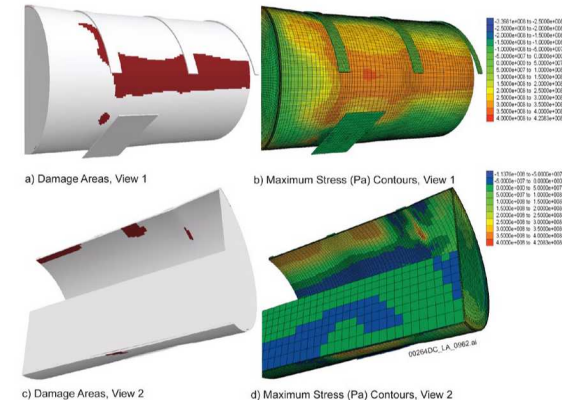
Two Release Scenarios

- Direct fault displacement ruptures waste packages
 - Minor contributor due to low probability of new fault formation
- Ground motion damages packages through
 - Vibratory motion and impact
 - Rockfall impact
 - Accumulated loading of rockfall

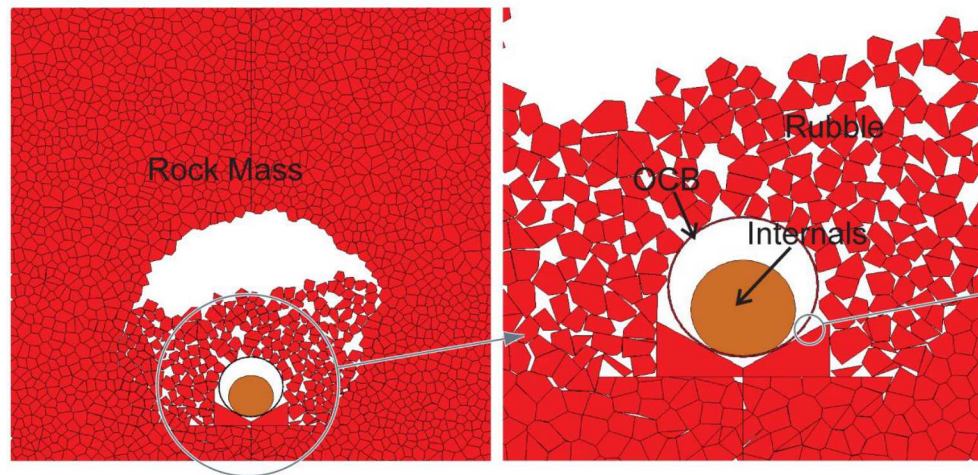
Waste package damage is a function of:

- Event magnitude
- Type of waste package
- Time-dependent package degradation

Right
Modeled Waste Package Damage and Stress Contours following vertical loading (DOE/RW-0573 Rev. 1, Figure 2.3.4-91)



Below
Model for Rubble-Waste Package Interactions (DOE/RW-0573 Rev. 1, Figure 2.3.4-88)



a) Drift Scale

b) WP Scale

Results of Seismic Consequence Models for Yucca Mountain



Seismic Fault Displacement Modeling Case

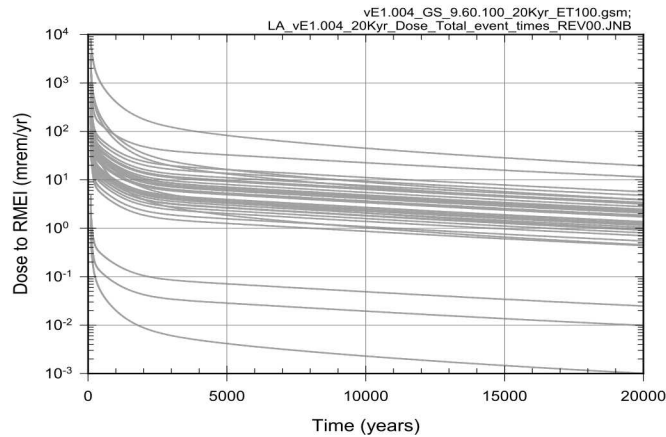
- Annual frequency approximately 2×10^{-7} / yr
- Fault displacements rupture waste packages and drip shields, allowing advection and diffusion
 - Size of rupture uncertain: 0 to cross-sectional area of WP
- Mean of ~ 47 waste packages and drip shields damaged

Seismic Ground Motion Damage Modeling Case

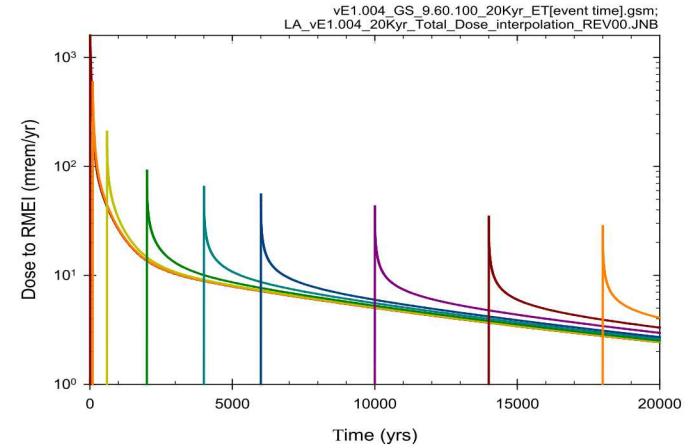
- Ground motions result in stress corrosion cracks that allow diffusive releases
 - Frequency of events that damage codisposal (CDSP) packages: $\sim 10^{-5}$ / yr
 - Frequency of events that damage transportation, aging, and disposal (TAD) packages for commercial spent nuclear fuel (CSNF): $\sim 10^{-8}$ / yr
- Cracked area accumulates with additional seismic events
- Repeated damage may cause package rupture ($<10^{-8}$ / yr)
- Drip shield thins by general corrosion and fails due to dynamic loading of accumulated rockfall

Ground Motion and Nominal scenarios combined for analysis

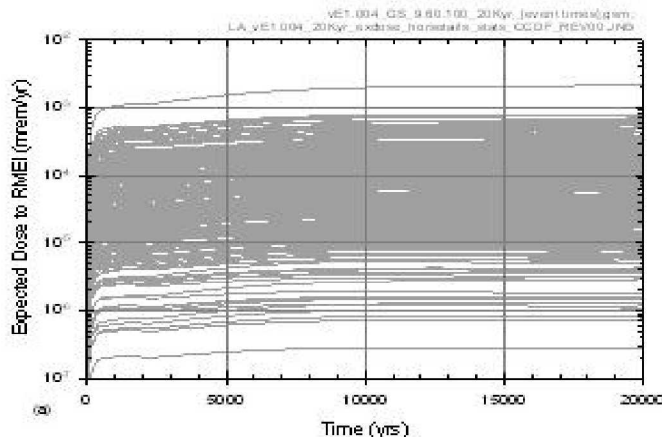
Estimating Mean Annual Dose from Unlikely Events: Eruptive Dose



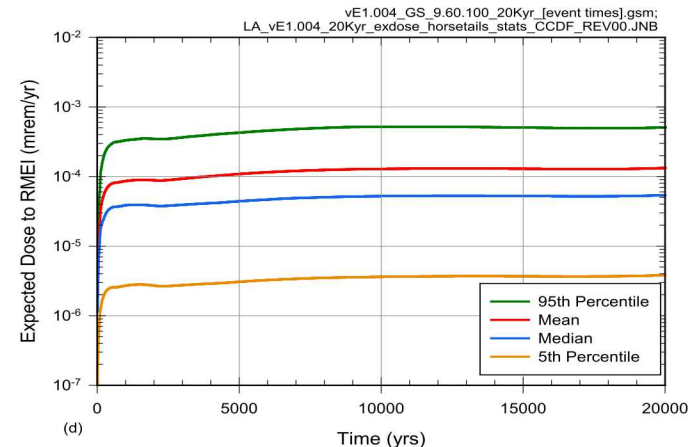
Eruptive dose: 40 realizations of aleatory uncertainty conditional on a single eruption of 1 WP at time zero



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



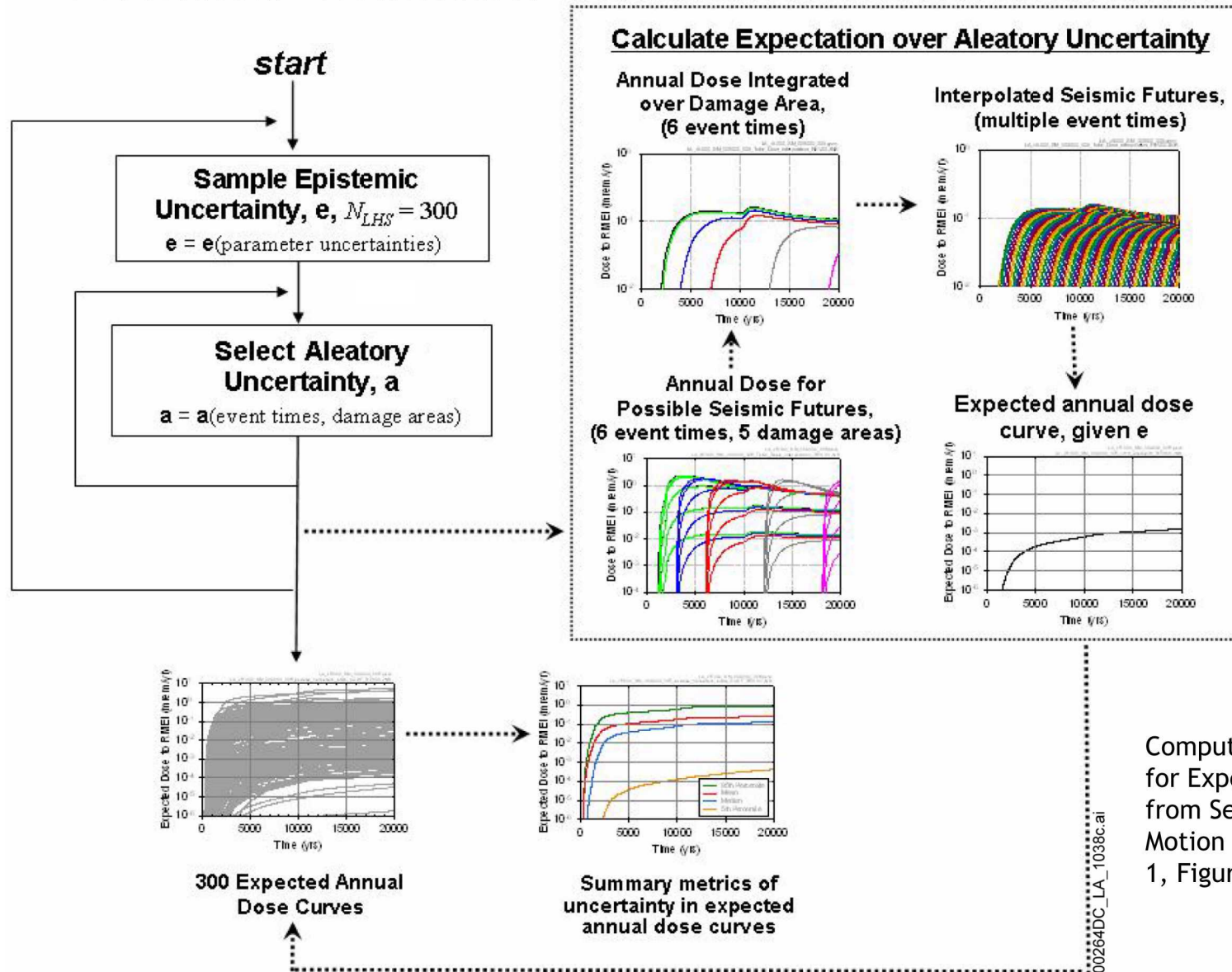
Expected eruptive dose; 300 realizations, each showing expected dose from a single sampling of epistemic uncertainty with events at all times



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>

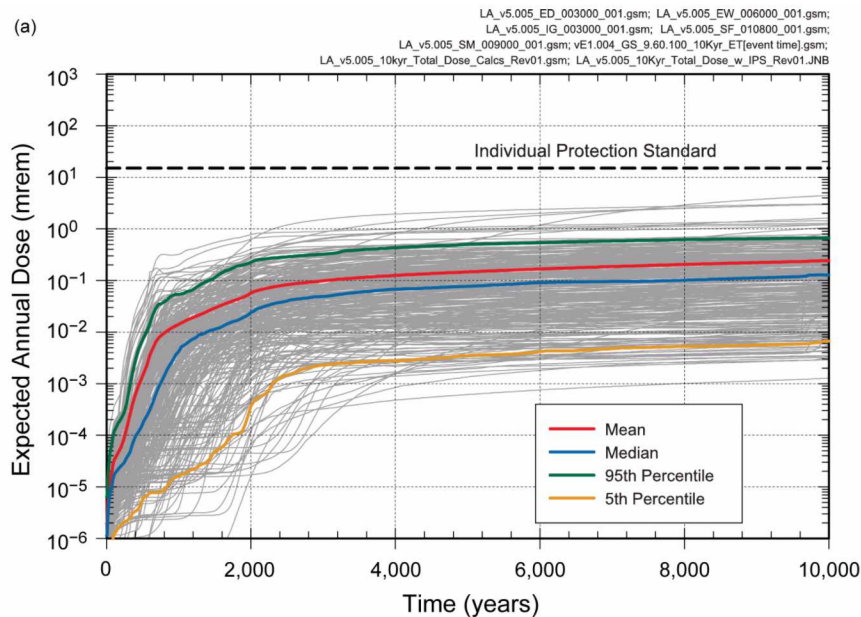
Estimating Mean Annual Dose from Unlikely Events: Seismic Ground Motion Dose





Summary of the Quantitative Estimates of Long-term Performance Presented in the Yucca Mountain License Application

Long-Term Performance of Yucca Mountain



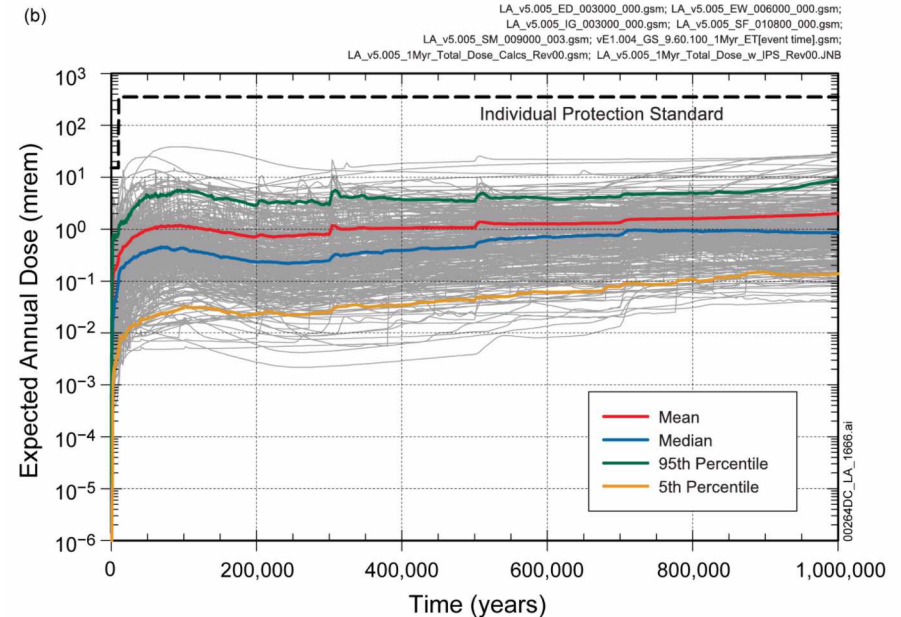
DOE/RW-0573 Rev 1 Figure 2.4-10

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)



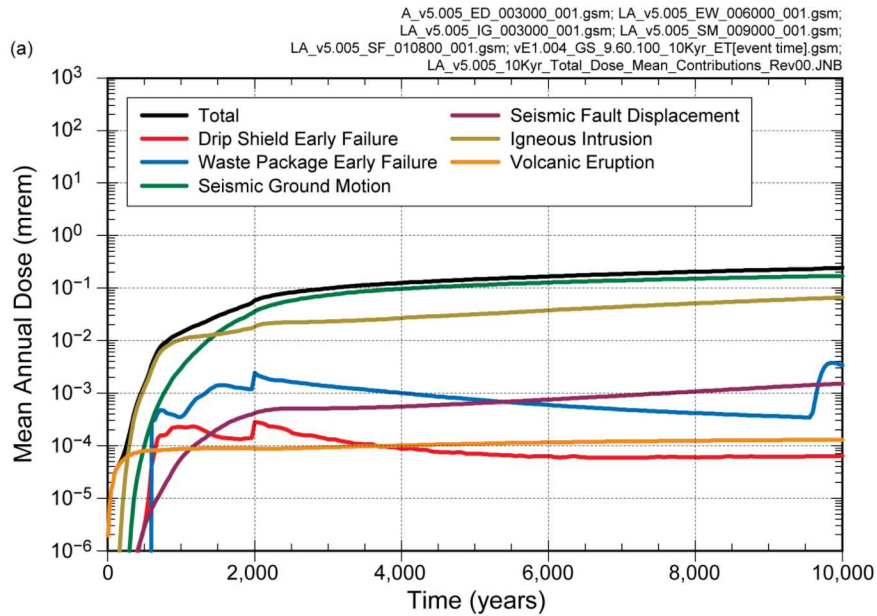
1,000,000 years

1,000,000-year Standard:

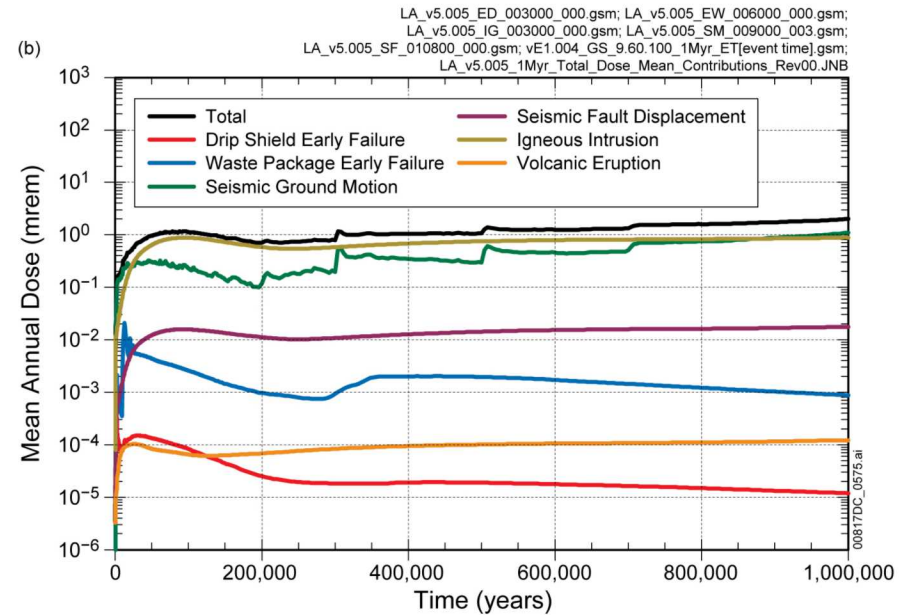
Mean annual dose no more than 1
mSv (100 mrem)

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

Modeling Cases Contributing to Total Mean Annual Dose



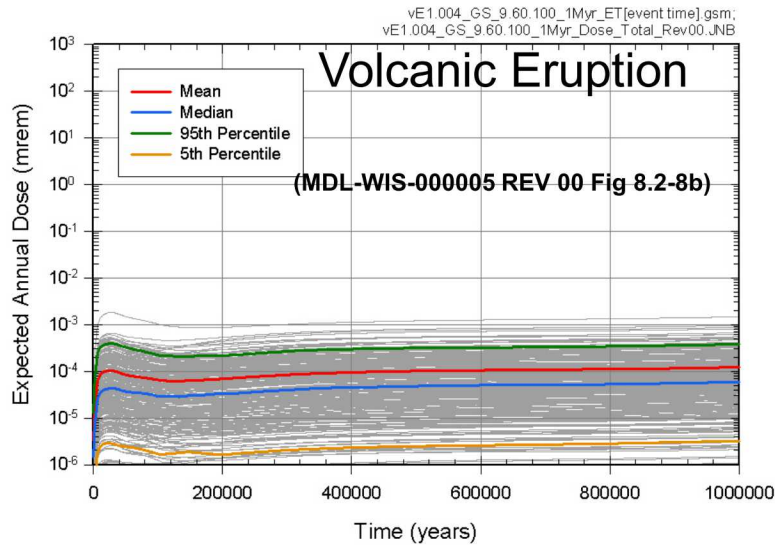
10,000 years



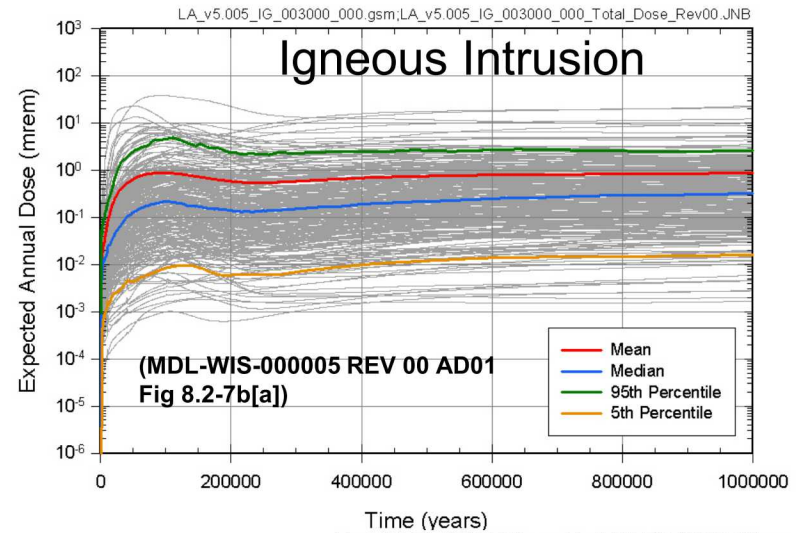
1,000,000 years

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

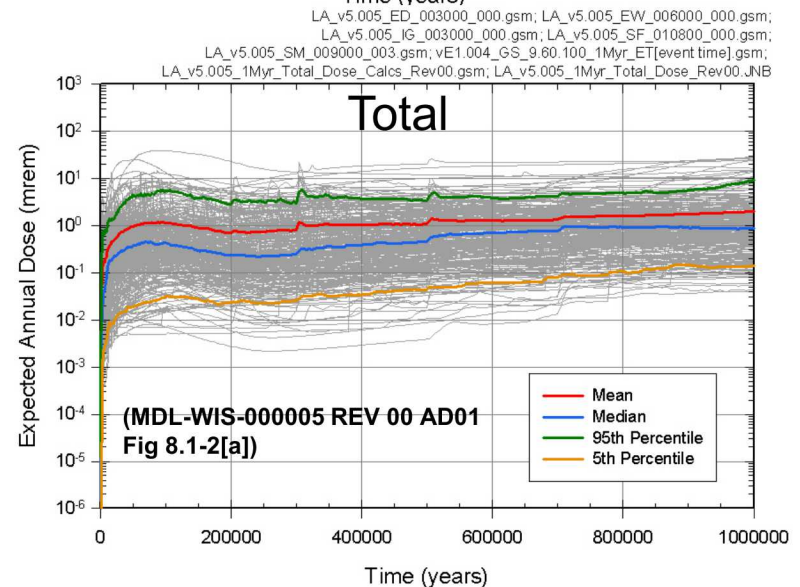
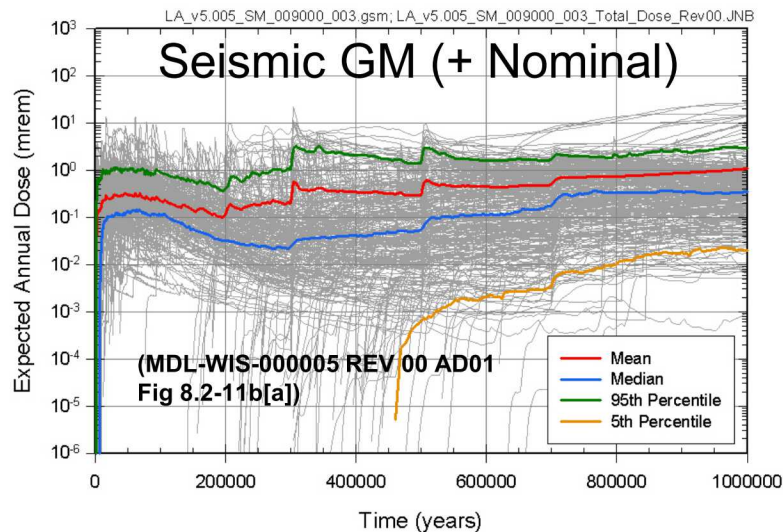
Construction of Total Dose



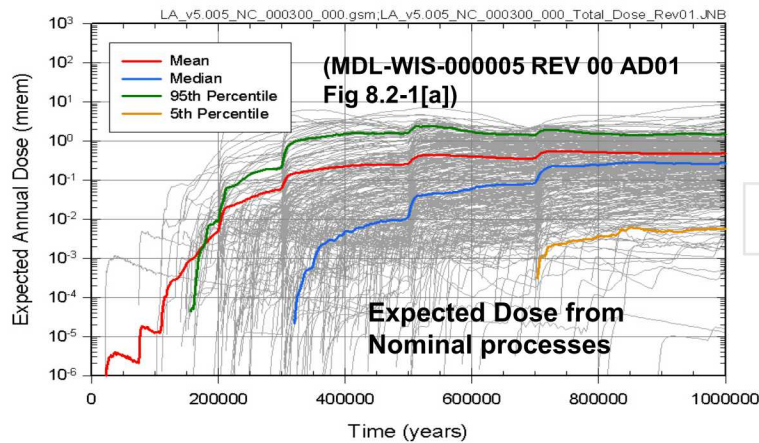
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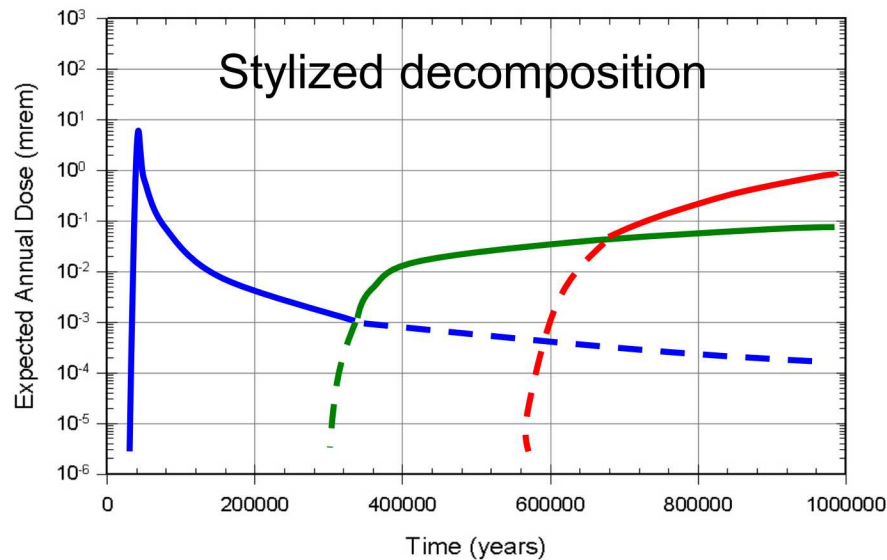
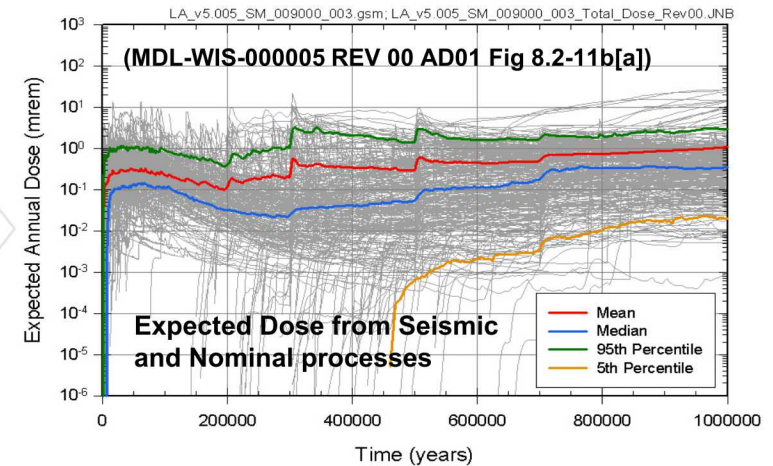
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Composition of Seismic Ground Motion Dose



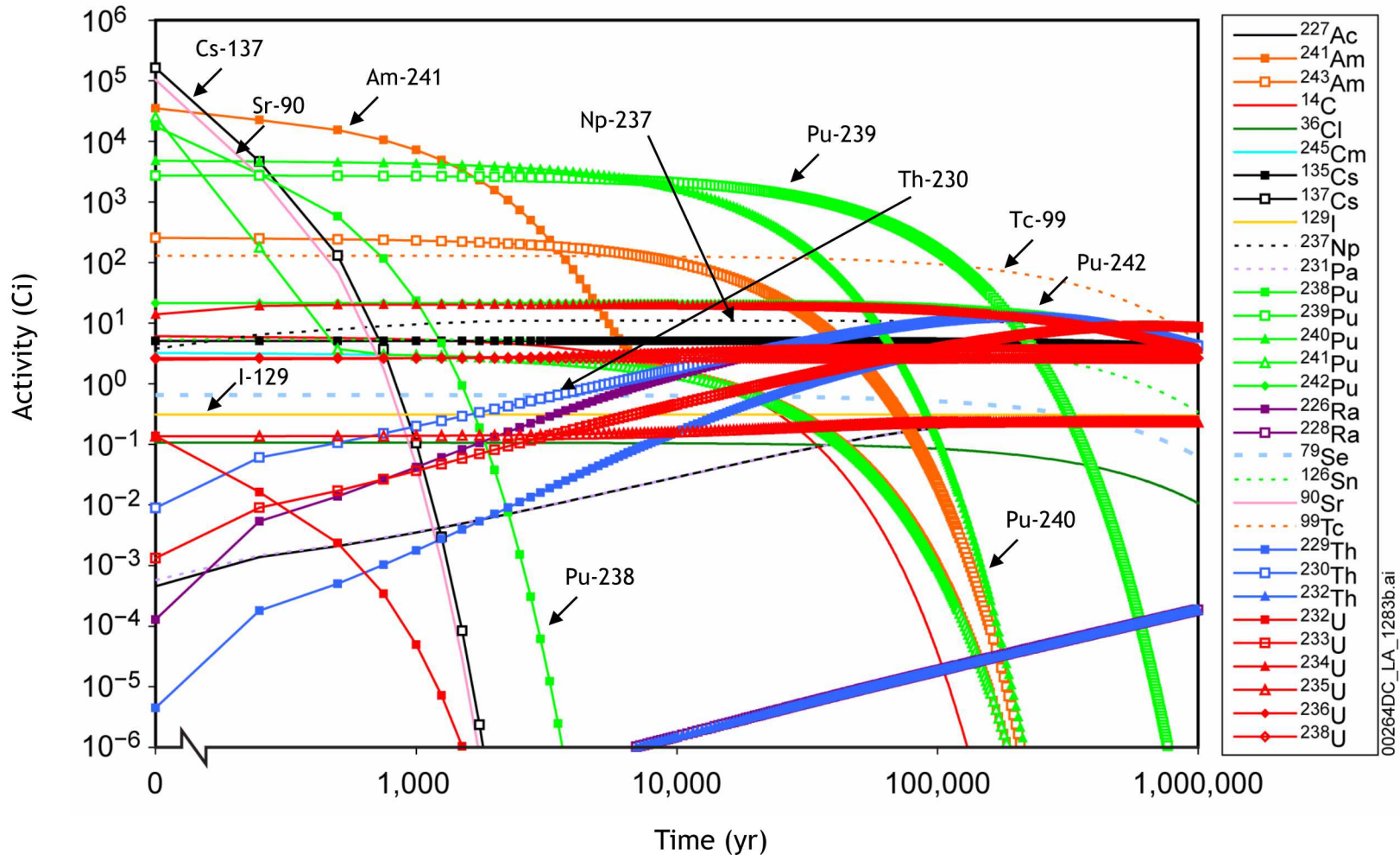
Included



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

Radionuclides Contributing to Estimates of Total Dose from Yucca Mountain

Commercial Used Nuclear Fuel Decay

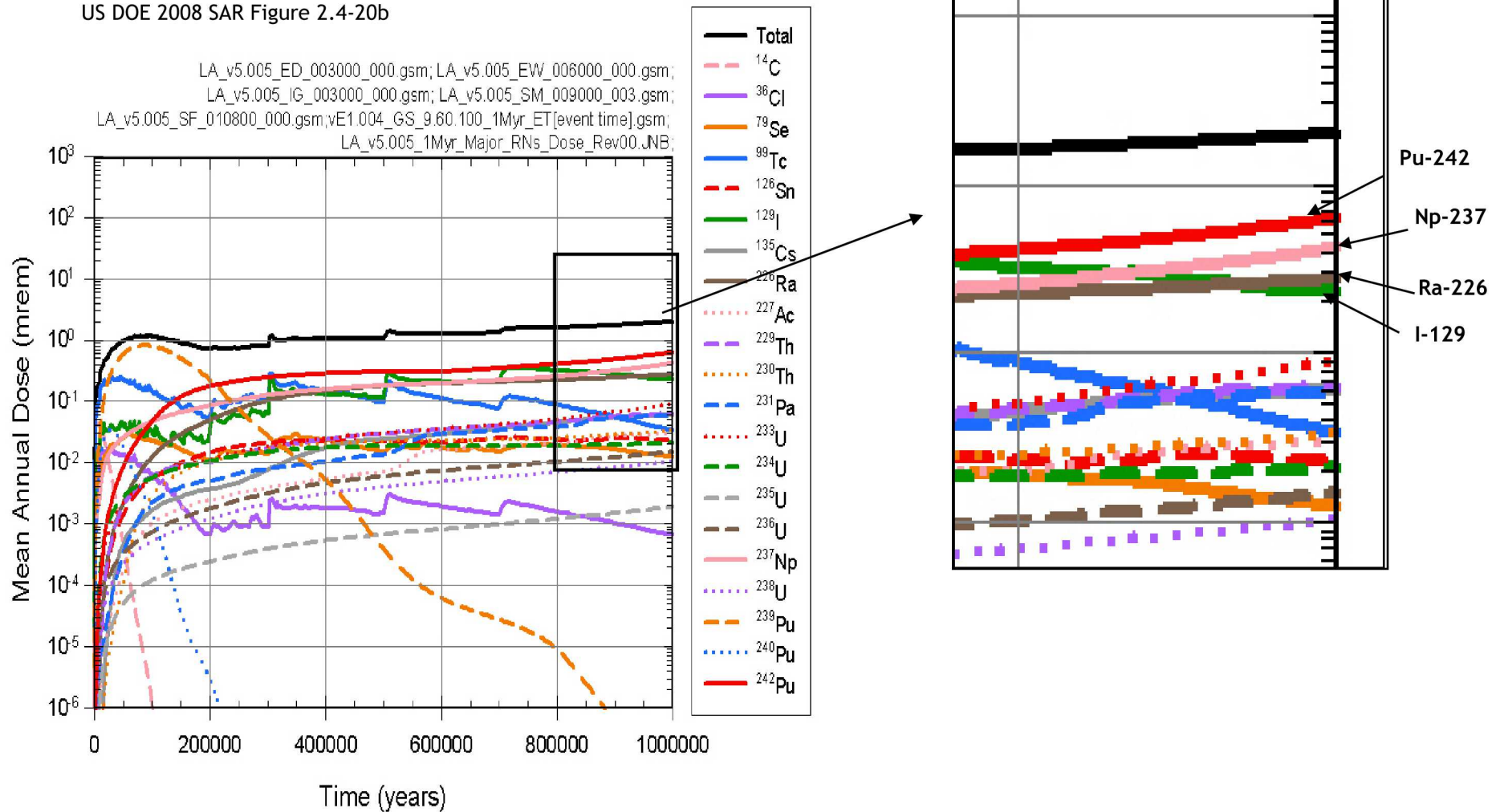


DOE/RW-0573 Rev 0, Figure 2.3.7-11, inventory decay shown for an single representative Yucca Mountain used fuel waste package, as used in the Yucca Mountain License Application, time shown in years after 2117.

Radionuclides Important to Mean Dose at Yucca Mountain



US DOE 2008 SAR Figure 2.4-20b



How Does Yucca Mountain Compare to Other Proposed Repositories?

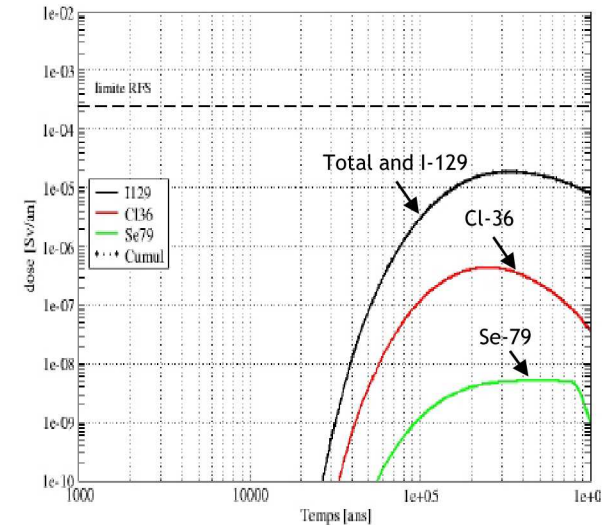


Unsaturated and oxidizing environment is unique

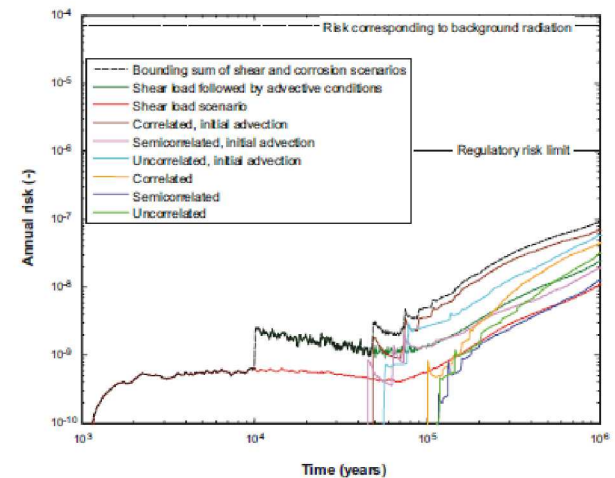
- Radionuclides contributing to total dose from Yucca Mountain include actinides (Pu, Np, U) and Tc-99
- Releases from repositories in saturated environments are dominated by species that are mobile in reducing conditions (I-129, Cl-36, Ra-226)

Peak dose estimates are in the range reported for other concepts

- Estimated peak dose for the French argillite site is approx. 0.02 mSv/yr (2 mrem/yr), occurring at approx. 330,000 years (ANDRA 2005, Table 5.5-8 and Figure 5.5-18)
- Dose dominated by diffusive releases of I-129
- Estimated peak dose for the Swedish Forsmark granite site is approx. 0.001 mSv/yr (0.1 mrem/yr), occurring at 1 Myr (SKB 2011, Figure 13-69)
- Dose dominated by advective releases of Ra-226 from low-probability package failure and subsequent rapid transport in fractures



Estimated doses for the French argillite repository concept, assuming direct disposal of spent fuel (Andra 2005, Figure 5.5-18)



Estimated risk for the Swedish Forsmark site (SKB 2011 Figure 13-69, assumes dose-to-risk conversion of 0.073Sv^{-1})

Qualitative Summary of the Long-Term Performance of Yucca Mountain



No significant releases for many tens of thousands of years if the site is undisturbed

- Dry climate, little groundwater flow
- Corrosion-resistant waste packages

Long-term estimated mean and median annual doses are well below natural background

Future disruption by unlikely geologic processes could cause releases and doses to humans; probability-weighted consequences are evaluated

- Site geology indicates probability of volcanic disruption is on the order of one chance in 10 million to one chance in 1 billion per year (mean $1.7 \times 10^{-8}/\text{yr}$)
- Disruption by seismic activity is reasonably likely over very long time periods; consequences meet regulatory requirements

All estimated radiation doses are within regulatory limits



Backup Materials & References

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