

Deep Geologic Disposal of Radioactive Waste at the Waste Isolation Pilot Plant and the Proposed Yucca Mountain Repository

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February 20, 2018



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The Waste Isolation Pilot Plant Southeastern New Mexico

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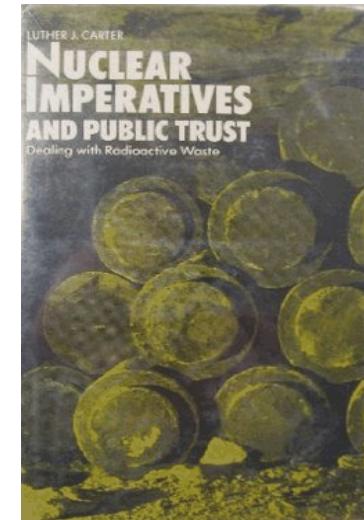
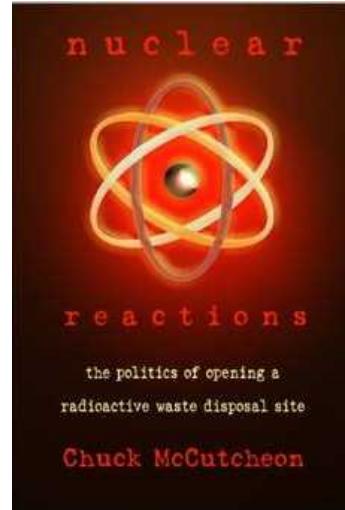
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Outline

- Project history
- Major elements of the disposal concept
 - Waste
 - Repository Design
 - Site geology
- Long-term performance
 - Regulatory Requirements
 - Undisturbed performance
 - Disruptive events
- Quantitative estimates of long-term performance
- Recent Events and Current Status

Key Reference for the History of WIPP

- Luther Carter, 1987, *Nuclear Imperatives and Public Trust: Dealing with Radioactive Waste*, Resources for the Future, Inc. Baltimore, MD: John Hopkins University Press
- Chuck McCutcheon, 2002, *Nuclear Reactions: The Politics of Opening a Radioactive Waste Disposal Site*, University of New Mexico Press.
- R.P. Rechard, 2000, “Historical Background on Performance Assessment for the Waste Isolation Pilot Plant,” *Reliability Engineering and System Safety* v. 69, p. 5-46 (See also other papers in this volume).

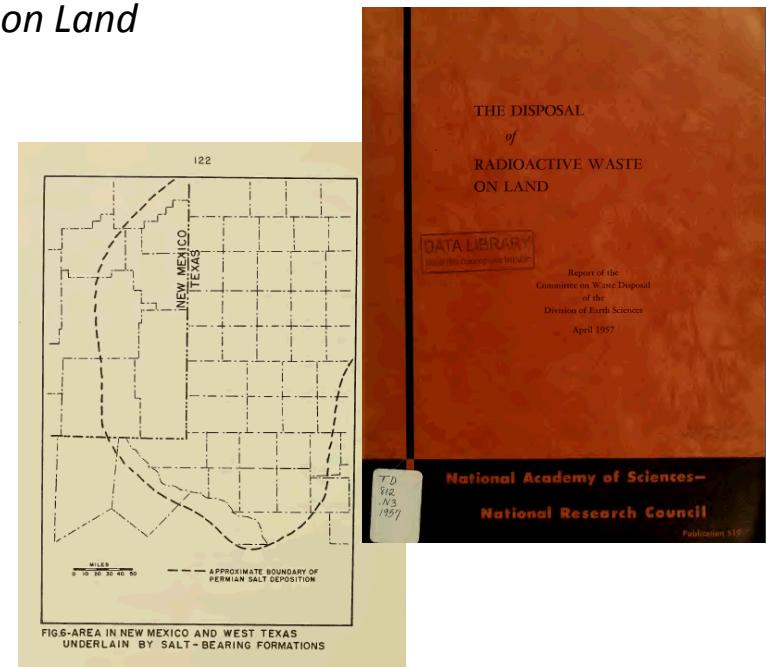


Background

- 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 (NAS) 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 is on disposal of liquid HLW

“Disposal in cavities mined in salt beds and salt domes is suggested as the possibility promising the most practical immediate solution of the problem.” (NAS 1957, p. 1)

“In part of the area a zone of potash salts is present which has been extensively developed near Carlsbad, New Mexico. The zone is about 250 feet thick and contains four workable beds of potash. The lowest bed is the thickest and averages about ten feet in thickness. A large area has been mined out since operations began about 25 years ago. Above the McNutt potash zone is a zone of halite about 500 feet thick, which has been named the Salado.” (NAS 1957, p. 121)



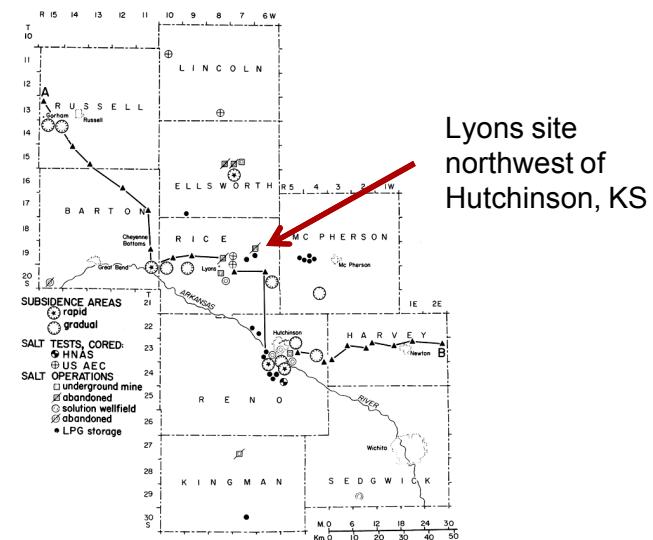
- 1961: AEC conducts Project Plowshare Gnome nuclear test in bedded salt near Carlsbad, NM

Background (cont.)

- 1969: Fire at Rocky Flats (Colorado) weapons production facility focuses attention on transuranic waste
 - Large volumes of transuranic fire waste shipped to Idaho for shallow trench disposal
- 1970: AEC commits to remove Rocky Flats fire waste from Idaho by 1980
- 1970: AEC selects salt mine at Lyons, Kansas as repository site
- 1971: AEC discovers old drill holes and solution mining at Lyons site
- 1971: City of Carlsbad, NM approaches NM congressional delegation seeking a repository
- 1972: AEC abandons Lyons site; announces plans for a “Retrievable Surface Storage Facility”
- 1972: City of Carlsbad meets privately with NM governor Bruce King and potash industry; governor King invites AEC to consider NM; AEC announces interest in NM salt August 14, 1972

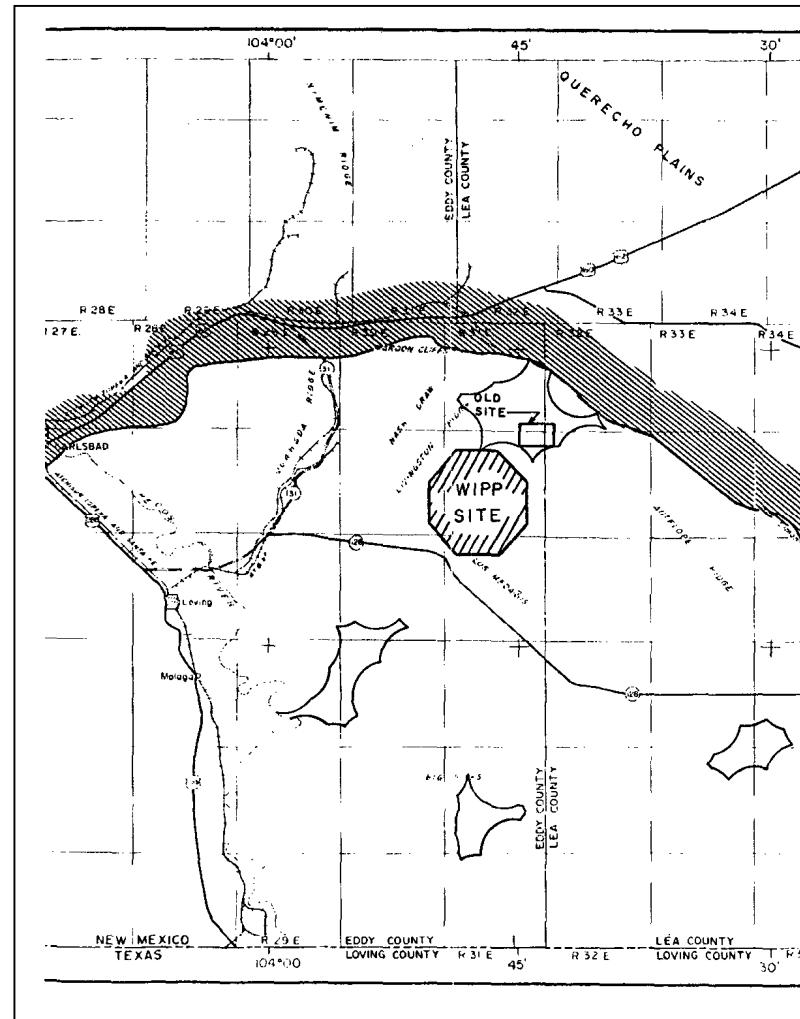


INEEL 2003, Figure 3-8 (INEEL Photo # 69-6138)



Background (cont.)

- 1972-1979: Political and administrative changes
 - 1974: AEC splits into the Nuclear Regulatory Commission (NRC) and Energy Research and Development Agency (ERDA)
 - 1977: ERDA becomes DOE
 - WIPP mission shifts repeatedly regarding inclusion or exclusion of HLW
 - 1979: Congress limits WIPP mission to defense TRU waste
- 1974: Oak Ridge National Laboratory begins field investigations in SE NM
- 1975: Sandia National Laboratories assumes lead science role; first site identified is found unsuitable
 - ERDA-6 borehole encounters steeply dipping salt beds and pressurized brine
 - Proposed site is moved 11 km SW
- 1976: Project is named Waste Isolation Pilot Plant
 - ERDA-9 borehole drilled near center of current site confirming suitable geology
- 1981: First shaft constructed at site, underground site characterization begins



Background (cont.)

- 1979-1993: Site characterization
 - Geological and hydrologic investigations
 - 40+ boreholes drilled from the surface
- 1985: Extensive testing begins in the WIPP underground
 - Thermal tests investigate simulate heat generating waste
 - Rock mechanics (salt creep); brine flow
- 1992: WIPP Land Withdrawal Act
 - Transfers land ownership to the DOE
 - Establishes EPA as principal regulator
 - Precludes HLW and SNF from the WIPP mission
- 1996: DOE submits the WIPP Compliance Certification Application to the EPA
- 1998: EPA certifies the WIPP for disposal operations
- 1999: First waste arrives at WIPP
 - 11,894 shipments prior to February 9, 2014
 - 12,034 shipments as of January 17, 2018 , all by truck
<http://www.wipp.energy.gov/shipments.htm>
- 2006, 2010, and 2017: EPA recertifies WIPP
 - Documentation at http://www.wipp.energy.gov/Documents_EPA.htm and <https://www.epa.gov/radiation/epas-role-waste-isolation-pilot-plant-wipp>



Heater Tests in WIPP Room B, 1985
from Matalucci 1987, SAND87-2382



First waste arrives at WIPP March 26, 1999

Major Elements of the WIPP Disposal Concept

The Premise for Isolation in Salt

- Intact salt is essentially impermeable
- Intact salt does not contain flowing groundwater
 - Water that is present in salt formations is salt-saturated brine, and incapable of further dissolution
- Salt creep will
 - Close fractures
 - Consolidate crushed salt backfill, and allow shaft seals to function like intact rock
 - Close disposal panels and eventually surround waste with salt
- Little reliance on waste packages for isolation
 - For WIPP, no long-term post-closure function whatsoever is assumed for packages
 - Waste is assumed to be exposed to the host rock environment as soon as the repository is closed

WIPP Transuranic Waste

- Derived from defense-related activities
 - Outside the scope of NRC regulation
 - Laboratory and industrial trash contaminated with transuranic radionuclides
 - Primarily alpha-emitting radionuclides, relatively little gamma emission and low thermal power
 - Fewer fission products than SNF/HLW
- Defined by law:

The term "transuranic waste" means waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years, except for—
 - (A) high-level radioactive waste;
 - (B) waste that the Secretary has determined, with the concurrence of the Administrator, does not need the degree of isolation required by the disposal regulations; or
 - (C) waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with part 61 of title 10, Code of Federal Regulations. (WIPP Land Withdrawal Act of 1992, Section 2)



WIPP Transuranic Waste (cont.)

- Most WIPP waste is “Contact-Handled TRU” (CH-TRU), and requires no additional shielding beyond that provided by drums and liners
- Some WIPP waste is “Remote-Handled TRU” (RH-TRU), with surface gamma radiation dose rates that require shielding
 - Defined by WIPP Land Withdrawal Act Section 2 as “transuranic waste with a surface dose rate of 200 millirem per hour or greater”



Images from http://www.wipp.energy.gov/Photo_Gallery_Images

WIPP Transuranic Waste Transportation

- Ten primary sites ship waste to WIPP
- All shipments by truck



Images from http://www.wipp.energy.gov/Photo_Gallery_Images

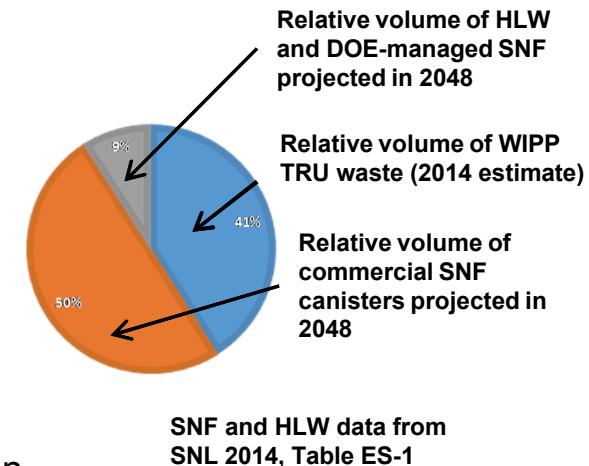
Relative Amounts of Transuranic Waste

Projected WIPP Inventory as of 2014 (WIPP Recertification Application, DOE 2014, section 24.8)		
	Projected Activity (curies)	Projected Volume (cubic meters)
CH-TRU	3.56×10^6	1.47×10^5
RH-TRU	3.89×10^5	3.84×10^3
total	3.95×10^6	1.51×10^5

$91,950 \text{ m}^3$ CH-TRU and 357 m^3 RH-TRU disposed of as of 17 Jan 2018

TRU volume is comparable to SNF and HLW

Total TRU activity is about 10,000 times less than SNF, but much of the SNF activity is short-lived fission products



Limits on WIPP disposal inventory set by the 1992 WIPP Land Withdrawal Act

TRANSURANIC WASTE LIMITATIONS.—

(1) REM LIMITS FOR REMOTE-HANDED TRANSURANIC WASTE.—

(A) 1,000 REMS PER HOUR.— No transuranic waste received at WIPP may have a surface dose rate in excess of 1,000 rems per hour.

(B) 100 REMS PER HOUR.— No more than 5 percent by volume of the remote-handled transuranic waste received at WIPP may have a surface dose rate in excess of 100 rems per hour.

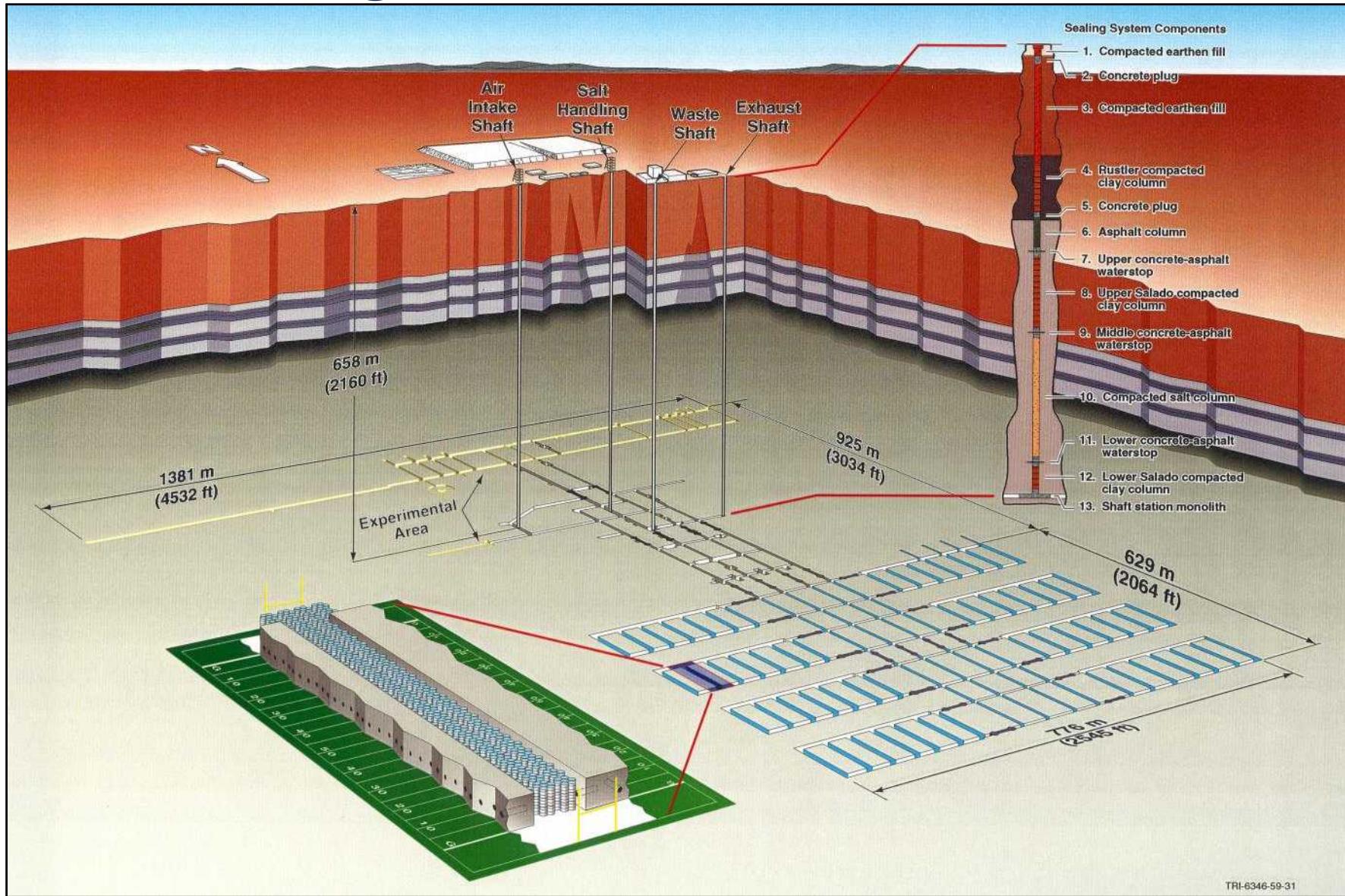
(2) CURIE LIMITS FOR REMOTE-HANDED TRANSURANIC WASTE.—

(A) CURIES PER LITER.— Remote-handled transuranic waste received at WIPP shall not exceed 23 curies per liter maximum activity level (averaged over the volume of the canister).

(B) TOTAL CURIES.— The total curies of the remote-handled transuranic waste received at WIPP shall not exceed 5,100,000 curies.

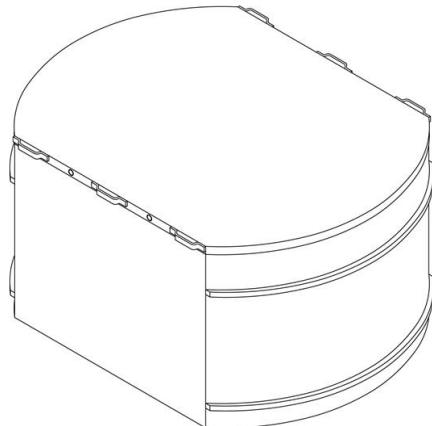
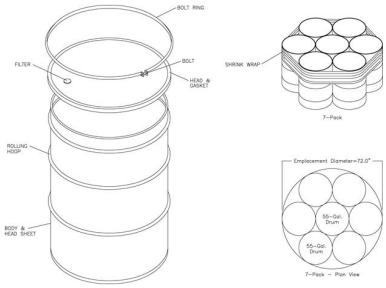
(3) CAPACITY OF WIPP.— The total capacity of WIPP by volume is 6.2 million cubic feet of transuranic waste.

WIPP Design



TRI-6346-59-31

WIPP Design (cont.)



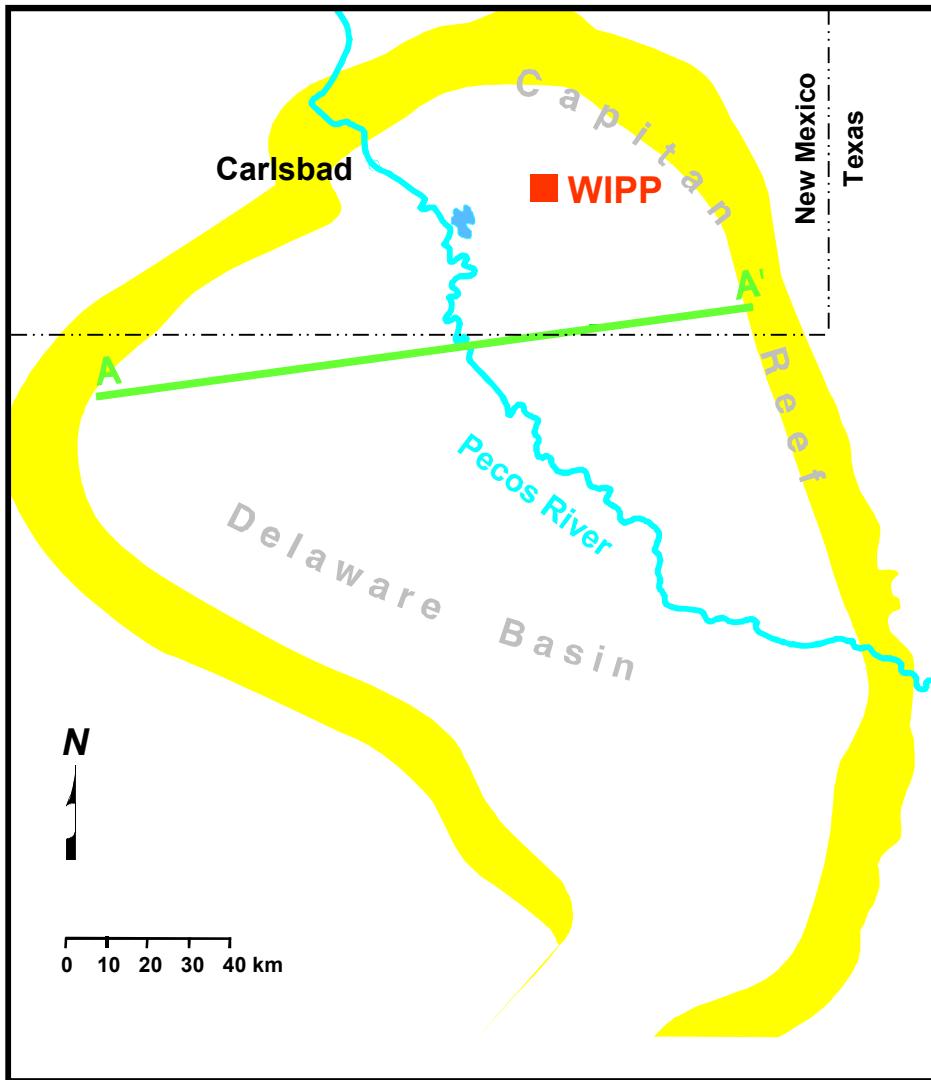
CH-TRU waste shipped and emplaced in drums (55, 85, and 100 gal) and “standard waste boxes”



Granular MgO emplaced above waste stacks to consume CO₂ and buffer pH to reduce actinide solubility in brine

Images from DOE 2014 Appendix DATA and <http://www.wipp.energy.gov>

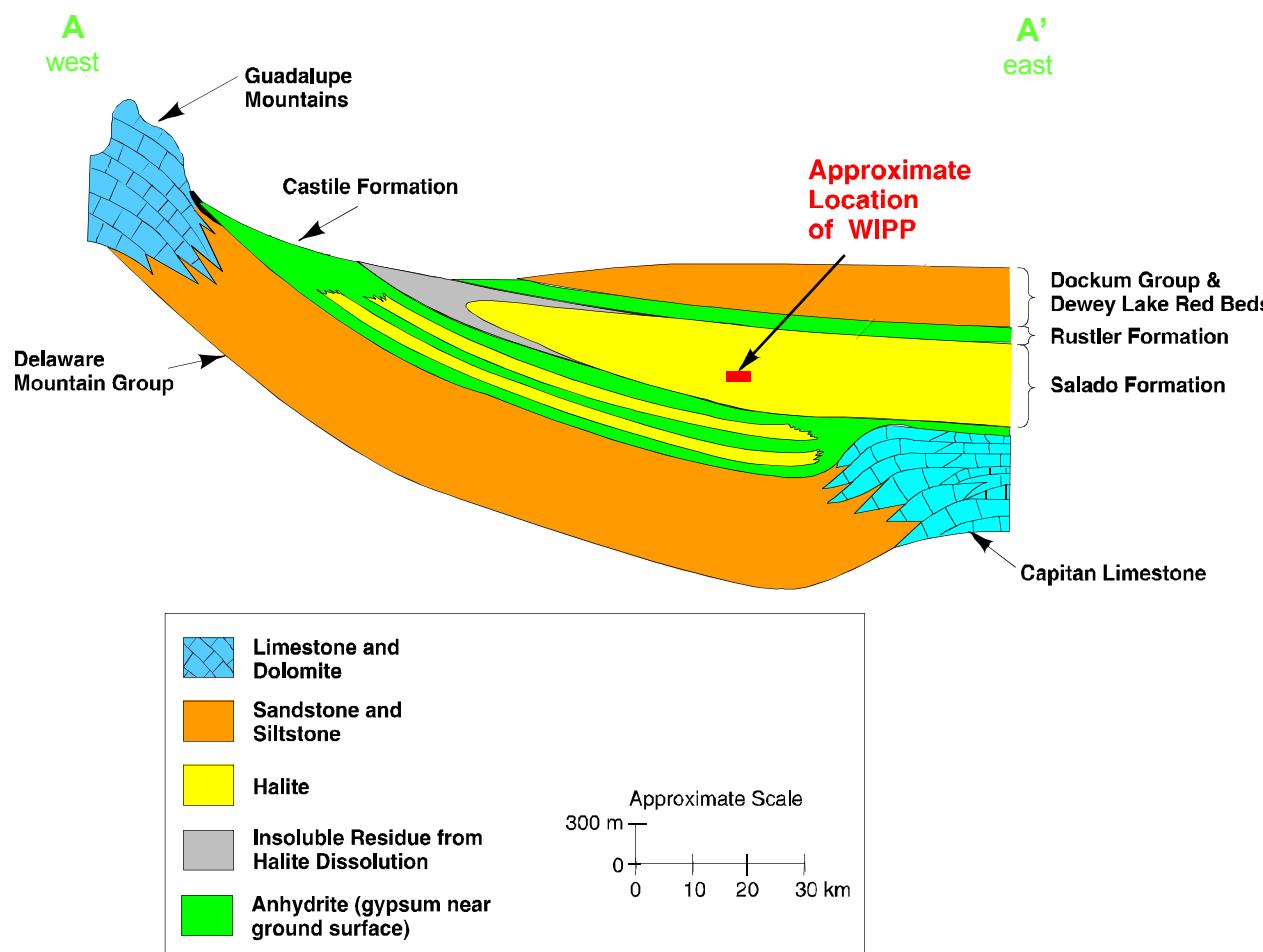
Site Geology



WIPP is located in the Delaware Basin, which is the modern geologic expression of a Permian-age (~ 255 Ma) topographic depression

Basin geology is broadly characterized by carbonate reef rocks (Capitan Formation) surrounding evaporite rocks deposited in a shallow sea

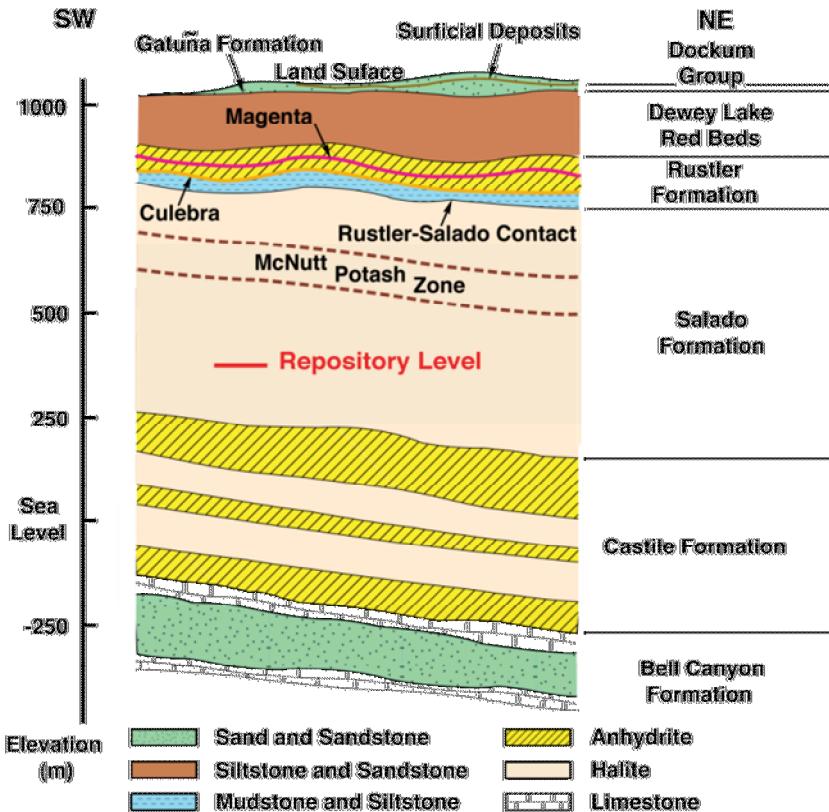
Site Geology (cont.)



Schematic West-East Geologic Cross Section of Delaware Basin

TRI-6342-1076-1

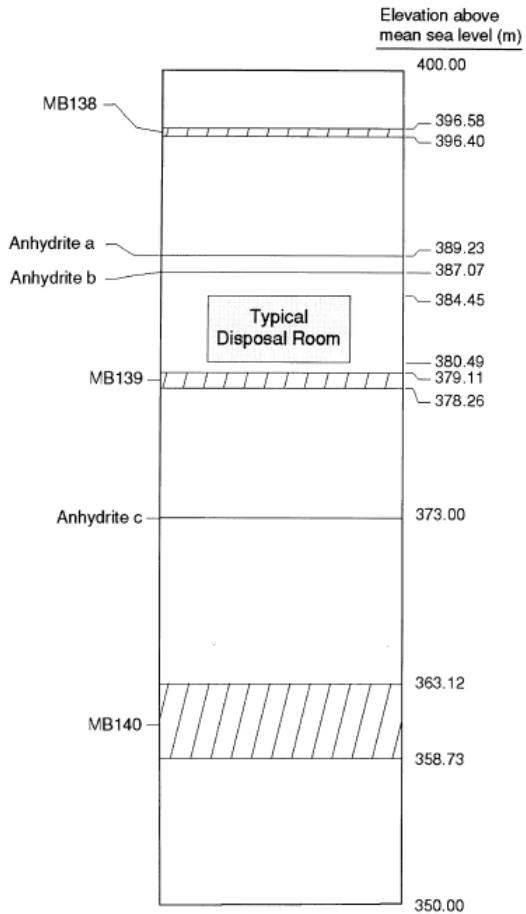
Local Stratigraphy at WIPP



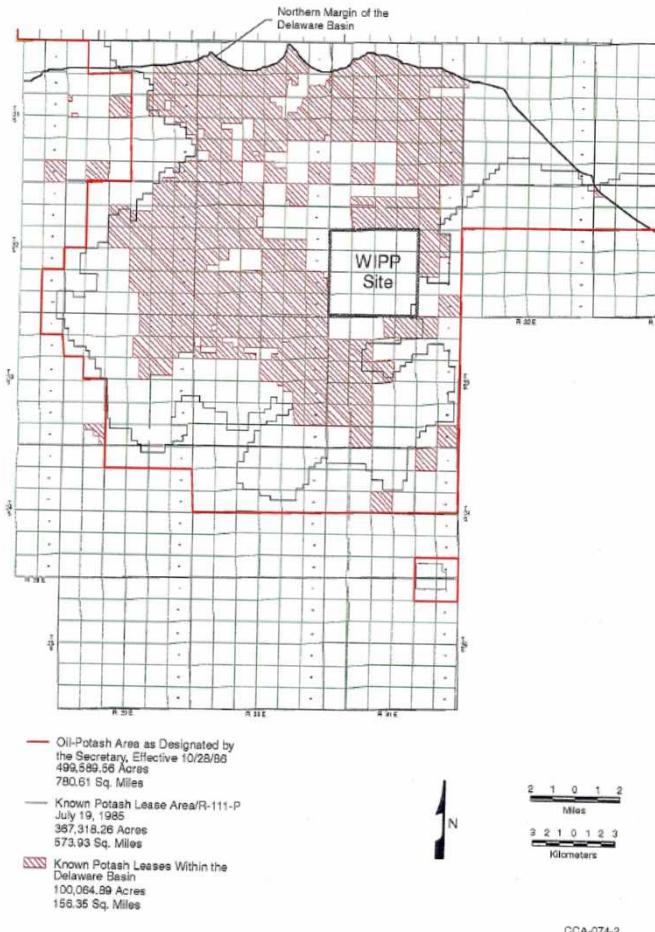
Within the Salado Formation, halite units are separated by laterally persistent interbeds of anhydrite, clay, and polyhalite.

Anhydrites "a" and "b" are thin seams 2 to 5 meters above the disposal horizon, and Marker Bed 139 (MB139) is a thicker interbed approximately 1 m below the disposal room.

Interbeds are planes of structural weakness and have relatively higher permeability than intact halite.



Natural Resources at WIPP



Potash leases in the WIPP region,
from DOE 1996 Figure 2-37

Oil and gas exploration in the WIPP region,
image from Google Maps 26 January 2018



Estimating Long-Term Performance

EPA's Regulatory Requirements

- 40 CFR part 191.13: Containment requirements

“(a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that the **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).”
- 40 CFR part 191.15: Individual protection requirements

“(a) Disposal systems for waste and any associated radioactive material shall be designed to provide a reasonable expectation that, for 10,000 years after disposal, **undisturbed performance** of the disposal system shall not cause the annual committed effective dose, received through all potential pathways from the disposal system, to any member of the public in the accessible environment, to exceed 15 millirems (150 microsieverts).”
- 40 CFR part 191.24: Groundwater protection standards

“(a) Disposal systems for waste and any associated radioactive material shall be designed to provide a reasonable expectation that 10,000 years of **undisturbed performance** after disposal shall not cause the levels of radioactivity in any underground source of drinking water, in the accessible environment, to exceed the limits specified in 40 CFR part 141 as they exist on January 19, 1994.”

(emphasis added)

Conceptual Model for Long-term Performance: 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

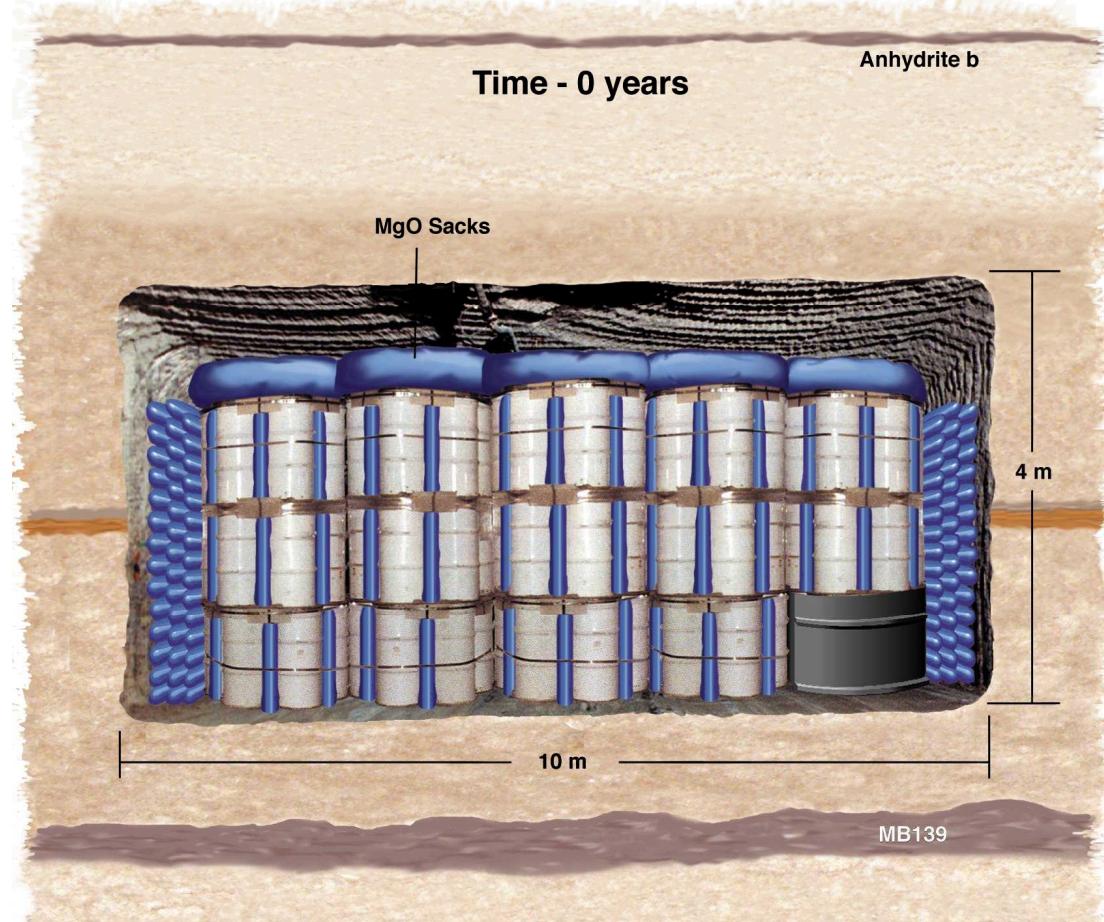
Salado salt

Argillaceous anhydrite
interbeds ("marker
beds")

Processes

Ground support

Ventilation

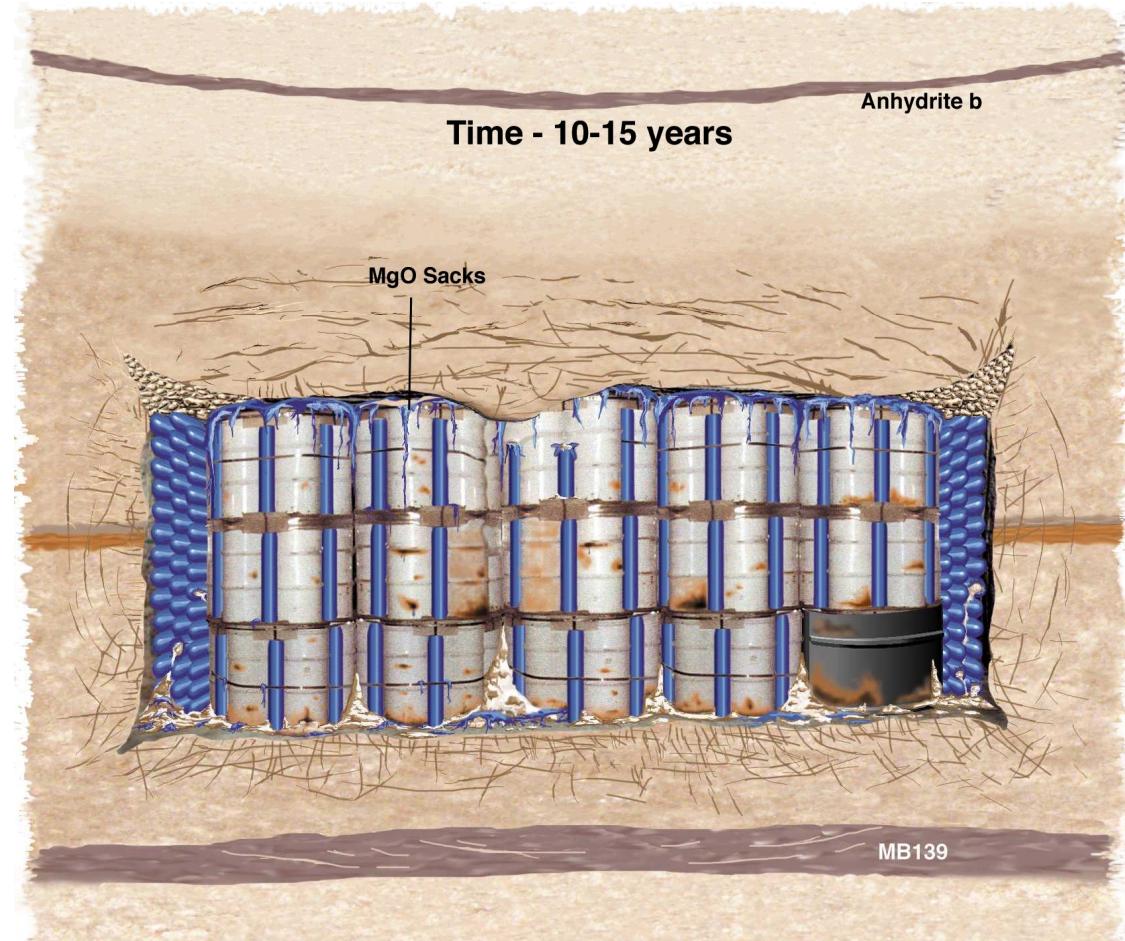


Conceptual Model for Long-term Performance: The Near Future

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



Conceptual Model for Long-term Performance: Final State?

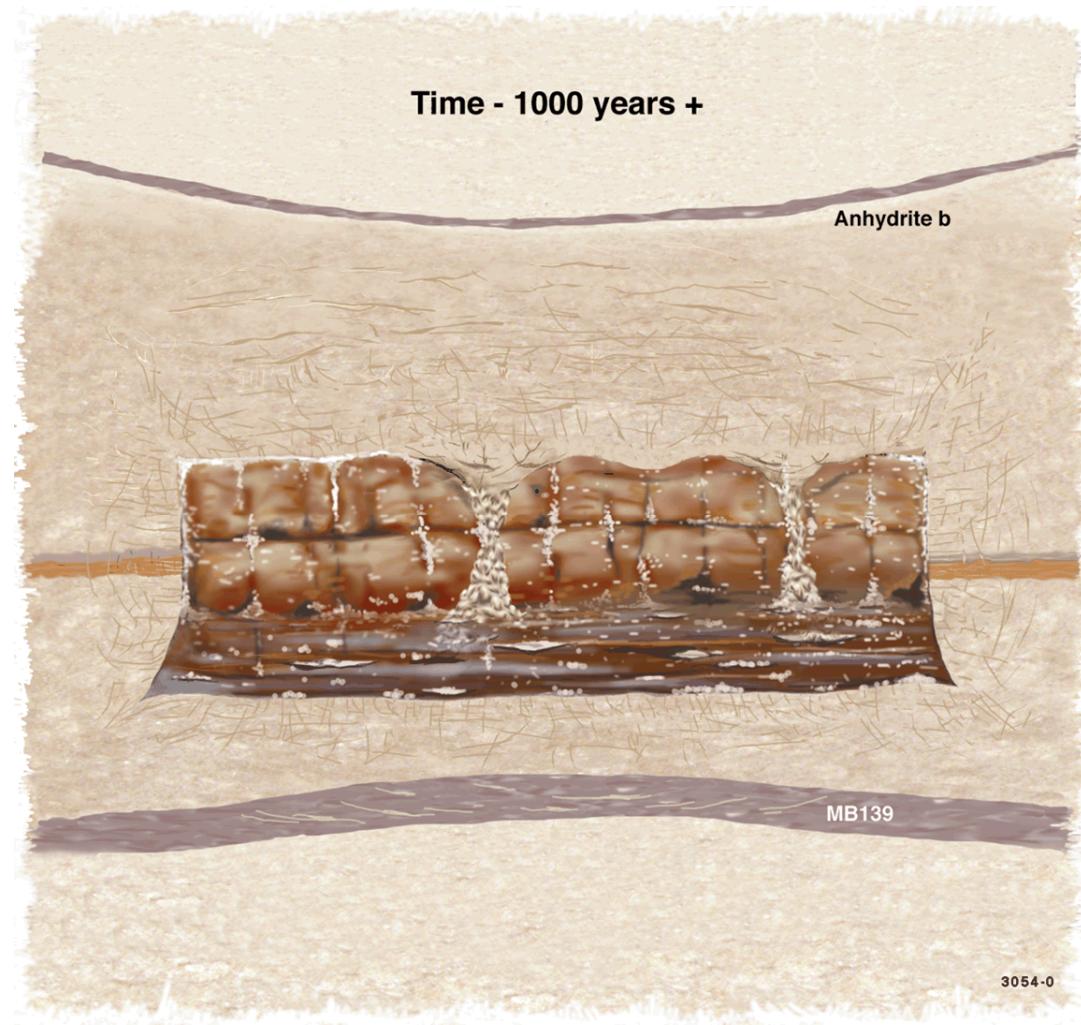
Salt Creep Encapsulates Waste

Processes

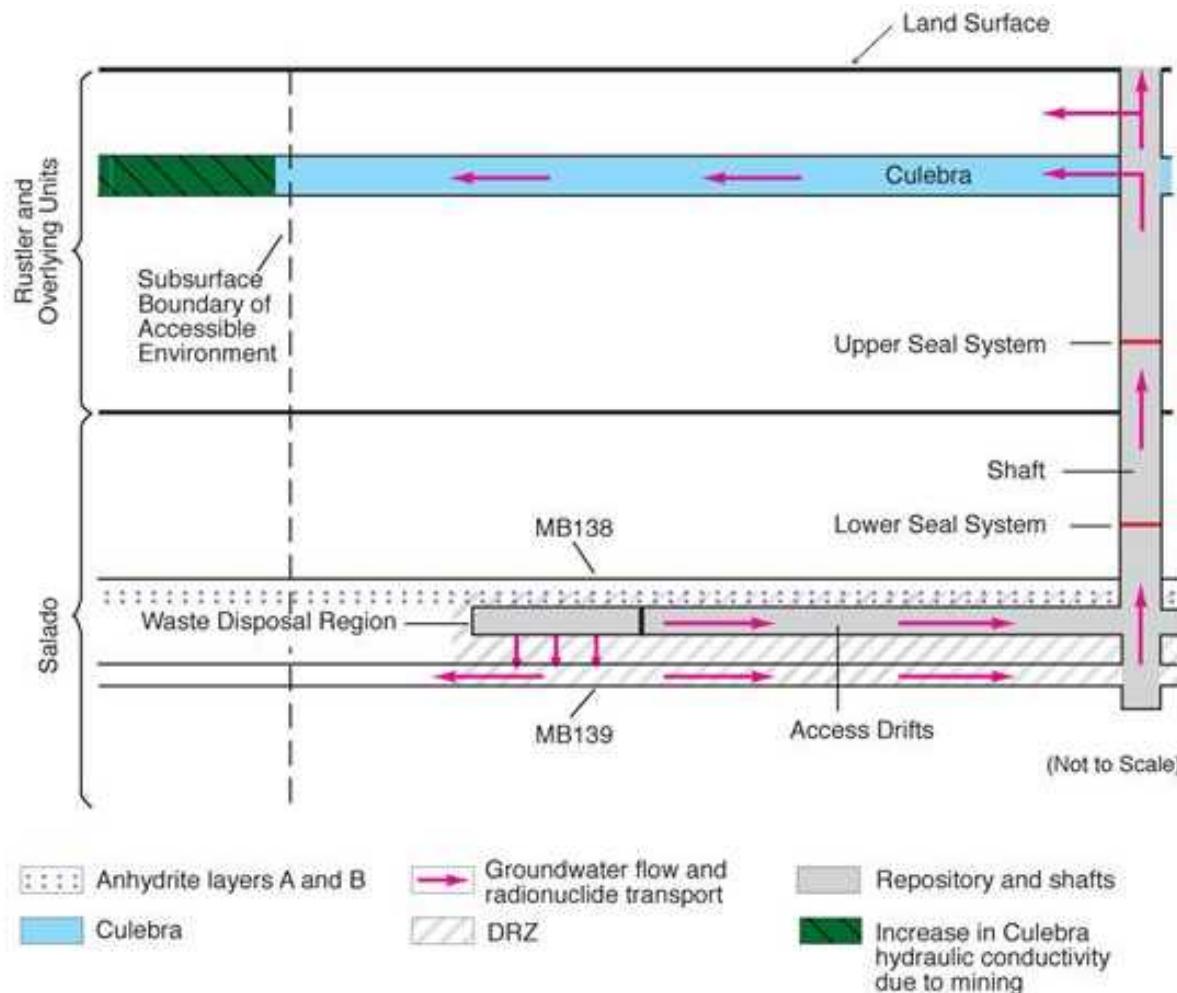
- Salt creep
- Consolidation and healing of fractures
- Porosity, permeability reduction
- Extensive corrosion of drums and degradation of waste

Processes of gas generation, brine inflow, and salt creep are highly coupled

Uncertainty remains about final extent of consolidation and brine saturation



Scenarios for WIPP Performance Assessment: *Undisturbed Performance*



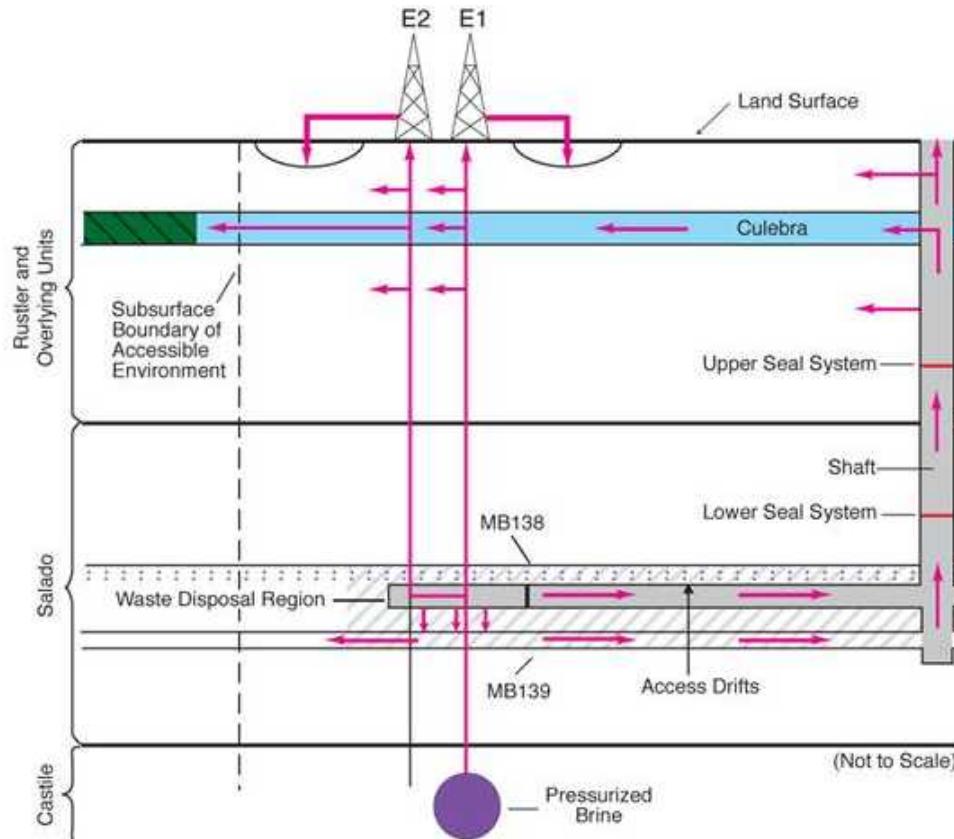
DOE 2014, Appendix PA Figure PA-5

CCA-009-2

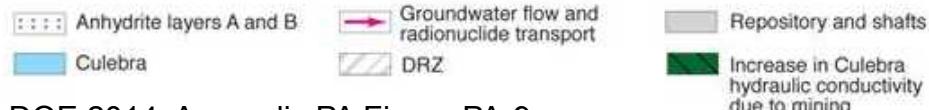
Scenarios for WIPP Performance Assessment: *Disturbed Performance*

This example shows two intrusion boreholes into the same disposal panel.

Variants include single intrusions with and without penetration of underlying brine reservoirs, and with and without potash mining impacting Culebra properties within the site boundary



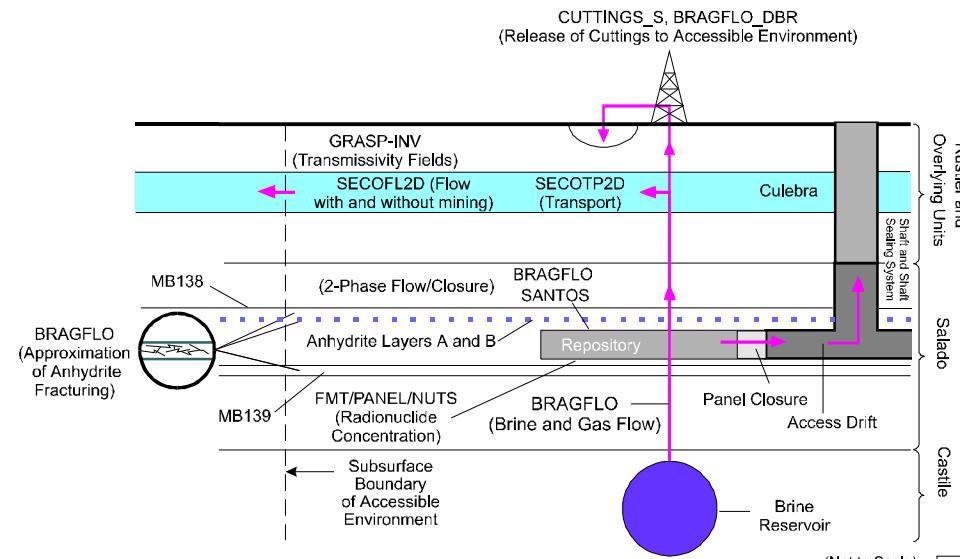
Note: Example shown includes only two boreholes, both of which penetrate waste and one of which penetrates pressurized brine in the underlying Castile. Pathways are similar for examples containing multiple boreholes. Arrows indicate hypothetical direction of groundwater flow and radionuclide transport.



DOE 2014, Appendix PA Figure PA-9

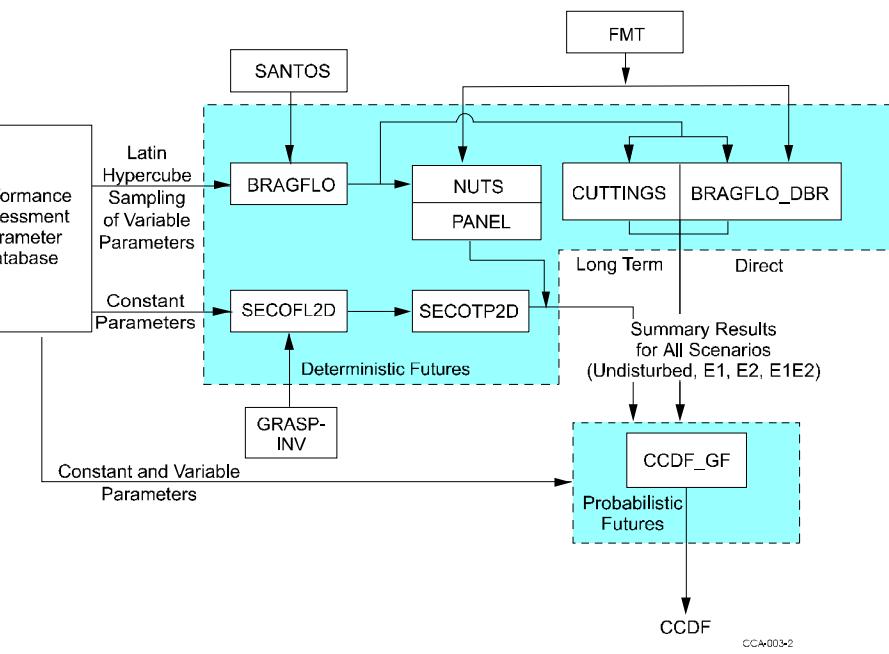
CCA-012-2

WIPP Performance Assessment Models



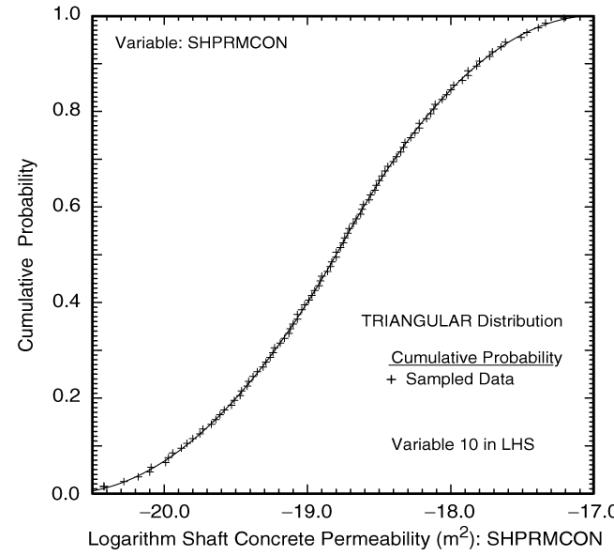
Models simulate major processes for each scenario

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



Perform Uncertainty Analysis Using Monte Carlo Simulations

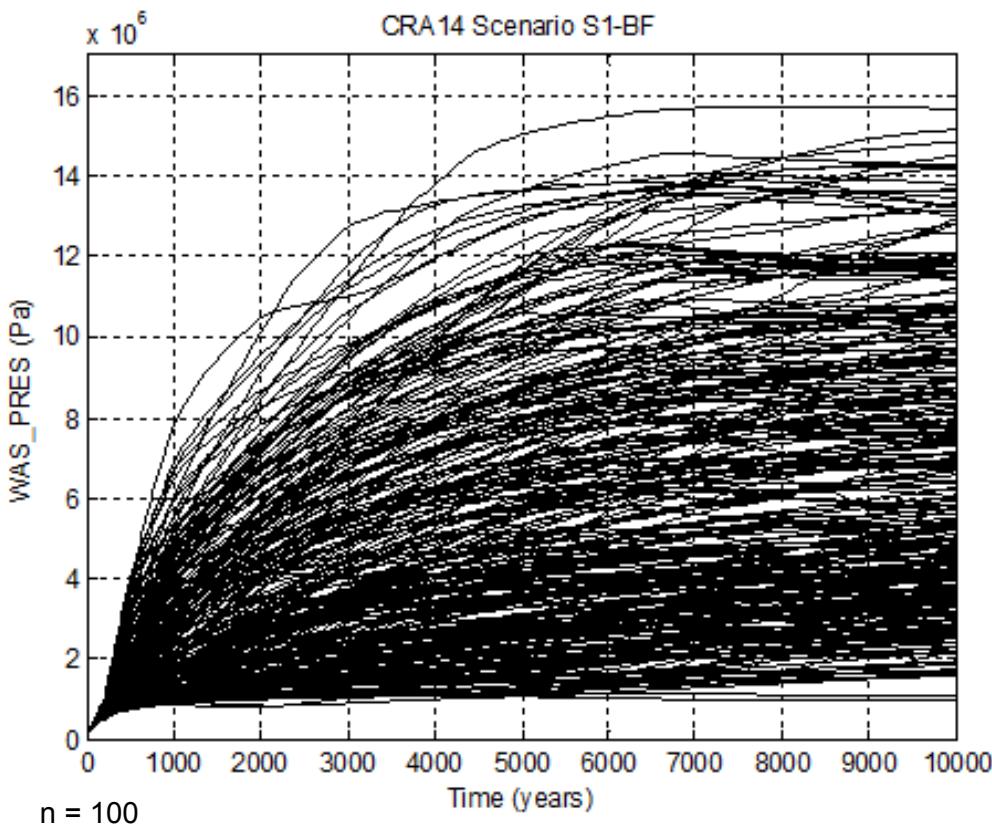
- Estimate the number of simulations needed (n)
- Draw n samples from distributions characterizing uncertainty in input parameters
 - Each simulation requires a different set of input values
- Perform a complete system simulation for each set of sampled input parameter values
 - Fixed-value parameters (constants) are the same in each simulation
- Each simulation 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

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

10,000-year Undisturbed Performance

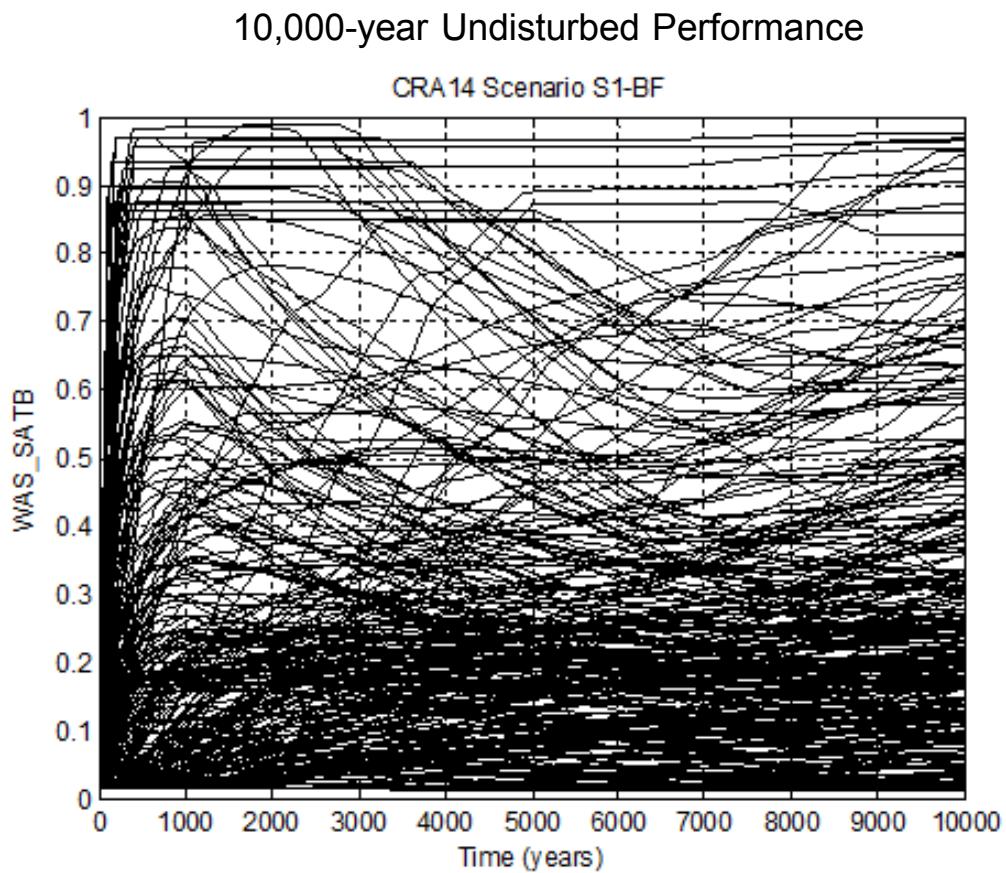


DOE 2014, Appendix PA, Figure PA-35

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

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

Summary of Long-term WIPP Performance



- Geologic barriers provide long-term isolation
 - Dry climate
 - Very low permeability of salt
 - No naturally-occurring disruptive events are sufficiently likely to impact 10,000-year performance
- No radionuclide releases to accessible environment during 10,000-year performance period without human intrusion
- Hypothetical borehole intrusions as a result of future oil and gas exploration are evaluated as part of the long-term performance assessment
 - Estimated releases due to multiple human intrusions are well below regulatory limits

2014 WIPP Events

- Mine haul truck fire Feb 5, 2014
- Radiological release Feb 14, 2014
- Disposal resumes Jan 9, 2017
- Recovery continues



All images from
<http://www.wipp.energy.gov/wipprecovery/recovery.html>



Key Documents for the 2014 WIPP Events

**U.S. Department of Energy
Office of Environmental Management**

Accident Investigation Report




Underground Salt Haul Truck Fire at the Waste Isolation Pilot Plant
February 5, 2014

March 2014

Fire Investigation Report,
(March 2014)

U.S. Department of Energy

Accident



Radiolo Was of

**U.S. Department of Energy
Office of Environmental Management**

Accident Investigation Report




Phase 2

Radiological Release Event at the Waste Isolation Pilot Plant, February 14, 2014

April 2015

Radiological Release
Investigation Report,
Phase 1 (April 2014)
and
Phase 2 (April 2015)

We put science to work.™

Savannah River National Laboratory
OPERATED BY SAVANNAH RIVER NATIONAL SECURITY

Waste Isolation Pilot Plant Technical Assessment Team Report

March 17, 2015
SRNL-RP-2014-01198
Revision 0

LAWRENCE LIVERMORE NATIONAL LABORATORY

OAK RIDGE National Laboratory

Pacific Northwest NATIONAL LABORATORY

Sandia National Laboratories

SRNL
Savannah River National Laboratory
OPERATED BY SAVANNAH RIVER NATIONAL SECURITY

SRNL.DOE.GOV

WIPP Technical
Assessment Team
Report (March 2015)

All available at <http://www.wipp.energy.gov/wipprecovery/recovery.html>

The Path Forward at WIPP

September 30, 2014:

“The recovery and resumption of TRU waste disposal operations at WIPP are central to the Department’s mission.”

“WIPP recovery costs are estimated to be approximately \$242 million.

...

Additionally, to restore WIPP to full operations, two capital asset project line items are required: (1) a new permanent ventilation system, with an estimated cost range of \$65 million–\$261 million, and (2) a supporting exhaust shaft, with an estimated cost range of \$12 million–\$48 million.”

Waste emplacement projected to resume in first quarter of 2016

January 9, 2017

Disposal operations resume with underground emplacement of waste stored on site.

April 10, 2017

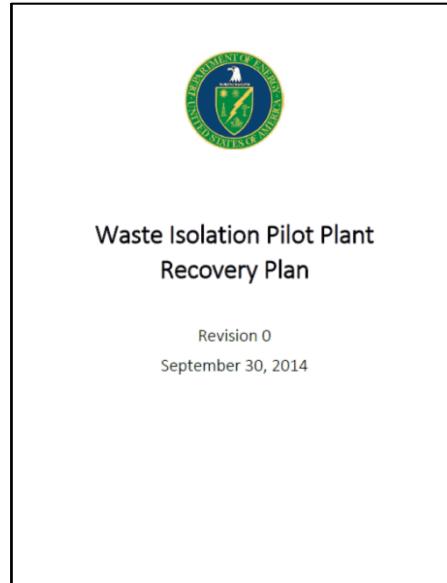
First off-site shipment of waste since reopening arrives from INL. Shipments continue at a rate of ~3.5 / week.

January 17, 2018

Mining resumes in panel 8 for future disposal operations

Future Plans

Future plans call for construction of a new shaft and ventilation system, allowing full-scale operations (operations prior to 2014 averaged >15 shipments per week; total (as of 17 Jan 2018) of 12,034 shipments, with all but 140 shipments occurring before February 2014



<http://www.wipp.energy.gov/wipprecovery/recovery.html>

References

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- Helton, JC and Marietta, MG, "The 1996 Performance Assessment for the Waste Isolation Pilot Plant," special issue of *Reliability Engineering and System Safety* v. 69, p. 1-454; 2000
- INEEL (Idaho National Engineering and Environmental Laboratory). *INEEL Subregional Conceptual Model Report Volume 3: Summary of Existing Knowledge of Natural and Anthropogenic Influences on the Release of Contaminants to the Subsurface Environment from Waste Source Terms at the INEEL*. INEEL/EXT-03-01169, Rev. 2; 2003
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- SRNL (Savannah River National Laboratory), Waste Isolation Pilot Plant Technical Assessment Team Report, SNRL-RP-2014-01198 Revision 0, March 17, 2015.
- U.S. DOE (US Department of Energy), Title 40 CFR Part 191, Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO 1996-2184; 1996
- U.S. DOE (US Department of Energy, Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2014 for the Waste Isolation Pilot Plant; 2014
- U.S. DOE (US Department of Energy, Waste Isolation Pilot Plant Recovery Plan, Revision 0, September 30, 2014.

Key Websites: <http://www.wipp.energy.gov/library/caolib.htm> and <http://www.wipp.energy.gov/wipprecovery/recovery.html>

WIPP backup material

EPA's Regulatory Requirements (cont.)



Key Points from 40 CFR Part 191

- Regulatory requirements define two scenarios: “Undisturbed Performance” and performance including “all significant processes and events”
 - Undisturbed performance gets defined explicitly:
 - The predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events.
 - Very unlikely events ($P < 10^{-8}/\text{yr}$) may be excluded from analysis
 - Disturbed performance implicitly includes human intrusion
- The containment requirements, which include consequences of human intrusion, are not a dose standard
 - The metric that drives compliance for WIPP is 10,000-year cumulative release, rather than annual dose

EPA's Regulatory Requirements (cont.)



- 40 CFR part 194.32: Scope of Performance Assessments

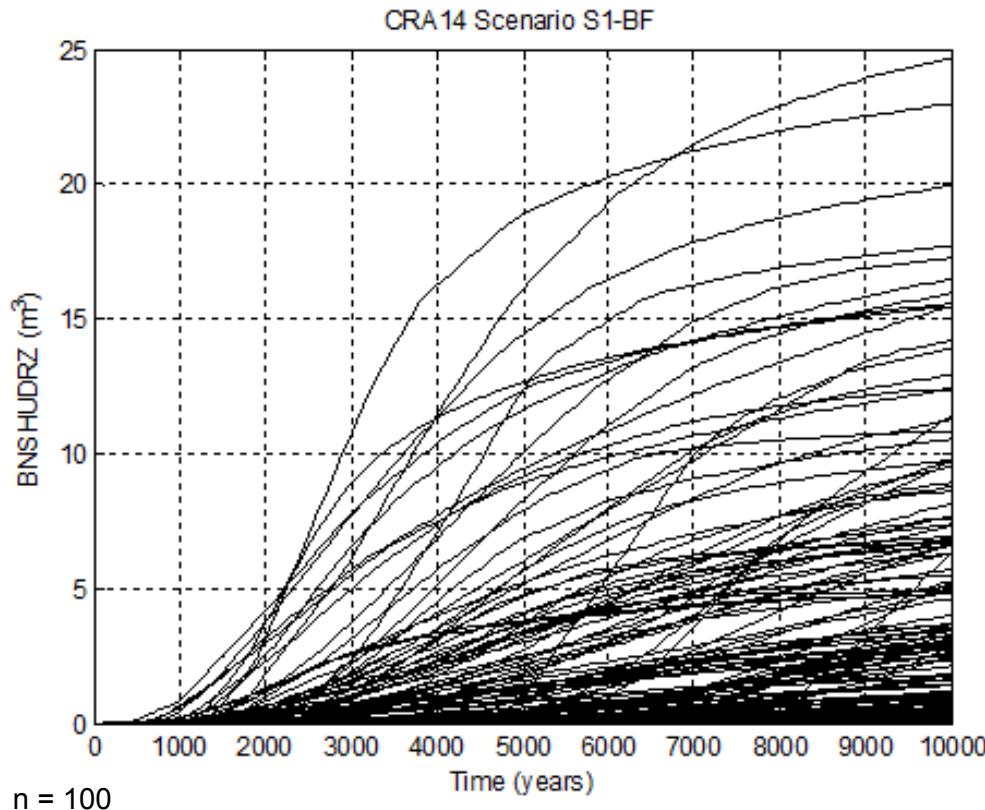
“(b) Assessments of mining effects may be limited to changes in the hydraulic conductivity of the hydrogeologic units of the disposal system from excavation mining for natural resources. Mining shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame.”
- 40 CFR part 194.33(b): Consideration of Drilling Events

“(2) In performance assessments, drilling events shall be assumed to occur in the Delaware Basin at random intervals in time and space during the regulatory time frame.

(3) The frequency of deep drilling shall be calculated in the following manner:
 - (i) Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.
 - (ii) The total rate of deep drilling shall be the sum of the rates of deep drilling for each resource.”
- Key Point
 - Disruption by mining above the disposal horizon and multiple human intrusions by deep drilling through the disposal region are essentially certain to occur in 10,000 years
 - Current 10,000-year drilling rate is 67.3 boreholes/km² (up from 46.8 in 1996) (DOE 2014, Section 33)

Example of Uncertainty in WIPP Performance: Brine Flow upward through Shaft Seals

10,000-year Undisturbed Performance



DOE 2014, Appendix PA, Figure PA-47

Brine flow upward in the shaft seals is a function of

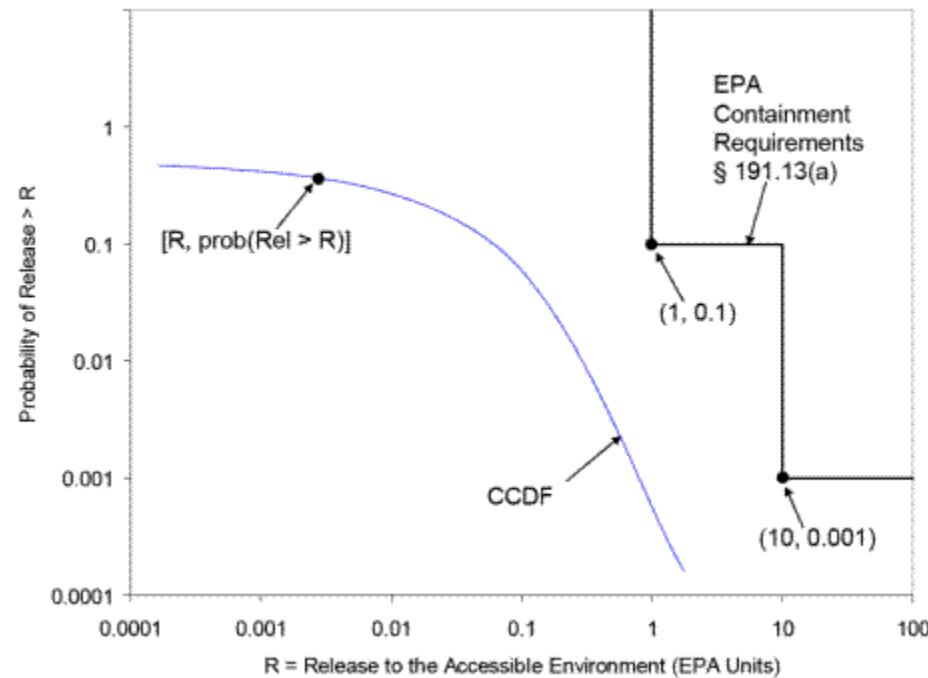
- Pressure in the repository
 - Function of multiple coupled processes
- Hydrologic properties of the shaft seals
 - Permeability

Quantitative Compliance Estimates

The EPA Containment Requirements at 40 CFR 191.13 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:

$$nR = \sum \frac{Q_i}{L_i} \left(\frac{1 \times 10^6 \text{ curies}}{C} \right)$$

DOE 2014, Appendix PA
Equation PA.1

where

Q_i = 10,000-year cumulative release (in curies) of radionuclide i

L_i = the Table 1 release limit (in curies) for radionuclide i

C = the total transuranic inventory (in curies)

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
Srtrontium-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-life greater than 20 years that does not emit alpha particles	1,000

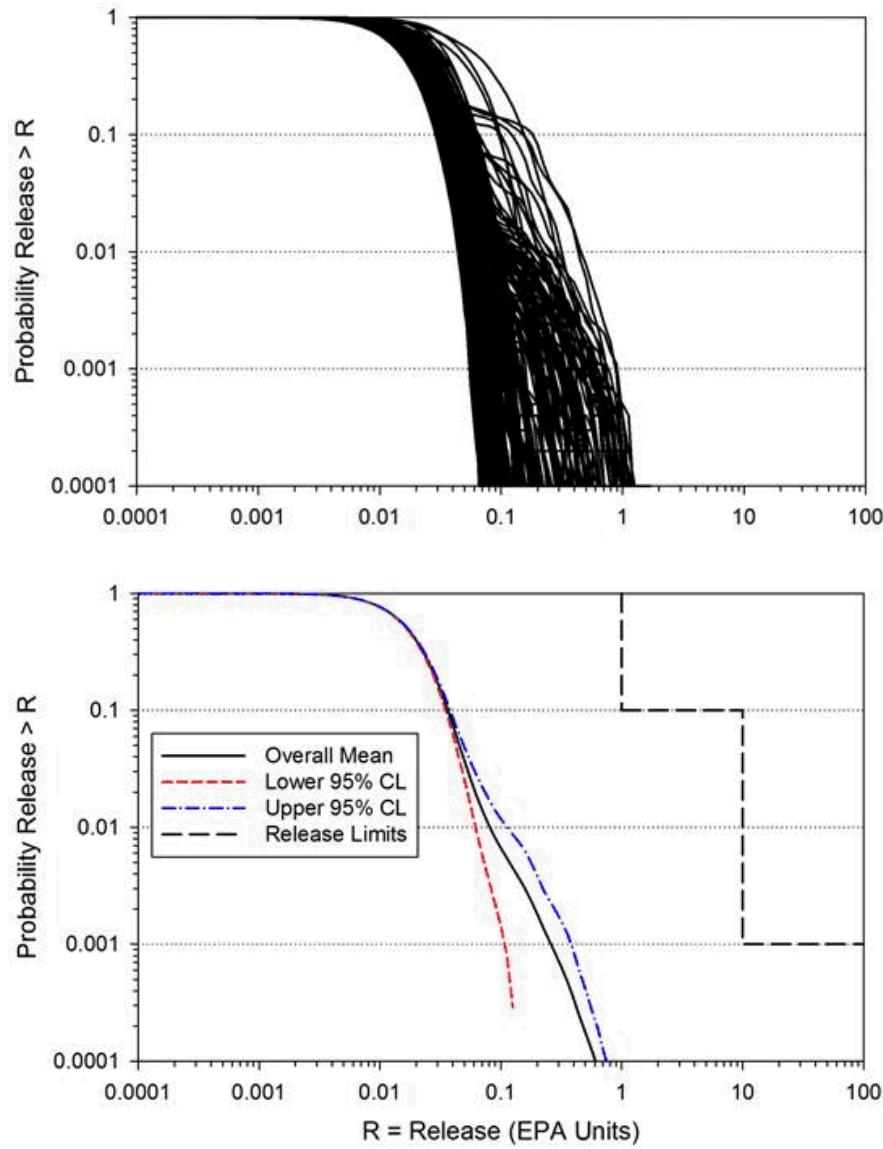
* Metric tons of heavy metal exposed to a burnup between 25,000 megawatt-days per metric ton of heavy metal (MWd/MTHM) and 40,000 MWd/MTHM.

CCDF of Total Normalized Releases From All Scenarios

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

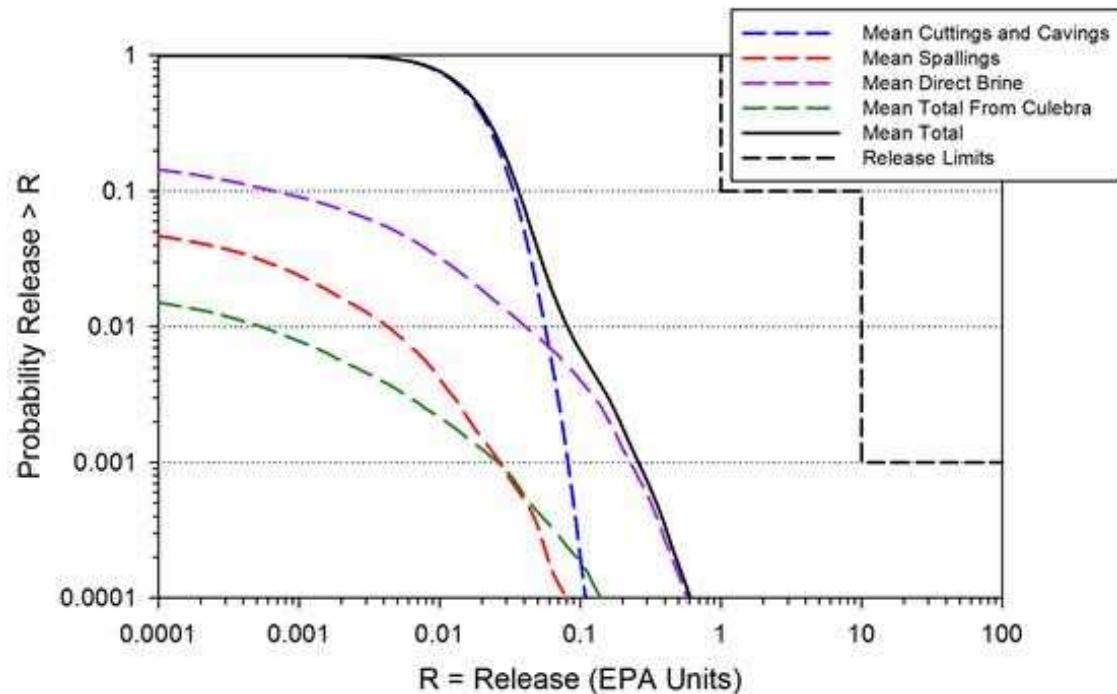
All releases are due to drilling intrusions

“Cuttings and Cavings” are the material brought to the surface during drilling

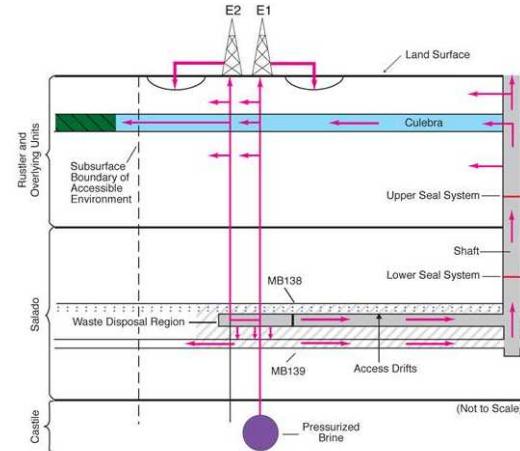
“Spallings” are solid material that is transported into the hole during depressurization and brought to the surface during drilling

“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)





The Proposed Repository at Yucca Mountain, Nevada

Peter Swift

Senior Scientist, Sandia National Laboratories

Stanford University

February 20, 2018



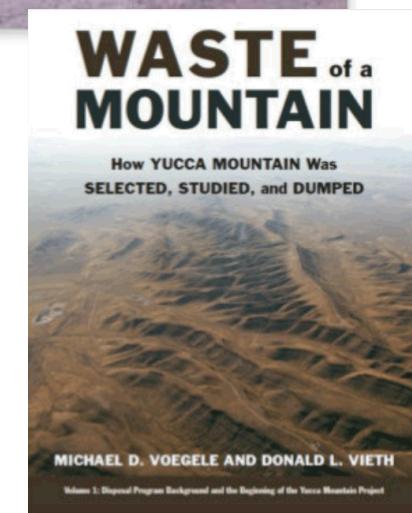
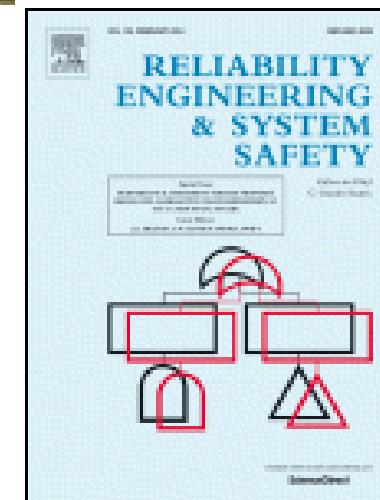
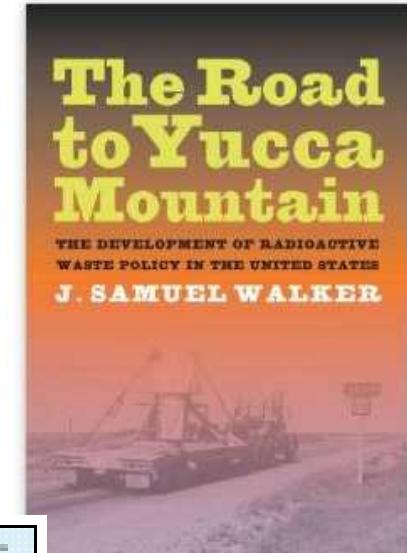
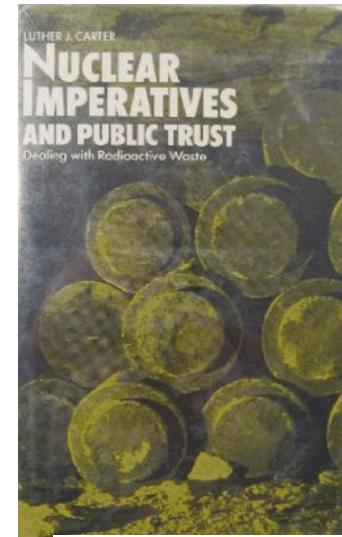
Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2018-xxxx

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
- J. Samuel Walker, 2009, *The Road to Yucca Mountain*. Berkeley, CA: University of California Press.
- R. P. Rechard, T.A. Cotton, and M.D. Voegle, 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]
- M. D. Voegle and D. L. Vieth, 2016, *Waste of a Mountain: How Yucca Mountain was Selected, Studied, and Dumped*, Nye County Press



Background

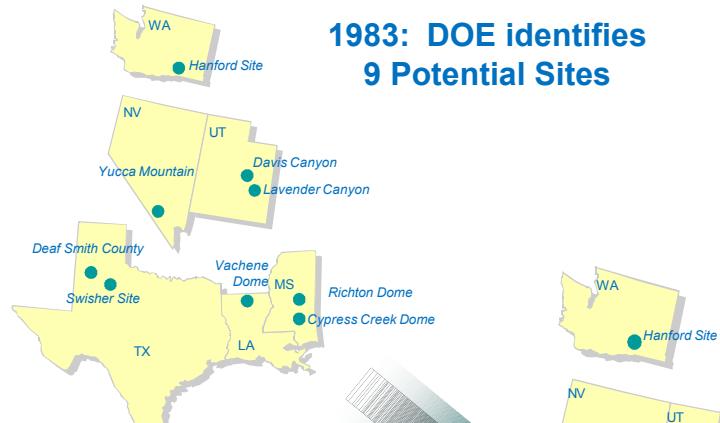
- 1940s: Manhattan Project generates first significant volumes of spent nuclear fuel (SNF) and high-level radioactive waste (HLW)
 - Waste managed on-site
- 1955: National Academy of Sciences convenes “Committee on Waste Disposal” at the request of the Atomic Energy Commission (AEC)
 - 1957 NAS report *“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; Eken 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 Commission (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) (Ekren 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)

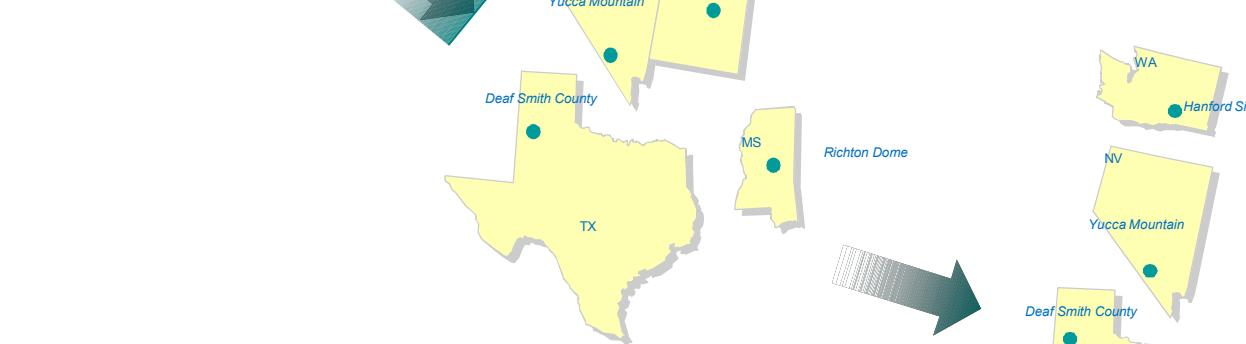


1982-1987: The Siting Process under the NWPA

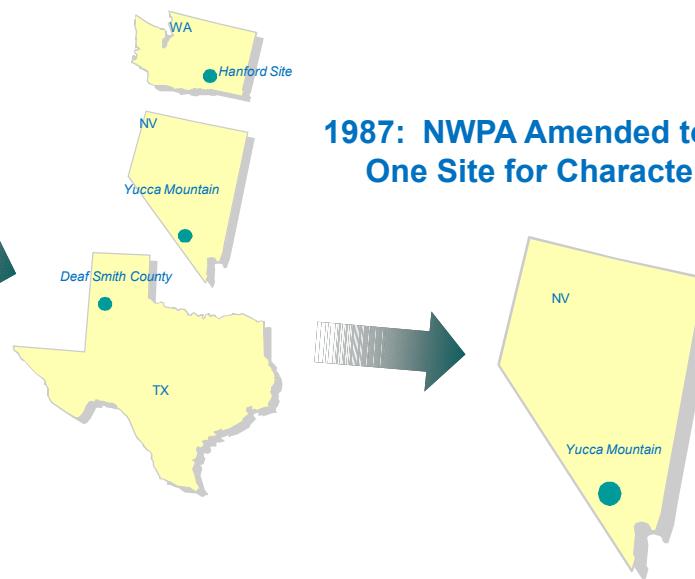


The NWPA of 1982 (sec. 112) requires DOE to consult with affected governors and issue siting guidelines
The Secretary to nominate at least five sites
The Secretary to recommend 3 sites for characterization

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



1987: NWPA Amended to Mandate One Site for Characterization

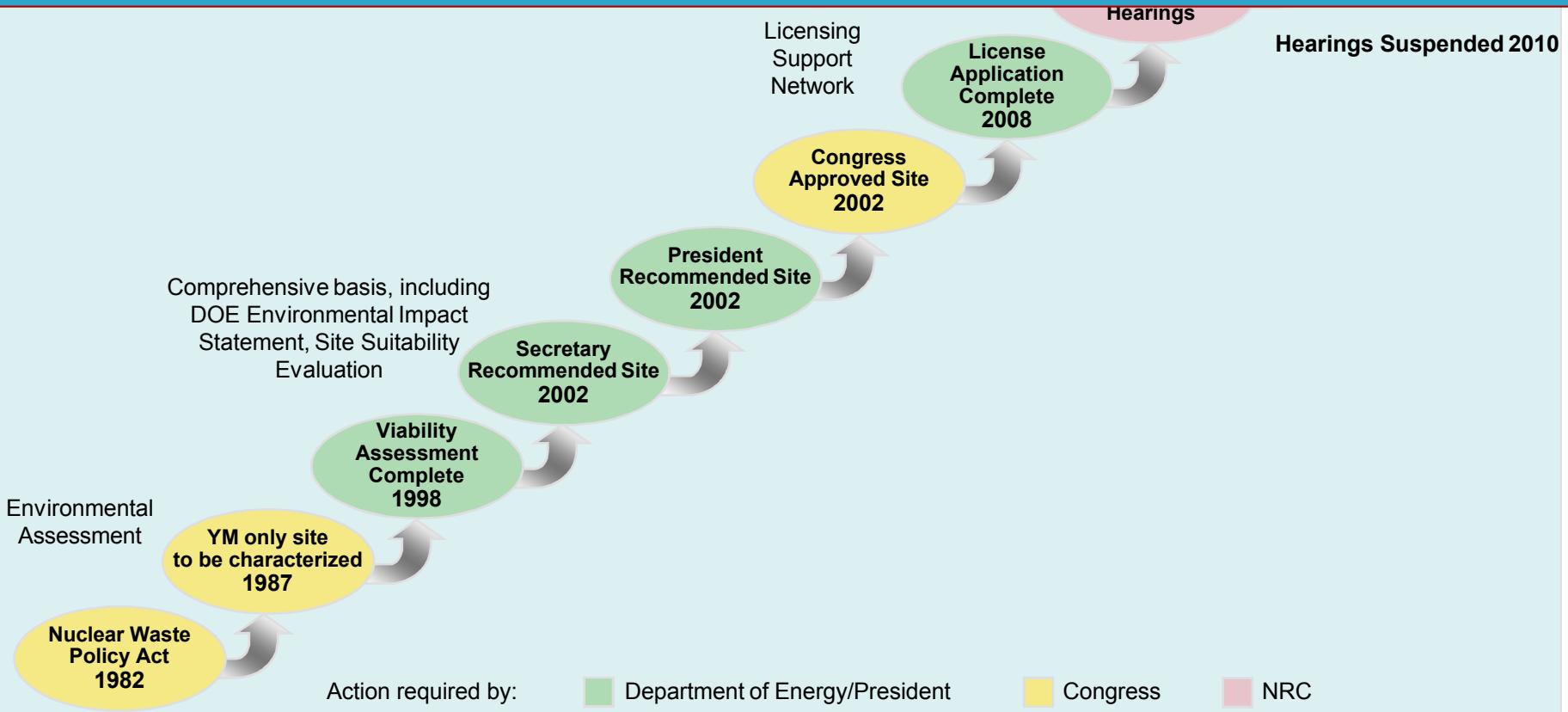


Yucca Mountain from 1987 to 2008



- 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 Civilian 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
 - DOE solicits public input on a plans for a separate defense repository and a consent-based siting process in 2016 and 2017
- 2018 President’s Budget Request includes \$120 million to restart Yucca Mountain license hearings, but Congress has not appropriated funds

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

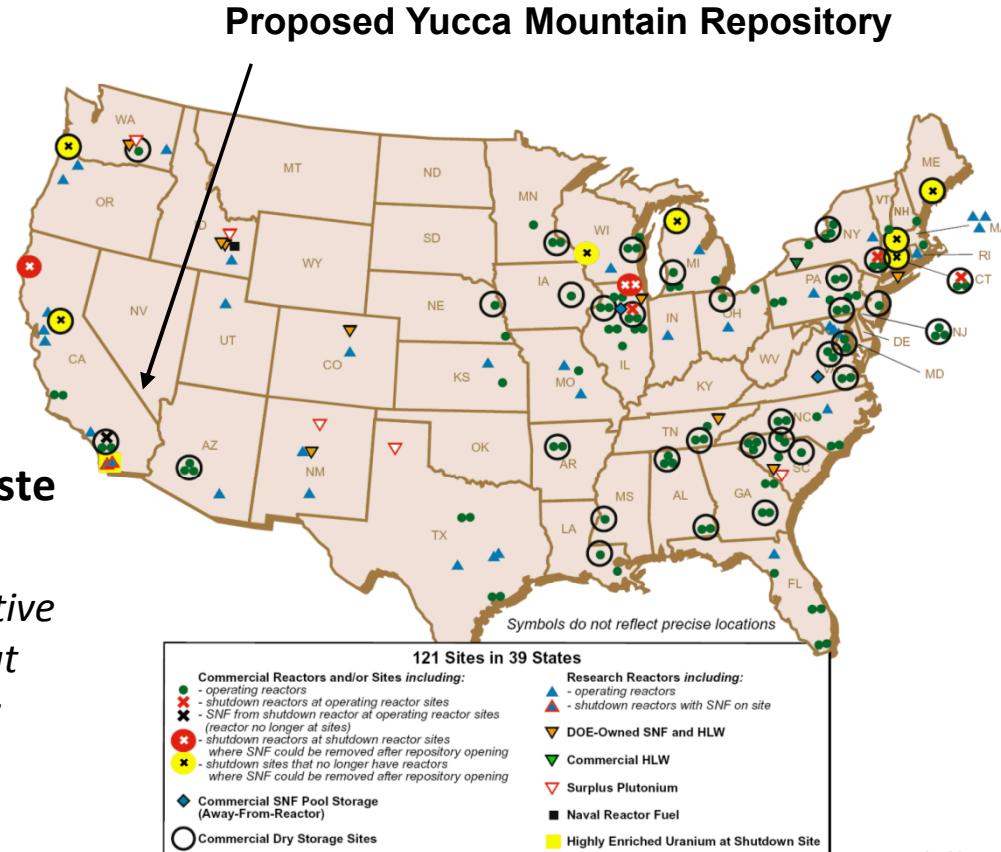
The Yucca Mountain Mission

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.



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)

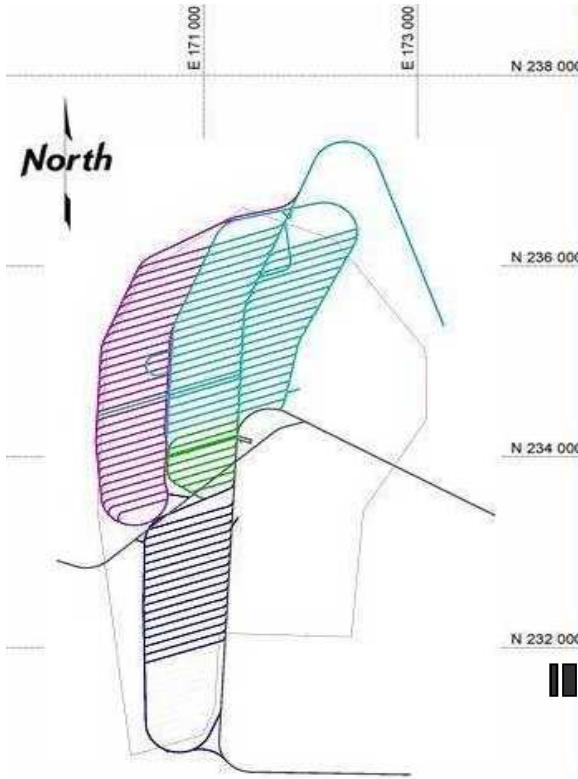


DOE & Commercial High-Level Waste:
4,667 MTHM
(~3000 waste packages of co-disposed DSNF and HLW)



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

Yucca Mountain Subsurface Design



Emplacement drifts

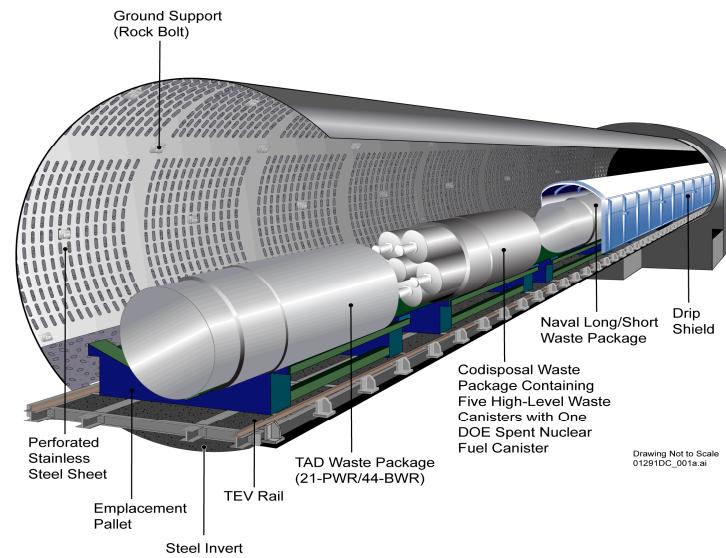
5.5 m diameter
approx. 100 drifts, 600-800 m long

Waste packages

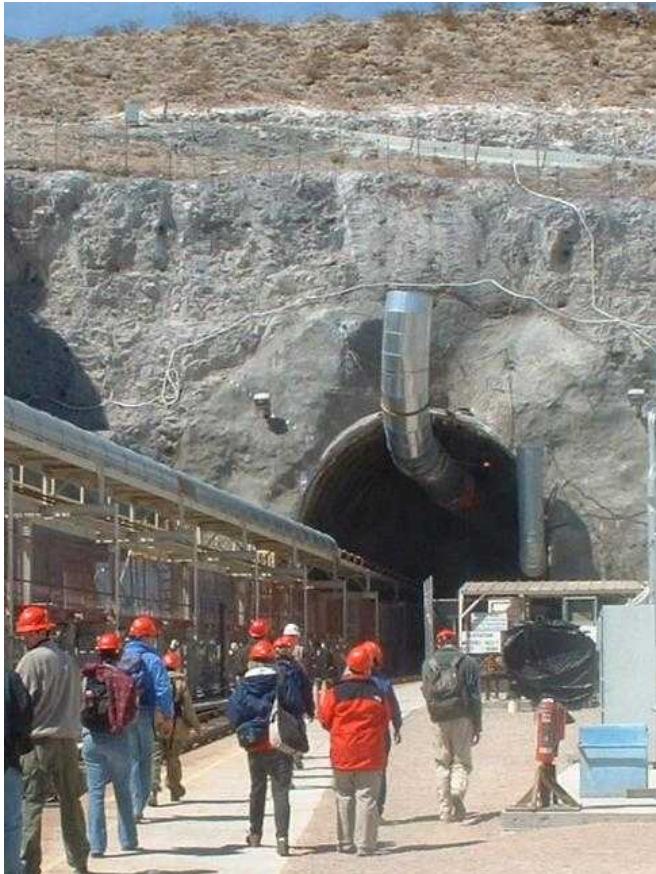
~11,000 packages
~ 5 m long, 2 m diameter
outer layer 2.5 cm Alloy 22 (Ni-Cr-Mo-V)
inner layer 5 cm stainless steel
Internal TAD (transportation, aging, and disposal) canisters
for commercial spent fuel, 2.5 cm stainless steel

Drip shields

free-standing 1.5 cm Ti shell

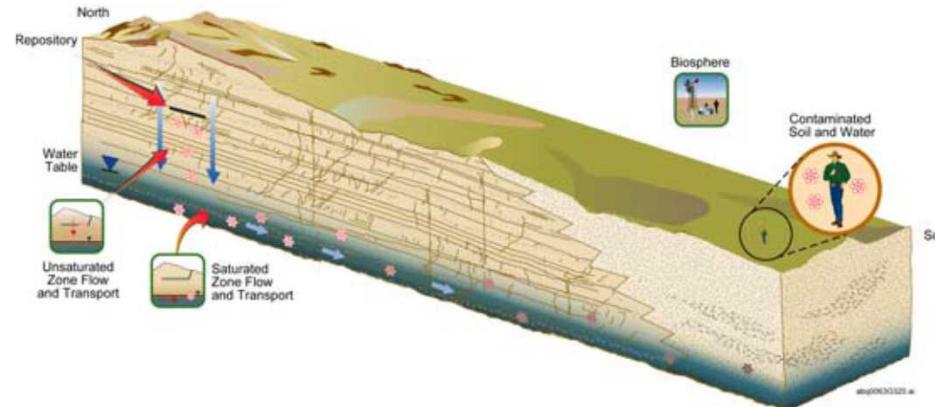


Yucca Mountain Exploratory Studies Facility



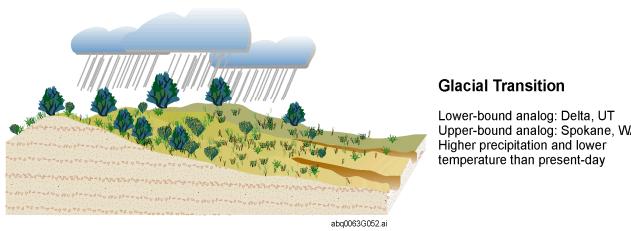
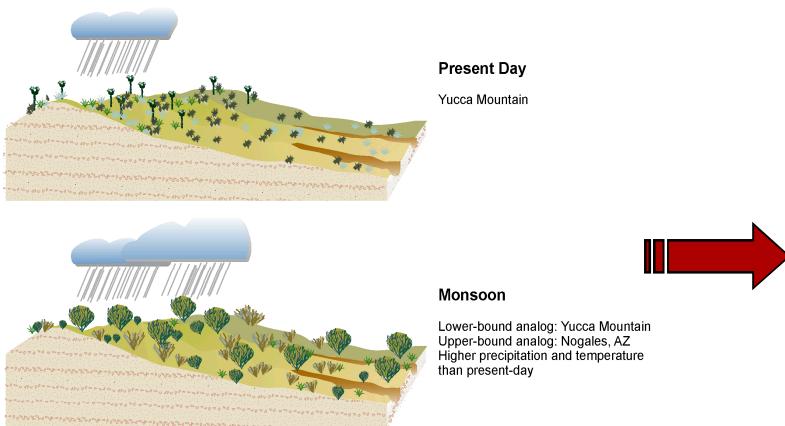
Long-term Performance of the Proposed Yucca Mountain Repository

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

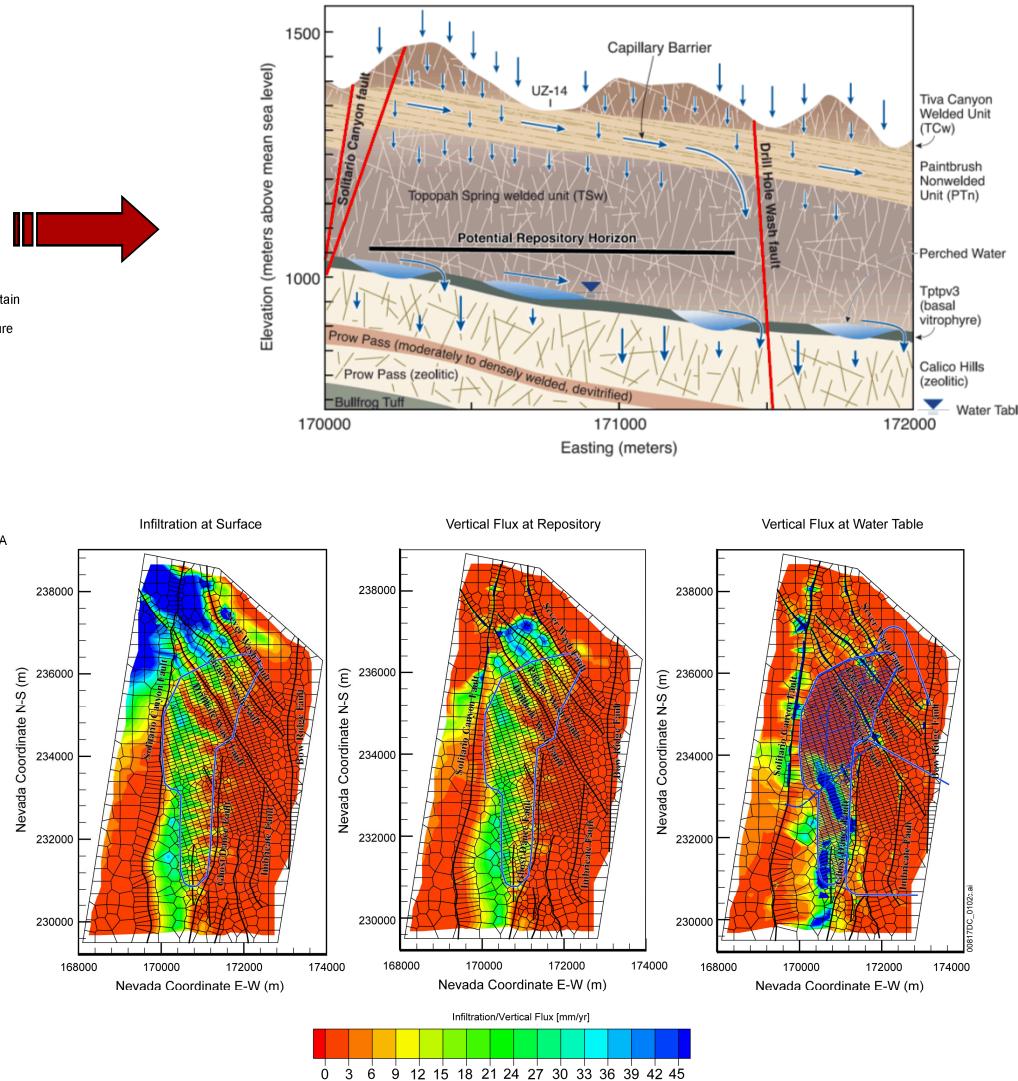


- Radionuclides are mobilized by seepage water and percolate downward to the water table
- Lateral transport in the saturated zone leads to biosphere exposure at springs or withdrawal wells

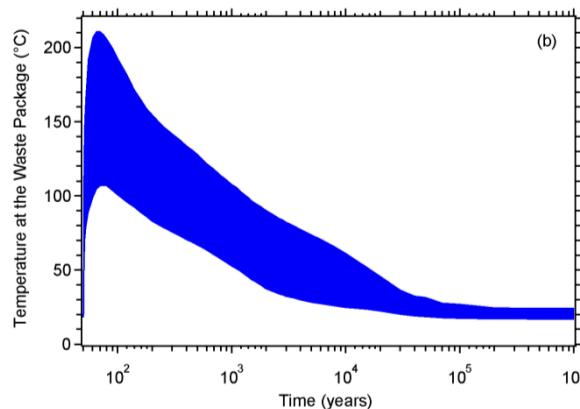
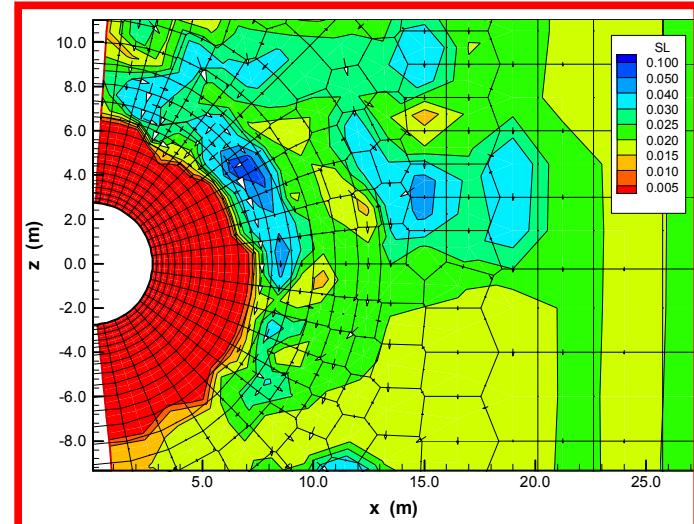
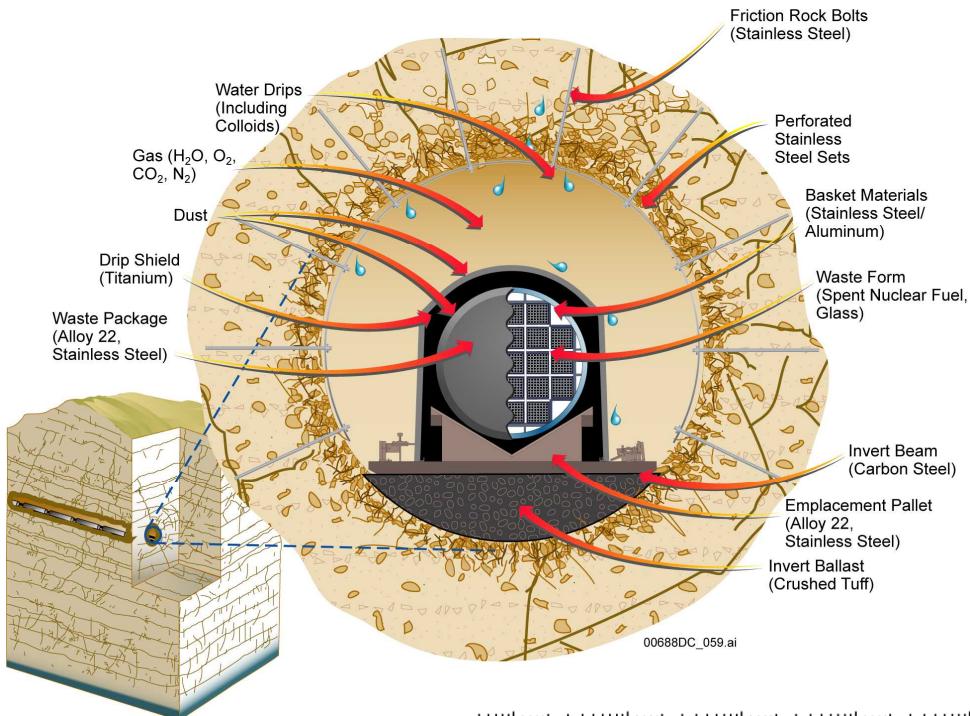
Groundwater Flow at Yucca Mountain



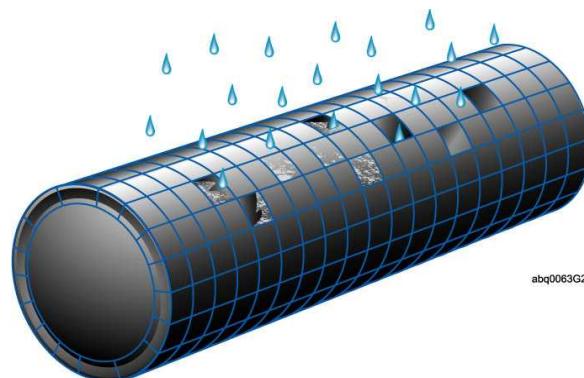
Field tests and models provide basis for understanding infiltration and flow in unsaturated rocks at Yucca Mountain



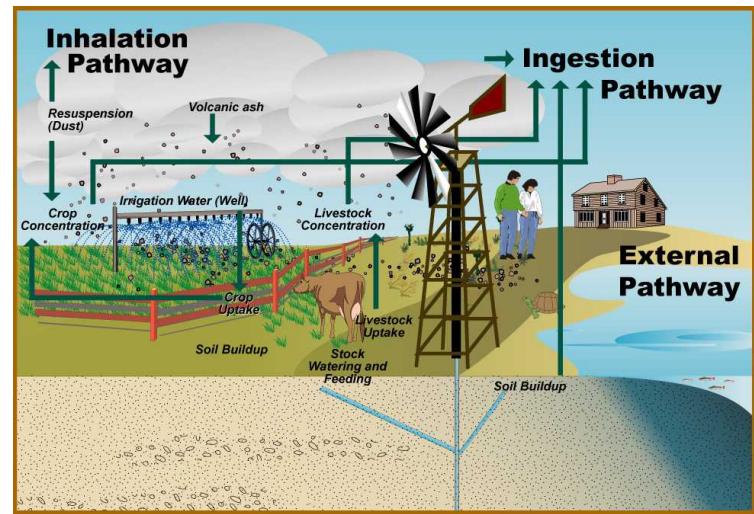
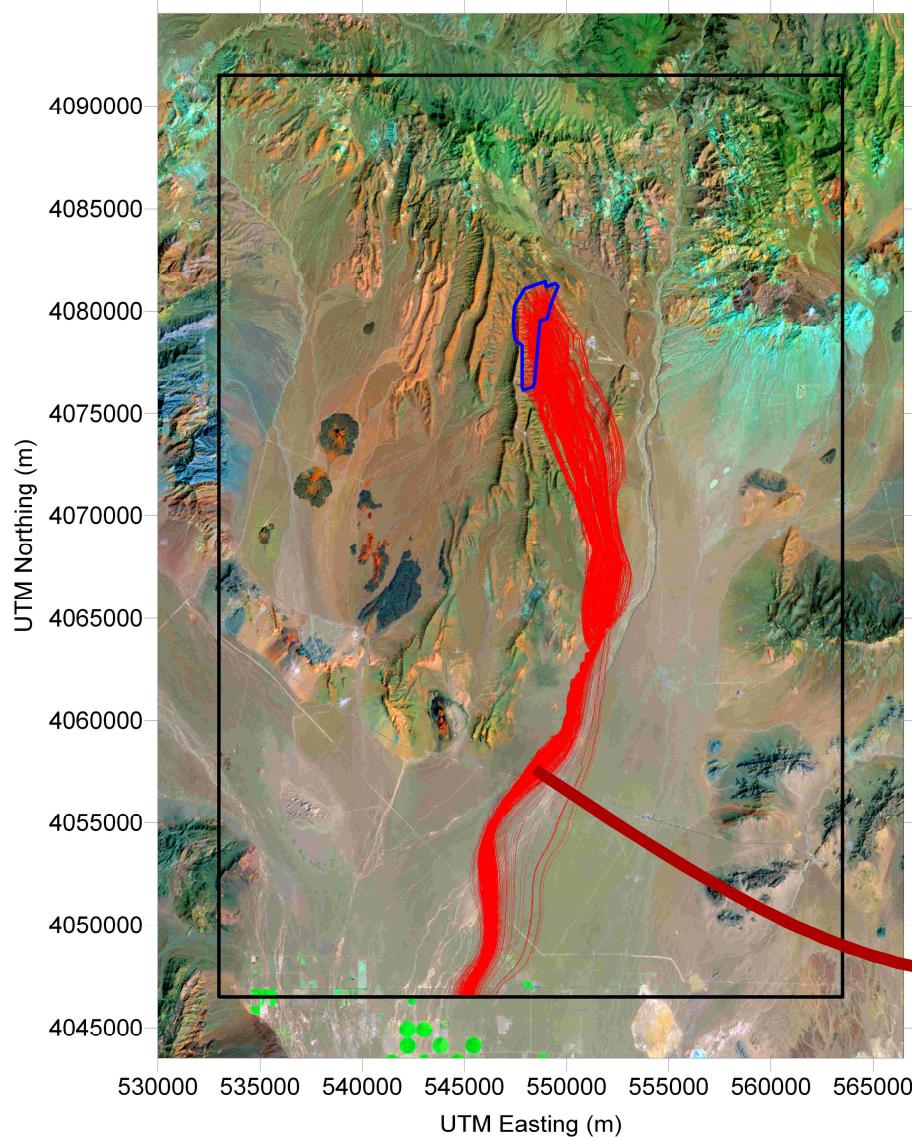
The Emplacement Environment at Yucca Mountain



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

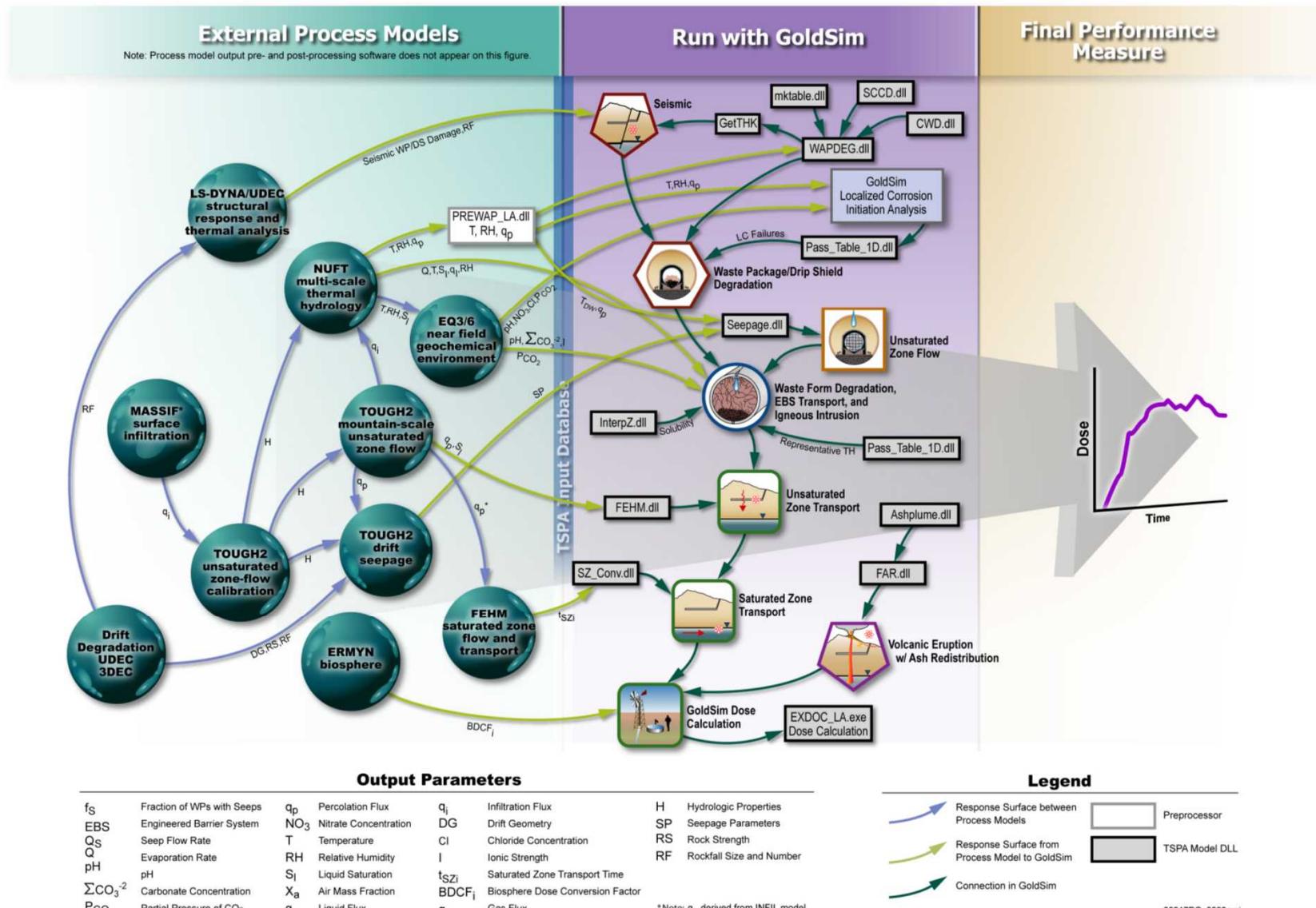
- U.S. Environmental Protection Agency defines the form of the post-closure safety assessment

“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

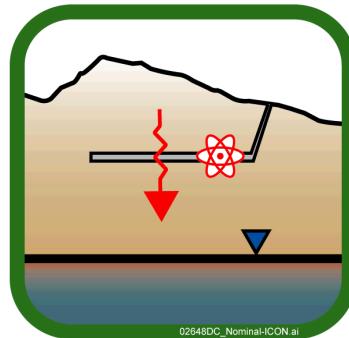


Defining Scenarios Based on Unlikely Events

Four scenario classes divided into seven modeling cases

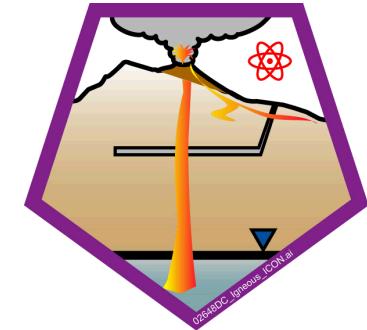
Nominal Scenario Class

- 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



Potential Disruptive Geologic Events at Yucca Mountain

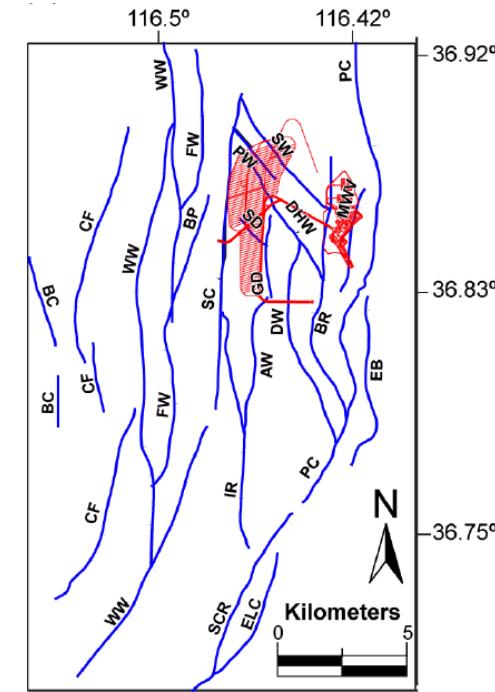


■ Seismicity

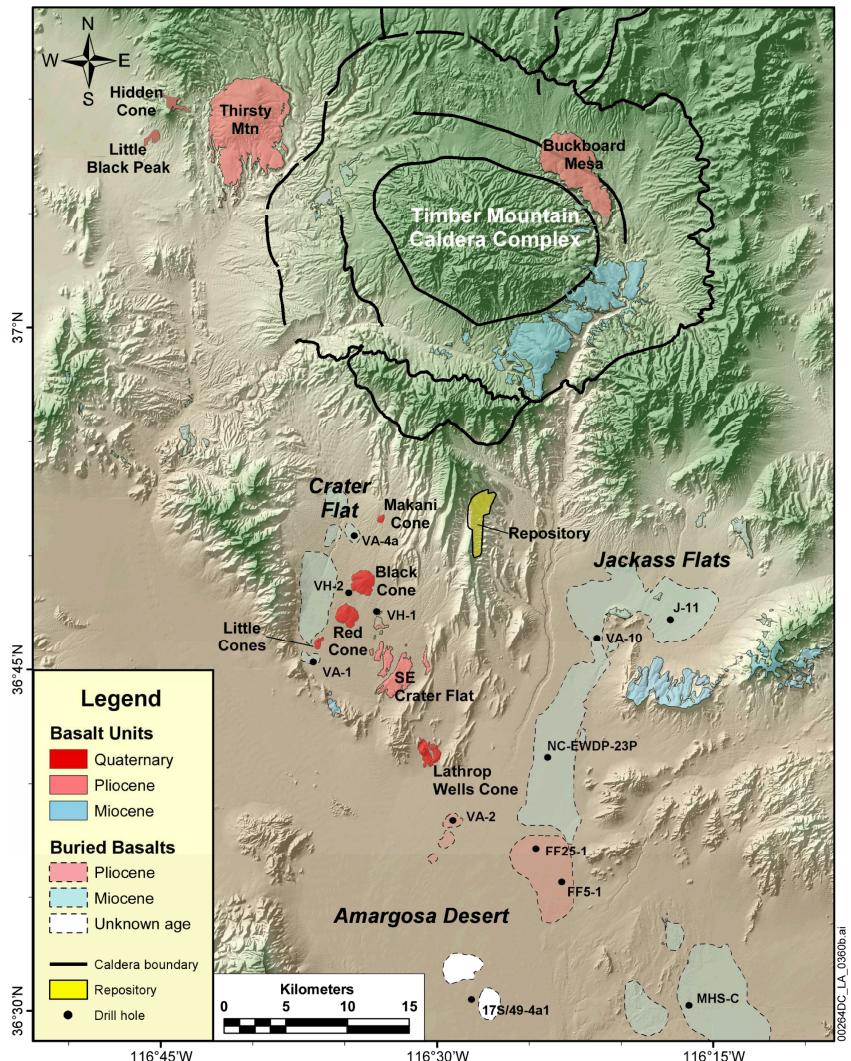
- Map shows Quaternary age faults (<1.5Myr) in the Yucca Mountain region (from US DOE 2008 GI Figure 5-35)

■ Volcanism

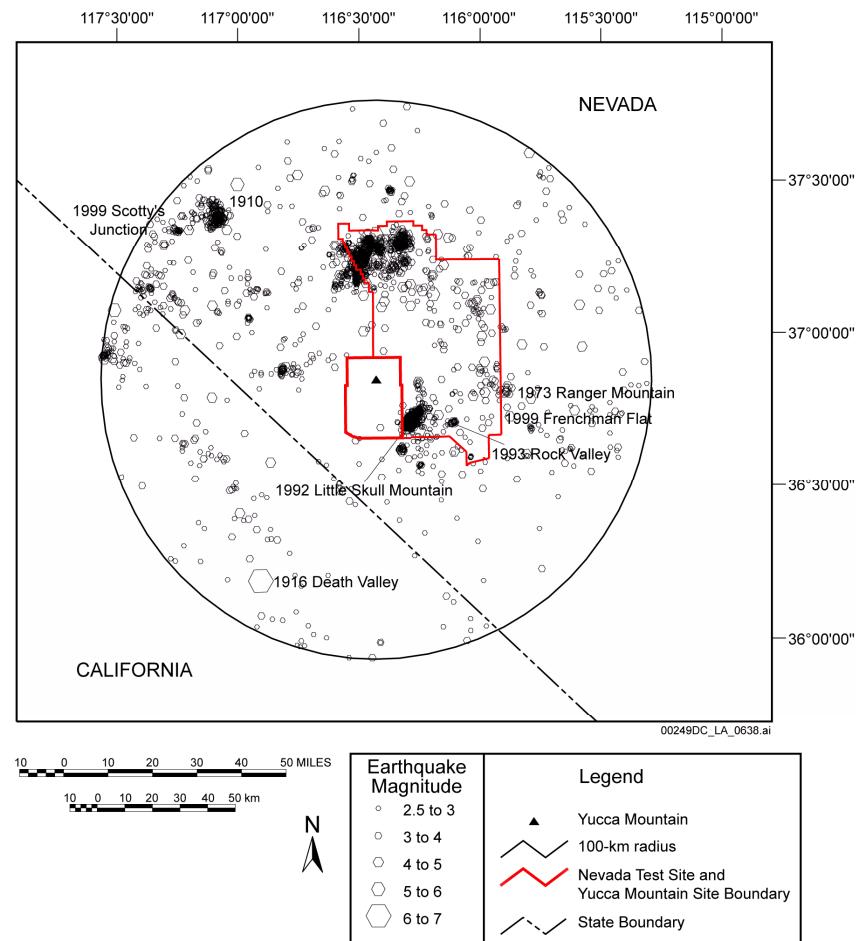
- Photo taken looking SW from Yucca Mountain crest shows small volcanic cones approximately 1 Myr old.



Igneous and Seismic Activity in the Yucca Mountain Region

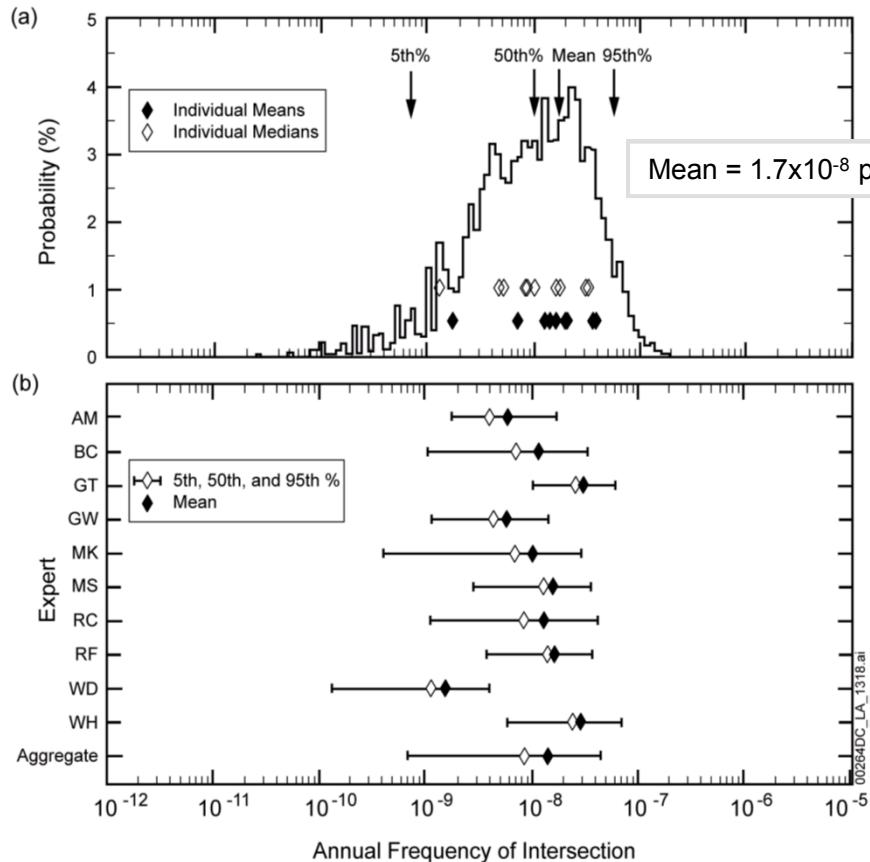


Distribution of Miocene and younger (< 5.3 Ma) Basaltic Rocks in the Yucca Mountain Region (DOE/RW-0573 Rev. 1, Figure GI 5-39)

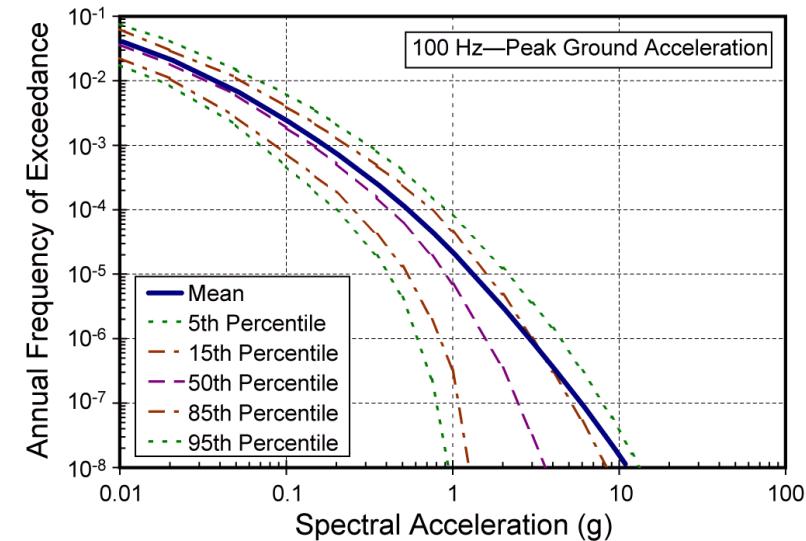


Historical Earthquake Epicenters with 100 km of Yucca Mountain (DOE/RW-0573 Rev. 1, Figure GI 5-38)

Yucca Mountain Event Probabilities Estimated by Formal Expert Elicitation

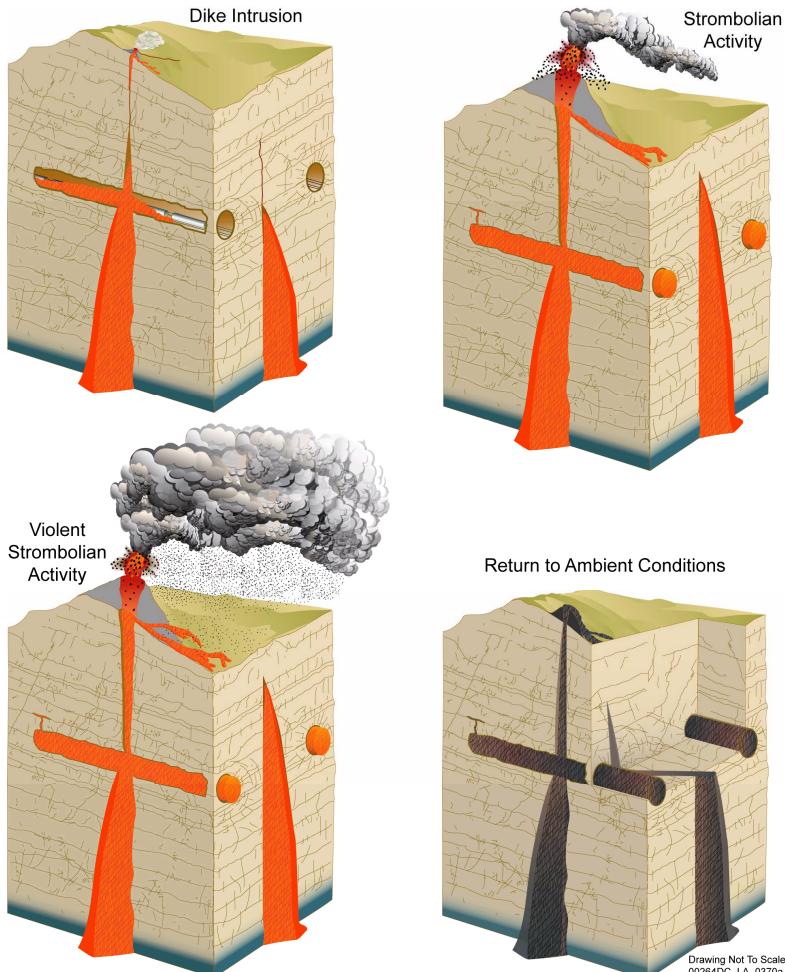


Estimated annual frequency of an igneous intrusion intersecting the repository footprint (DOE/RW-0573 Rev. 1, Figure 2.3.11-8)



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

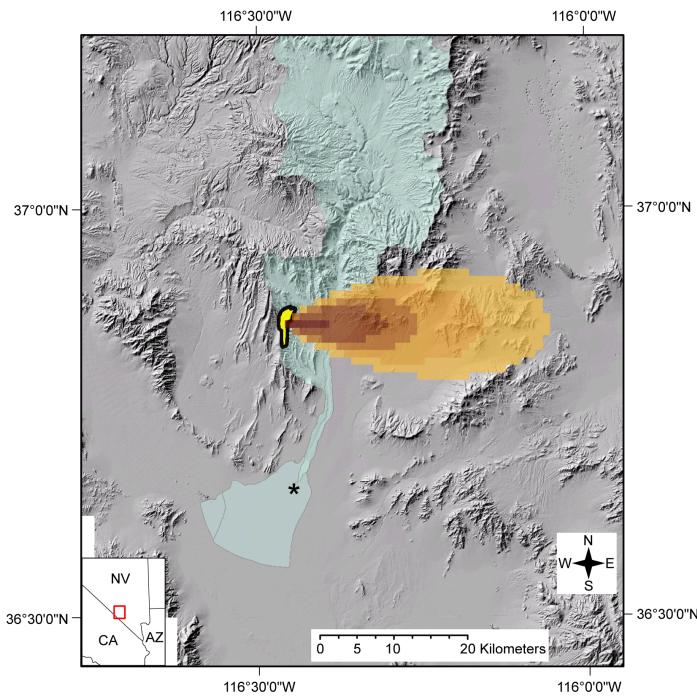


Schematic Drawing of an Igneous Event at Yucca Mountain (DOE/RW-0573 Rev. 1, Figure 2.3.11-5)

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

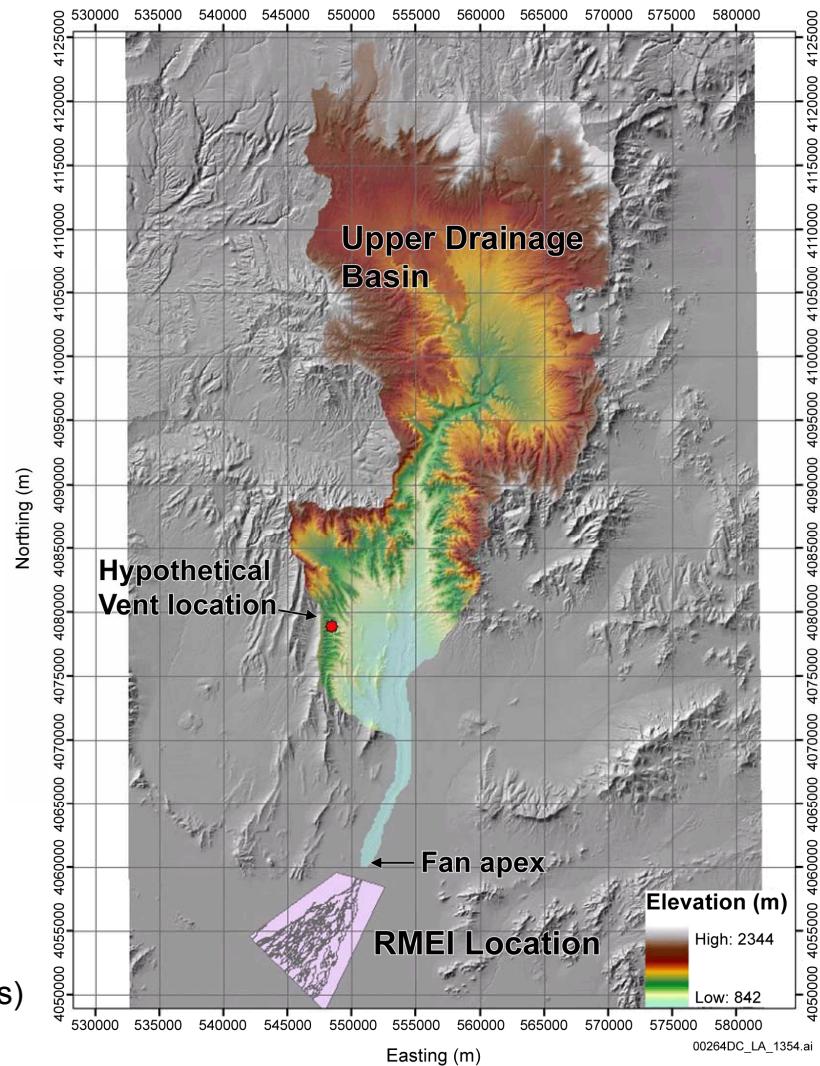
Modeling Consequences of Volcanic Eruption



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)

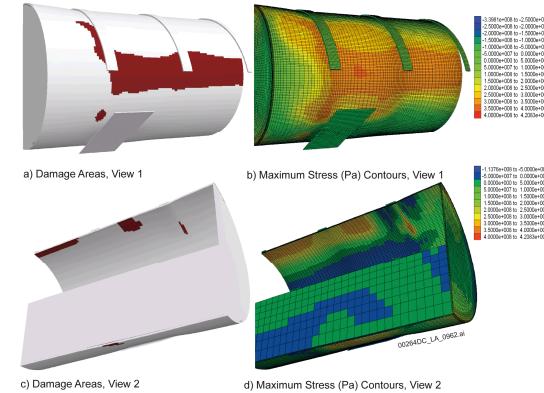


Model domain for surface redistribution of ash (DOE/RW-0573 Rev. 1, Figure 2.3.11-5)

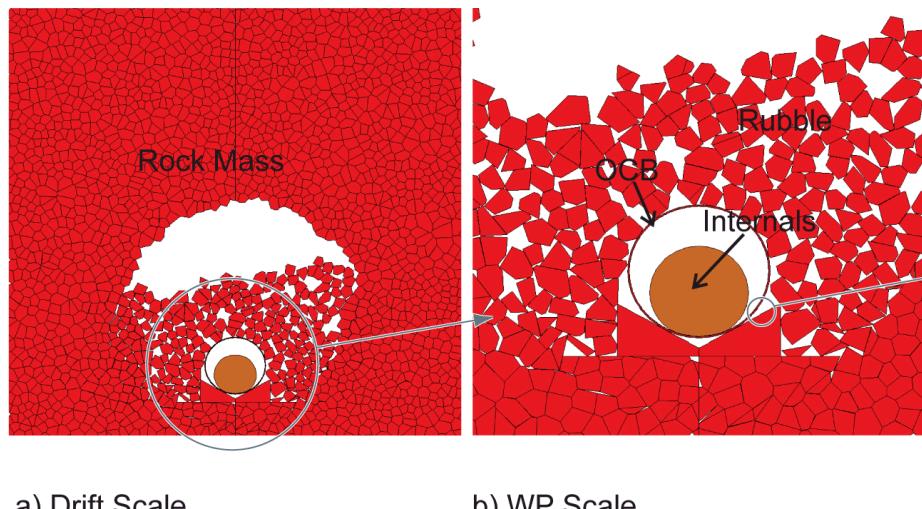
Consequence Models for Seismic Disruption at Yucca Mountain

- 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)



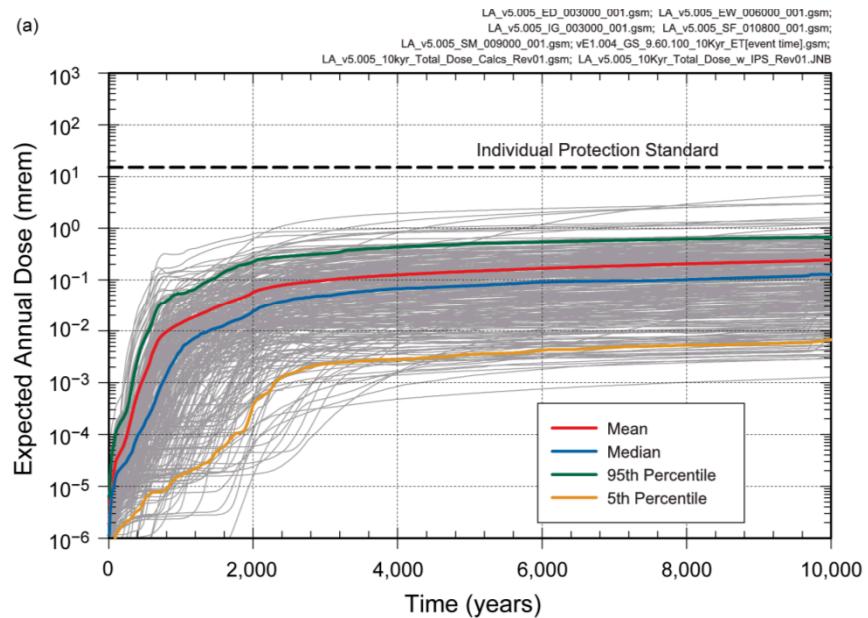
a) Drift Scale

b) WP Scale

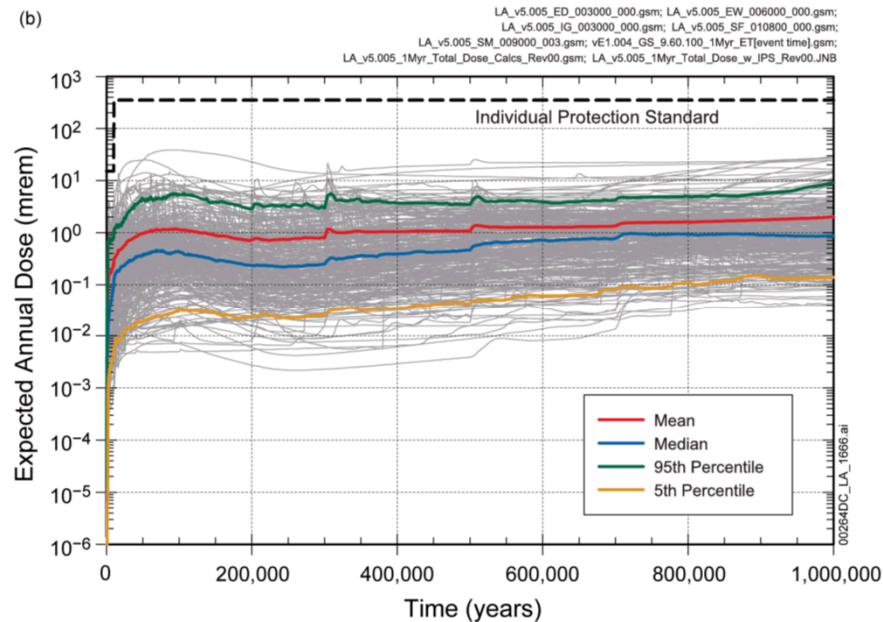
Summary of the Quantitative Estimates of Long-term Performance Presented in the Yucca Mountain License Application

Long-Term Performance of Yucca Mountain

(a)



(b)



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)**

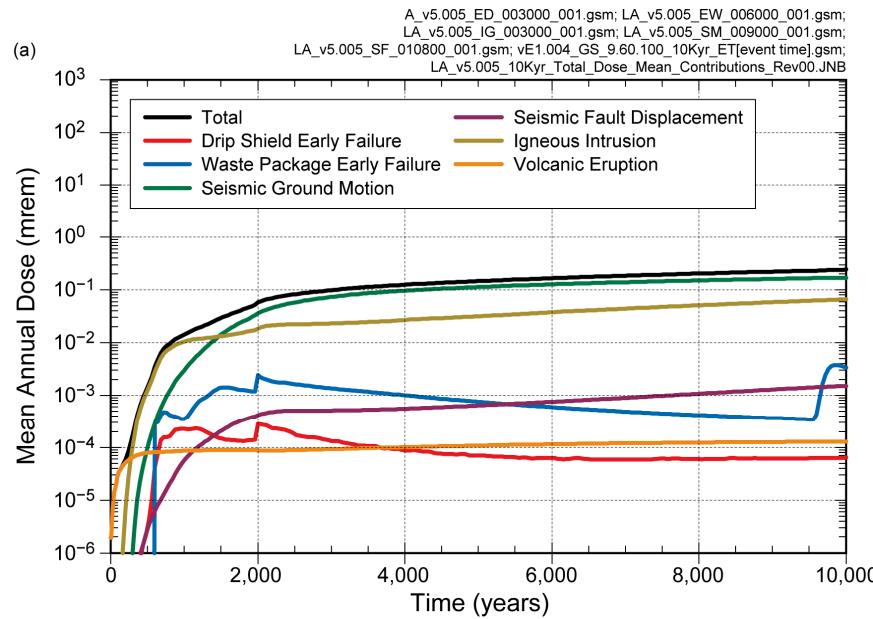
1,000,000 years

1,000,000-year Standard:

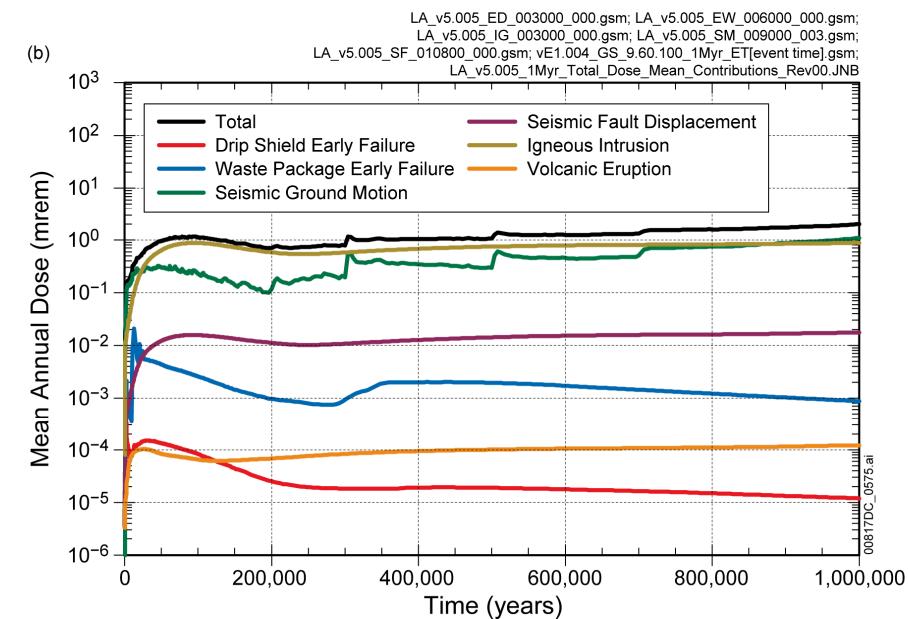
Mean annual dose no more than 1
mSv (100 mrem)

**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

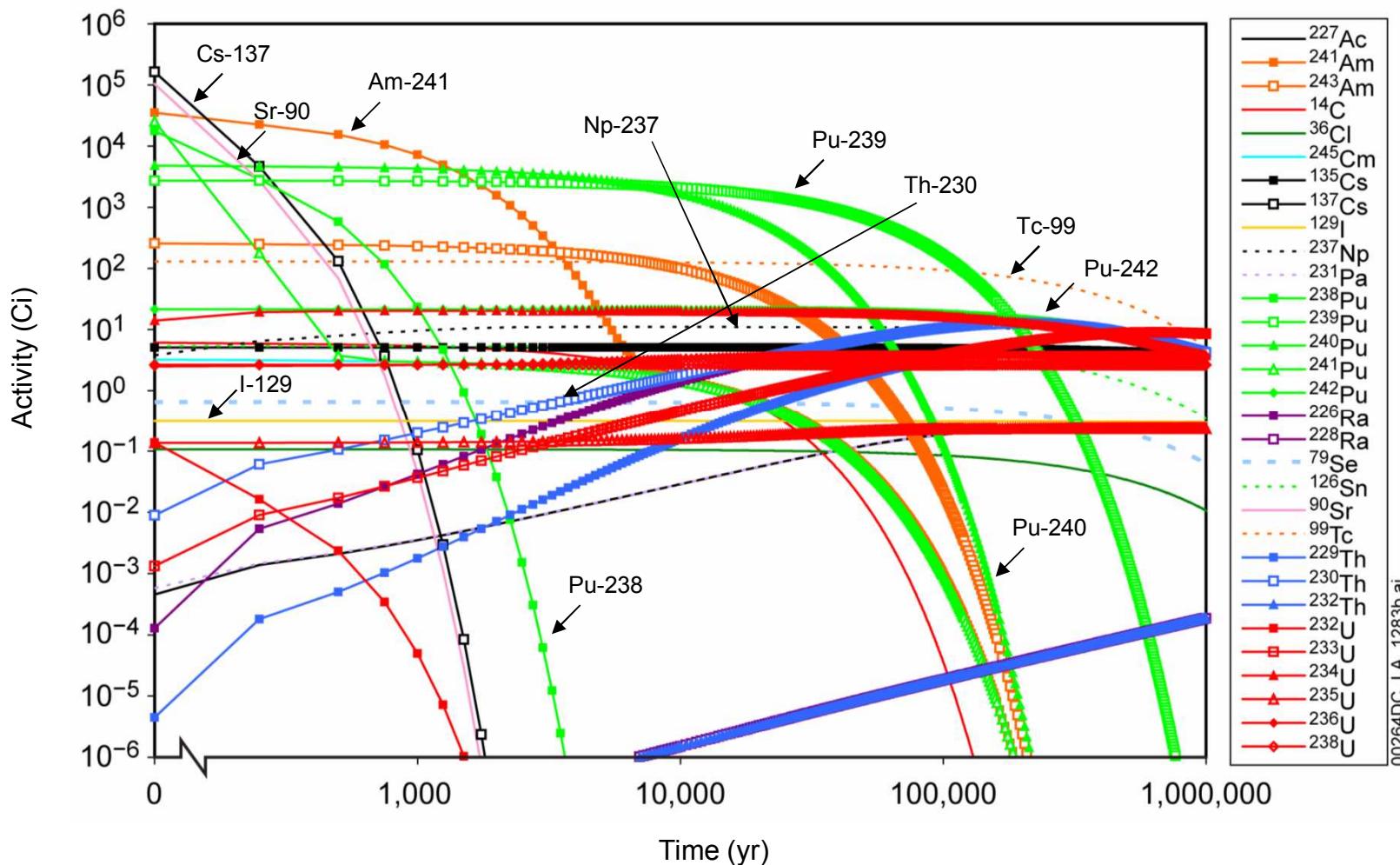


1,000,000 years

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

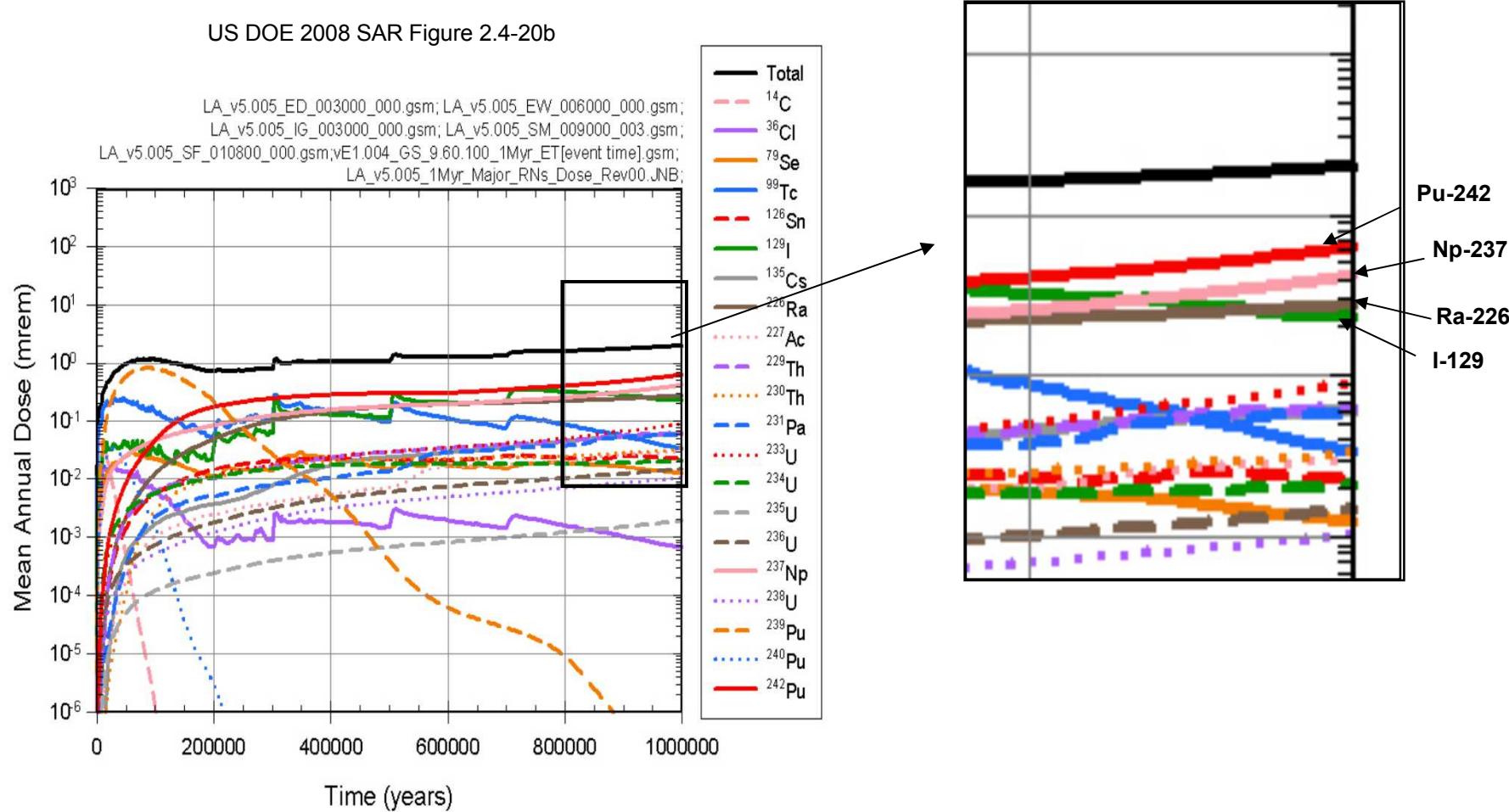
Radionuclides Contributing to Estimates of Total Dose from Yucca Mountain

Commercial Used Nuclear Fuel Decay



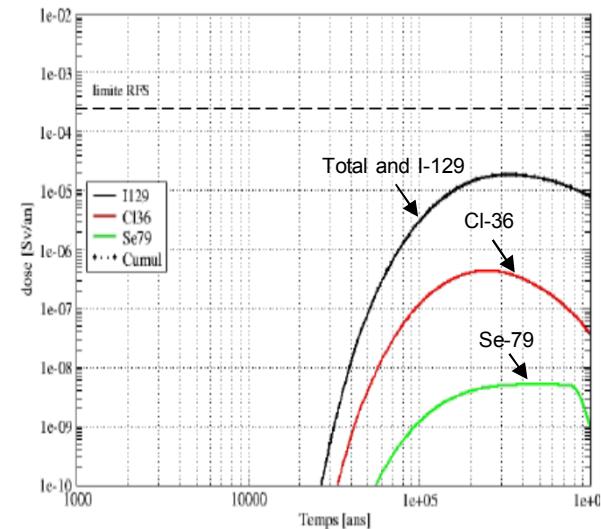
DOE/RW-0573 Rev 0, Figure 2.3.7-11, inventory decay shown for a single representative Yucca Mountain used fuel waste package, as used in the Yucca Mountain License Application, time shown in years after 2117.

Radionuclides Important to Mean Dose at Yucca Mountain

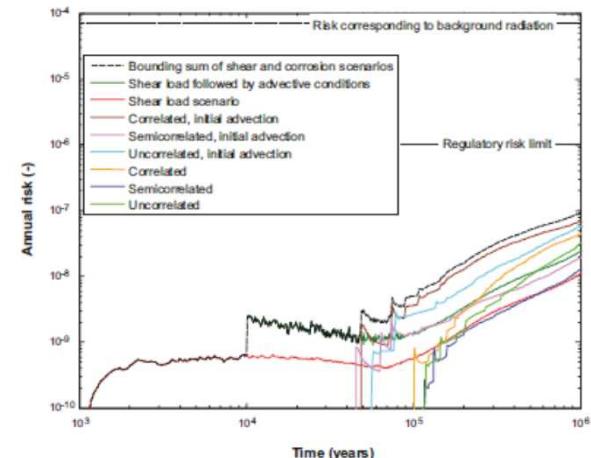


How Does Yucca Mountain Compare to Other Proposed Repositories?

- 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

References

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- 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.
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- Voegeli, MD and DL Vieth, Waste of a Mountain: How Yucca Mountain was Selected, Studied, and Dumped, Nye County Press, 2016
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Key Website: <http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app.html>

Yucca Mountain backup material

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)

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*

Results of Seismic Consequence Models for Yucca Mountain

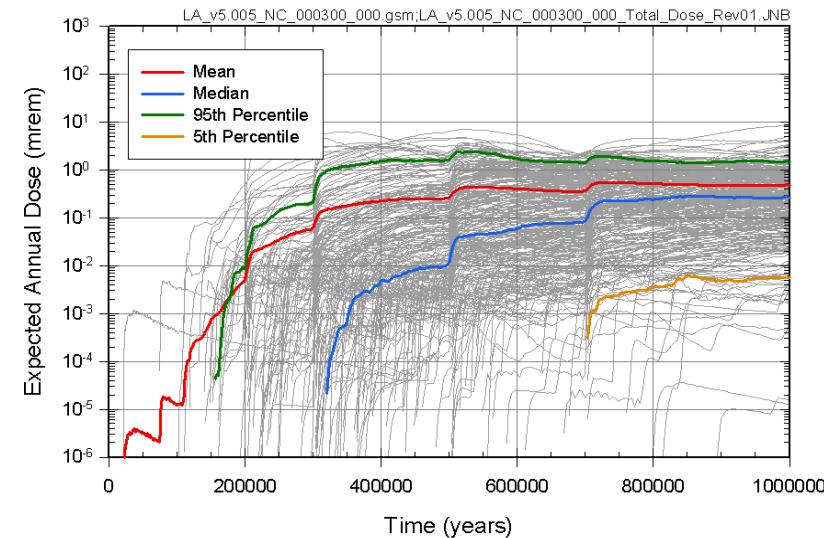
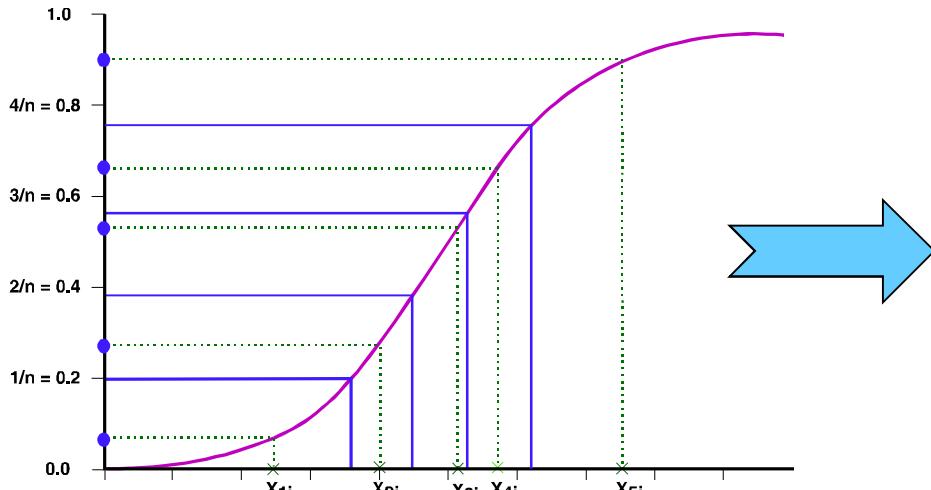
- Seismic Fault Displacement Modeling Case
 - Annual frequency approximately 2×10^{-7} / yr
 - Fault displacements rupture waste packages and drip shields, allowing advection and diffusion
 - Size of rupture uncertain, 0 to cross-sectional area of WP
 - Mean of ~ 47 waste packages and drip shields damaged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

Treatment of Epistemic Uncertainty

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

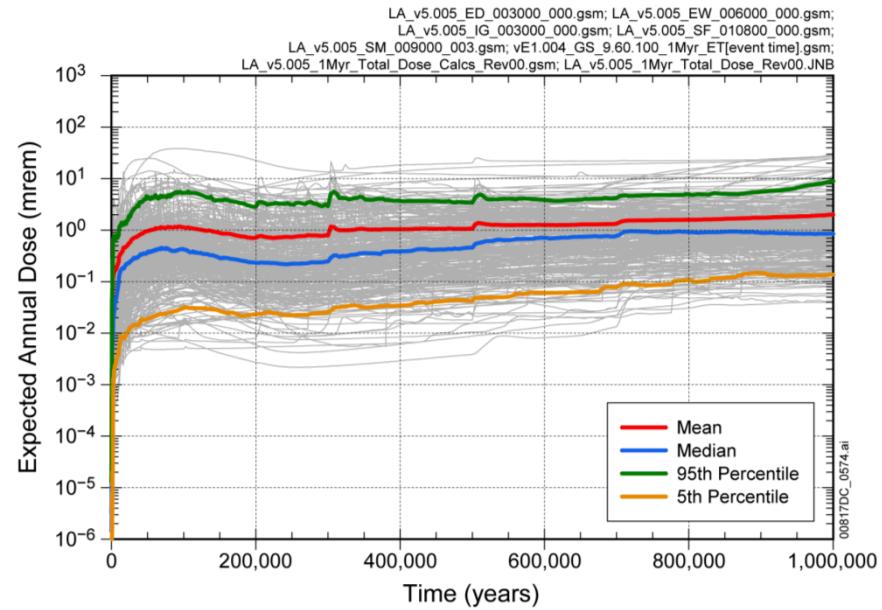
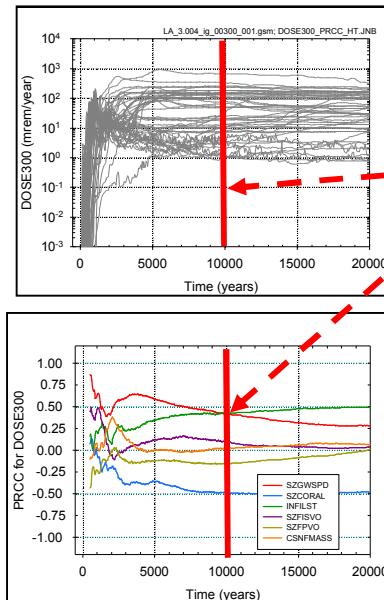
Uncertainty in external process models incorporated through multiple realizations (e.g., multiple infiltration maps for different climate states lead to multiple maps of seepage entering the repository drifts)

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

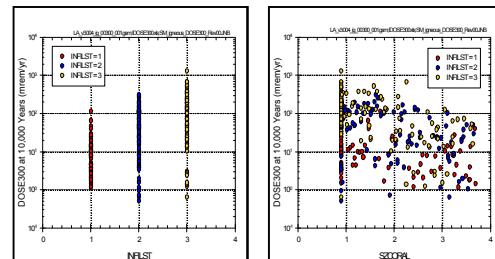


Interpreting the Importance of Epistemic Uncertainty on Performance Assessment Results

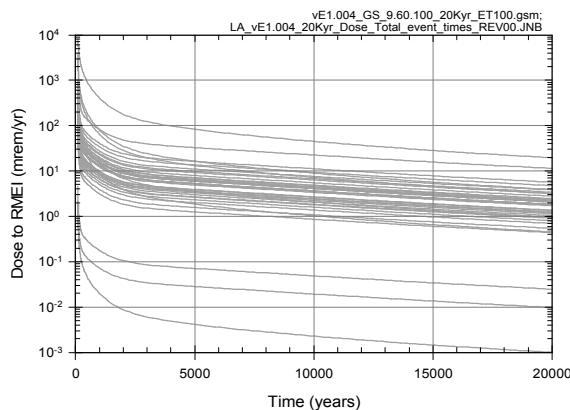
Monte Carlo estimates of overall performance
(Example dose histories from Yucca Mountain Total System Performance Assessment for the License Application, total expected dose from all scenarios)



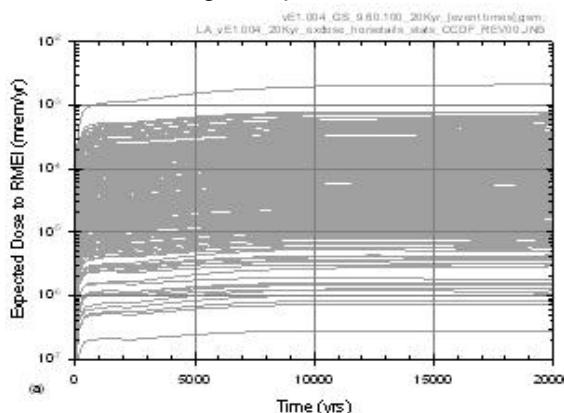
Sensitivity and Uncertainty Analyses
Identify model inputs important to uncertainty in performance estimates



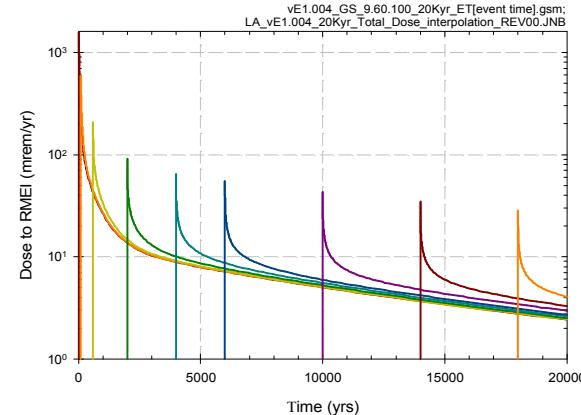
Estimating Mean Annual Dose from Unlikely Events: Eruptive Dose



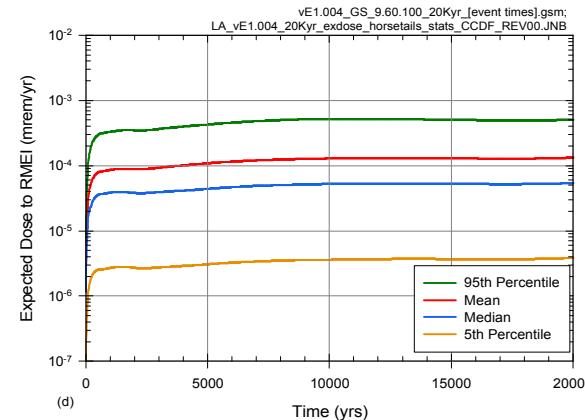
Eruptive dose: 40 realizations of aleatory uncertainty conditional on a single eruption of 1 WP at time zero



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



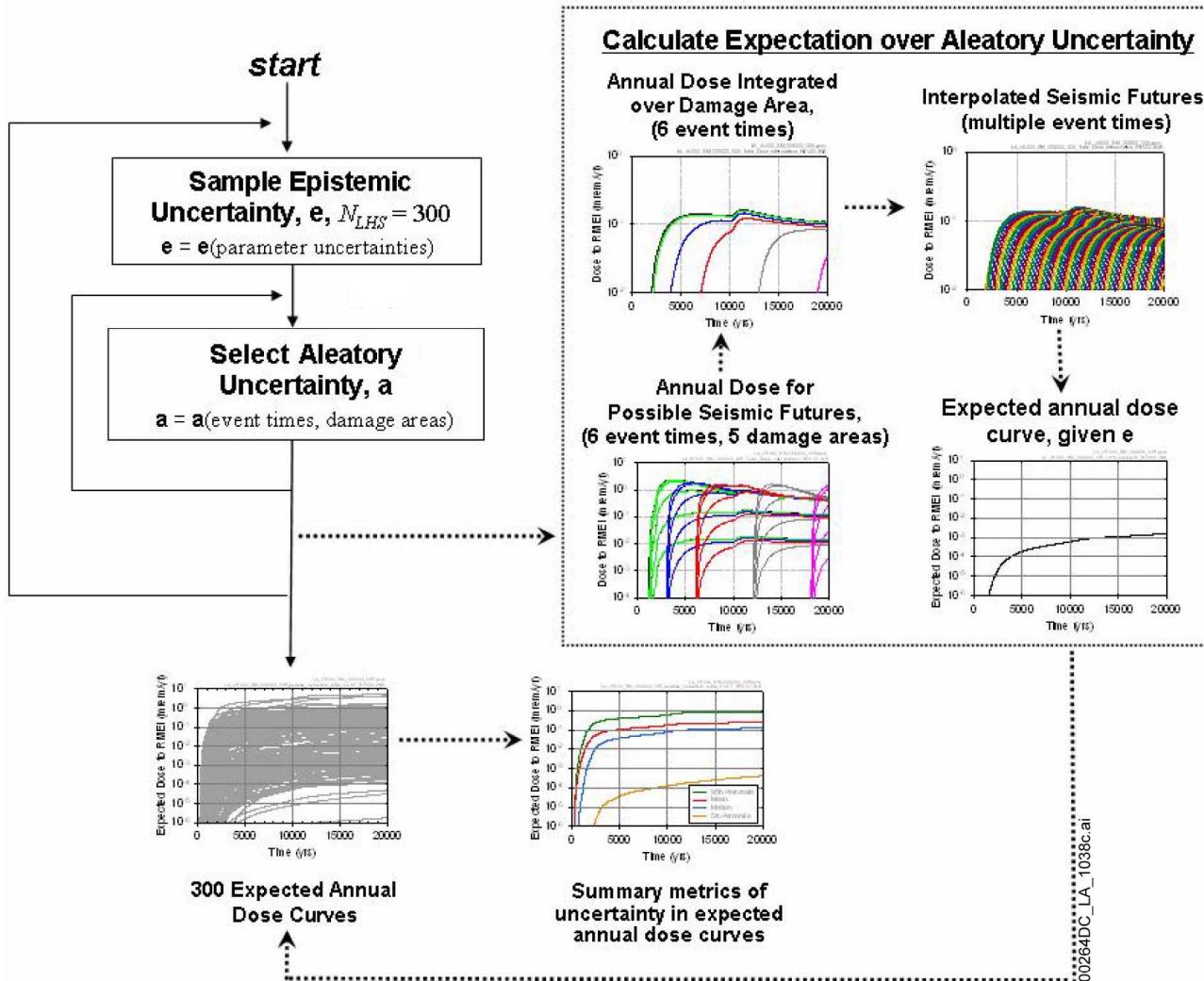
Eruptive dose averaged over aleatory uncertainty associated with a single eruption of 1 WP, eruptions at multiple times



Summary curves showing overall mean dose from eruption

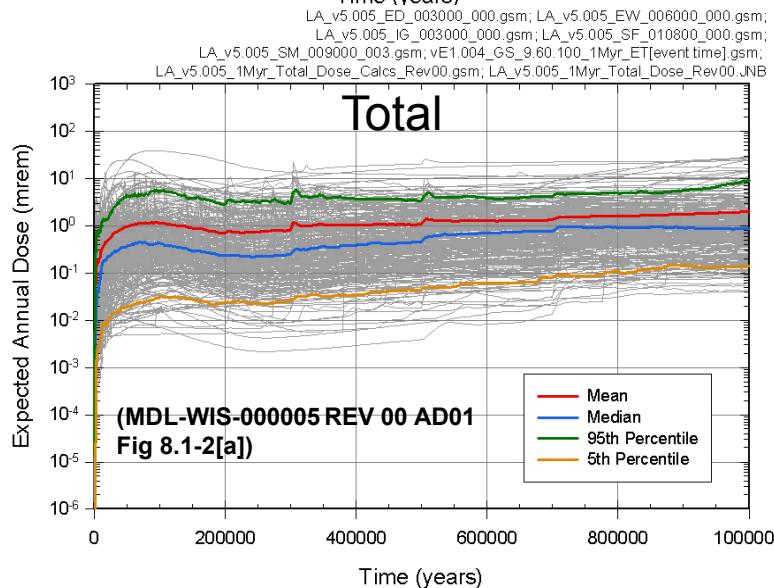
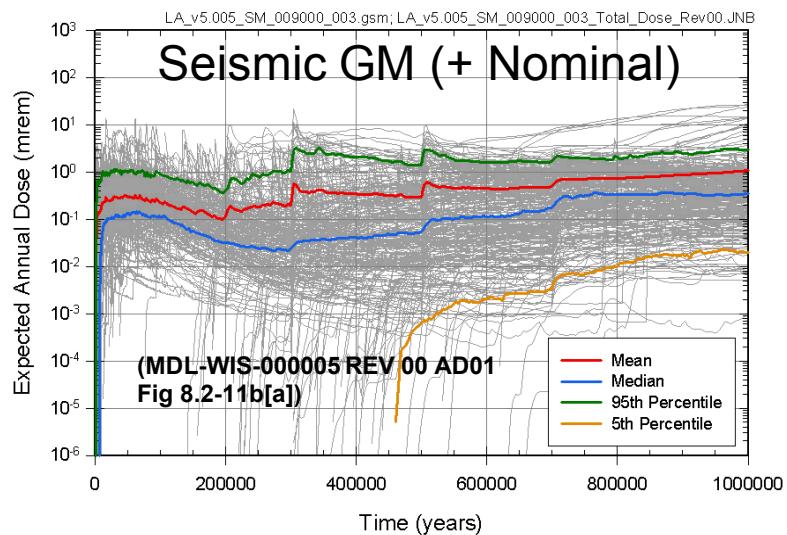
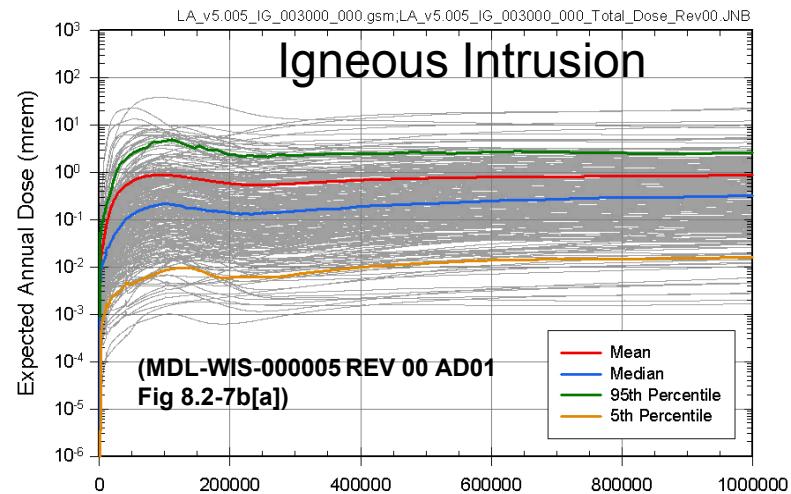
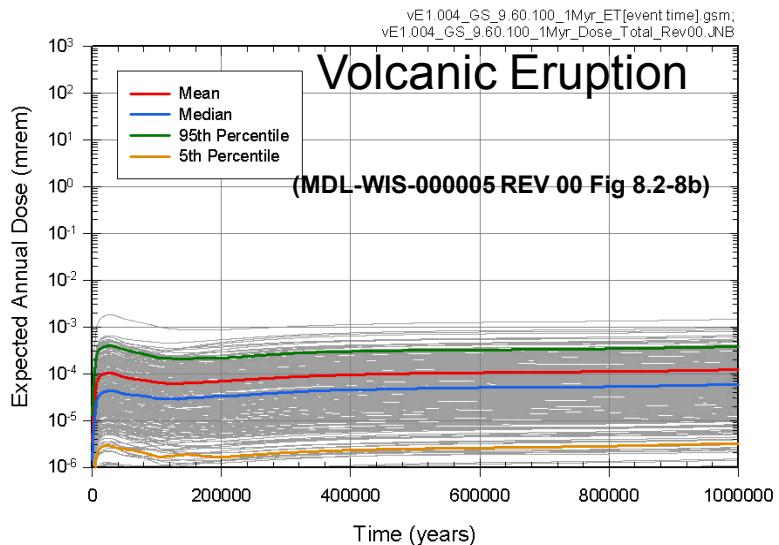
MDL-WIS-PA-000005 Rev 00, Figures J7.3-1, 3.2, & 3.4,
<http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app/references.html>

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

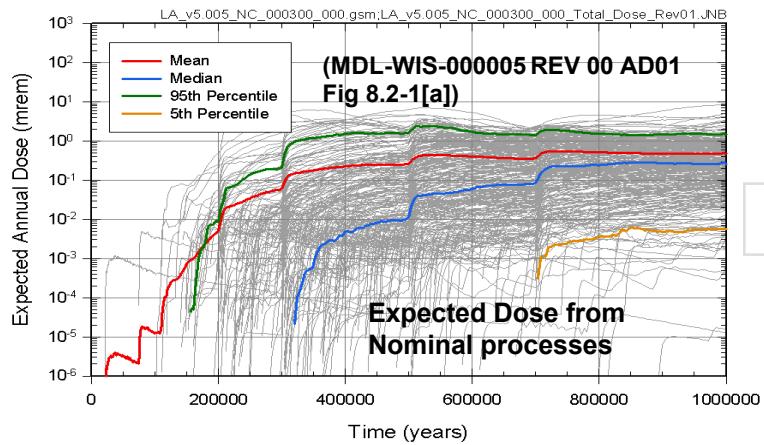


Computational Strategy for Expected Annual Dose from Seismic Ground Motion (DOE/RW-0573 Rev. 1, Figure 2.4-8)

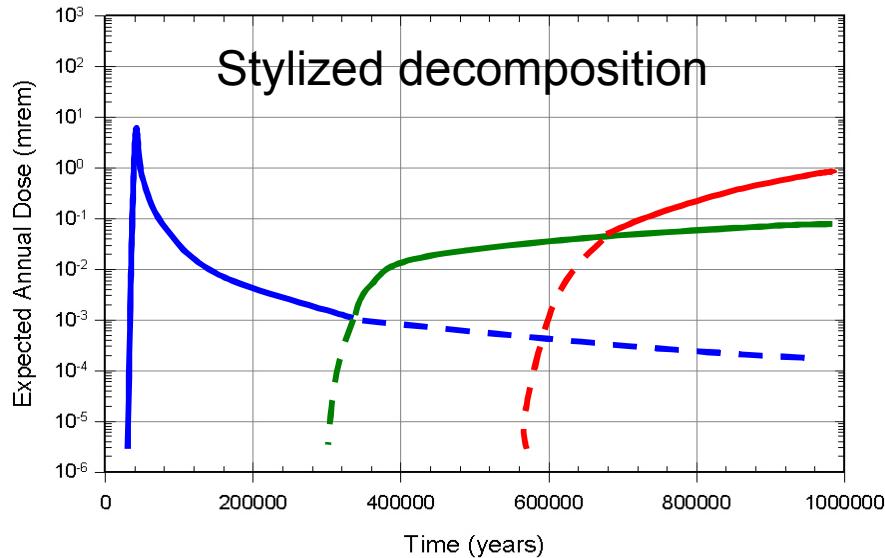
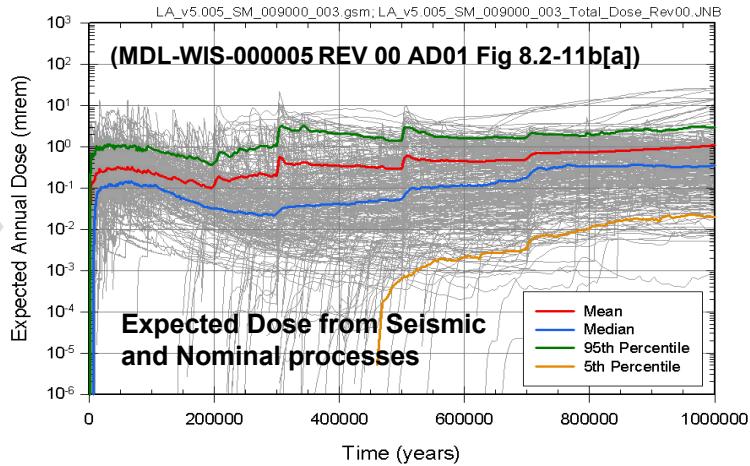
Construction of Total Dose



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)