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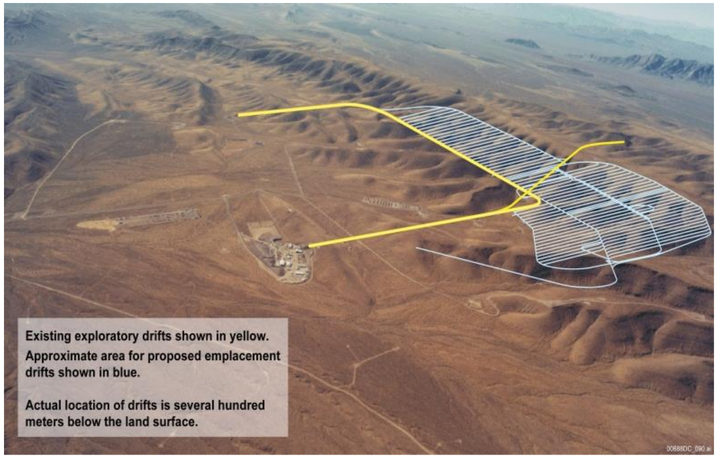
Exceptional service in the national interest



The Proposed Yucca Mountain Repository: A Case Study

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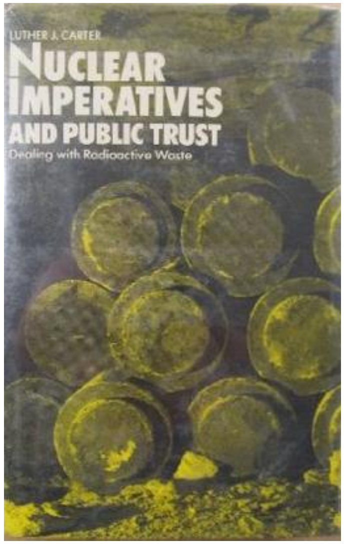
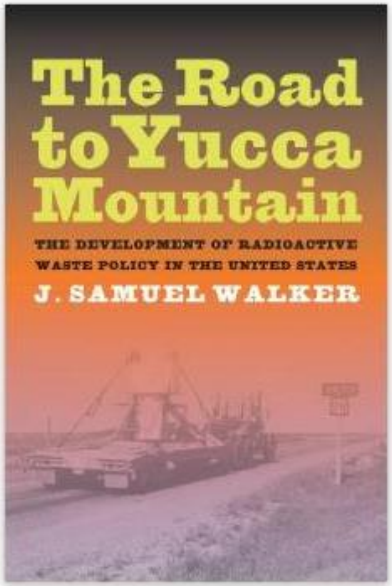
Outline

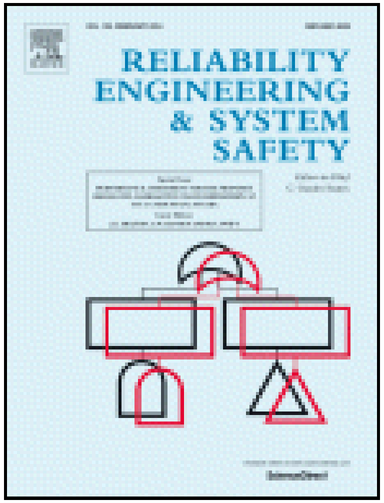
- Project history
- Major elements of the disposal concept
  - Waste
  - Repository Design
  - Site geology
- Long-term performance
  - Undisturbed performance
  - Disruptive events
- Quantitative estimates of annual dose
- Conclusions

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. Voegele, 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 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;

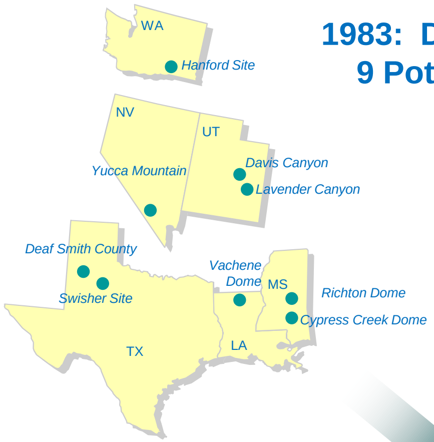
(Nevada Assembly Joint Resolution 15, May 17, 1975)

- 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)

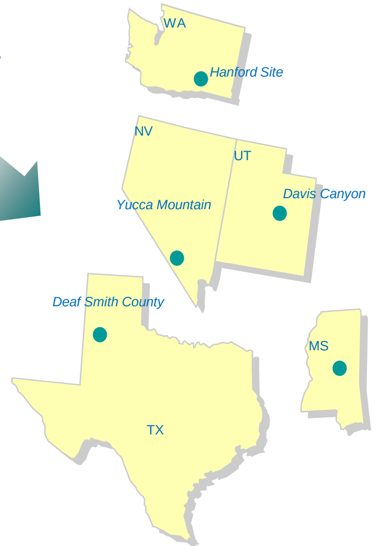
1982-1987: The Siting Process under the NWPA

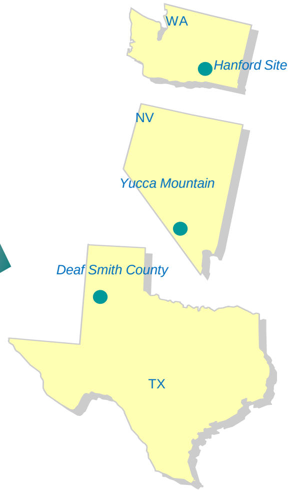
The NWPA of 1982 (sec. 112) requires
- *DOE to consult with affected governors and issue siting guidelines*
- *The Secretary to nominate at least five sites*
- *The Secretary to recommend 3 sites for characterization*

1983: DOE identifies 9 Potential Sites

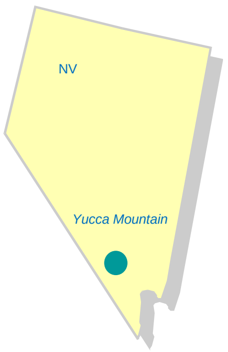


1986: Secretary of Energy Nominates 5 Sites, 3 Approved for Further Study





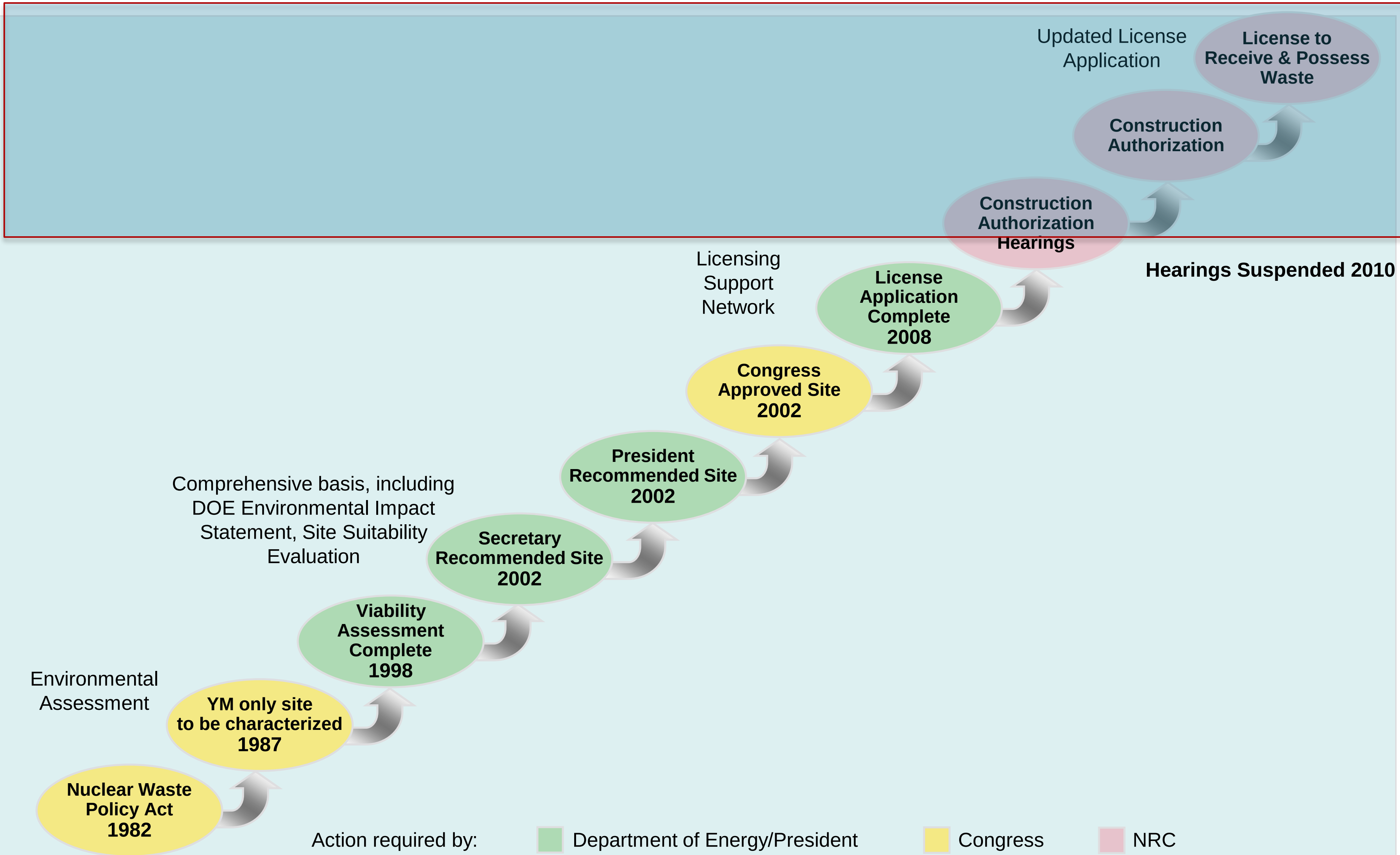
1987: NWPA Amended to Mandate One Site for Characterization



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 and high-level radioactive waste have moved to the DOE Office of Nuclear Energy

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

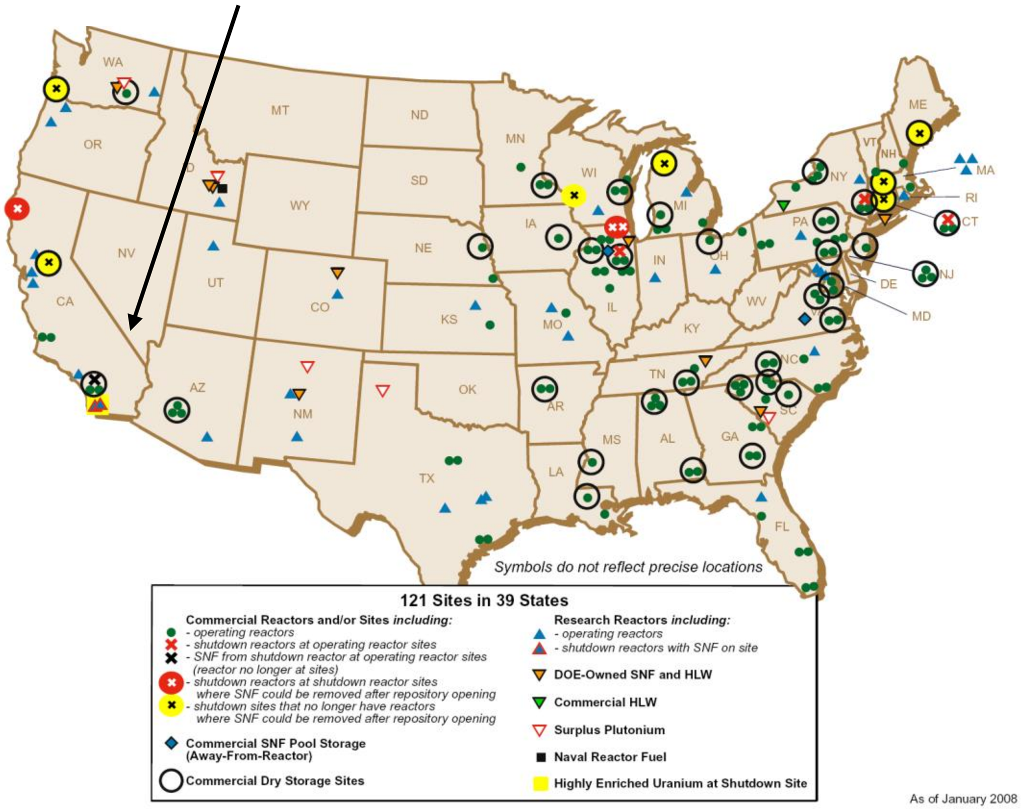
Long-term performance of the repository relies on natural and engineered barriers working together to isolate the waste

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]

Proposed Yucca Mountain Repository



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

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

Waste for Yucca Mountain

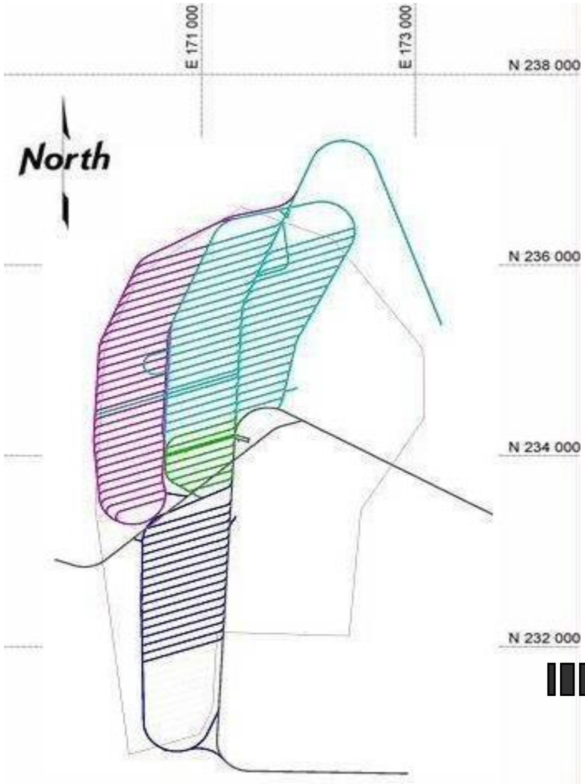
Commercial Spent Nuclear Fuel:
63,000 MTHM (~7500 waste packages)

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

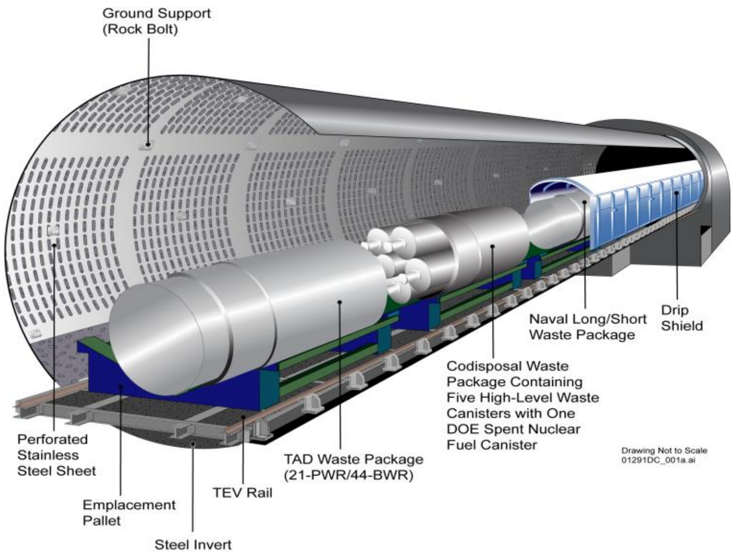
Yucca Mountain Subsurface Design



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

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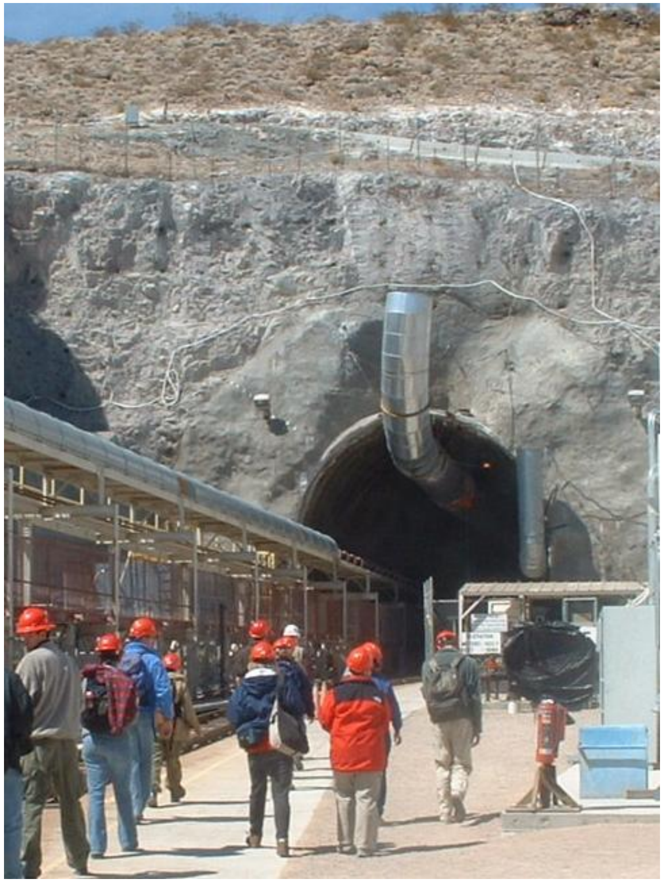
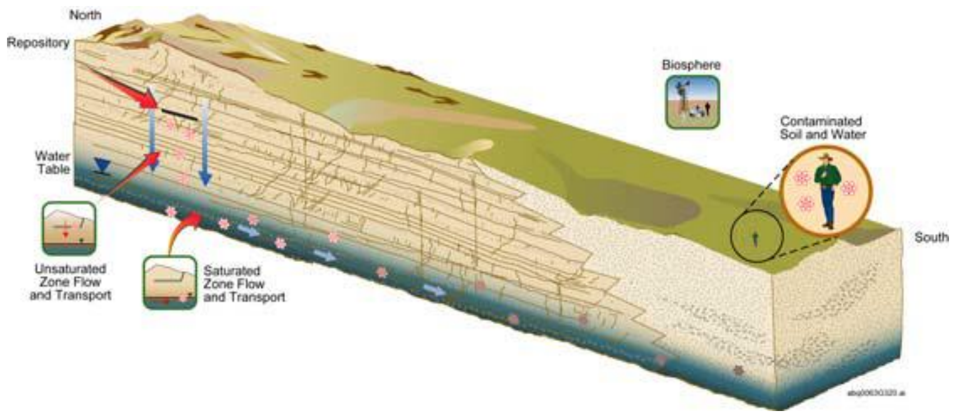


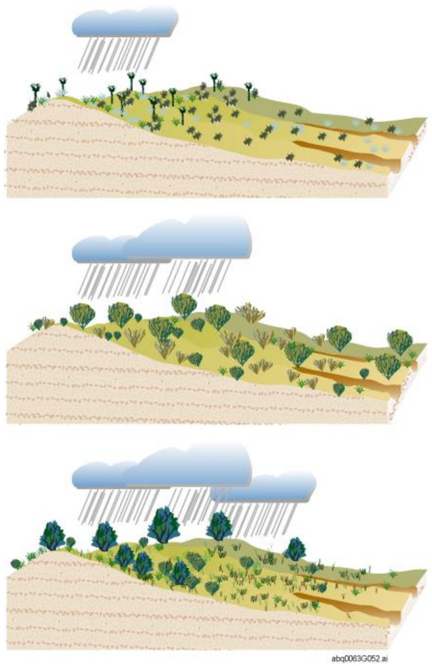
Long-term Performance of the Proposed Yucca Mountain Repository

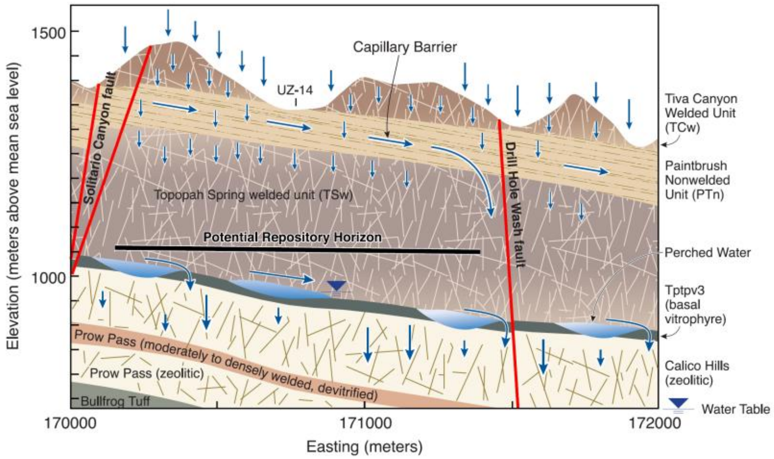
- Water provides the primary release mechanism
  - Precipitation infiltrates and percolates downward through the unsaturated zone
  - Corrosion processes degrade engineered barriers, including the waste form

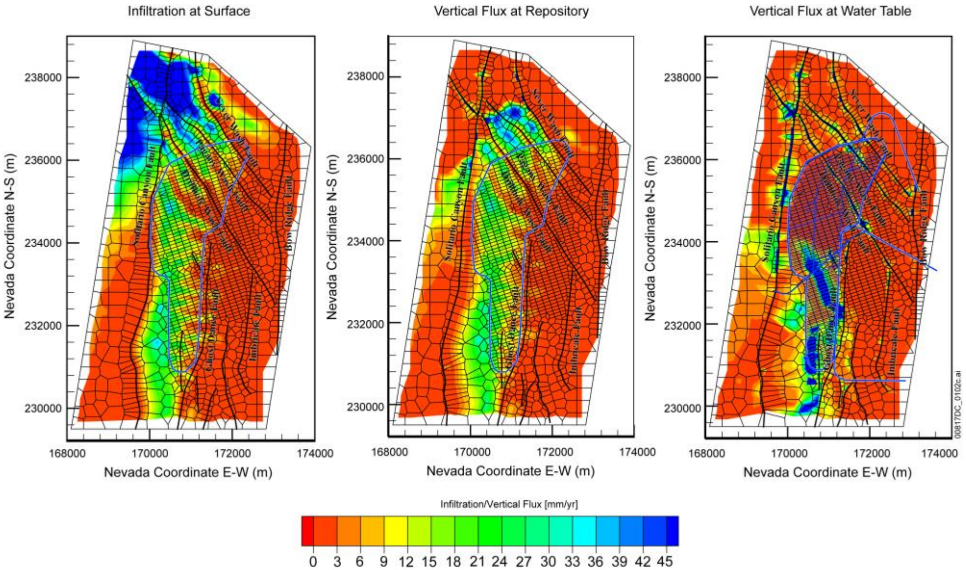


  - Radionuclides are mobilized by seepage water and percolate downward to the water table
  - Lateral transport in the saturated zone leads to biosphere exposure at springs or withdrawal wells

Groundwater Flow at Yucca Mountain

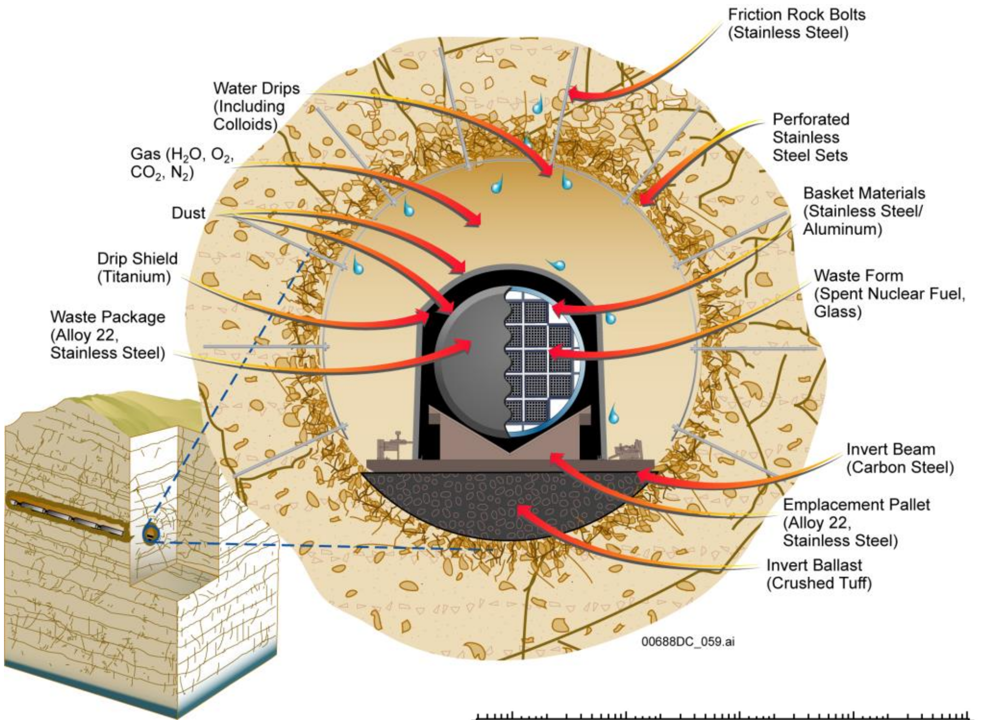


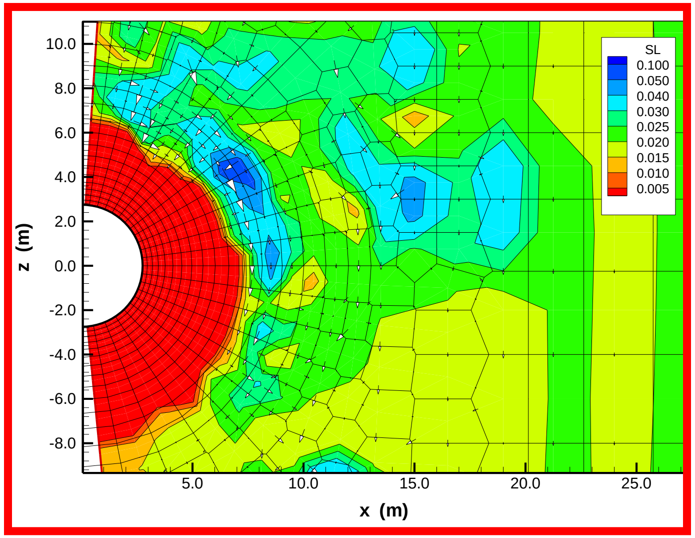




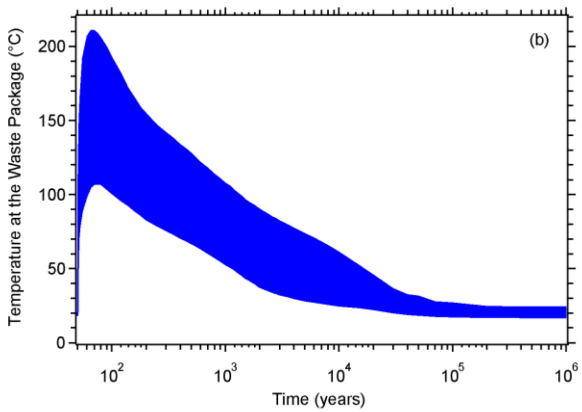
Field tests and models provide basis for understanding infiltration and flow in unsaturated rocks at Yucca Mountain

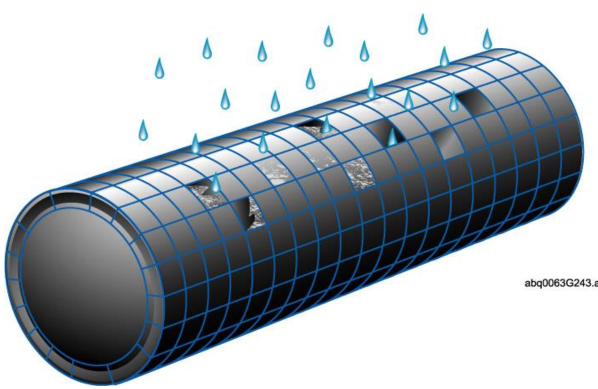
The Emplacement Environment at Yucca Mountain



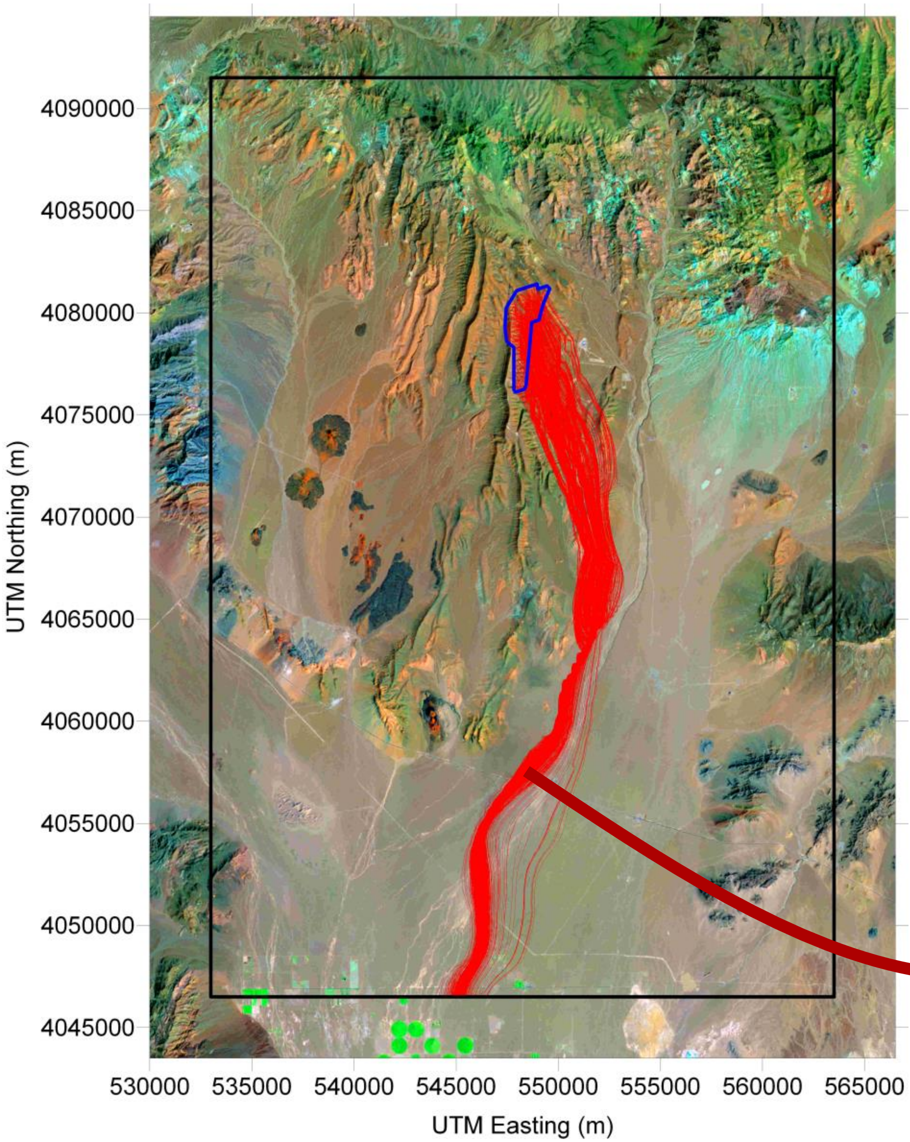


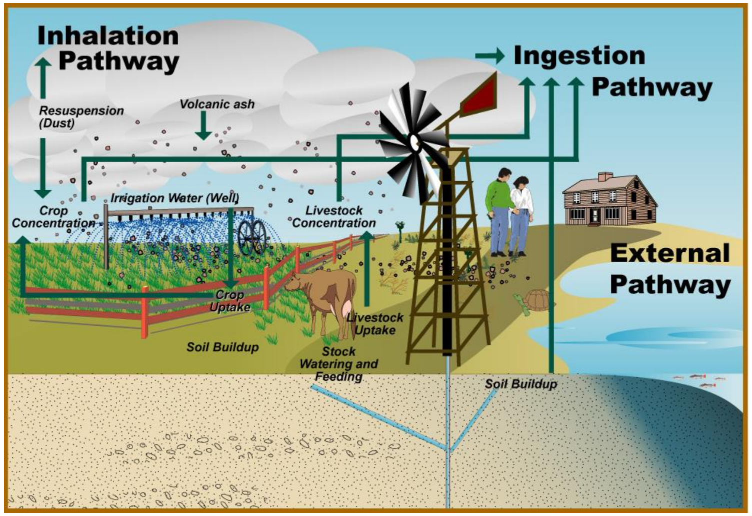
Material testing and models characterize performance of the engineered barriers





Estimating Dose to Hypothetical Future Humans





Modeled groundwater flow paths and hypothetical exposure pathways

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)

Yucca Mountain Total System Performance Assessment

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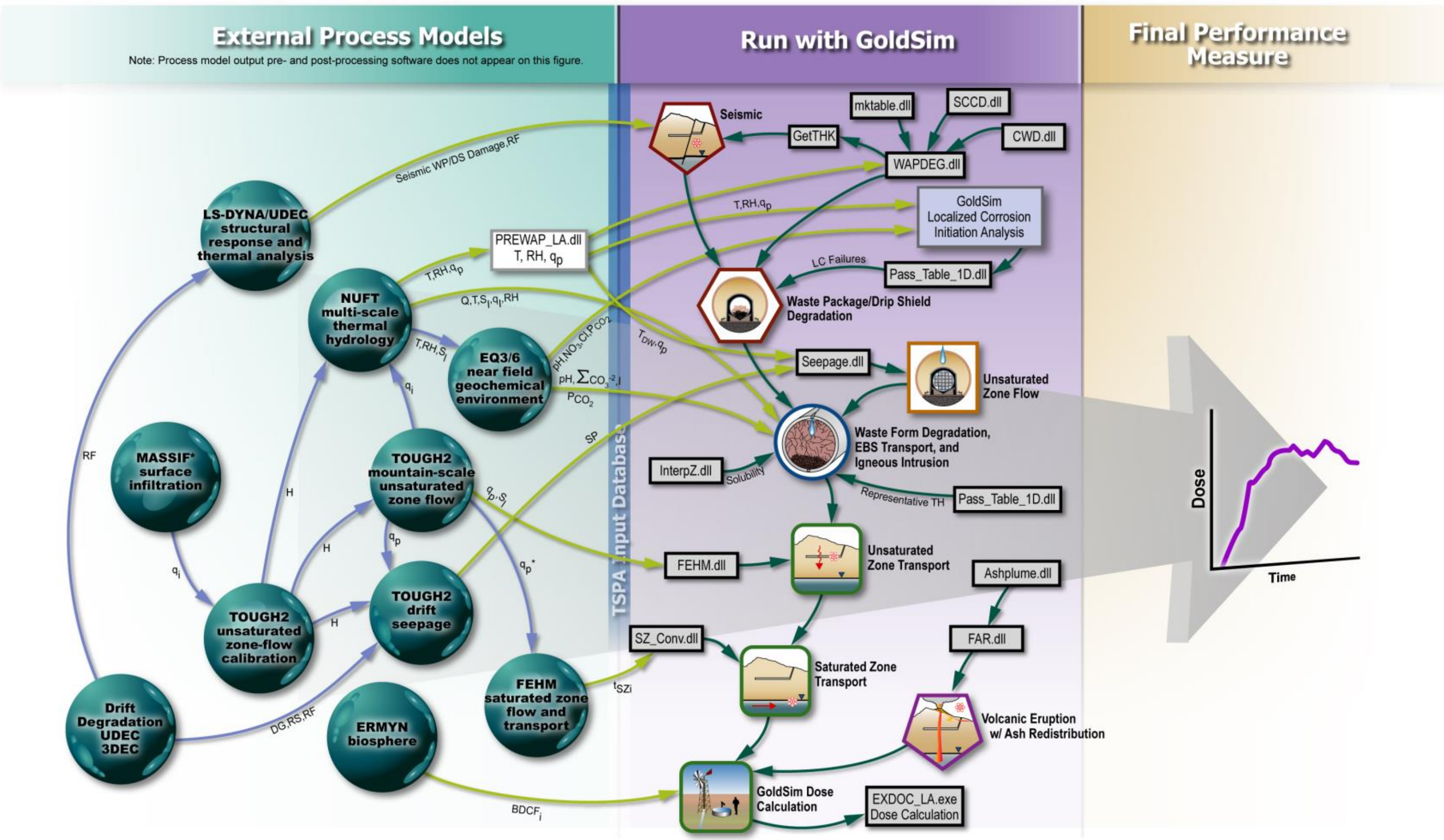

Output Parameters

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

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Uncertainty in the Yucca Mountain TSPA

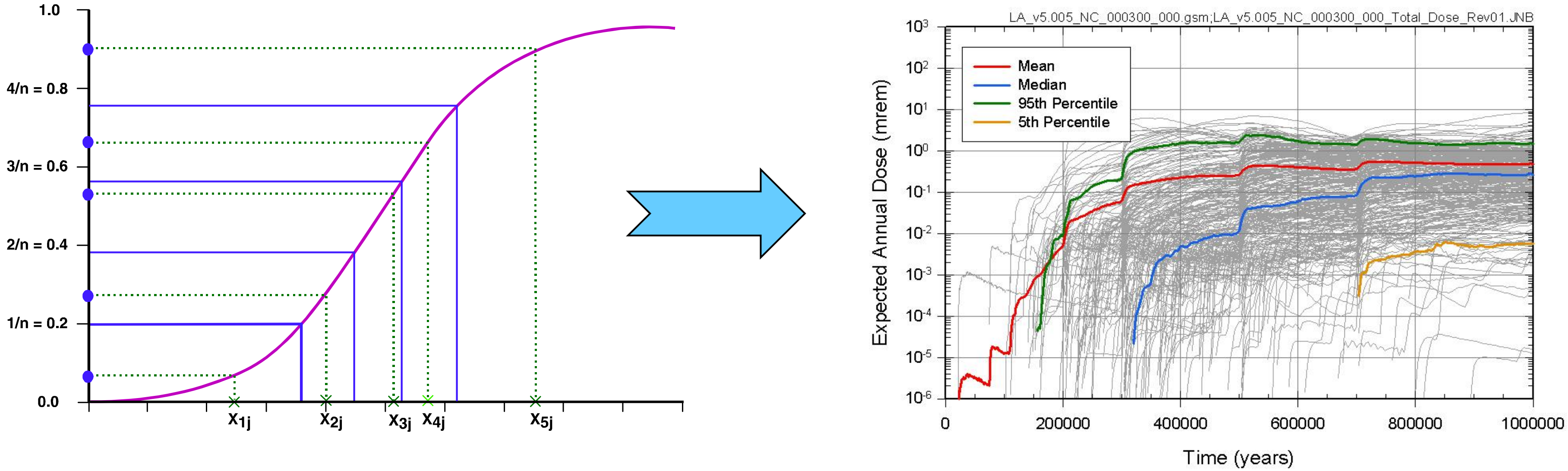
Aleatory Uncertainty
− Inherent randomness in events that could occur in the future
− Alternative descriptors: irreducible, stochastic, intrinsic, type A
− Examples:
➢ *Time and size of an igneous event*
➢ *Time and size of a seismic event*

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

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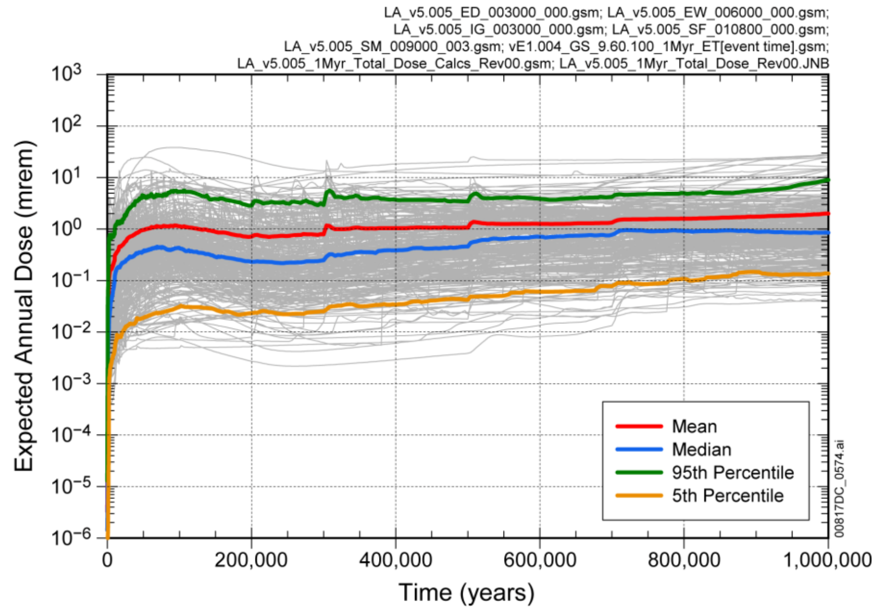
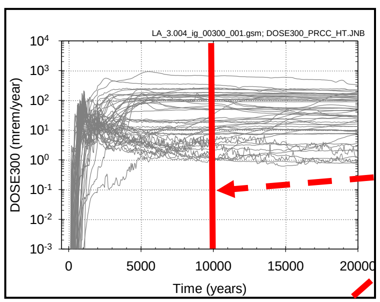
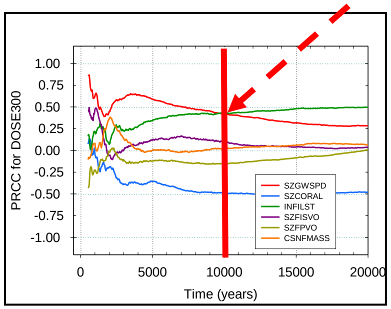
Monte Carlo estimates of overall performance
(Example dose histories from Yucca Mountain Total System Performance Assessment for the License Application, total expected dose from all scenarios)

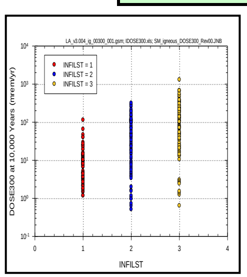


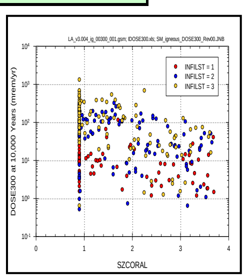


DOSE300: 10,000 yr

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

Treatment of Aleatory Uncertainty: Defining Scenarios Based on Unlikely Events

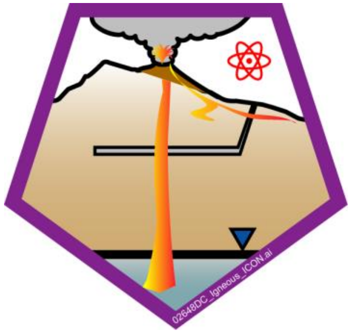
Four scenario classes divided into seven modeling cases

Nominal Scenario Class

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

Igneous Scenario Class

- **Intrusion Modeling Case**
- **Eruption Modeling Case**

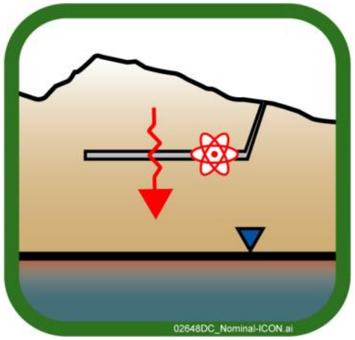


Early Failure Scenario Class

- **Waste Package Modeling Case**
- **Drip Shield Modeling Case**

Seismic Scenario Class

- **Ground Motion Modeling Case**
- **Fault Displacement Modeling Case**



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.

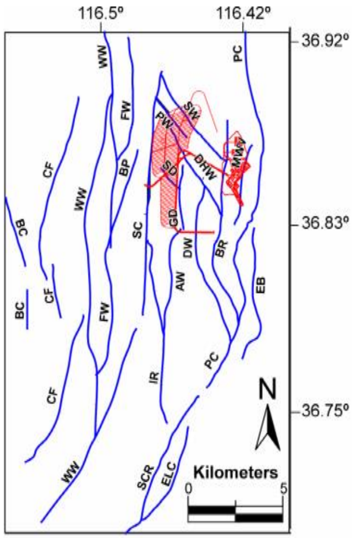
…

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)

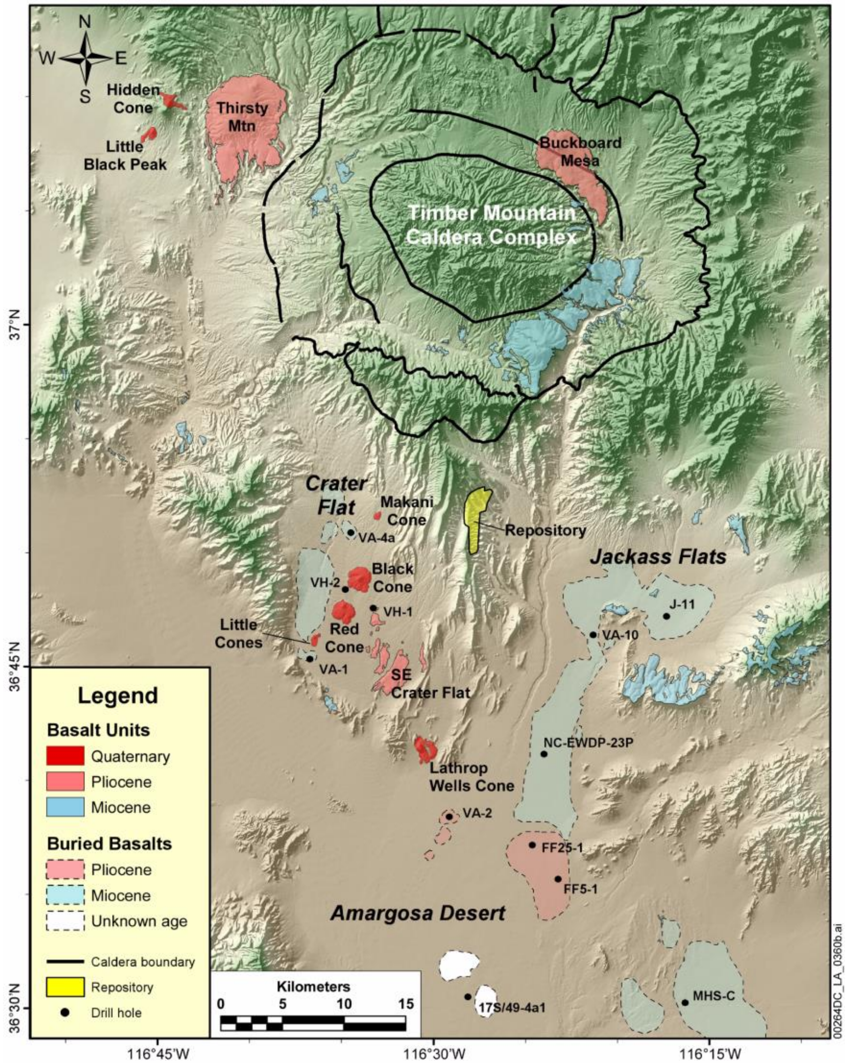
Potential Disruptive Geologic Events at Yucca Mountain

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

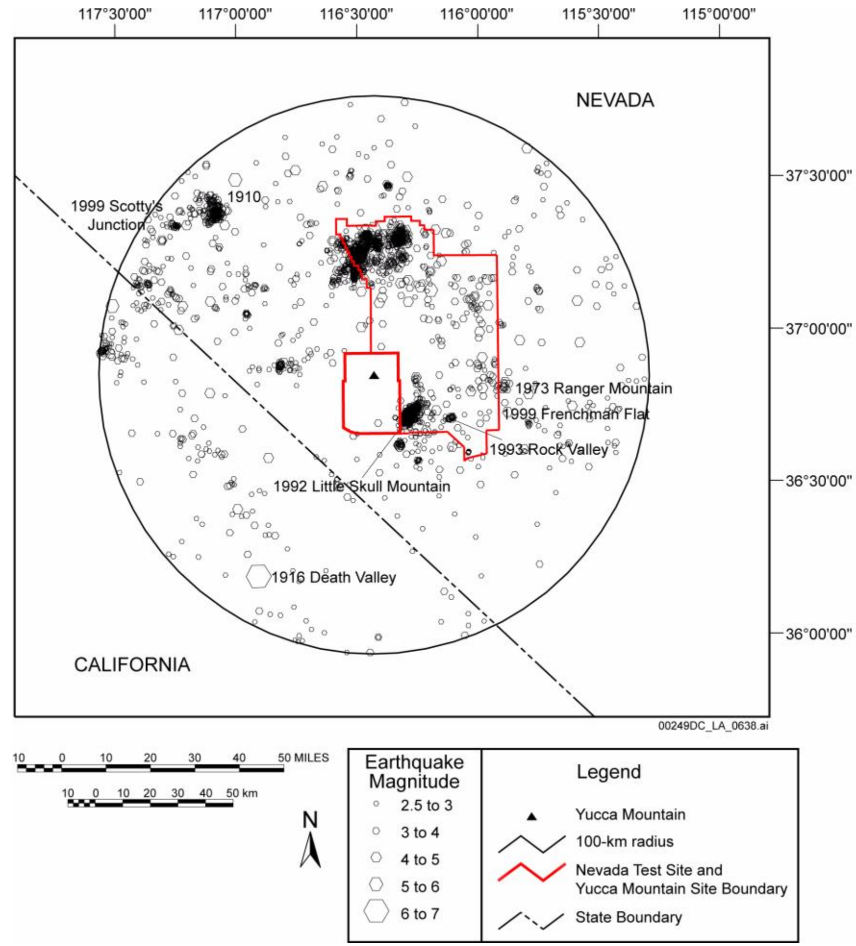


- **Seismicity**
  - Map shows Quaternary age faults (<1.5Myr) in the Yucca Mountain region

Igneous and Seismic Activity in the Yucca Mountain Region

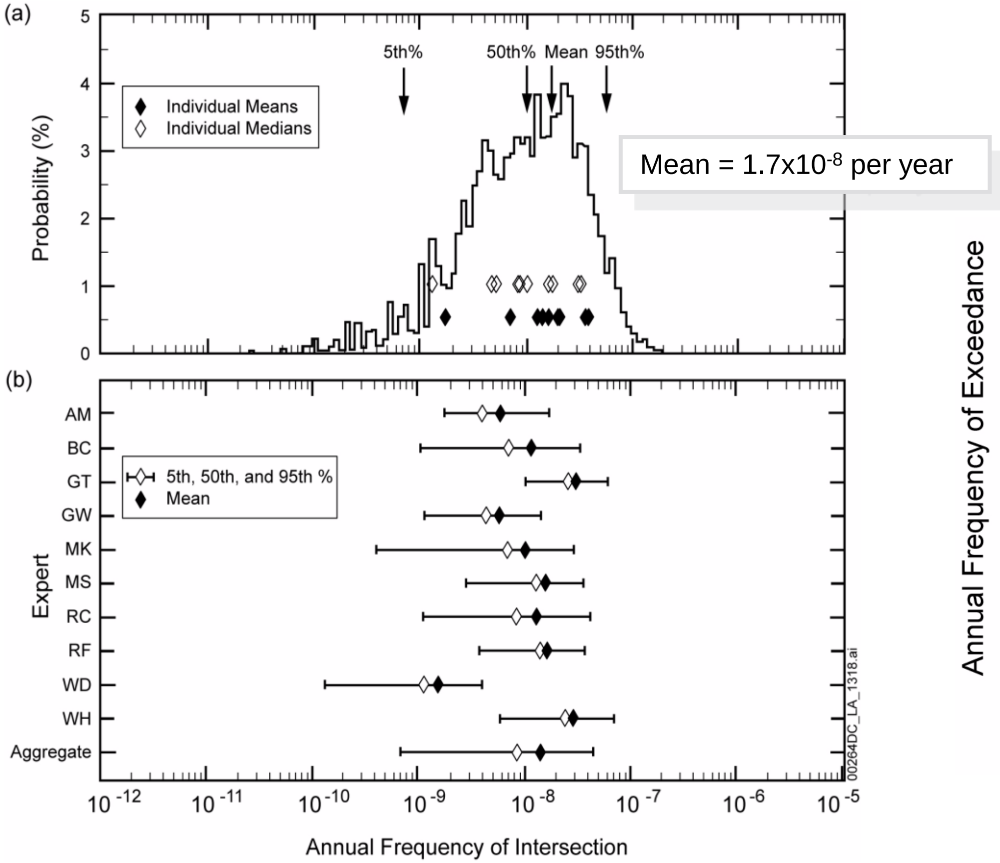


Distribution of Miocene and younger (< 5.3 Ma) Basaltic Rocks in the Yucca Mountain Region (DOE/RW-0573 Rev. 1, Figure GI 5-39)

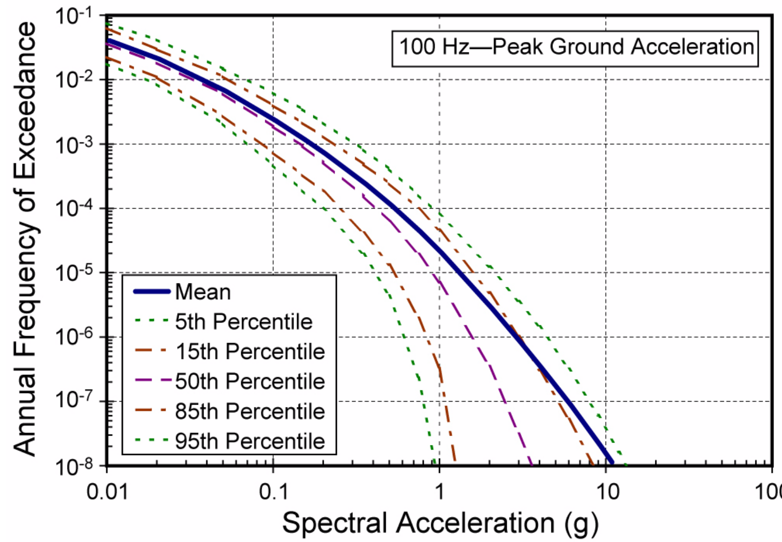


Historical Earthquake Epicenters with 100 km of Yucca Mountain (DOE/RW-0573 Rev. 1, Figure GI 5-38)

Yucca Mountain Event Probabilities Estimated by Formal Expert Elicitation

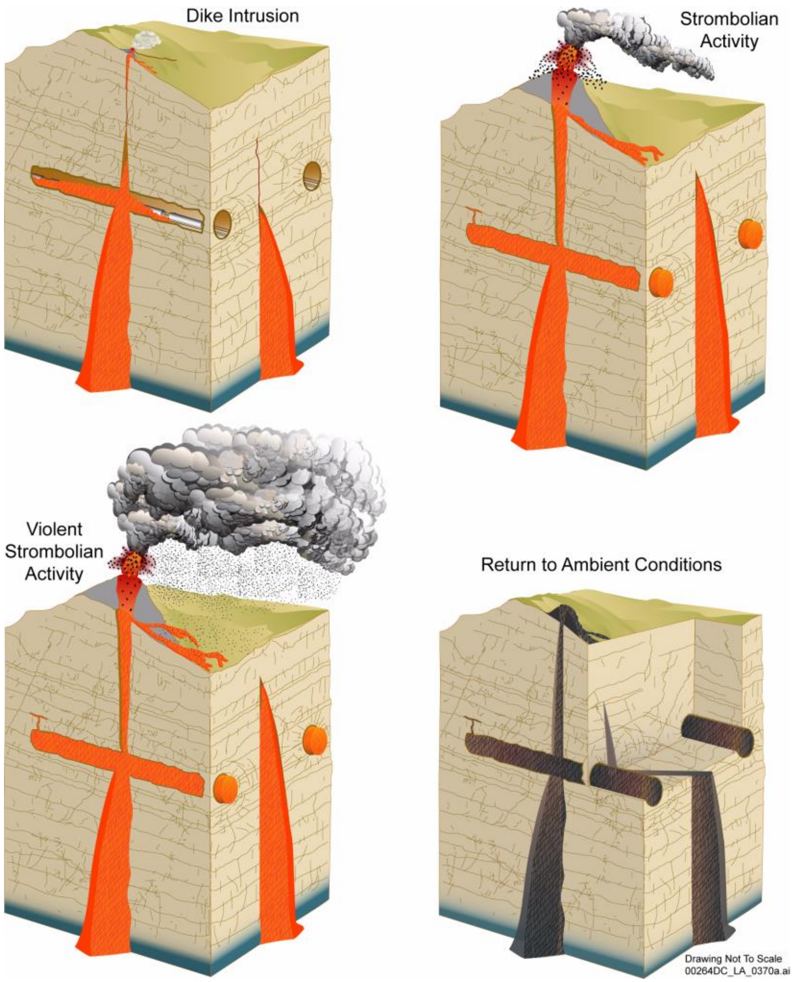


Estimated annual frequency of an igneous intrusion intersecting the repository footprint (DOE/RW-0573 Rev. 1, Figure 2.3.11-8)



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

Consequence Models for Igneous Disruption at Yucca Mountain

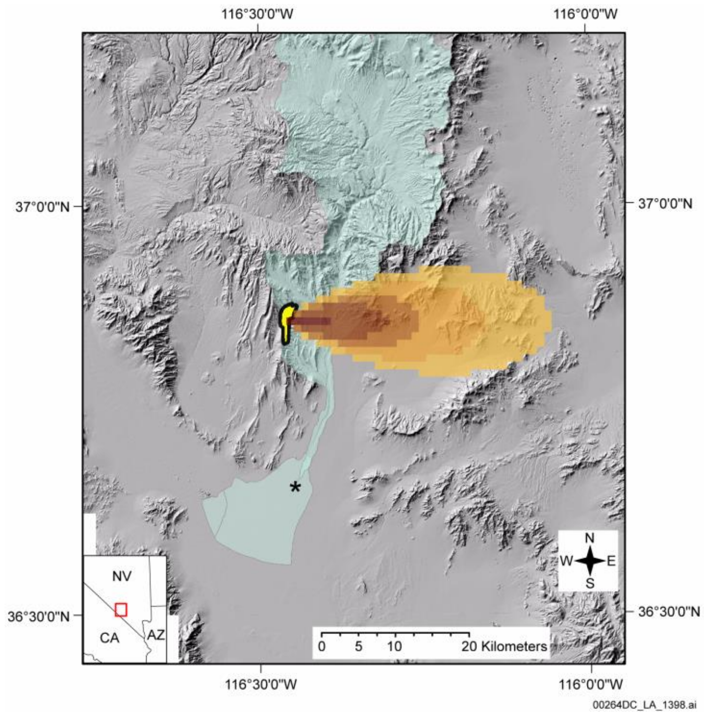


Schematic Drawing of an Igneous Event at Yucca Mountain (DOE/RW-0573 Rev. 1, Figure 2.3.11-5)

Two Release Scenarios

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

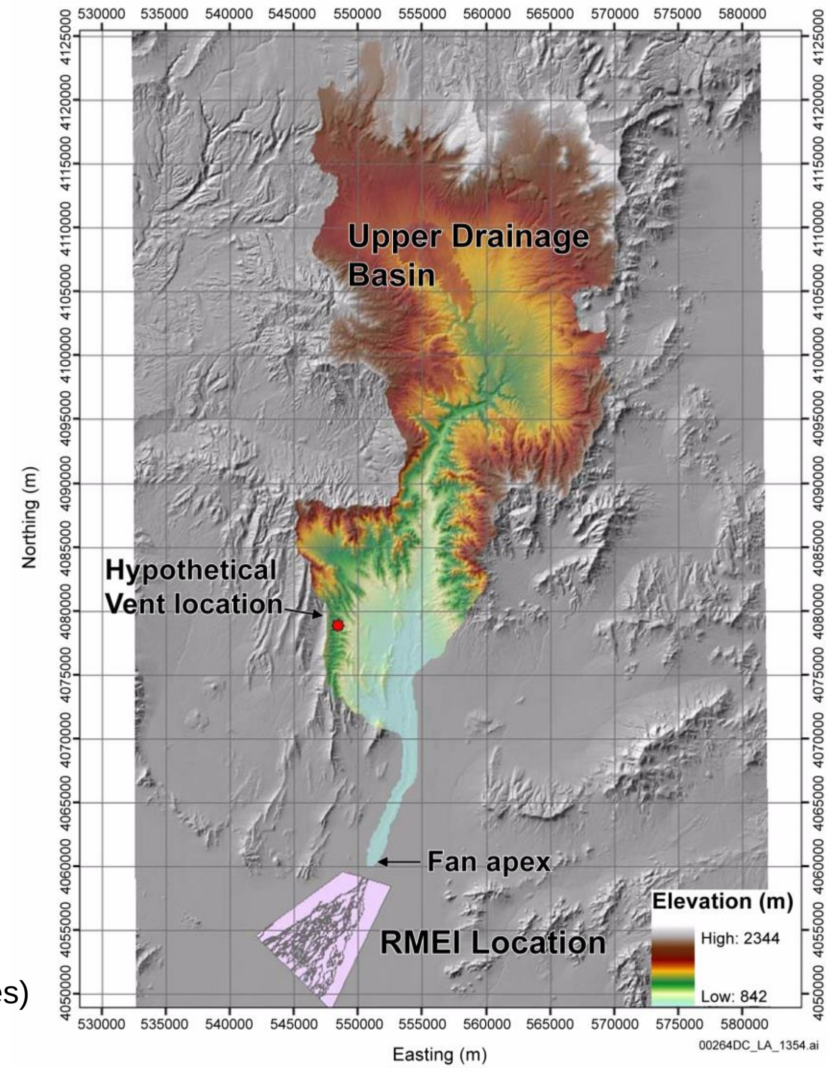
Modeling Consequences of Volcanic Eruption



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

Uncertain variables include:

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

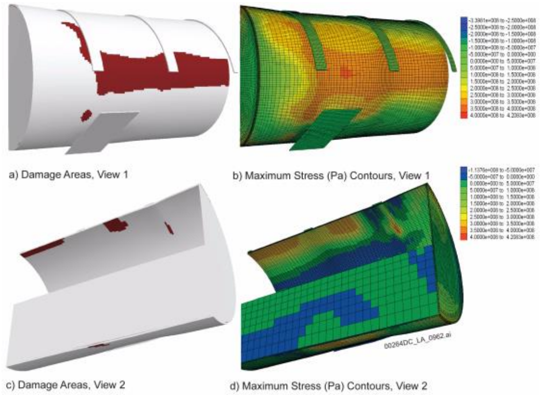


Model domain for surface redistribution of ash (DOE/RW-0573 Rev. 1, Figure 2.3.11-5)

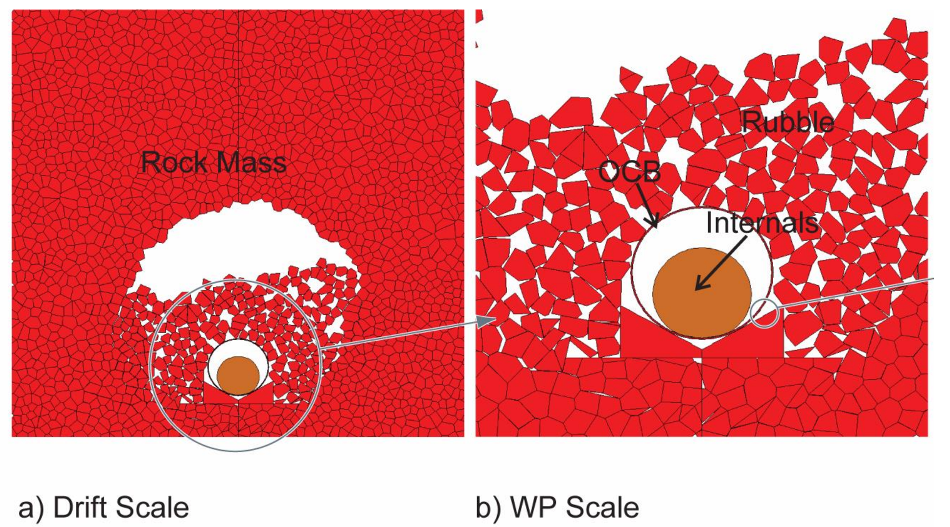
Consequence Models for Seismic Disruption at Yucca Mountain

- 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)



Results of Seismic Consequence Models for Yucca Mountain

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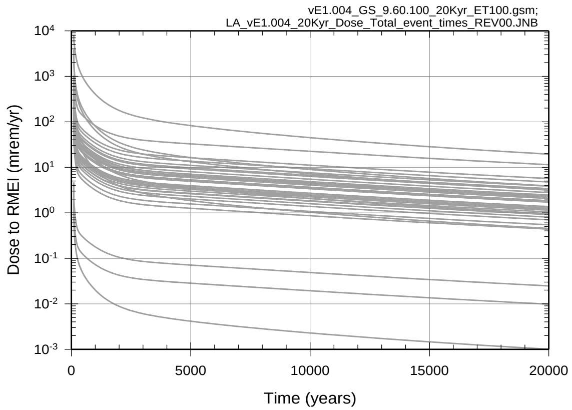
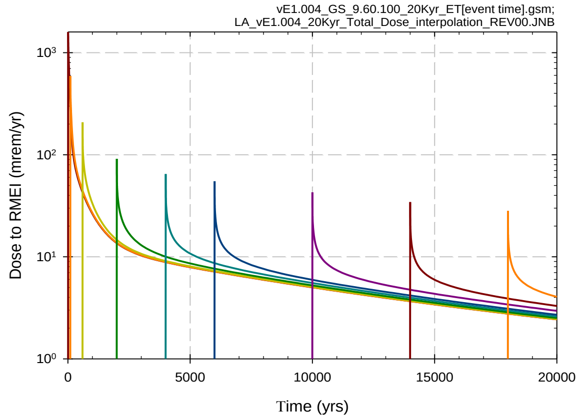
- Seismic Fault Displacement Modeling Case
  - Annual frequency approximately 2×10^{-7} / yr
  - Fault displacements rupture waste packages and drip shields, allowing advection and diffusion
    - Size of rupture uncertain, 0 to cross-sectional area of WP
  - Mean of ~ 47 waste packages and drip shields 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: ~ 10^{-5} / yr
    - Frequency of events that damage transportation, aging, and disposal (TAD) packages for commercial spent nuclear fuel (CSNF): ~ 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

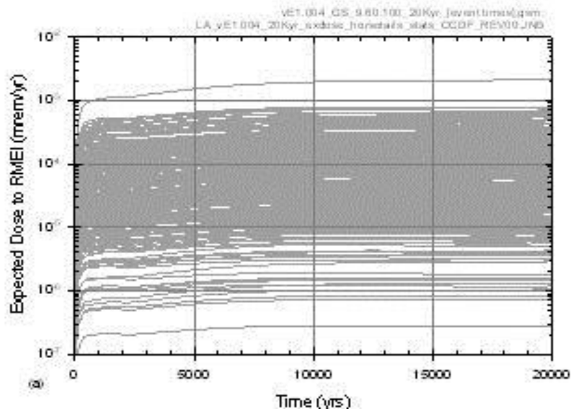
Estimating Mean Annual Dose from Unlikely Events: Eruptive Dose



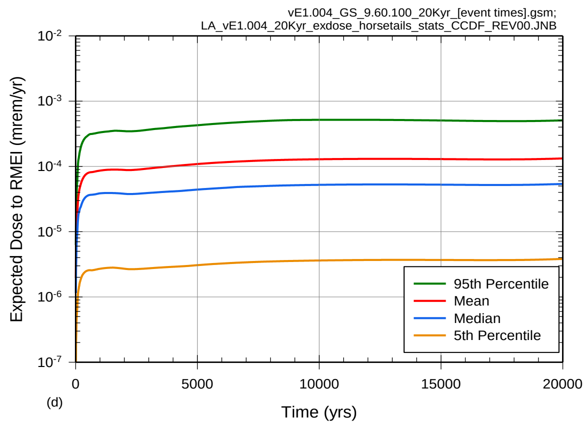
Eruptive dose: 40 realizations of aleatory uncertainty conditional on a single eruption of 1 WP at time zero



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



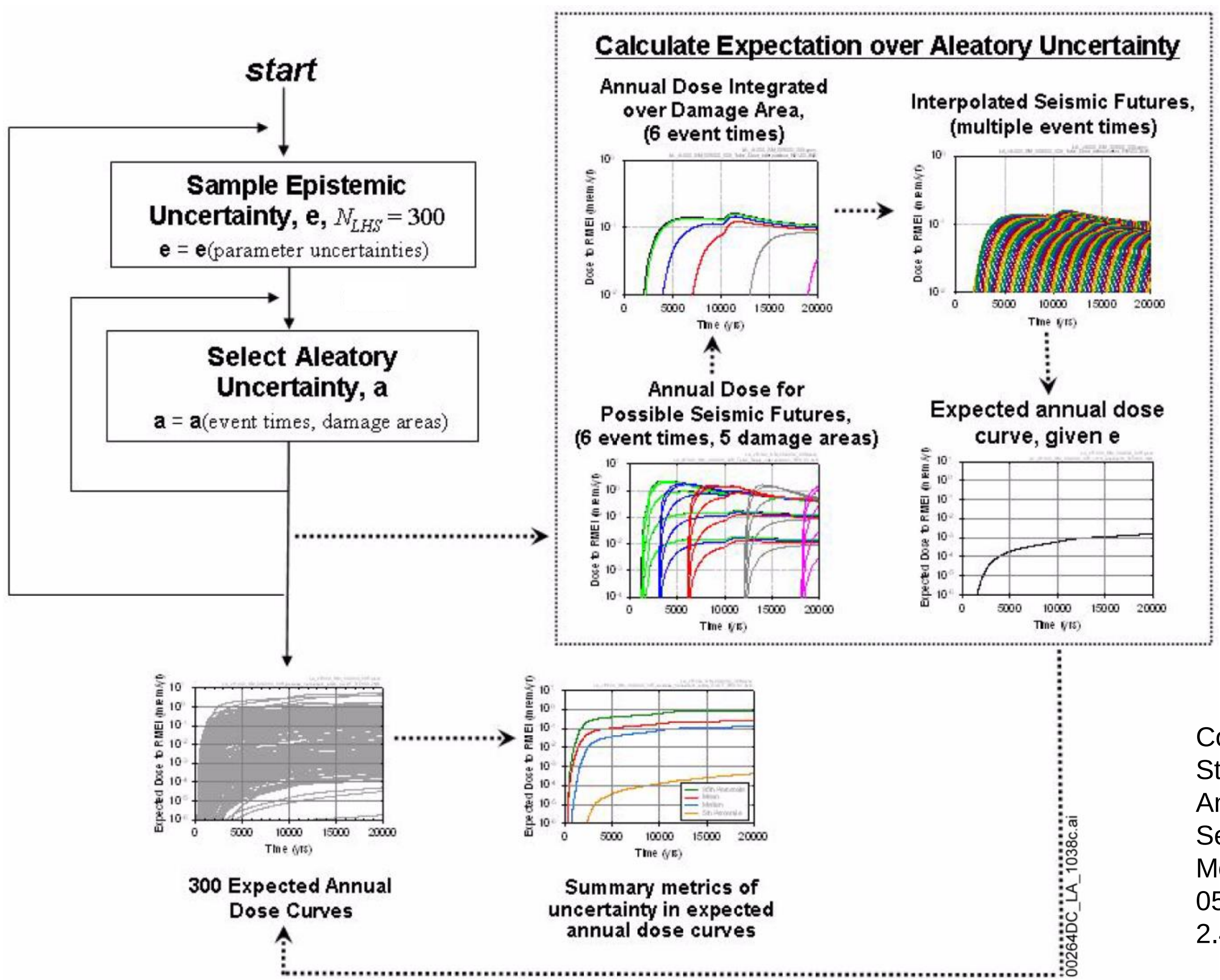
Expected eruptive dose; 300 realizations, each showing expected dose from a single sampling of epistemic uncertainty with events at all times



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

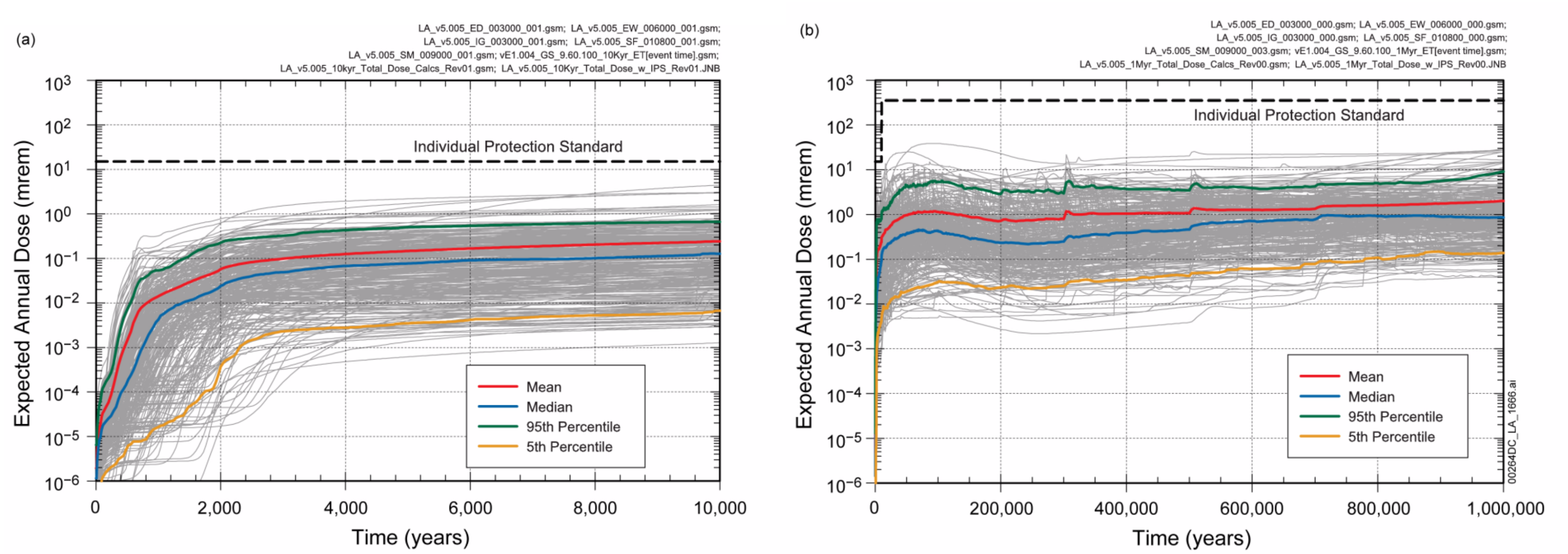
Estimating Mean Annual Dose from Unlikely Events: Seismic Ground Motion Dose



Computational Strategy for Expected Annual Dose from Seismic Ground Motion (DOE/RW-0573 Rev. 1, Figure 2.4-8)

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)

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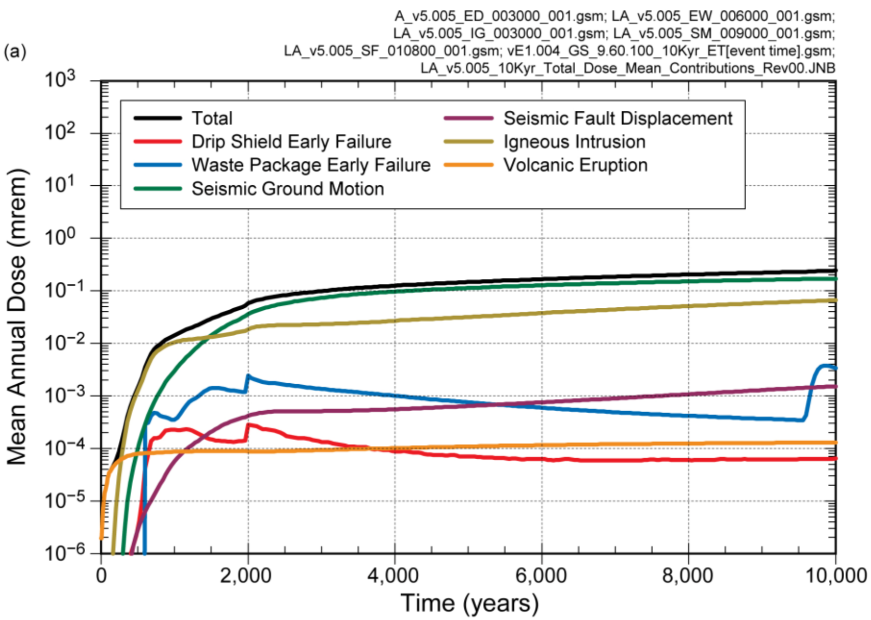
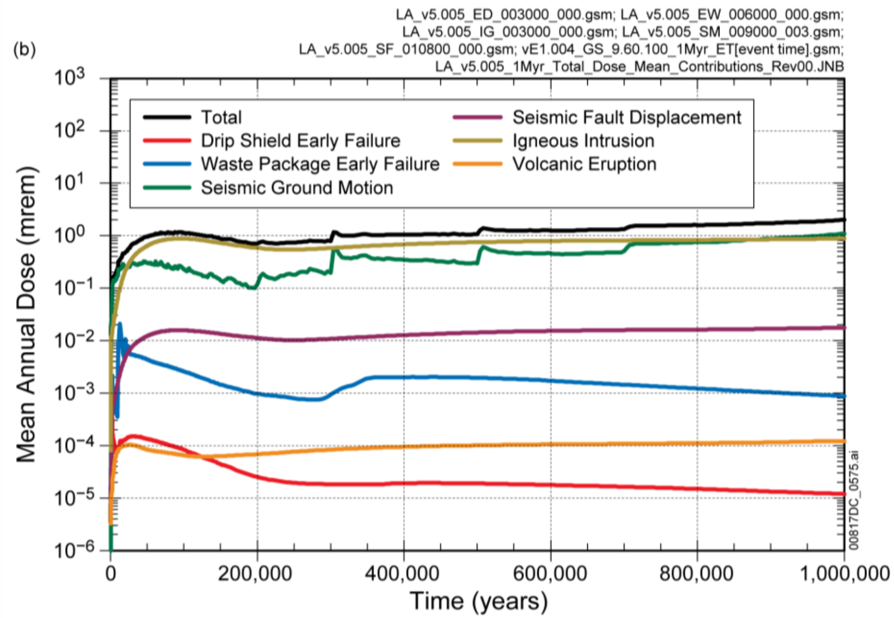
Modeling Cases Contributing to Total Mean Annual Dose



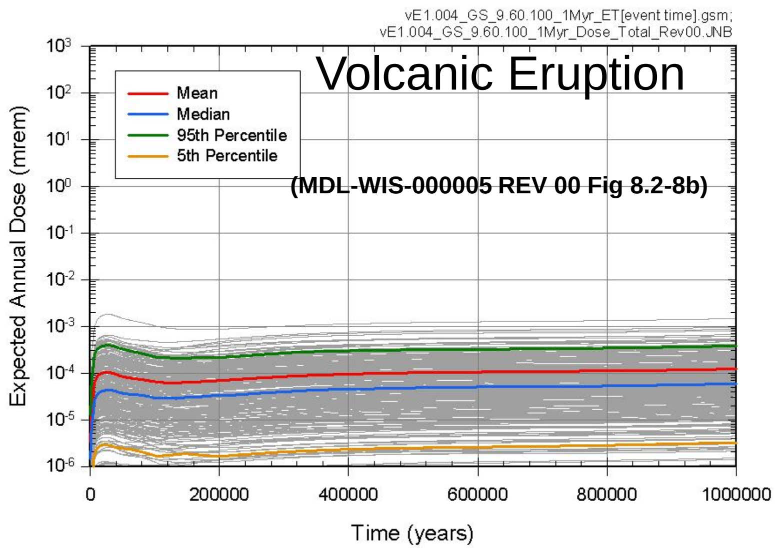
10,000 years



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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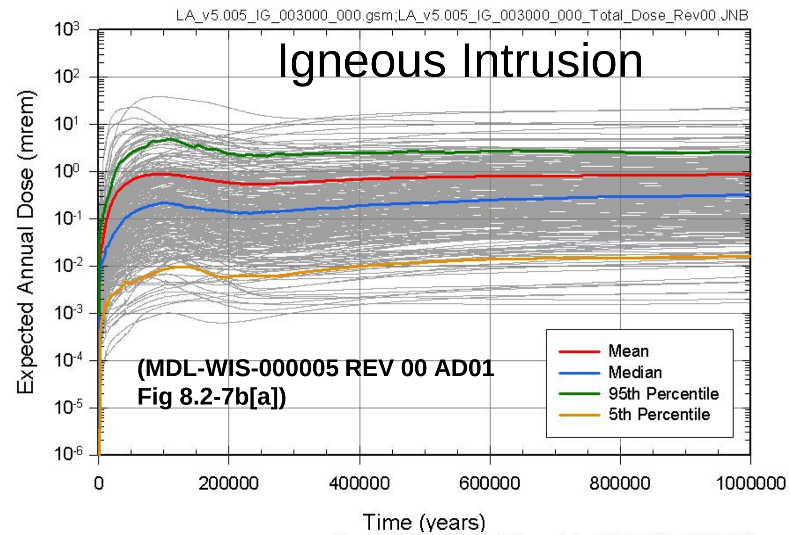

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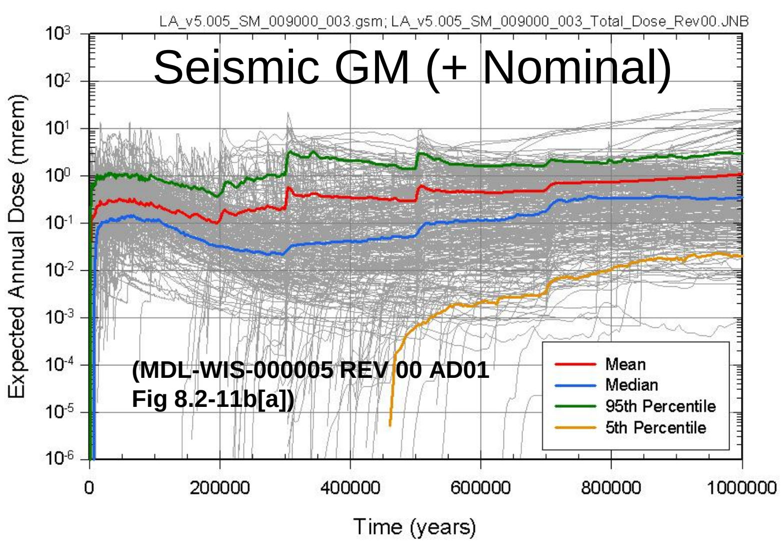
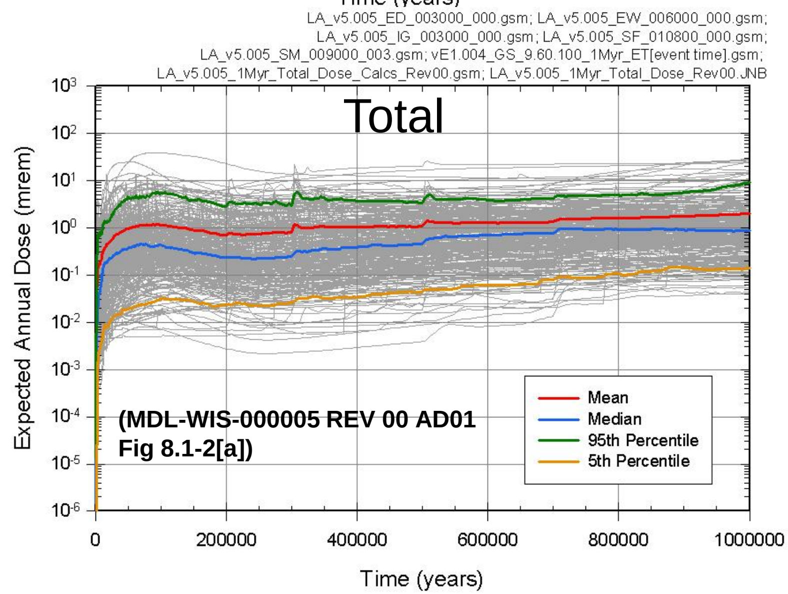
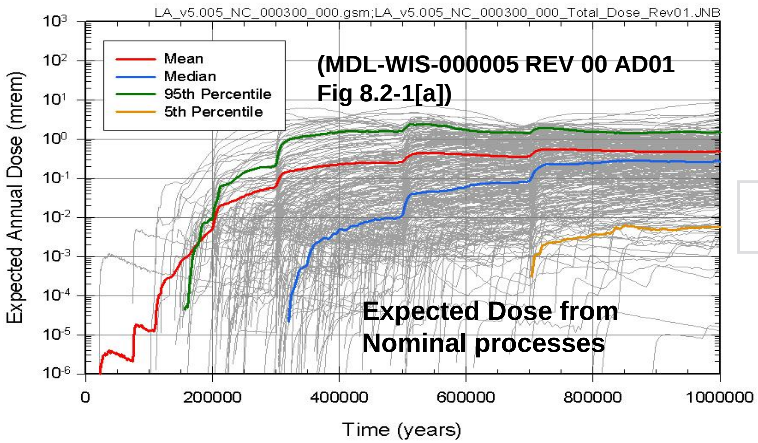
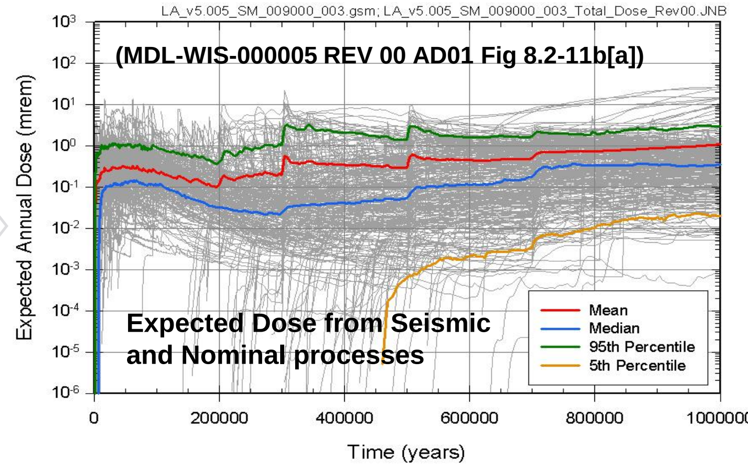


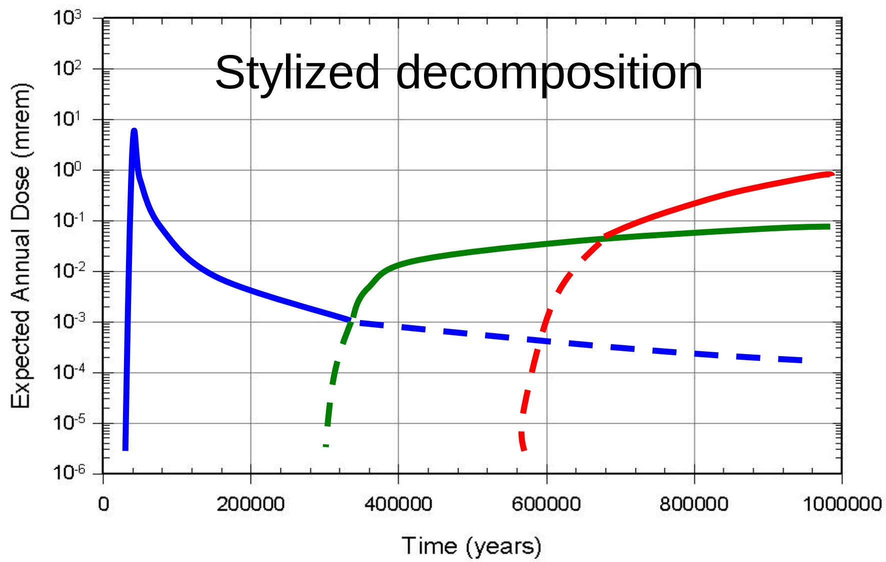


Composition of Seismic Ground Motion Dose



Included





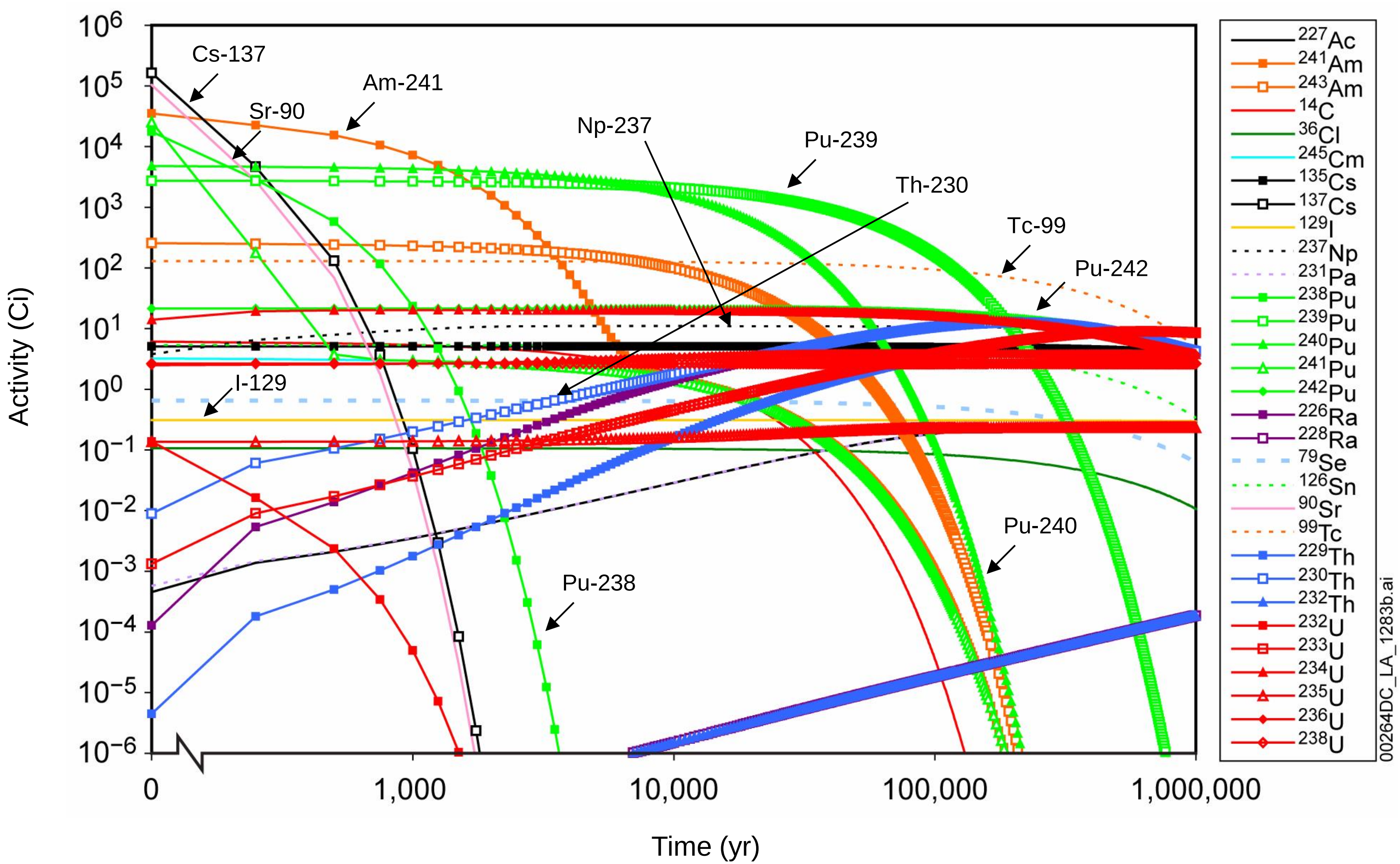
From seismic damage to CDSP WP (diffusion)

From SCC failure of CSNF WP (diffusion)

From general corrosion failure of both WPs (advection)

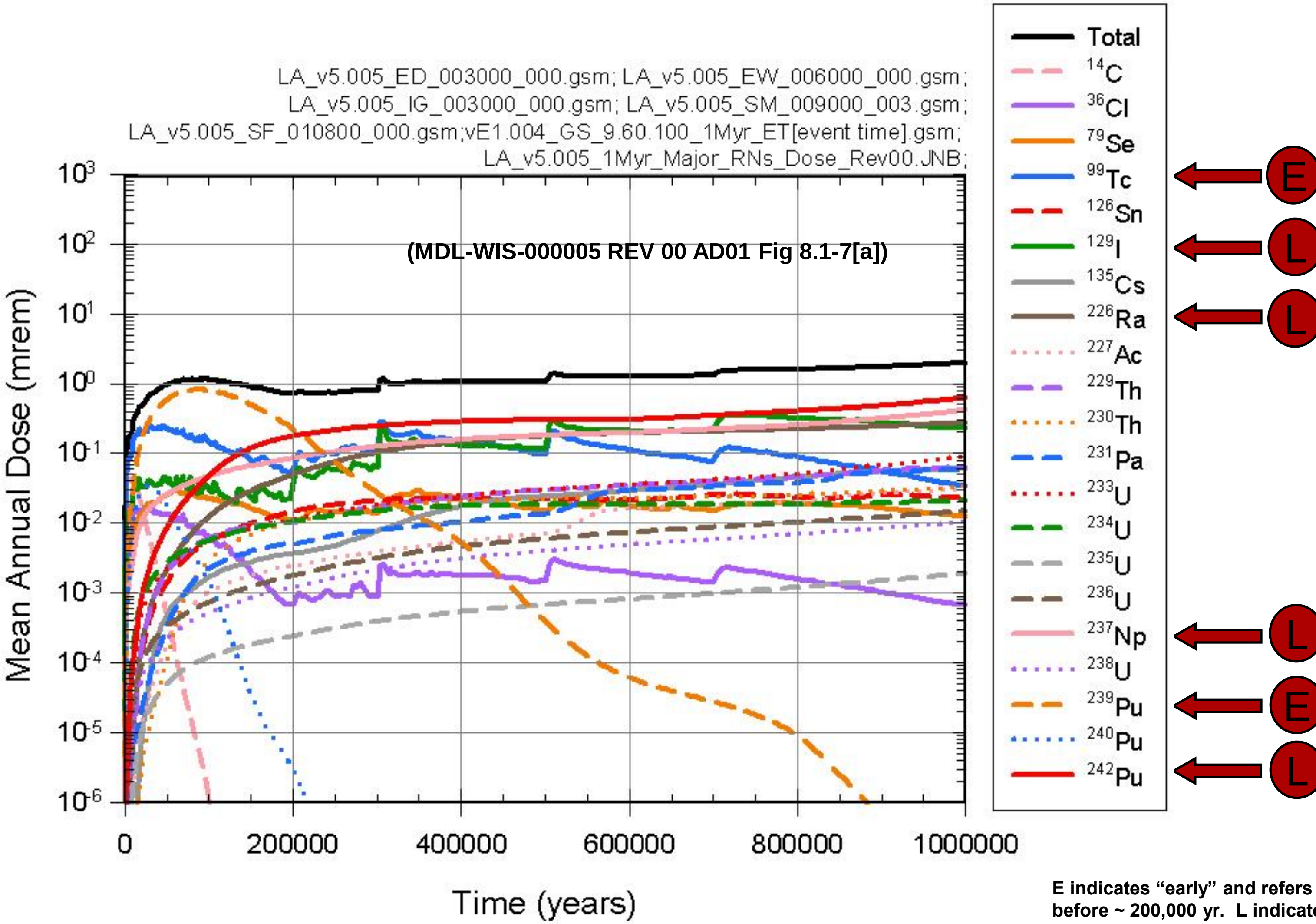
Radionuclides Contributing to Estimates of Total Dose from Yucca Mountain

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



E indicates "early" and refers to the time period before ~ 200,000 yr. L indicates "late" and refers to the time period after ~ 200,000 yr

How Does Yucca Mountain Compare to Other Proposed Repositories?

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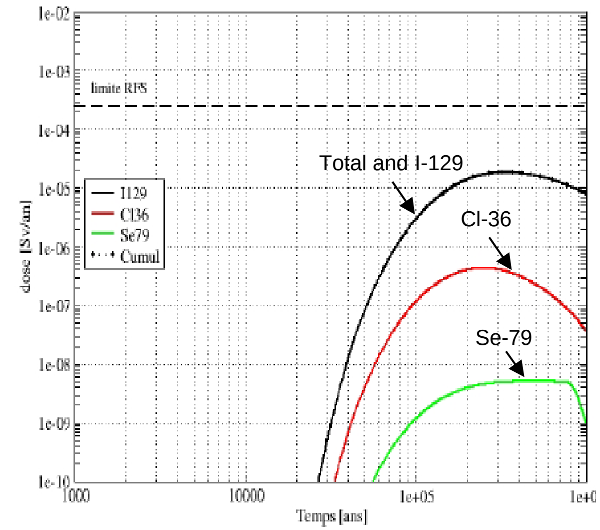
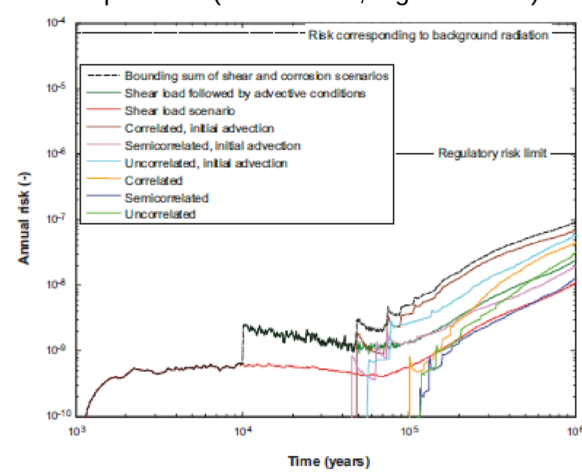
- Unsaturated and oxidizing environment is unique
  - Radionuclides contributing to total dose from Yucca Mountain include actinides (Pu, Np, U) and Tc-99
  - Releases from repositories in saturated environments are dominated by species that are mobile in reducing conditions (I-129, Cl-36, Ra-226)
- 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 $0.073 Sv^{-1}$)

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
- Over hundreds of thousands of years, 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 1.7×10^{-8}/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

References

- ANDRA Agence nationale pour la gestion des déchets radioactifs), *Dossier 2005: Argile. Tome: Safety Evaluation of a Geological Repository* (English translation: original documentation written in French remains ultimately the reference documentation); 2005
- Carter LJ. Nuclear imperatives and public trust: dealing with radioactive waste, resources for the Future, Inc. Baltimore, MD: John Hopkins University Press; 1987
- Ekren, E.B., Dinwiddie, G.A., Mytton, J.W., Thordarson, W., Weir, J.E., Jr., Hinrichs, E.N., and Schroder, L.J., Geologic and Hydrologic Considerations for Various Concepts of High-Level Radioactive Waste Disposal in Conterminous United States, U.S. Geologic Survey Open-File Report 74-158
- McKelvey V. Major assets and liabilities of the Nevada Test Site as a high- level radioactive waste repository. Letter from Dr. V. McKelvey (USGS) to R. W. Roberts (US Energy Research and Development Administration), July 9, 1976
- National Academies/National Research Council (NA/NRC). The disposal of radioactive waste on land. Publication 519. Washington, DC: National Academy Press. National Academies/National Research Council; 1957
- Rechard RP, Cotton TA, Voegele M. 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; 2014
- Roseboom EH. Disposal of high-level nuclear waste above the water table in arid regions. Circular 903. Denver, CO: US Department of the Interior, Geological Survey; 1983.
- SKB (Svensk Kärnbränslehantering AB). Long-term safety for the final repository for spent nuclear fuel at Forsmark, Technical Report TR-11-01; 2011.
- Spengler RW, Muller DC, Livermore RB. Preliminary report on the geology and geophysics of drill hole UE25a-1, Yucca Mountain, Nevada Test Site. Denver, CO: US Geological Survey; 1979 Open-File Report 79-926
- Schneider KJ, Platt AM. High-level radioactive waste management alternatives. Washington, DC: Atomic Energy Commission; 1974 WASH-1297
- SNL (Sandia National Laboratories). 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; 2008.

References (cont.)

- U.S. Department of Energy (DOE). Final environmental impact statement, management of commercially generated radioactive waste. DOE/EIS-0046F. Washington, DC: US Department of Energy; 1980
- U.S. Department of Energy (DOE). Site characterization plan: Yucca Mountain Site, Nevada research and development area, Nevada: Consultation draft, Nuclear Waste Policy Act. DOE/RW-0160-vol.1–vol. 9. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 1988
- U.S. DOE (US Department of Energy). Viability assessment of a repository at Yucca Mountain. DOE/RW-0508. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 1998
- U.S. DOE (U.S. Department of Energy). Yucca Mountain site suitability evaluation. DOE/RW-0549. Las Vegas, NV: U.S. Department of Energy; 2002.
- U.S.DOE (U.S. Department of Energy).Final environmental impact statement for a geologic repository for the disposal of spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nye County, Nevada. DOE/EIS-0250F. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management; 2002
- U.S. DOE (U.S. Department of Energy). Yucca Mountain repository license application safety analysis report. DOE/RW-0573, Update no. 1. Las Vegas, NV: U.S. Department of Energy; 2008
- U.S. DOE (United States Department of Energy), "U.S. Department of Energy's Motion to Withdraw," filed March 3, 2010 with the United States of America Nuclear Regulatory Commission Atomic Safety and Licensing Board, Docket no. 63.001, ASLBP no. 09-892-HLW-CAB04; 2010
- U.S. Nuclear Regulatory Commission (NRC). *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; 2014.
- U.S. Nuclear Regulatory Commission (NRC). *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, 2015
- Walker JS. The road to Yucca Mountain. Berkeley, CA: University of California Press; 2009

Key Website: http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app.html