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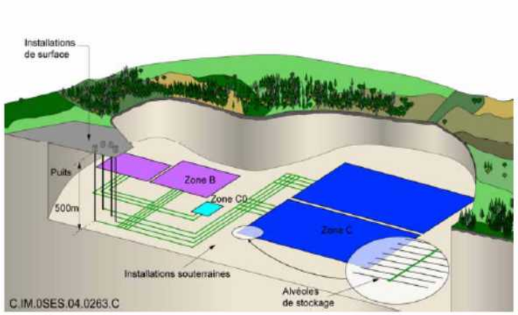

Current Status of Repository Programs in the United States: WIPP and Yucca Mountain

Charles Bryan
Sandia National Laboratories

Presentation to ENVS 101
University of New Mexico
December 8, 2016

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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Outline

- The Waste Isolation Pilot Plant
  - Project History
  - “transuranic” Waste
  - Repository design and site geology: isolation concept
  - Performance assessment
  - Recent incidents and current status
- The formerly proposed Yucca Mountain Repository
  - Spent nuclear fuel and high level waste: definitions and where it is now
  - Yucca Mountain location and geology
  - Yucca Mountain Project Performance Assessment
  - Submission of the site license application and current status

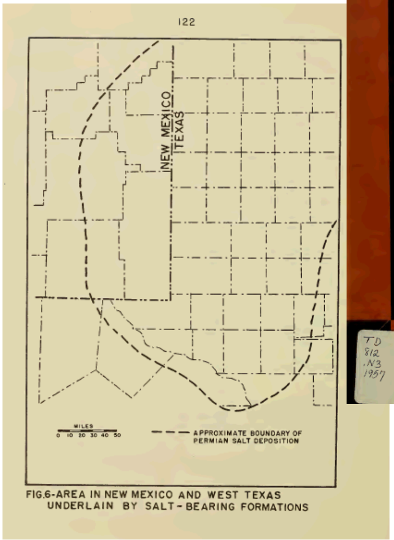
Disposal of Transuranic Waste: The Waste Isolation Pilot Plant

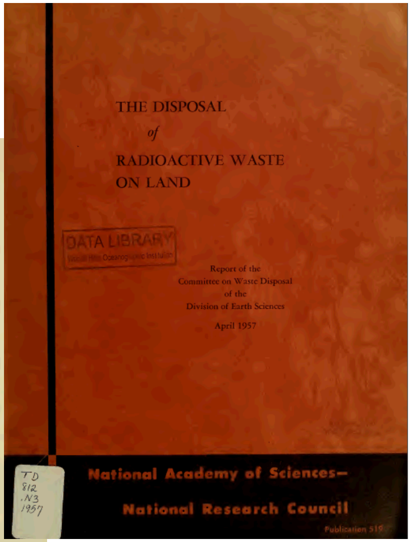
Background

- 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)

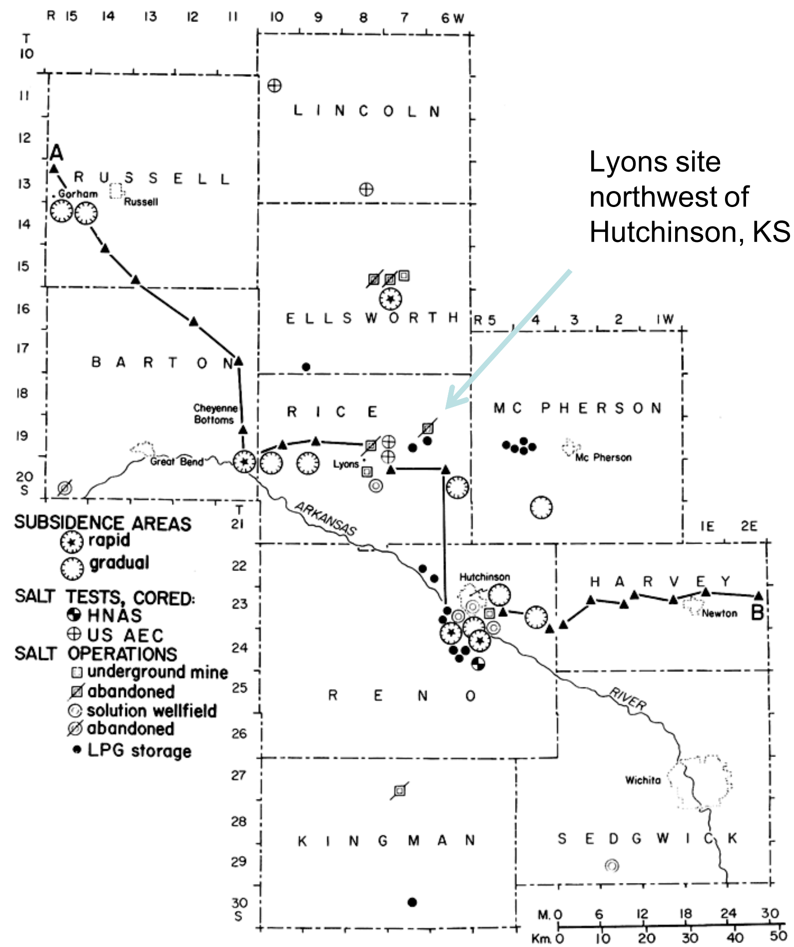
"In part of the area a zone of potash salts is present which has been extensively developed near Carlsbad, New Mexico. The zone is about 250 feet thick and contains four workable beds of potash. The lowest bed is the thickest and averages about ten feet in thickness. A large area has been mined out since 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)





Background (cont.)

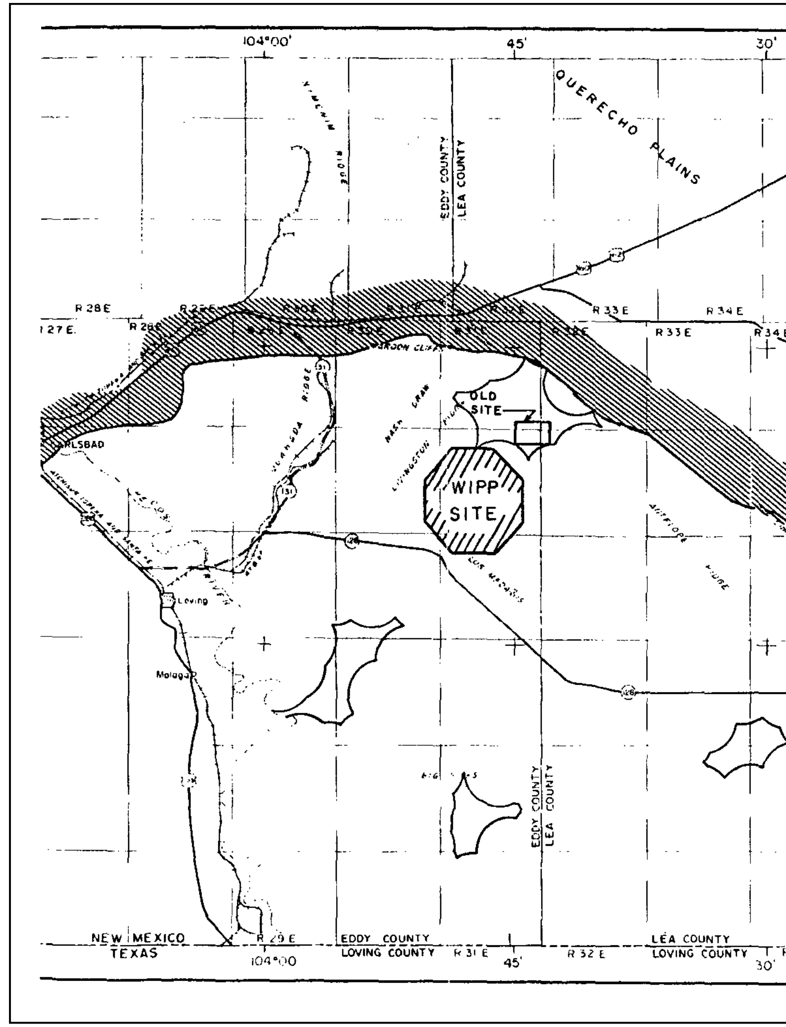
- 1970: Atomic Energy Commission (AEC) selects salt mine at Lyons, Kansas as repository site
- 1971: AEC discovers old drill holes and solution mining at Lyons site
- 1971: City of Carlsbad, NM approaches NM congressional delegation seeking a repository
- 1972: AEC abandons Lyons site
- 1972: City of 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



Lyons site northwest of Hutchinson, KS

Background (cont.)

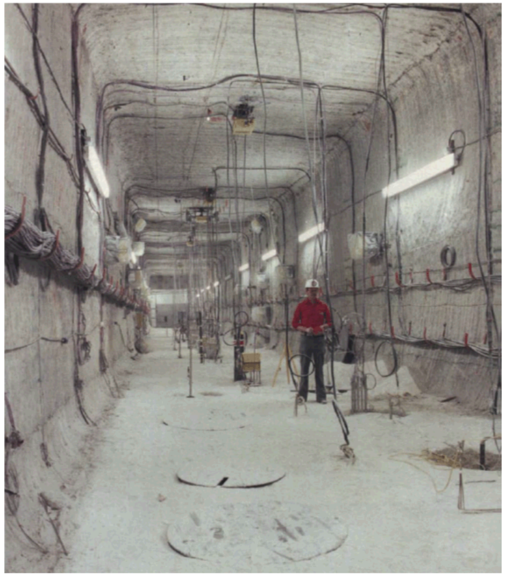
- 1974: Oak Ridge National Laboratory begins field investigations in SE NM
- 1975: Sandia National Laboratories assumes lead science role; first site identified is found unsuitable
  - ERDA-6 borehole encounters steeply dipping salt beds and pressurized brine
  - Proposed site is moved 11 km SW
- 1976: Project is named Waste Isolation Pilot Plant (WIPP)
- 1979: Congress limits WIPP mission to defense transuranic (TRU) waste
- 1981: First shaft constructed at site, underground site characterization begins



From DOE 1996, Appendix GCR, Figure 2-3

Background (cont.)

- 1979-1993: Site characterization: Geological and hydrologic investigations
- 1985: Extensive testing begins in the WIPP underground: thermal tests, 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 to date, all by truck http://www.wipp.energy.gov/shipments.htm
- 2006 and 2010: EPA recertifies WIPP
- EPA action pending on 2014 Recertification Application (delayed by recent incidents at the site)



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

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.)

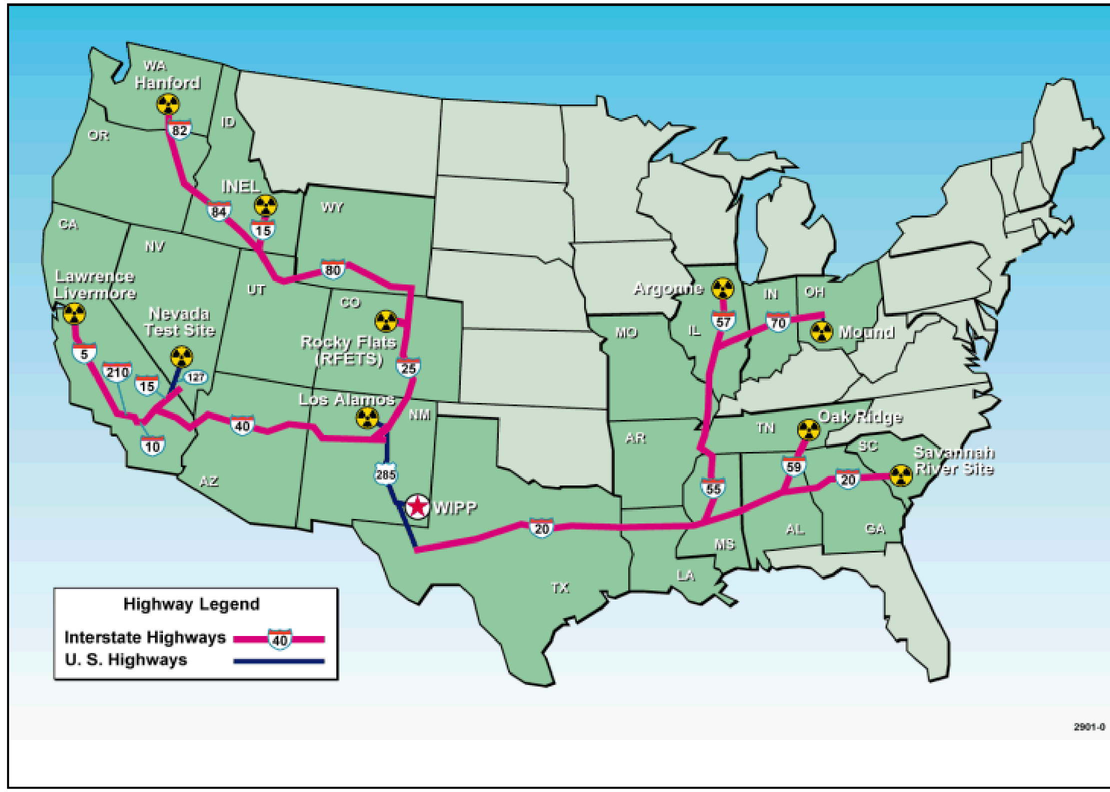
- Most WIPP waste is "Contact-Handled TRU" (CH-TRU), and requires no additional shielding beyond that provided by drums and liners
- Some WIPP waste is "Remote-Handled TRU" (RH-TRU), with surface gamma radiation dose rates that require shielding
  - Defined by WIPP Land Withdrawal Act Section 2 as "transuranic 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

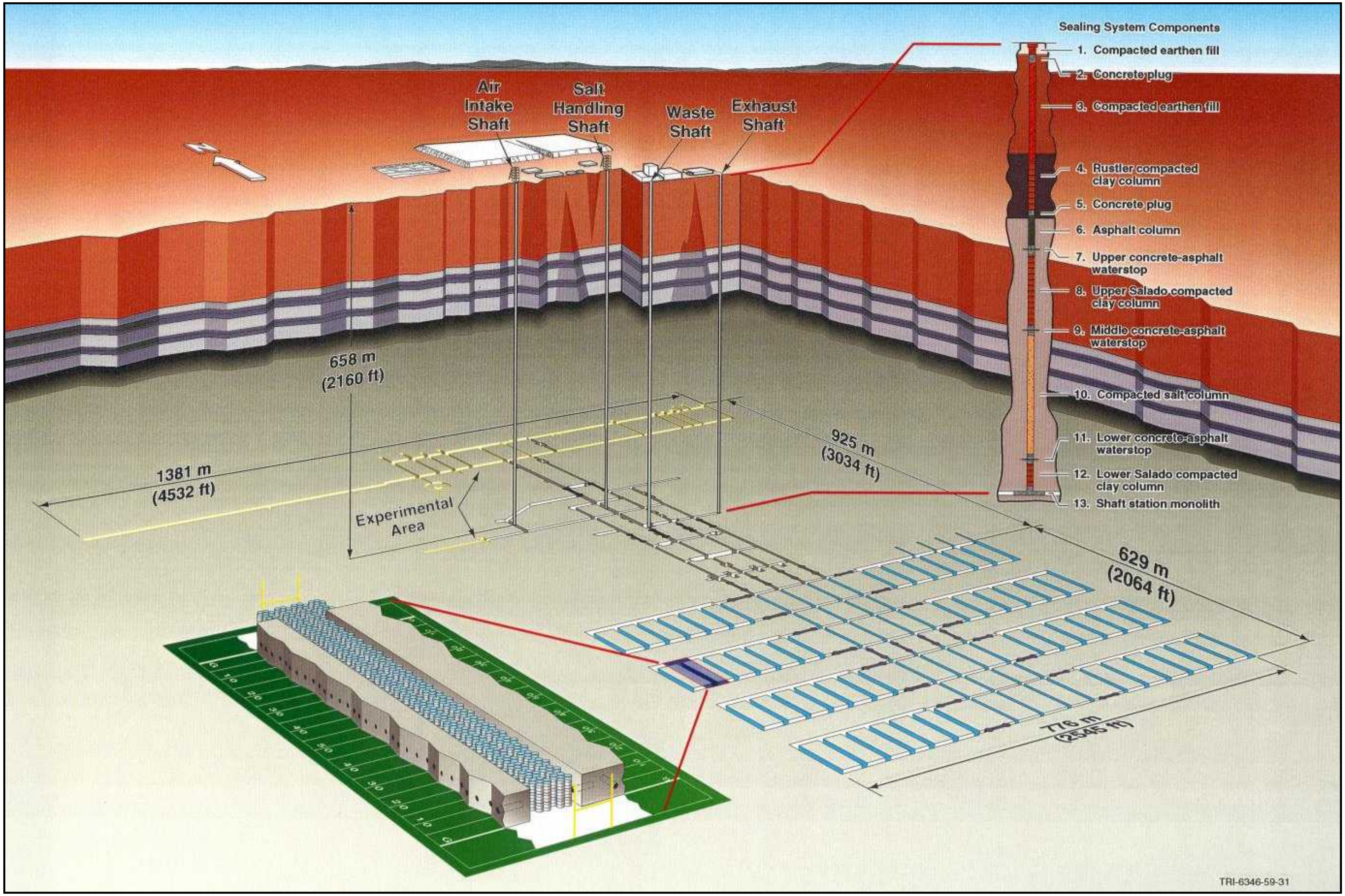
Sandia National Laboratories

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



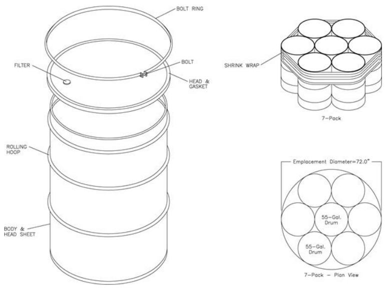
Images from http://www.wipp.energy.gov/Photo_Gallery_Images

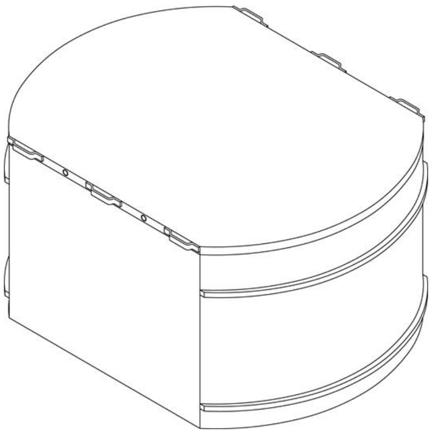
WIPP Design



Sealing System Components
1. Compacted earthen fill
2. Concrete plug
3. Compacted earthen fill
4. Rustler compacted clay column
5. Concrete plug
6. Asphalt column
7. Upper concrete-asphalt waterstop
8. Upper Salado compacted clay column
9. Middle concrete-asphalt waterstop
10. Compacted salt column
11. Lower concrete-asphalt waterstop
12. Lower Salado compacted clay column
13. Shaft station monolith
Air Intake Shaft
Salt Handling Shaft
Waste Shaft
Exhaust Shaft
658 m
(2160 ft)
1381 m
(4532 ft)
925 m
(3034 ft)
Experimental Area
629 m
(2064 ft)
776 m
(2545 ft)
TRI-6346-59-31

WIPP Design (cont.)



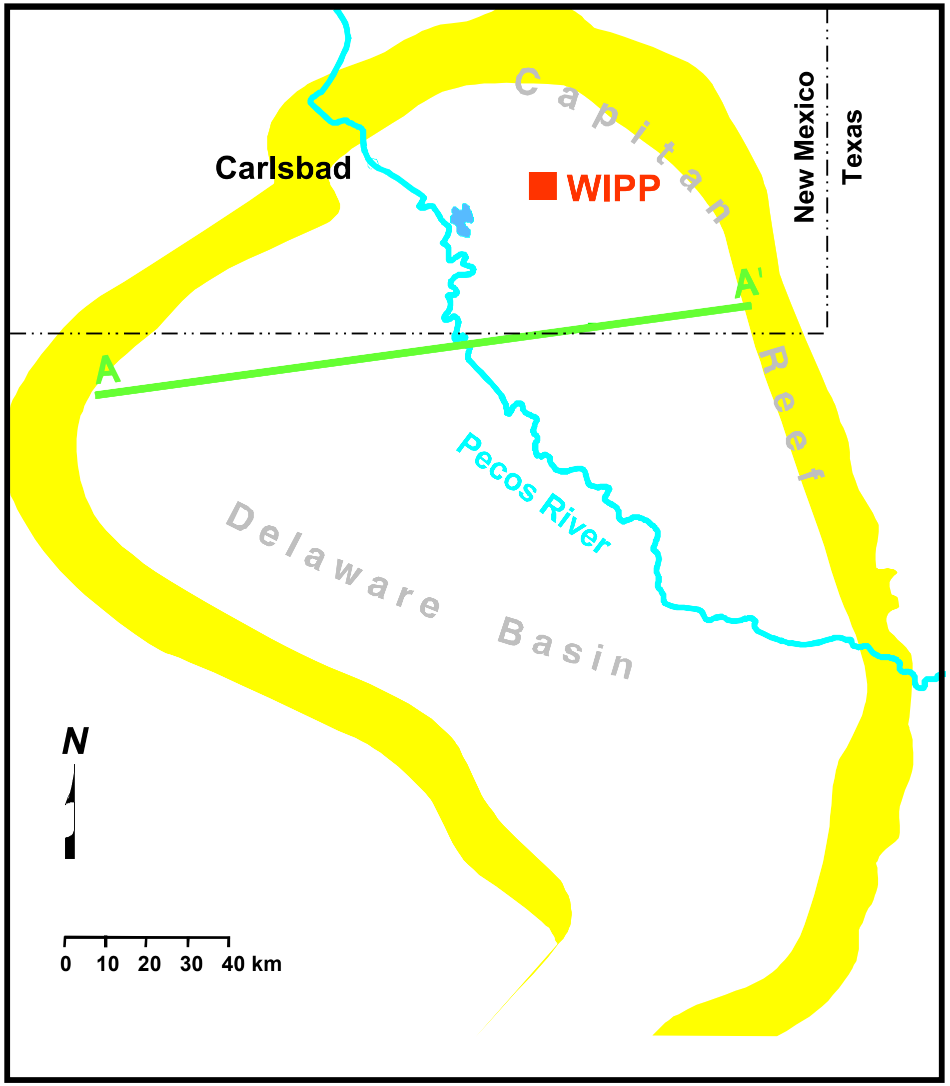


CH-TRU waste shipped and emplaced in drums (55, 85, and 100 gal) and “standard waste boxes”

Granular MgO emplaced above waste stacks to consume CO_2 and buffer pH to reduce actinide solubility in brine

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

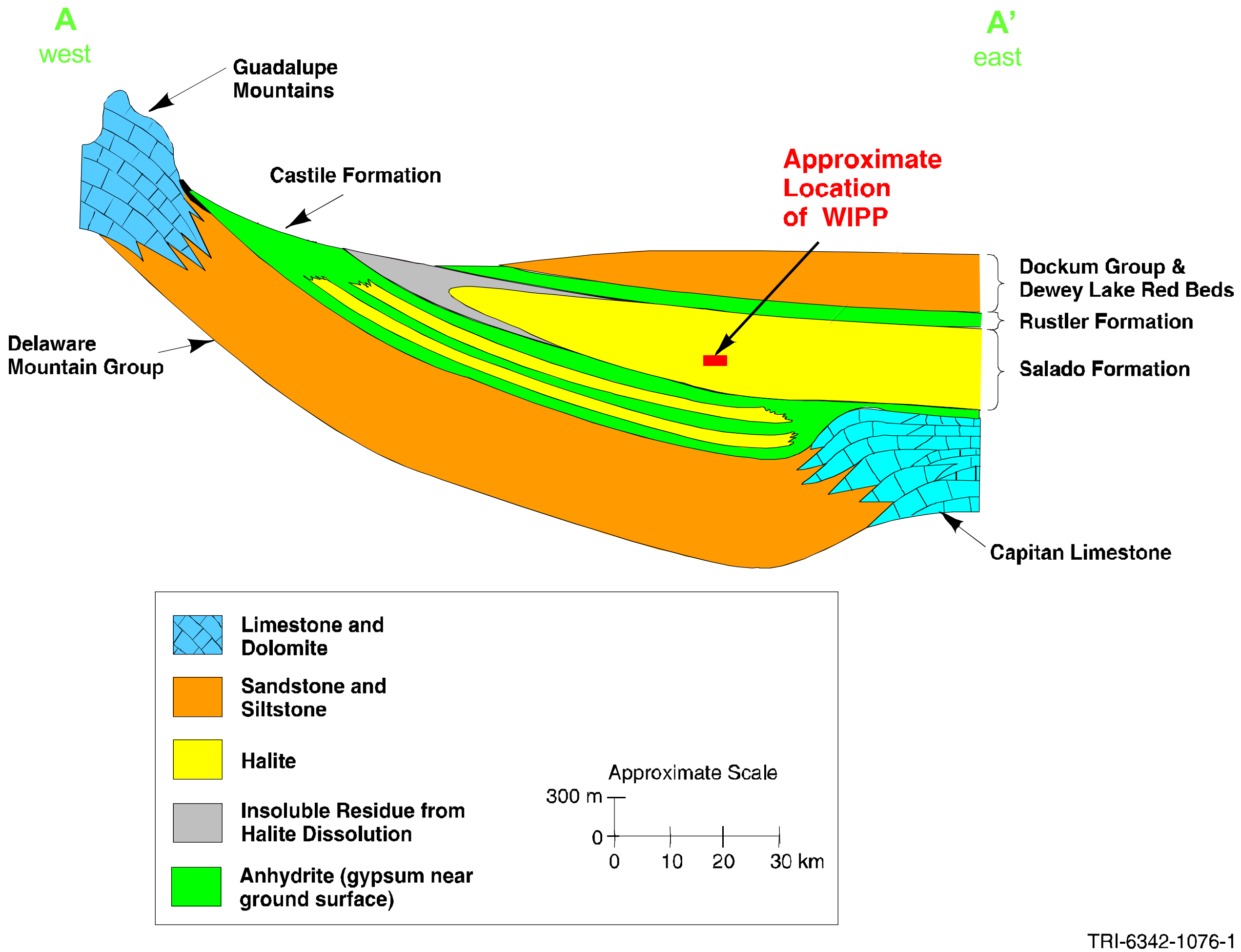
Site Geology



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

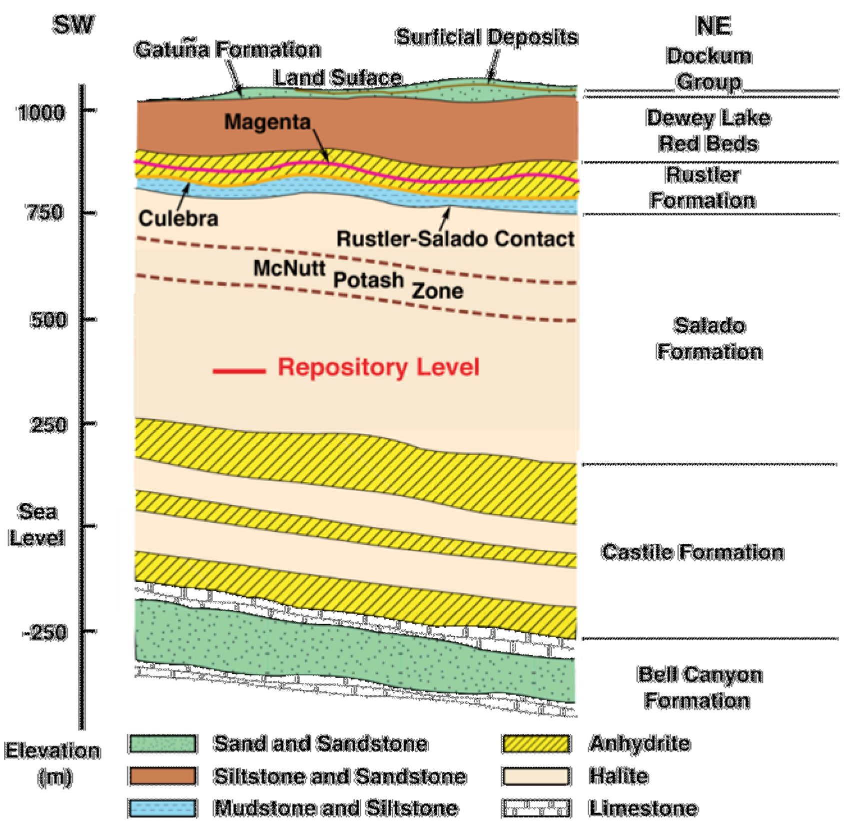
Site Geology (cont.)



Schematic West-East Geologic Cross Section of Delaware Basin

Note extreme vertical exaggeration

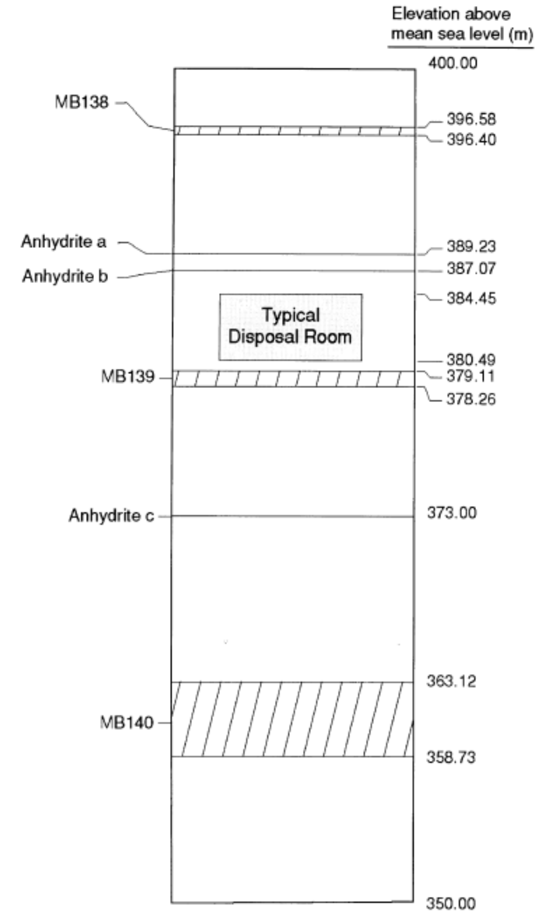
Local Stratigraphy at WIPP



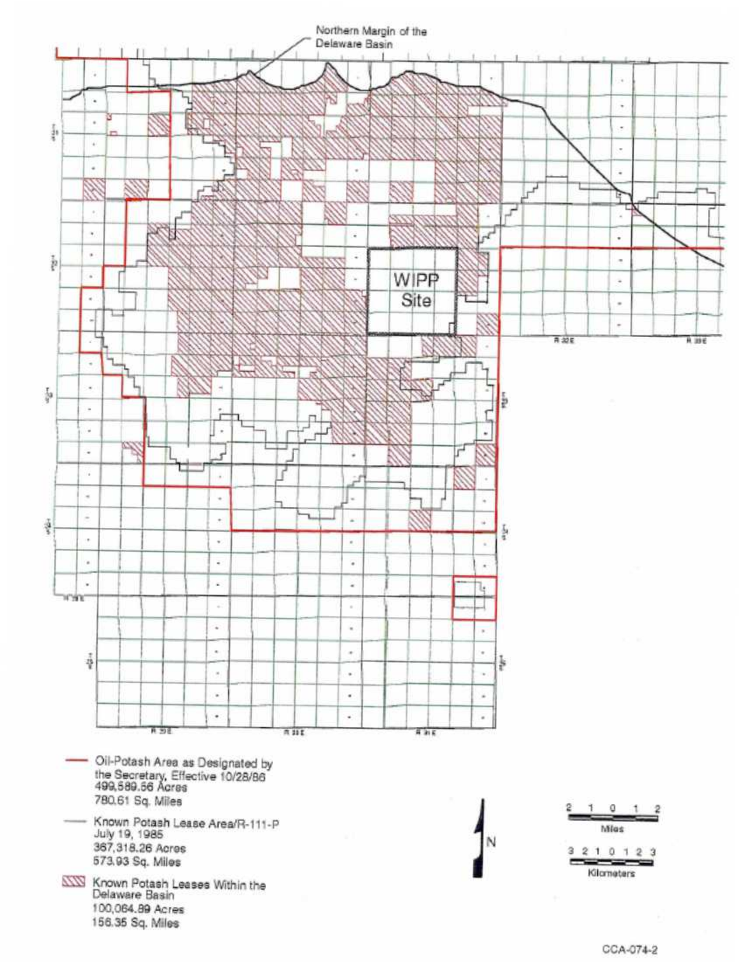
Within the Salado Fm, halite units are separated by laterally persistent interbeds of anhydrite, clay, and polyhalite.

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, from Google Maps 12/6/2016

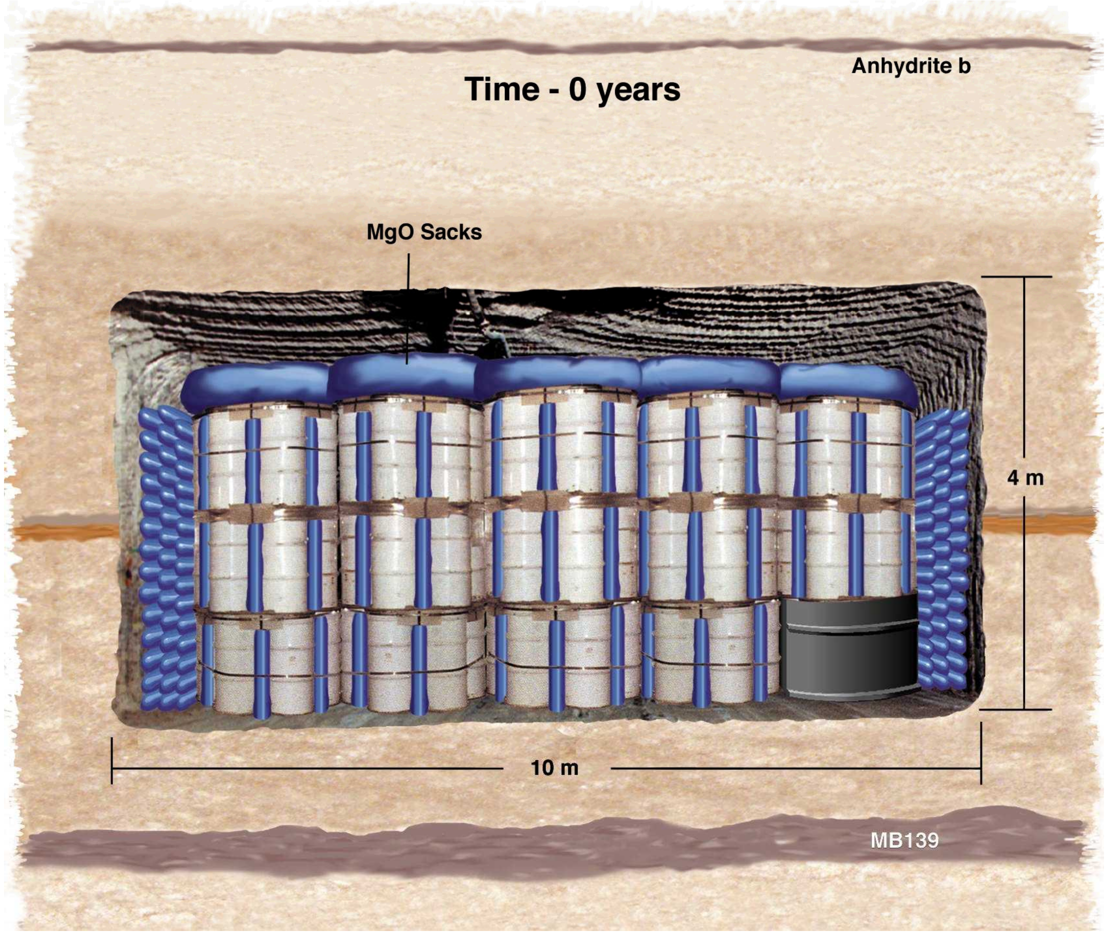
The Premise for Isolation in Salt

- 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

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

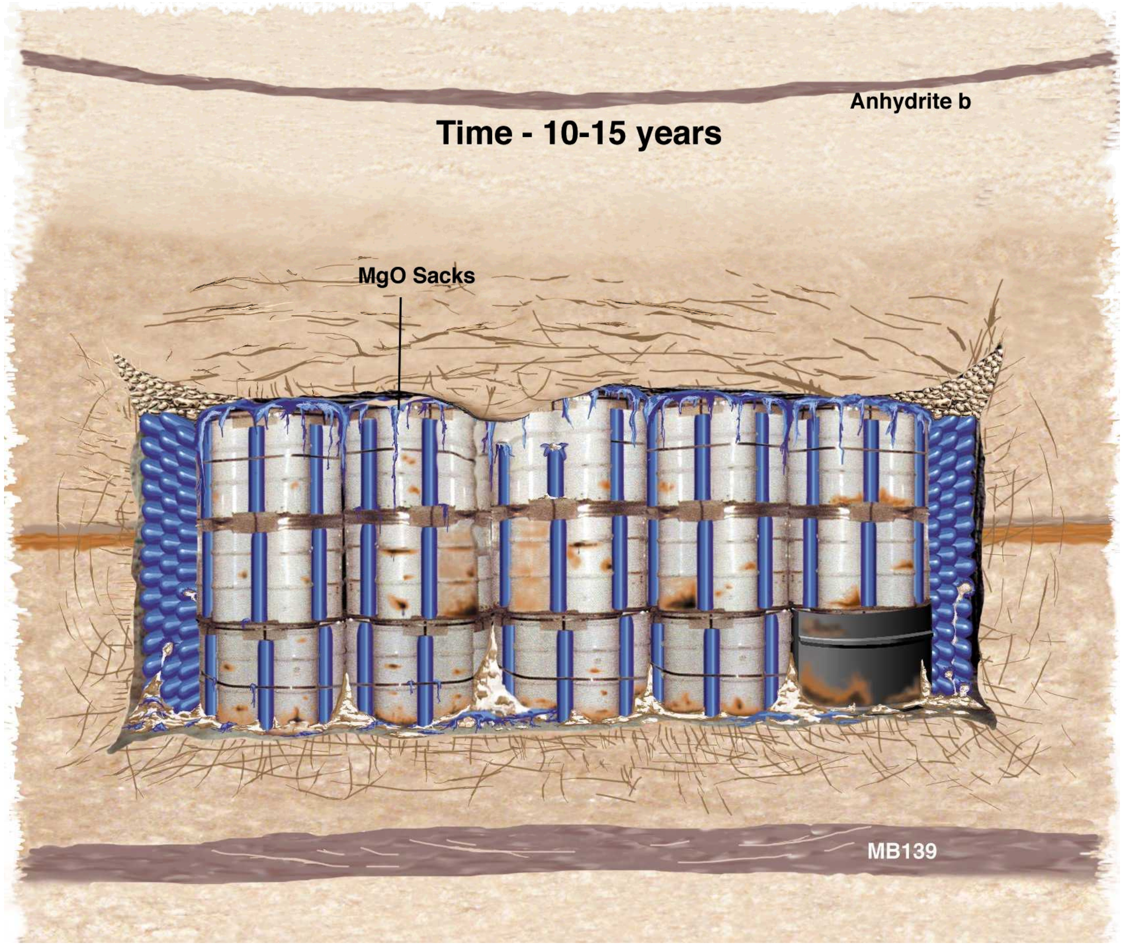


Conceptual Model for Long-term Performance: The Near Future

Rapid Salt Creep Partially Encapsulates Waste

Processes

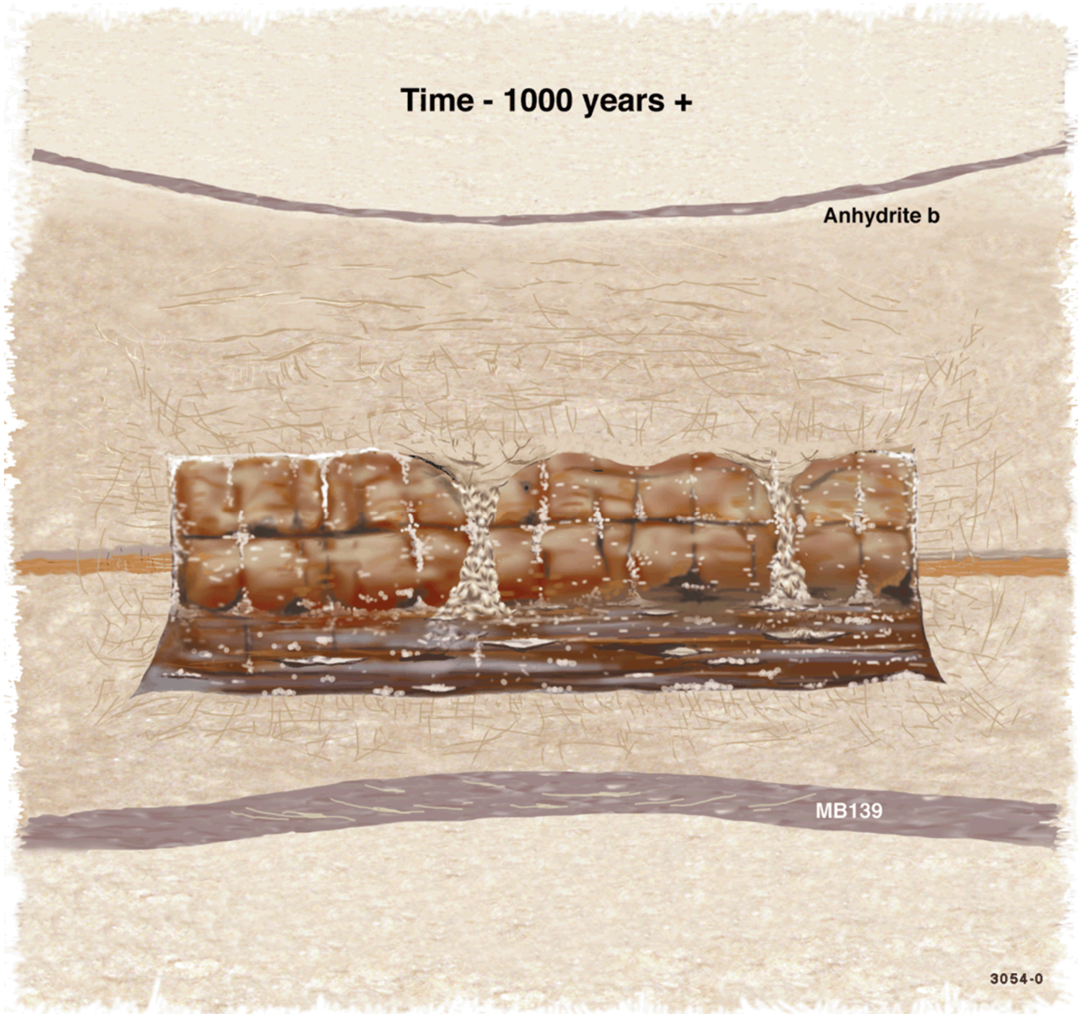
- Salt creep
- Floor heave
- Roof fall
- Collapse of salt into waste
- Disturbed-rock-zone dewatering
- Drum crushing
- Porosity, permeability reduction
- Breaching of MgO sacks
- Minor corrosion
- Degradation of organic waste



Conceptual Model for Long-term Performance: Final State?

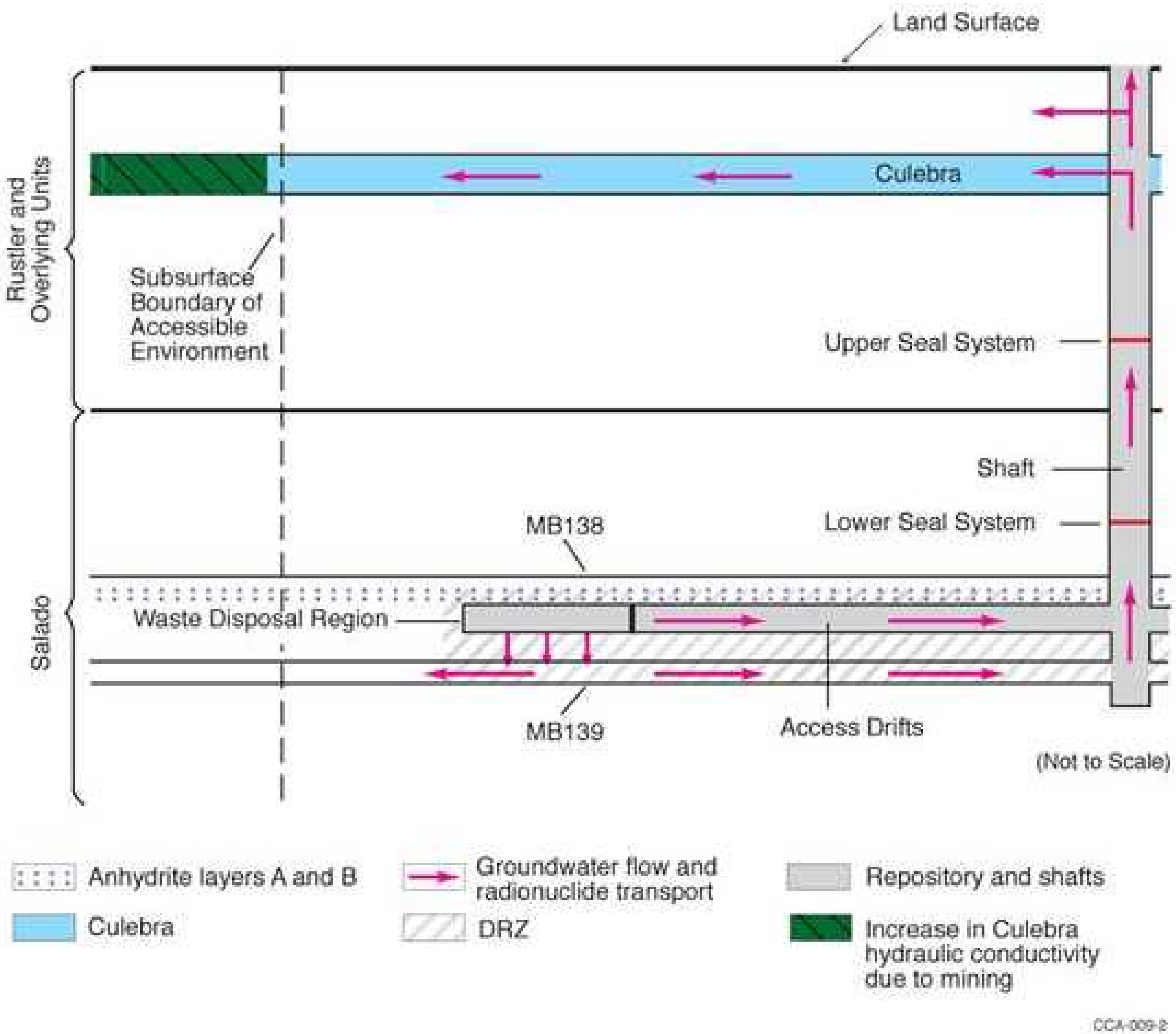
Salt Creep Encapsulates Waste

- 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 (no accidental drilling)



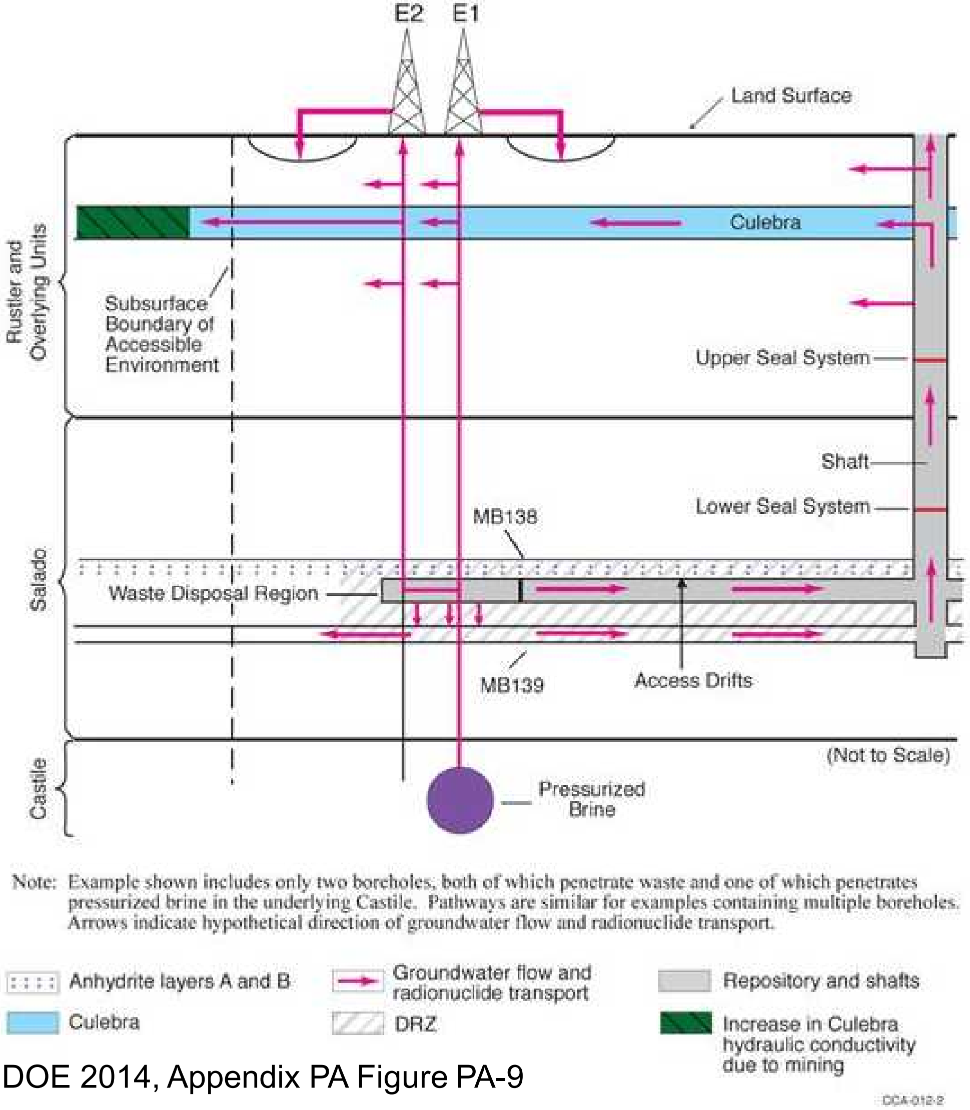
DOE 2014, Appendix PA Figure PA-5

Scenarios for WIPP Performance Assessment:

Disturbed Performance (drilling through repository)

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



DOE 2014, Appendix PA Figure PA-9

Release Mechanisms Contributing to the Overall Radiation Release

Undisturbed performance results in zero release

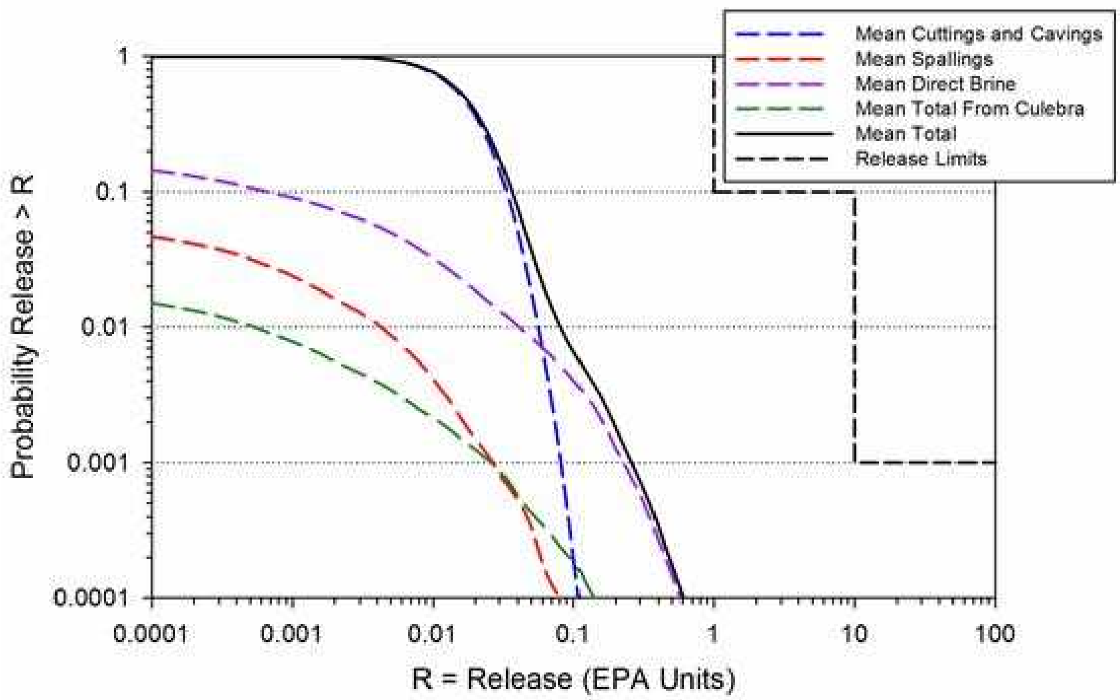
All releases are due to drilling intrusions

“**Cuttings and Caving**s” are the material brought to the surface during drilling

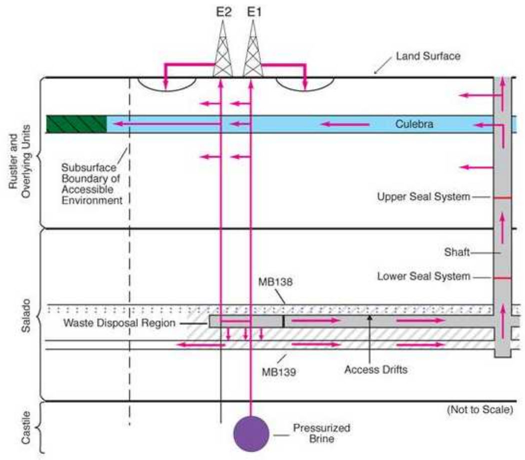
“**Spallings**” are solid material that is transported into the hole during depressurization and brought to the surface during drilling

“**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)



Summary of Long-term WIPP Performance

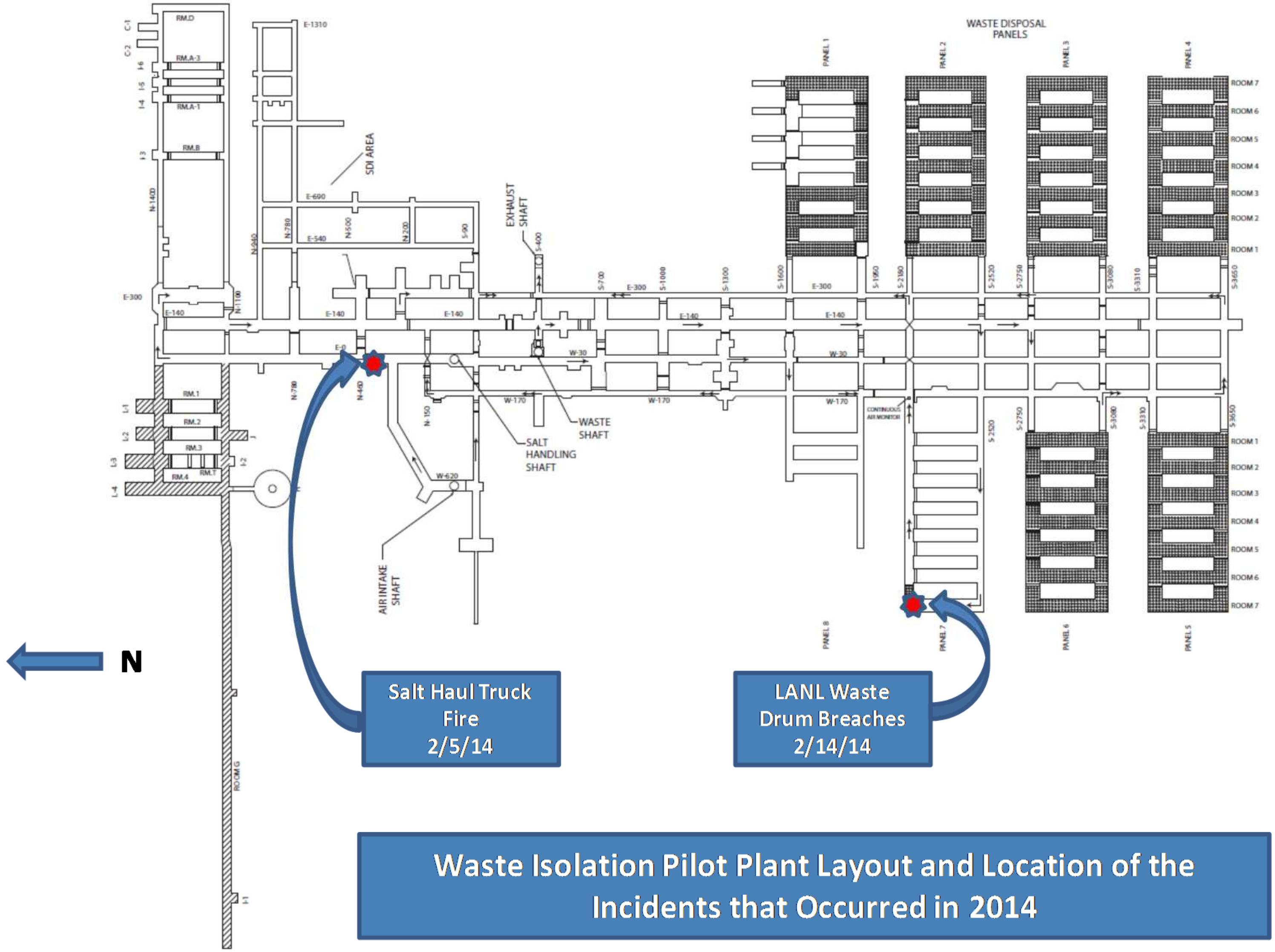
- Geologic barriers provide long-term isolation
  - Dry climate
  - Very low permeability of salt
  - No naturally-occurring disruptive events are sufficiently likely to impact 10,000-year performance
- No radionuclide releases to accessible environment during 10,000-year performance period without human 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

Recent WIPP Events

- Mine haul truck fire Feb 5, 2014
- Barrel of waste ignites and radiological release occurs (unrelated to haul truck fire) Feb 14, 2014
- Rock falls Sept-Nov, 2016

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

Haul Truck Fire and Waste Drum Breach



Waste Isolation Pilot Plant Layout and Location of the Incidents that Occurred in 2014

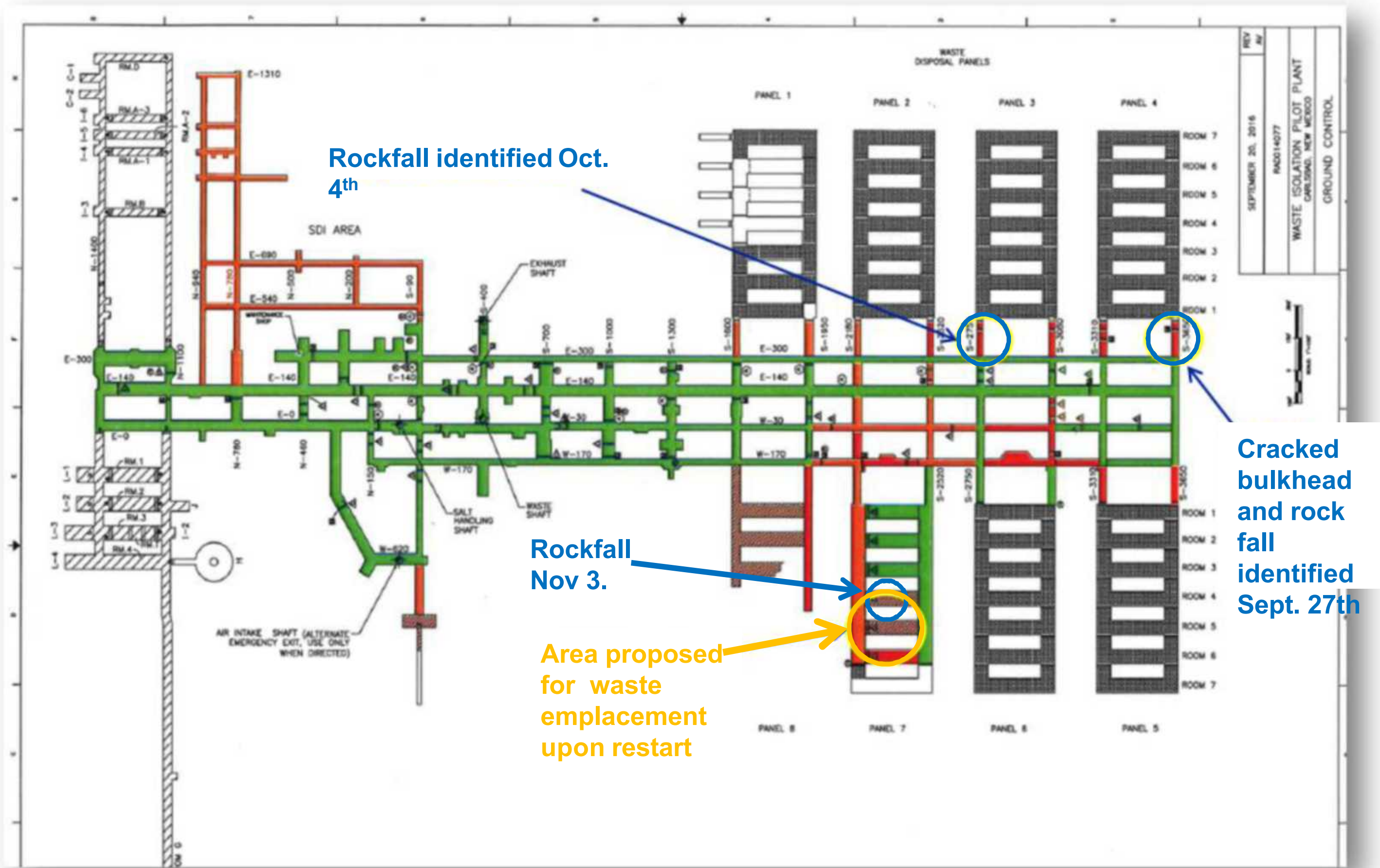
Rockfalls

Salt creep requires that be filled rapidly after excavation, and that access tunnel walls and ceilings continuously be “cleaned” to avoid rockfalls. Since the radioactive release incident, access restrictions have limited cleaning.

(1) Panel 4 (area closed 2010), identified Sept 27, 2016

(2) Panel 3 (area closed 2007), identified Oct. 4, 2016

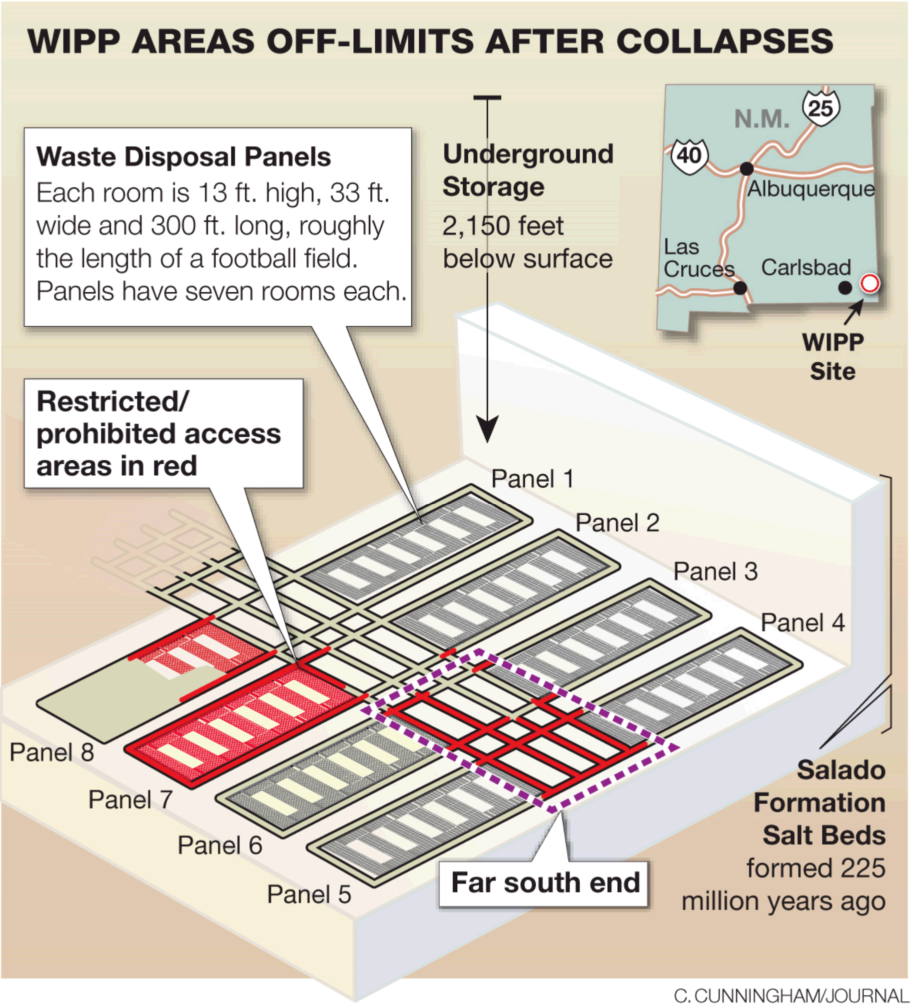
(3) Panel 7 Room 4 (area active, proposed for waste emplacement upon restart), Nov. 3, 2016



Rockfalls, cont.

Proposed Mitigations

- Potentially hazardous areas are now restricted-access
- Seal off the south end of facility where the two early rockfalls occurred
- Stabilize room ceilings with rockbolts in Panel 7 to allow waste emplacement (abandon panel if necessary)



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."

July 31, 2015:

"In the light of the safety-related activities that must be completed before waste emplacement begins, a new target date for the restart of waste emplacement operations in 2016 must be established."

Cleanup efforts continue…

August 19, 2016:

LA Times estimates final cost of the WIPP cleanup could be more than $2B.

Spent Nuclear Fuel and High Level Radioactive Waste Disposal: the Yucca Mountain Project

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

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)

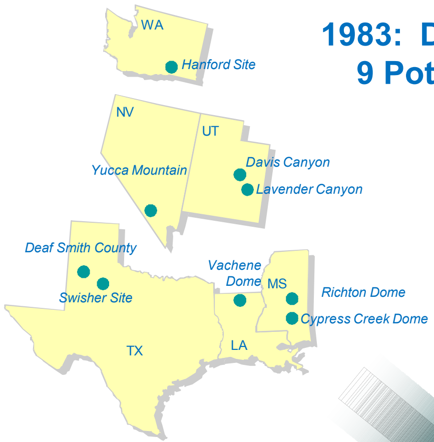
DOE & Commercial High-Level Waste:
4,667 MTHM
(~3000 waste packages of co-disposed DSNF and HLW)

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

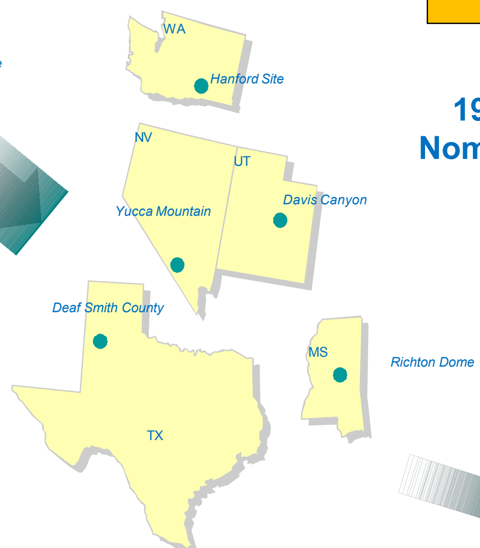
1982-1987: The Siting Process under the NWPA

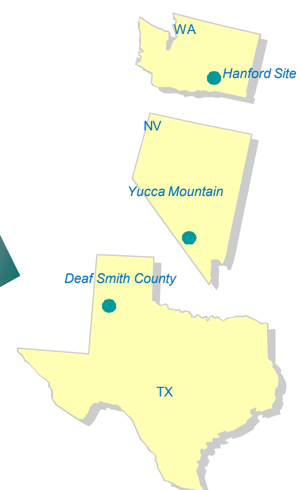
The NWPA of 1982 (sec. 112) requires
- *DOE to consult with affected governors and issue siting guidelines*
- *The Secretary to nominate at least five sites*
- *The Secretary to recommend 3 sites for characterization*

1983: DOE identifies 9 Potential Sites

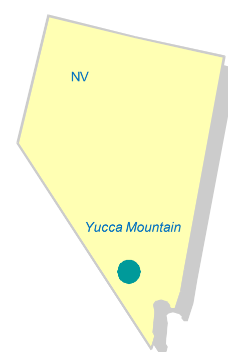


1986: Secretary of Energy Nominates 5 Sites, 3 Approved for Further Study

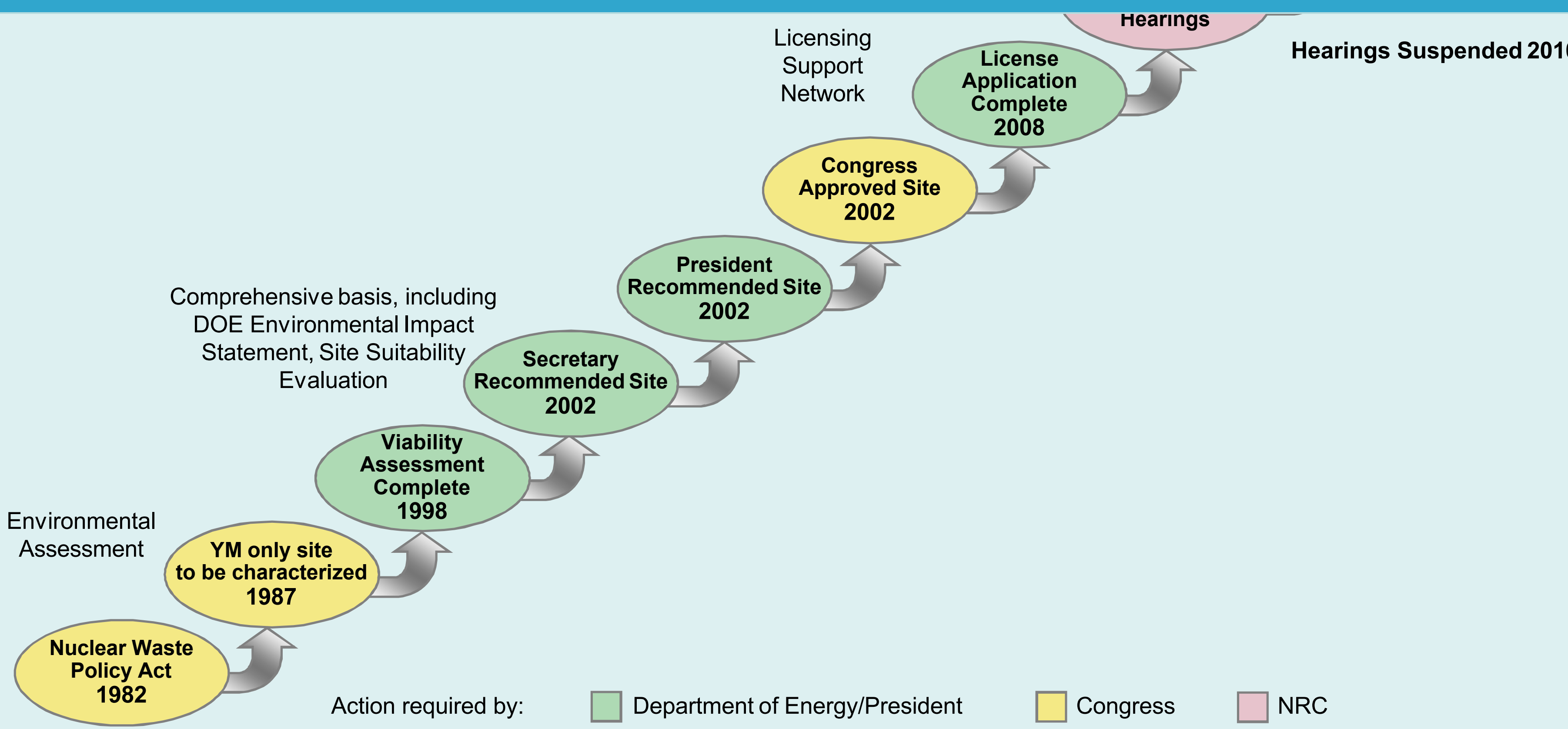




1987: NWPA Amended to Mandate One Site for Characterization



Yucca Mountain under the NWPA



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

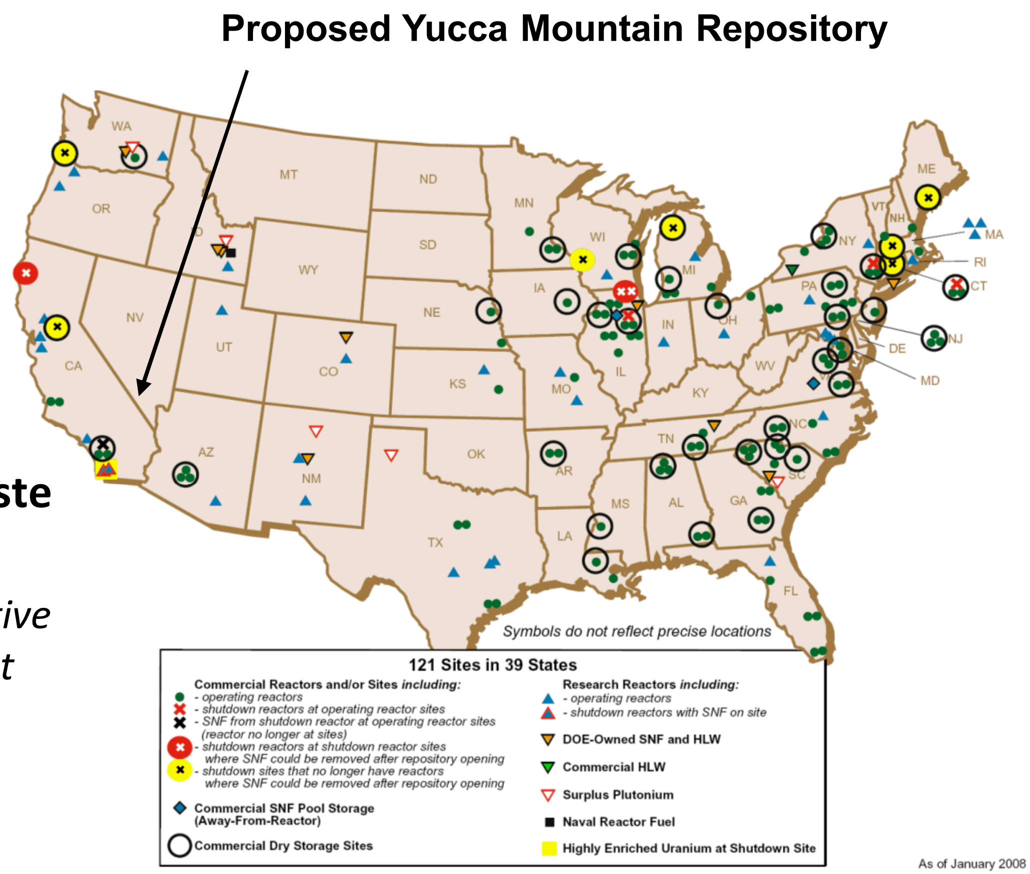
The Yucca Mountain Mission

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

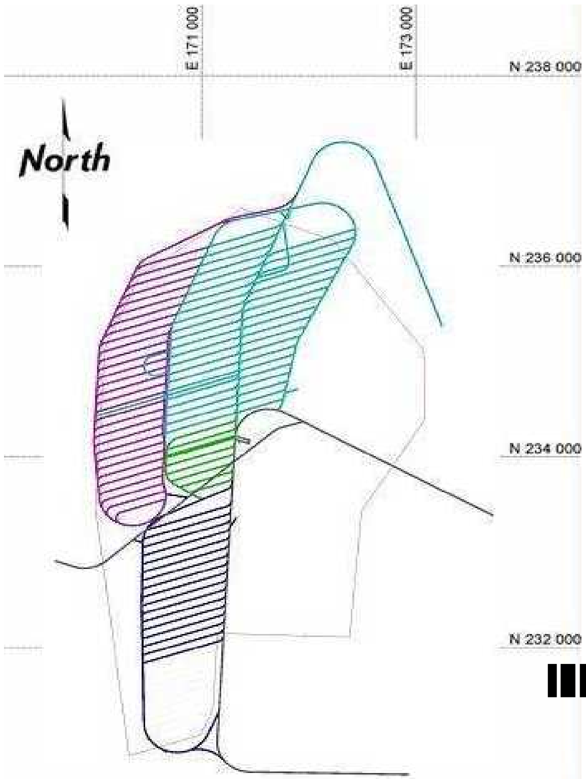
[121 sites in 39 states]

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.



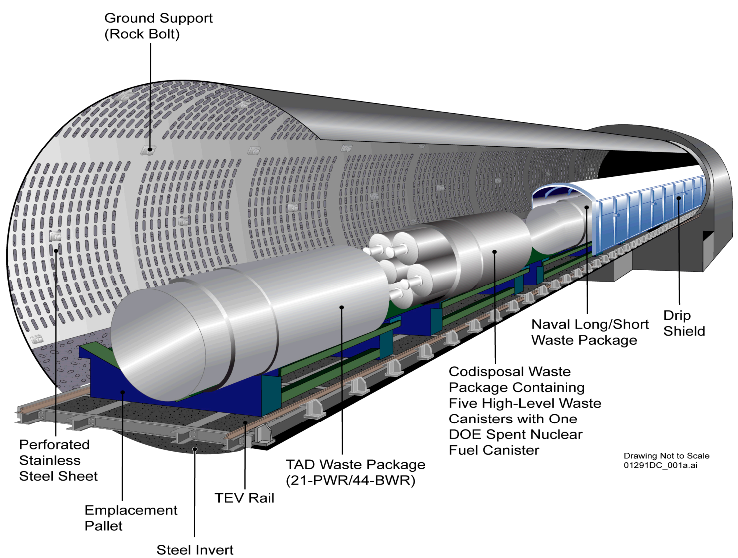
Yucca Mountain Subsurface Design



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

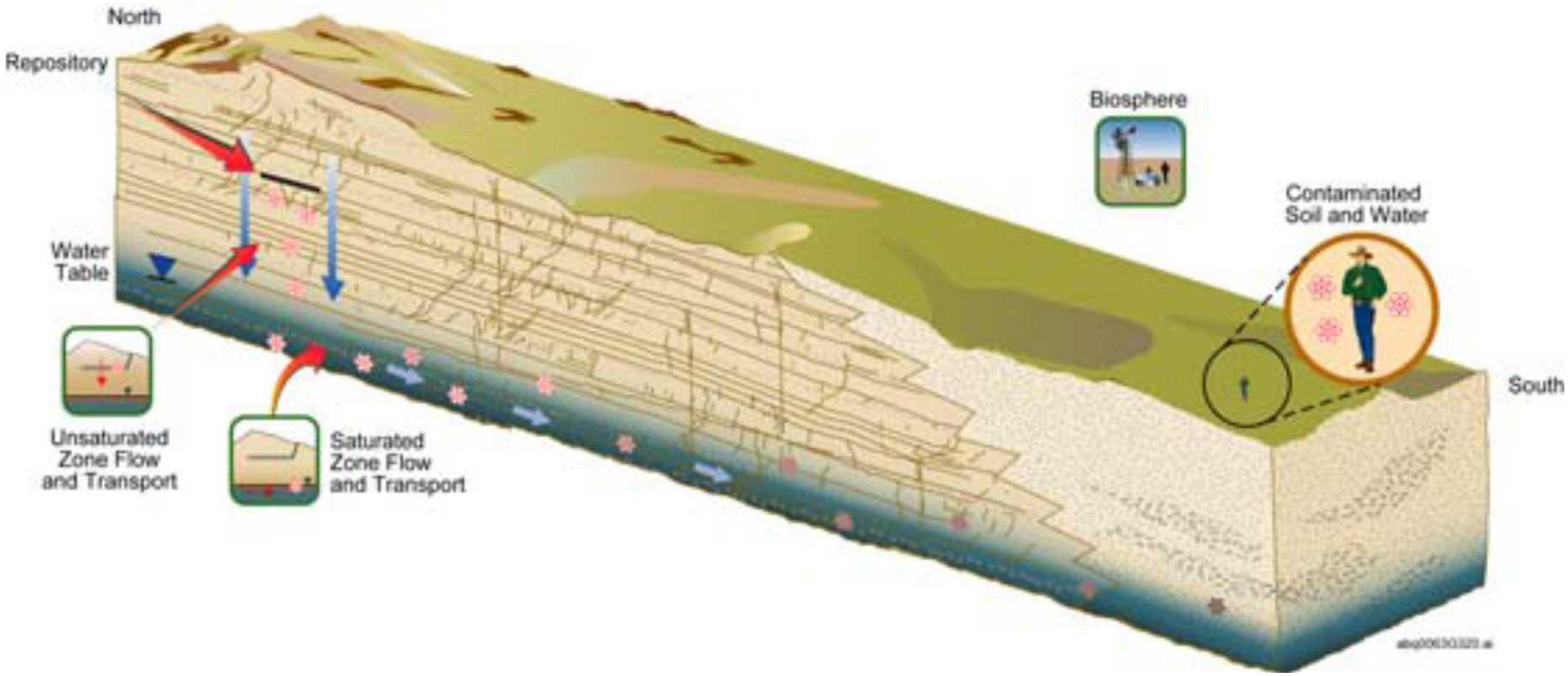
Drip shields
- free-standing 1.5 cm Ti shell



Yucca Mountain Exploratory Studies Facility

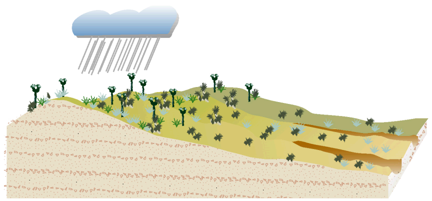
Long-term Performance of the Proposed Yucca Mountain Repository

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



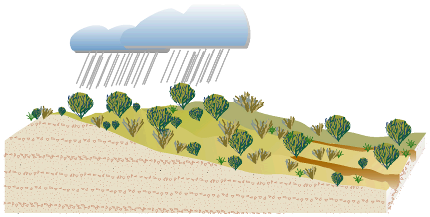
  - Radionuclides are mobilized by seepage water and percolate downward to the water table
  - Lateral transport in the saturated zone leads to biosphere exposure at springs or withdrawal wells

Groundwater Flow at Yucca Mountain



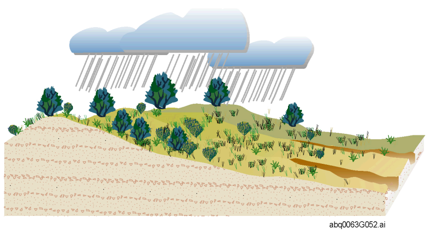
Present Day

Yucca Mountain



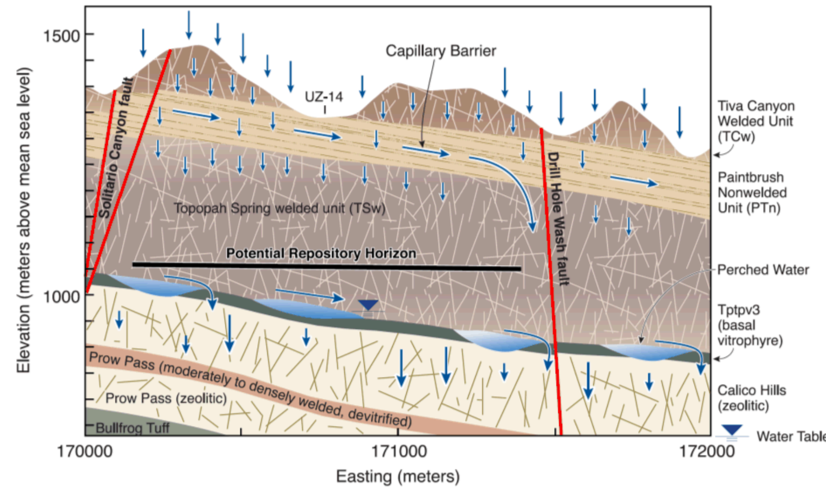
Monsoon

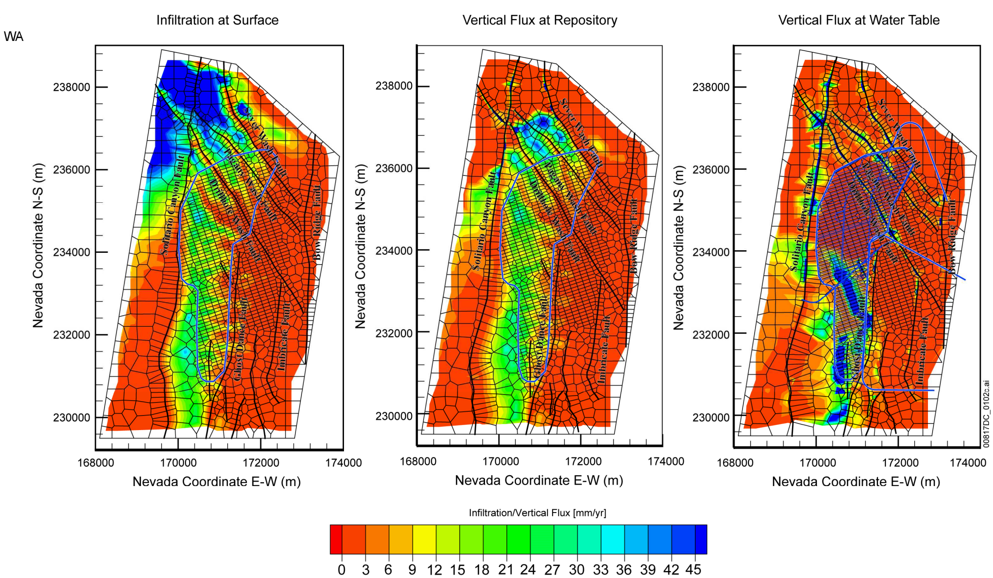
Lower-bound analog: Yucca Mountain
Upper-bound analog: Nogales, AZ
Higher precipitation and temperature than present-day



Glacial Transition

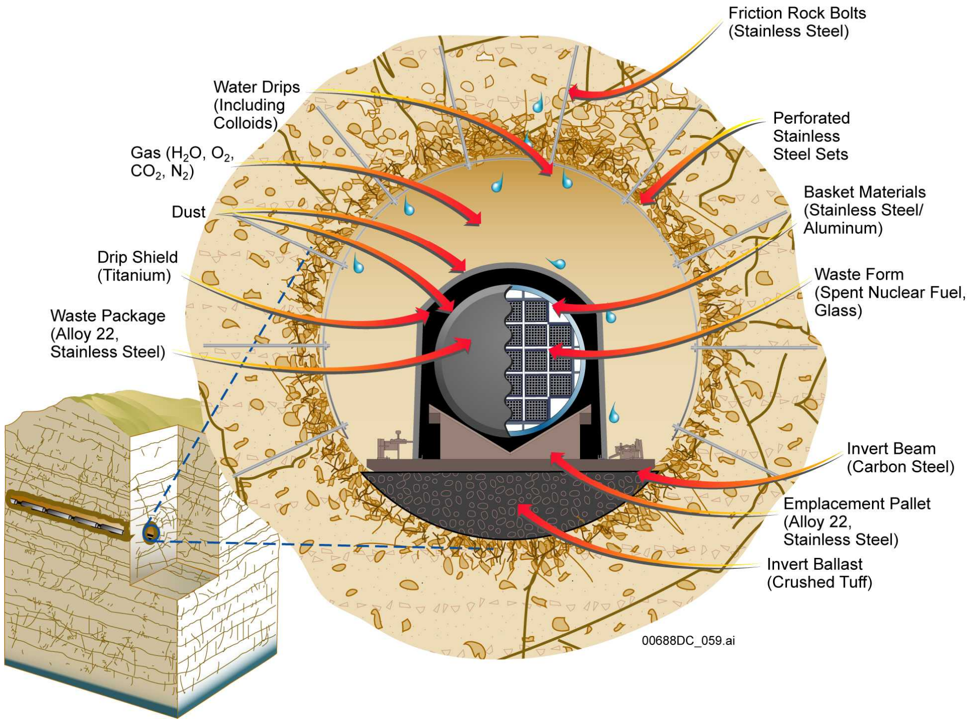
Lower-bound analog: Delta, UT
Upper-bound analog: Spokane, WA
Higher precipitation and lower temperature than present-day

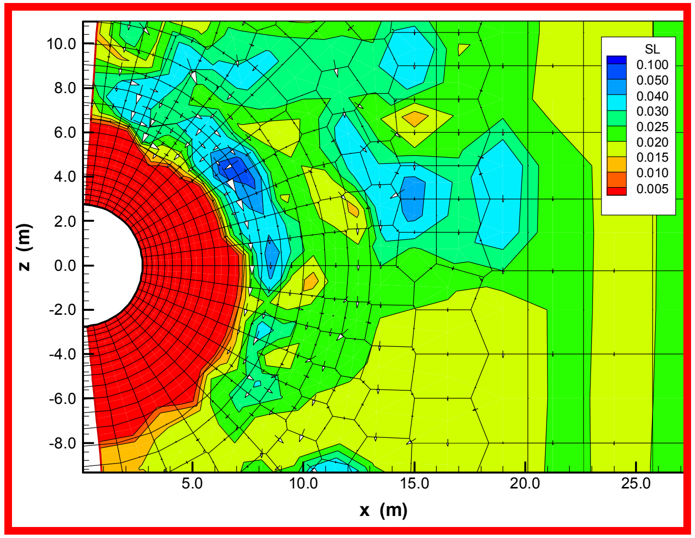




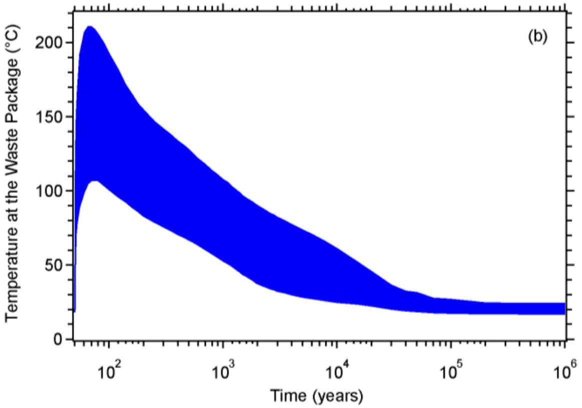
Field tests and models provide basis for understanding infiltration and flow in unsaturated rocks at Yucca Mountain

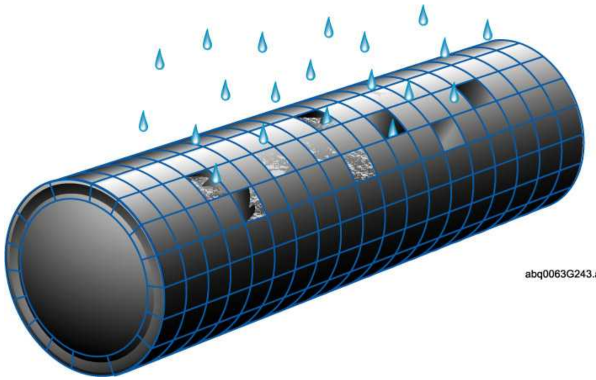
The Emplacement Environment at Yucca Mountain



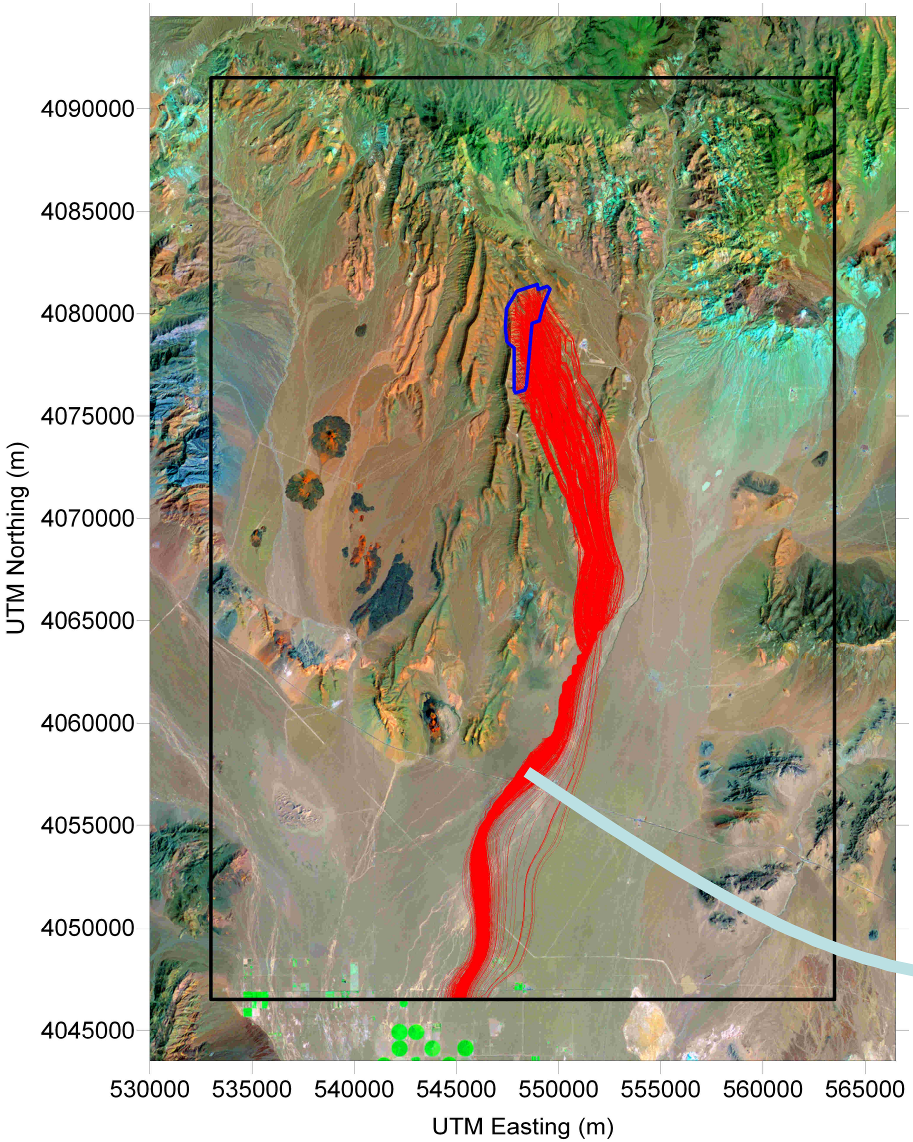


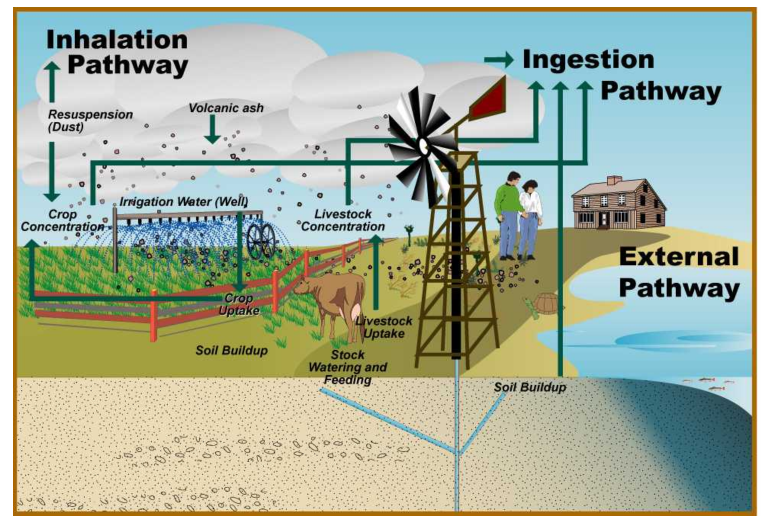
Material testing and models characterize performance of the engineered barriers





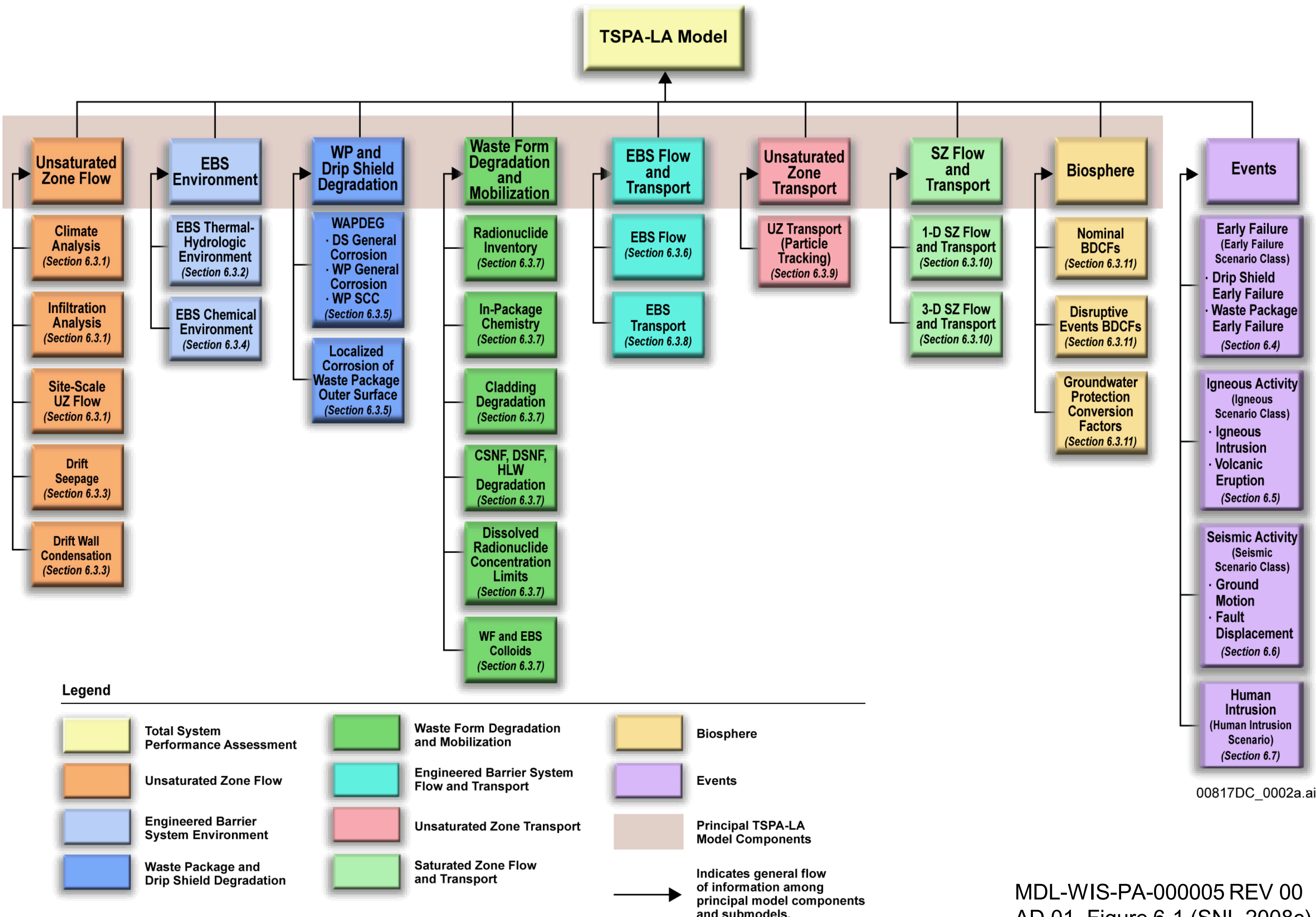
Estimating Dose to Hypothetical Future Humans





Modeled groundwater flow paths and hypothetical exposure pathways

Postclosure Science Supporting the TSPA



MDL-WIS-PA-000005 REV 00 AD 01, Figure 6-1 (SNL 2008c)

Uncertainty in the Yucca Mountain TSPA

Sandia National Laboratories

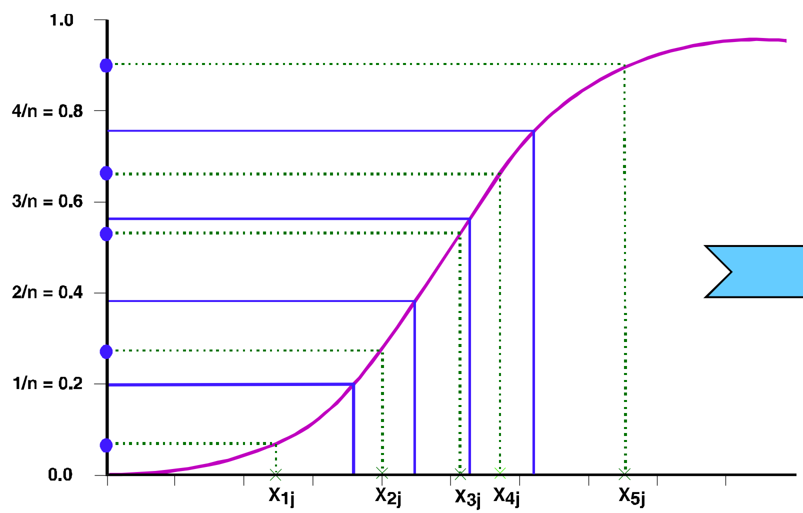
Aleatory Uncertainty
− Inherent randomness in events that could occur in the future
− Alternative descriptors: irreducible, stochastic, intrinsic, type A
− Examples:
➢ *Time and size of an igneous event*
➢ *Time and size of a seismic event*

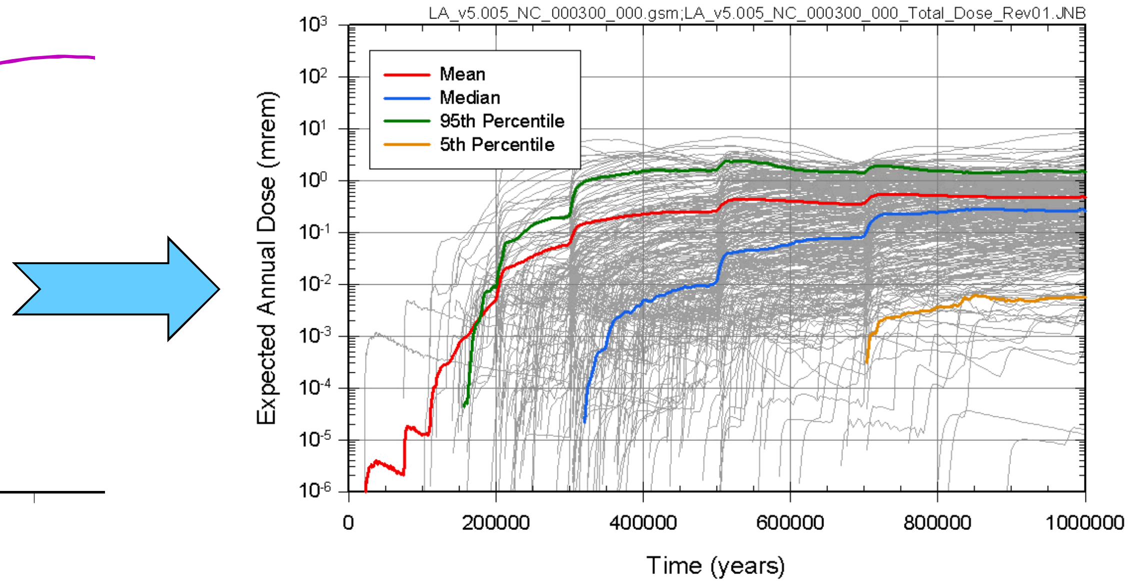
Epistemic uncertainty
− Lack of knowledge about appropriate value to use for a quantity assumed to have a fixed value
− Alternative descriptors: reducible, subjective, state of knowledge, type B
− Examples:
➢ *Spatially averaged permeabilities, porosities, sorption coefficients, …*
➢ *Rates defining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

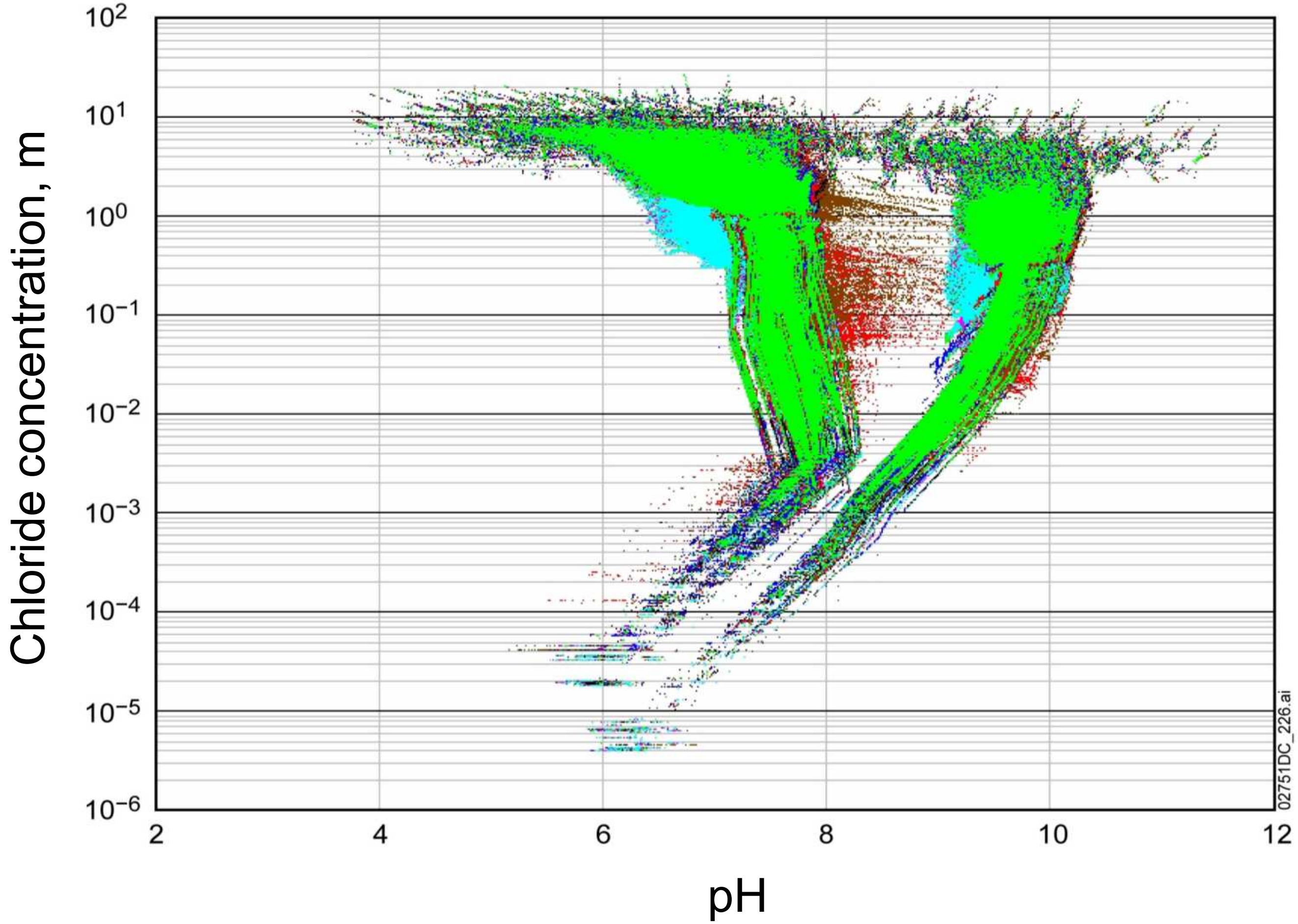




Example of Epistemic Uncertainty

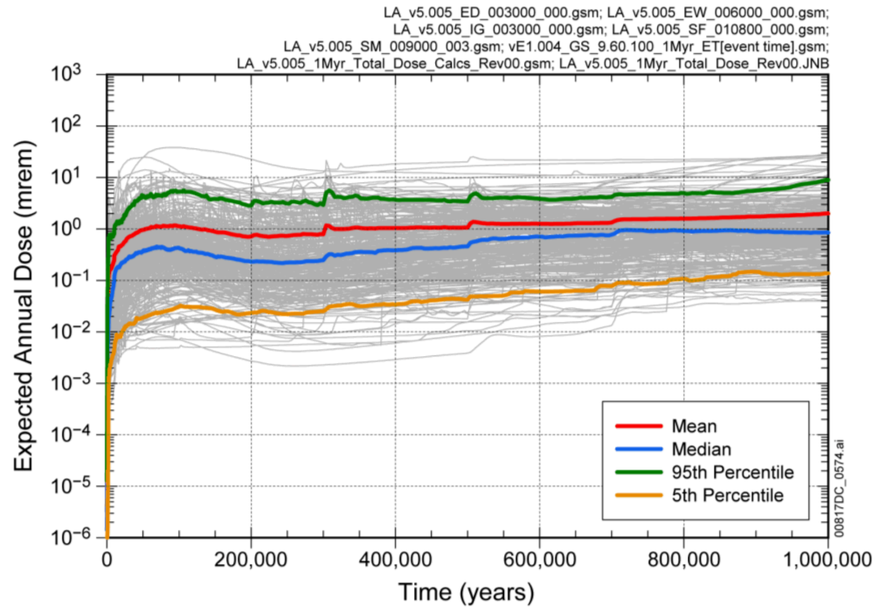
Composition of water contacting the waste package

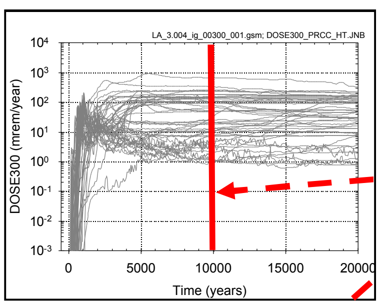
Graph summarizing 23 million of the over 600 million water compositions generated by the Waste Package Degradation (WAPDEG) model.



Interpreting the Importance of Epistemic Uncertainty on Performance Assessment Results

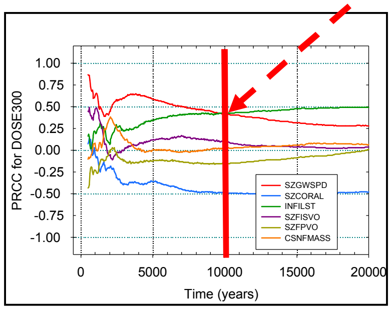
Monte Carlo estimates of overall performance
(Example dose histories from Yucca Mountain Total System Performance Assessment for the License Application, total expected dose from all scenarios)

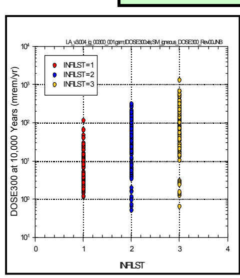


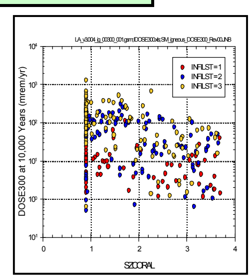


DOSE300: 10,000 yr

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







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

Treatment of Aleatory Uncertainty: Defining Scenarios Based on Unlikely Events

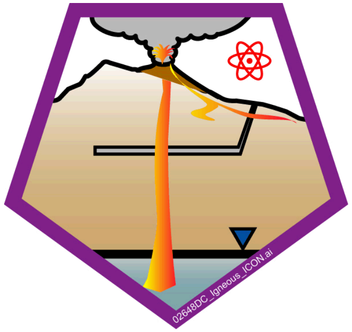
Four scenario classes divided into seven modeling cases

Nominal Scenario Class

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

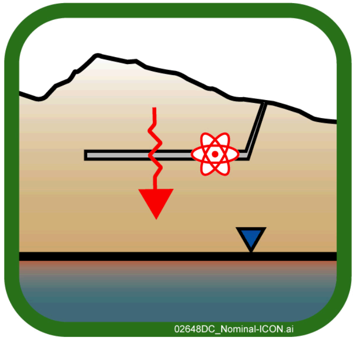
Igneous Scenario Class

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



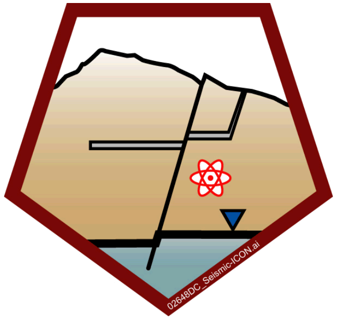
Early Failure Scenario Class

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



Seismic Scenario Class

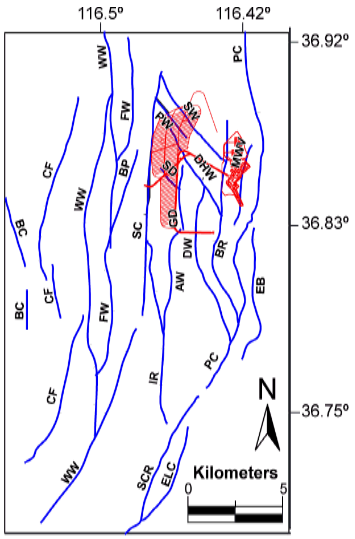
- **Ground Motion Modeling Case**
- **Fault Displacement Modeling Case**



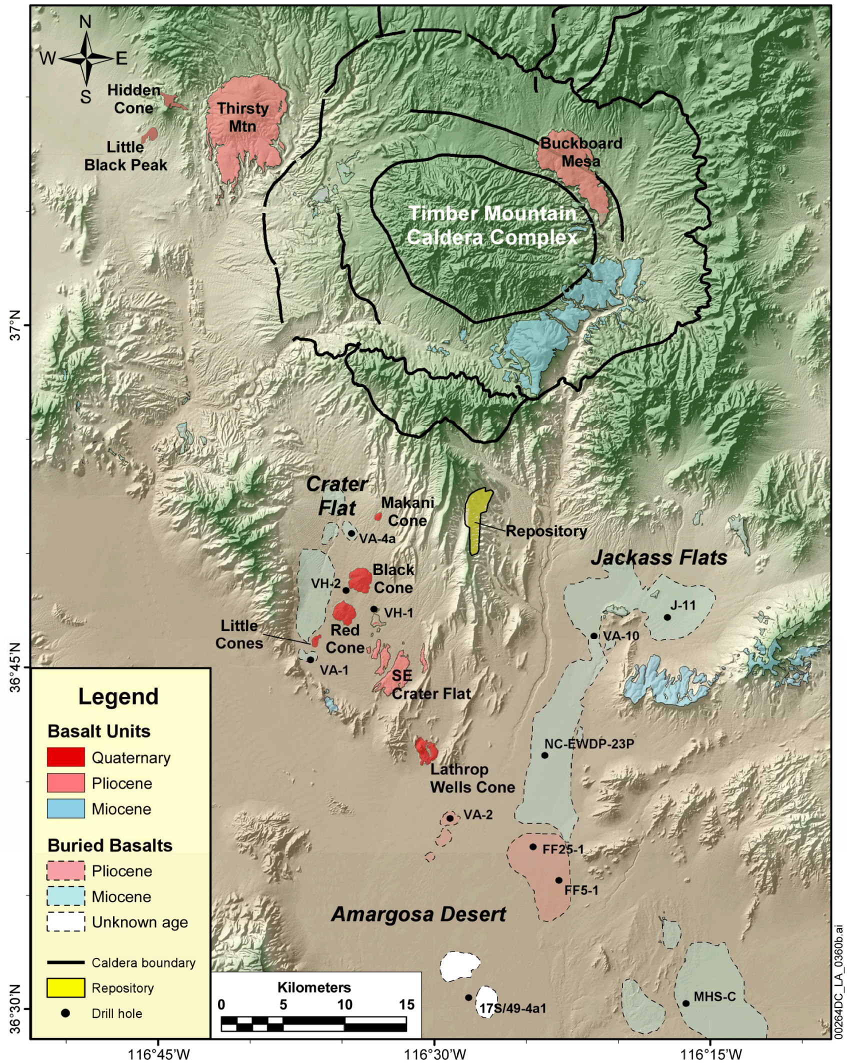
Potential Disruptive Geologic Events at Yucca Mountain

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

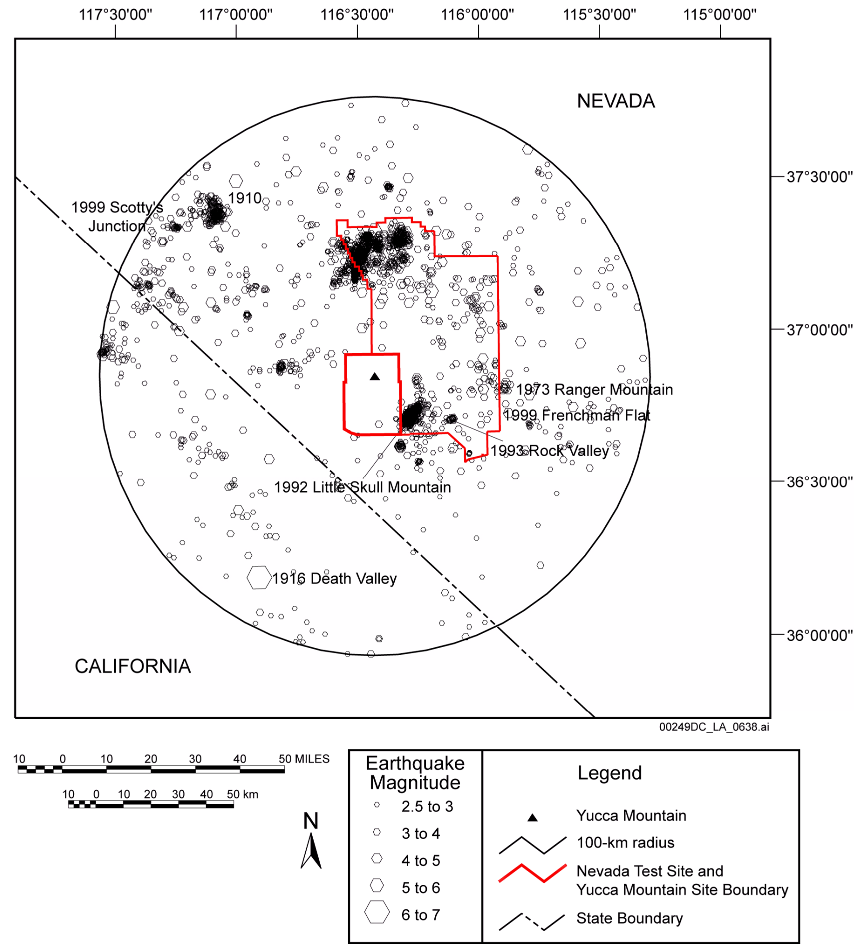
- **Seismicity**
  - Map shows Quaternary age faults (<1.5Myr) in the Yucca Mountain region



Igneous and Seismic Activity in the Yucca Mountain Region

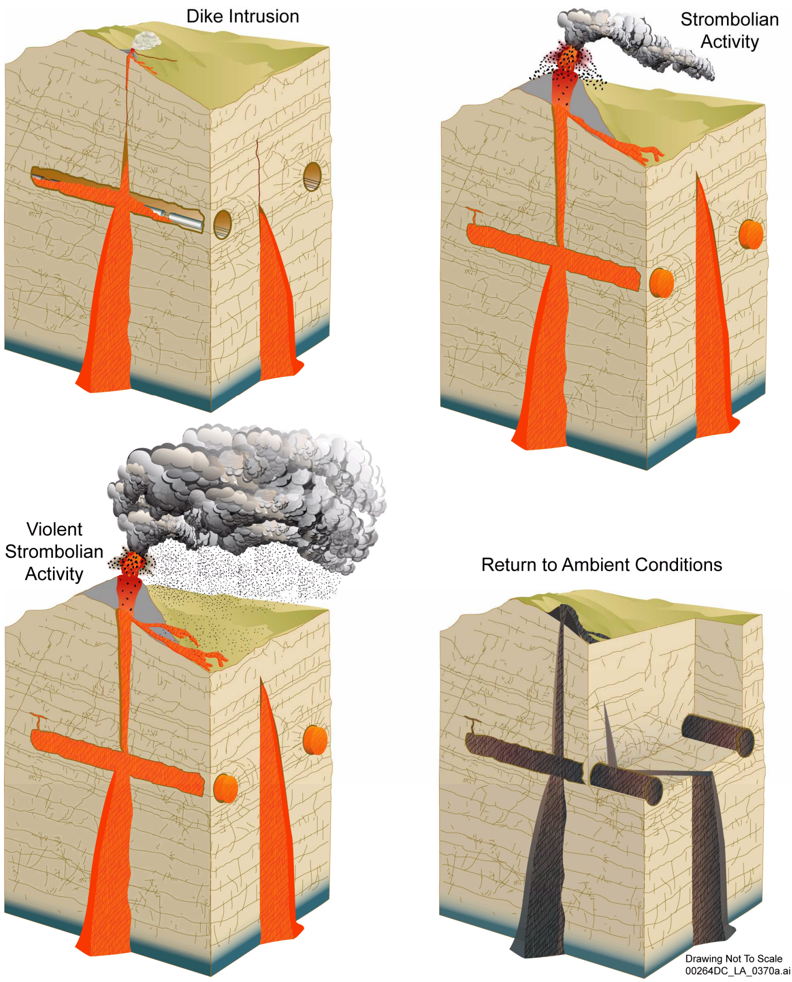


Distribution of Miocene and younger (< 5.3 Ma) Basaltic Rocks in the Yucca Mountain Region (DOE/RW-0573 Rev. 1, Figure GI 5-39)



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

Consequence Models for Igneous Disruption at Yucca Mountain

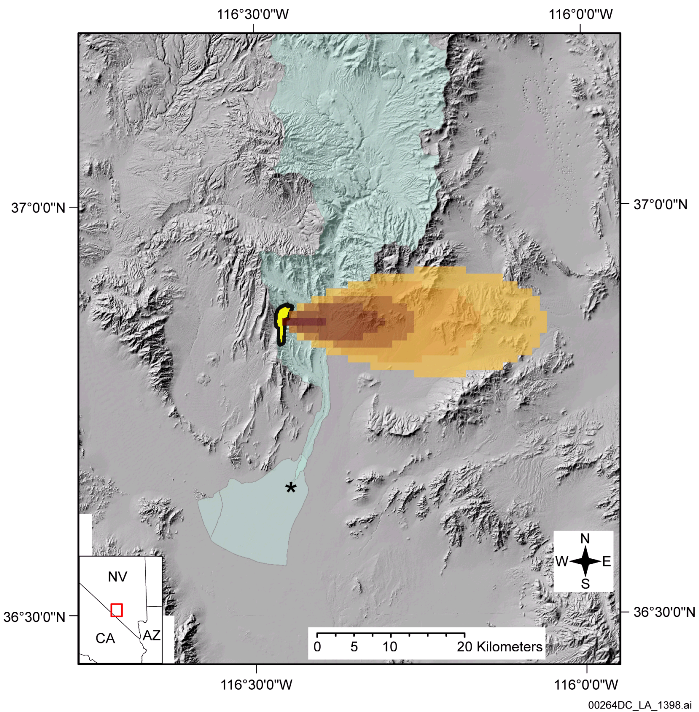


Schematic Drawing of an Igneous Event at Yucca Mountain (DOE/RW-0573 Rev. 1, Figure 2.3.11-5)

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

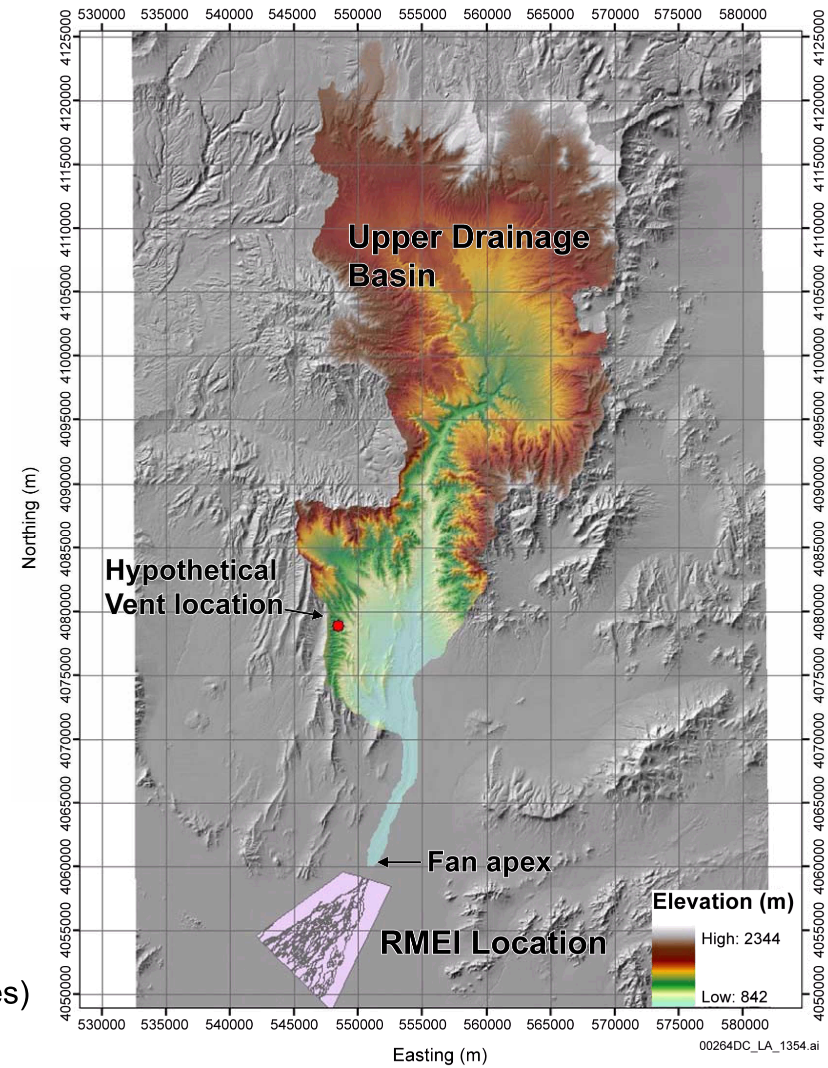
Modeling Consequences of Volcanic Eruption



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)

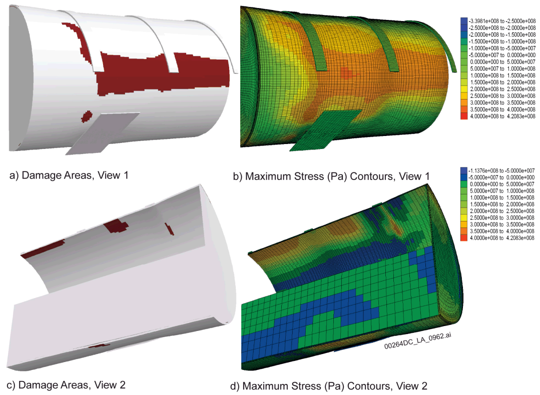


Model domain for surface redistribution of ash (DOE/RW-0573 Rev. 1, Figure 2.3.11-5)

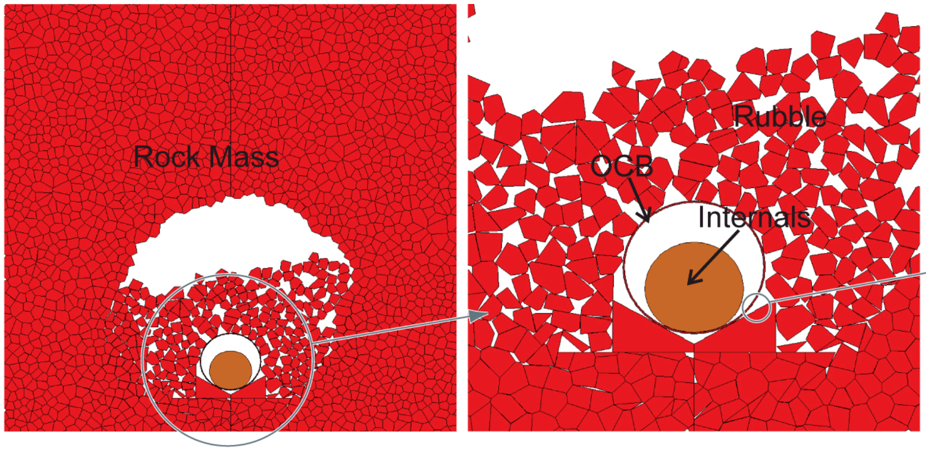
Consequence Models for Seismic Disruption at Yucca Mountain

- 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)



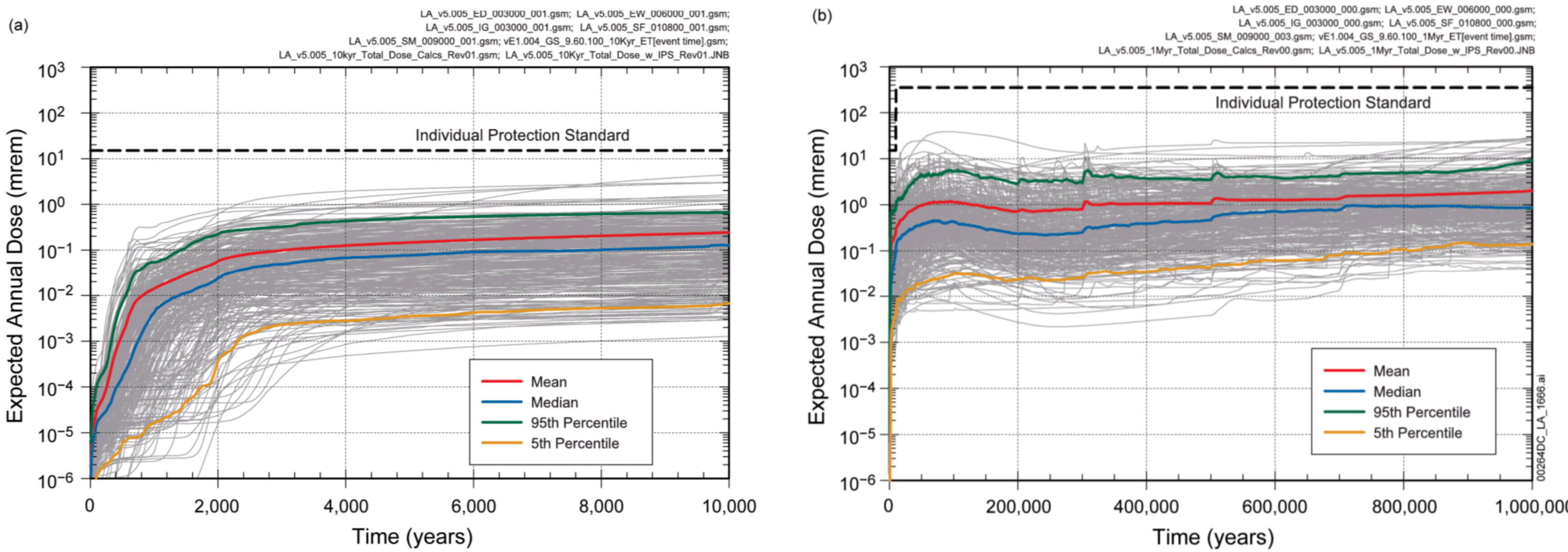
Below
Model for Rubble-Waste Package Interactions (DOE/RW-0573 Rev. 1, Figure 2.3.4-88)



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



DOE/RW-0573 Rev 1 Figure 2.4-10

10,000 years

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

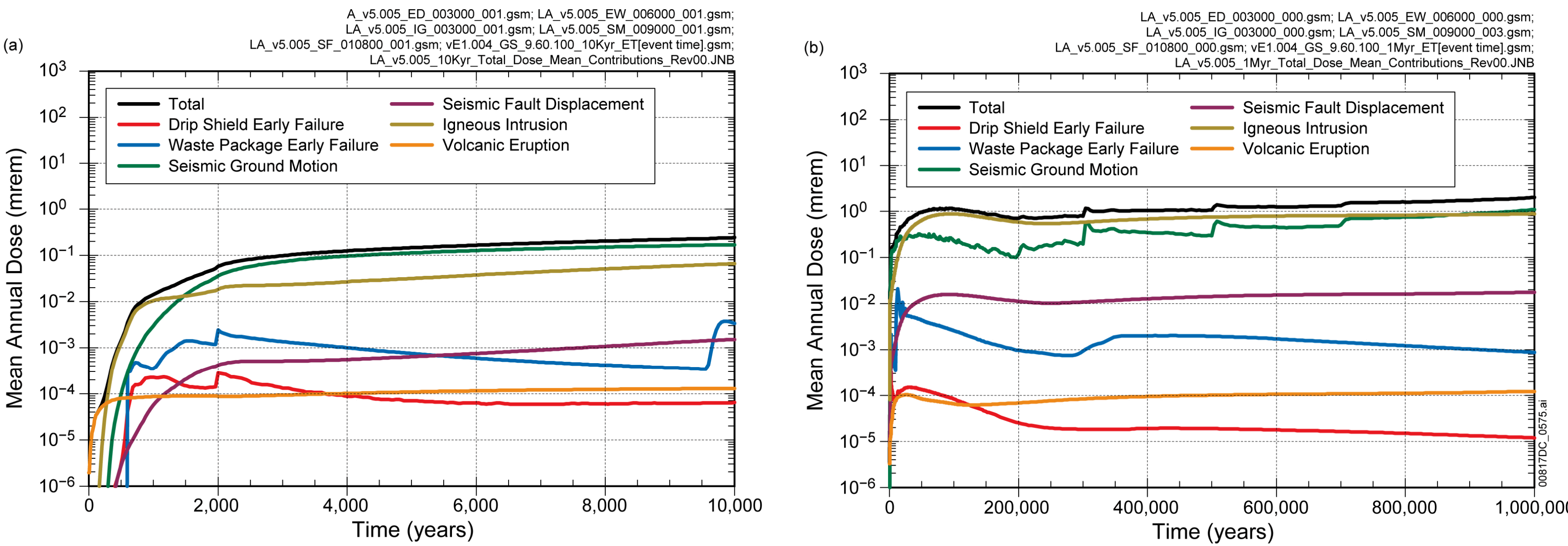
TSPA-LA estimated 10,000 yr maximum mean annual dose: 0.0024 mSv (0.24 mrem)

1,000,000 years

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

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

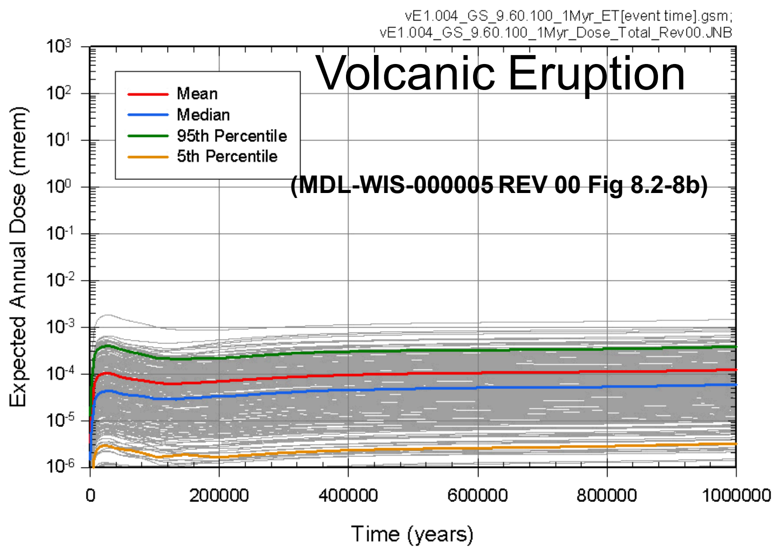
Modeling Cases Contributing to Total Mean Annual Dose



10,000 years **1,000,000 years**

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

Construction of Total Dose



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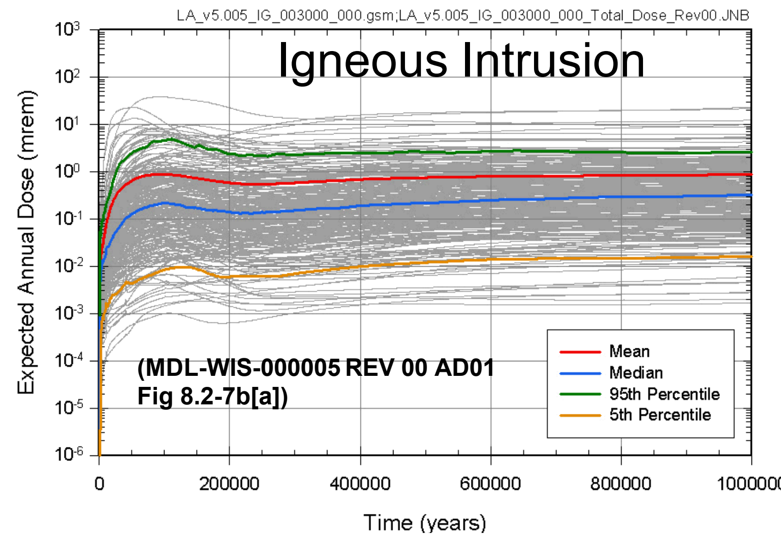

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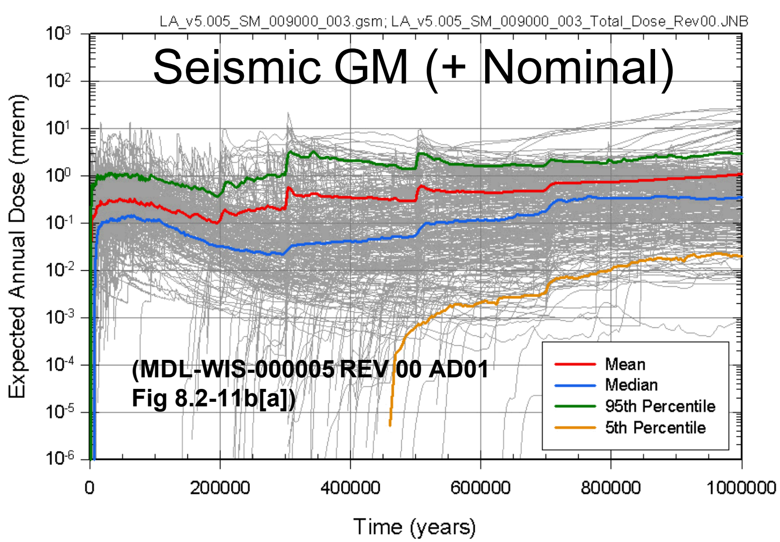
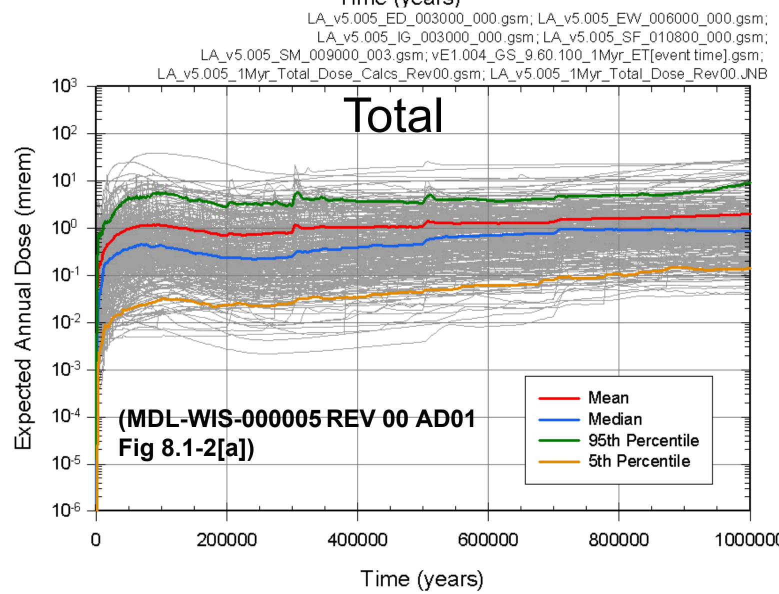
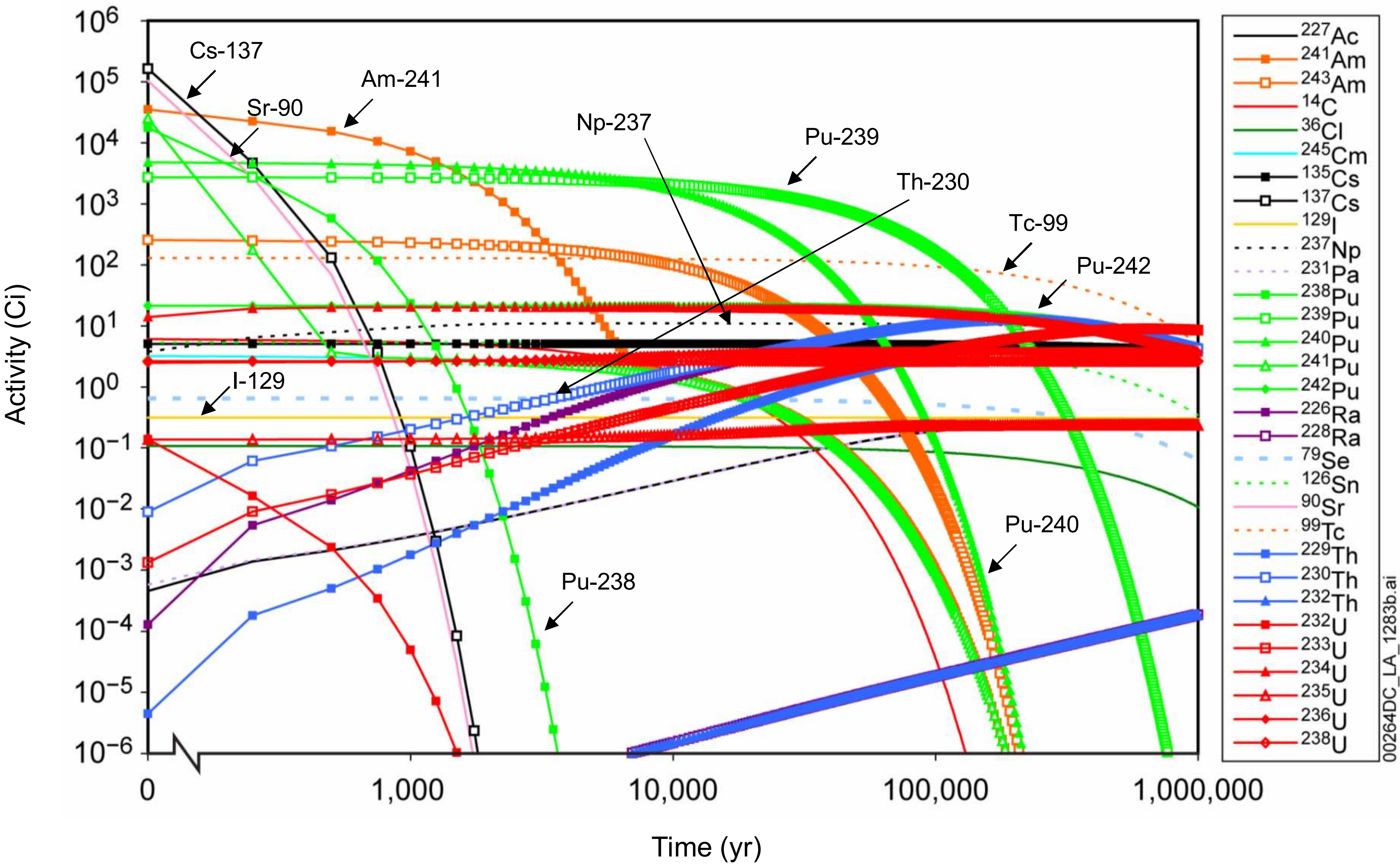




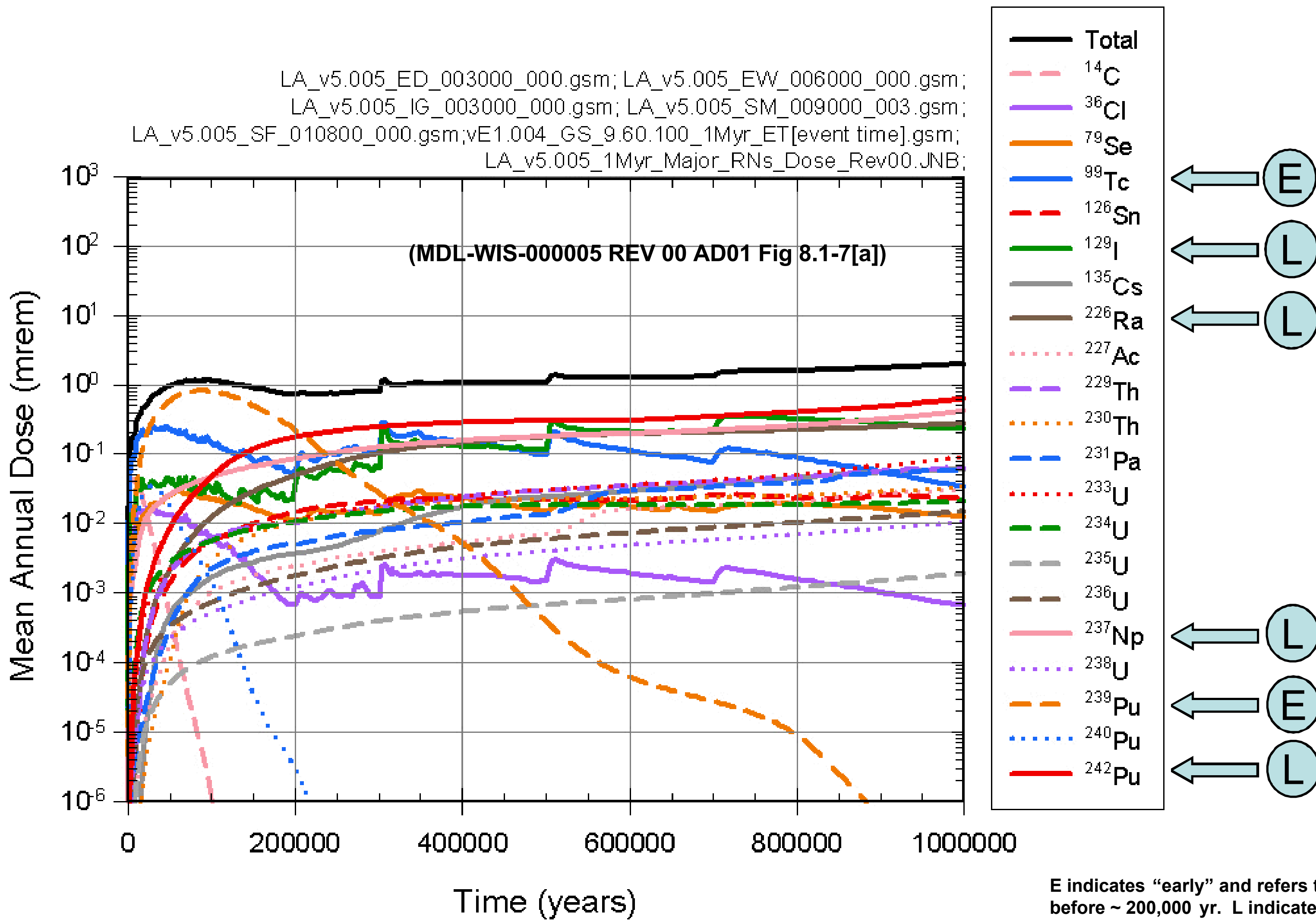
Radionuclides Contributing to Estimates of Total Dose from Yucca Mountain

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

Qualitative Summary of the Long-Term Performance of Yucca Mountain

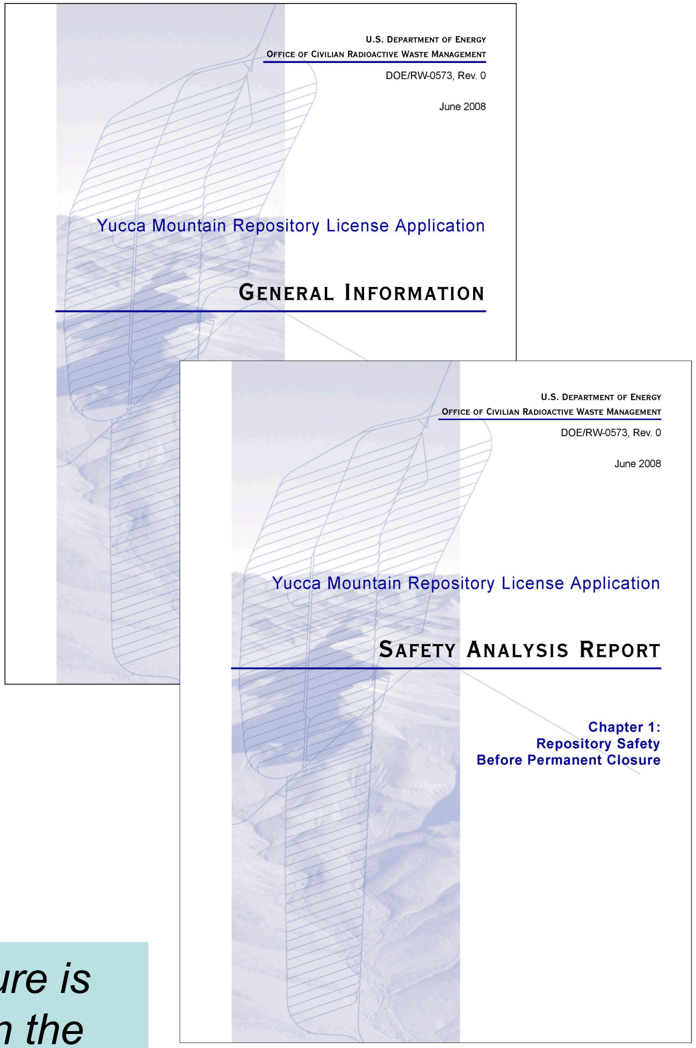
- No significant releases for many tens of thousands of years if the site is undisturbed
  - Dry climate, little groundwater flow
  - Corrosion-resistant waste packages
- Over hundreds of thousands of years, estimated mean and median annual doses are well below natural background
- Future disruption 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

Yucca Mountain Milestones

- 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
  - Characterization of 5 sites as a possible repository location begins. Upon the recommendation of the U.S. Geological survey based on several years of study, unsaturated rocks at Yucca Mountain (NTS) are included
- 1987: NWPA amended to focus on one site on the edge of the NTS, Yucca Mountain
- 2002: The Site Recommendation is issued, finding Yucca Mountain to be a suitable site.
  - Per NWPA, Nevada utilizes state veto power to veto the site
  - Per NWPA, both houses of Congress vote to override the veto
- 2008: DOE submits the Yucca Mountain License Application to the NRC
- 2010: DOE decides Yucca Mountain is not a suitable site, and attempts to withdraw the license application
  - Atomic Safety and Licensing Board declines to let the DOE withdraw the application
  - But DOE terminates the safety review by the NRC
- 2013: Following lawsuits by states with nuclear waste, the U.S. Circuit Court mandates that the Yucca Mountain License Application safety review by the NRC be resumed.
- 2015: NRC competes its review, and concludes that Yucca Mountain could meet the technical requirements. However, DOE did not complete all the required steps, such as land withdrawal or completion of hearings on contentions filed by Intervenors.
- 2016: Completion of the Yucca Mountain Supplementary Environmental Impact Statement (SEIS) by the NRC.
- 2016: Yucca Mountain licensing process remains suspended, and approximately 300 technical contentions remain to be heard before a licensing board can reach a decision.

What is in a License Application?

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



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

What Does a Repository License Application Look Like?

The 2008 Yucca Mountain License Application (LA) included

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

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

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

(nearly all remain unresolved)

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

Backup Slides

Spent Nuclear Fuel and High Level Radioactive Waste: Current Status

Spent nuclear fuel and high-level radioactive waste comes from three major sources

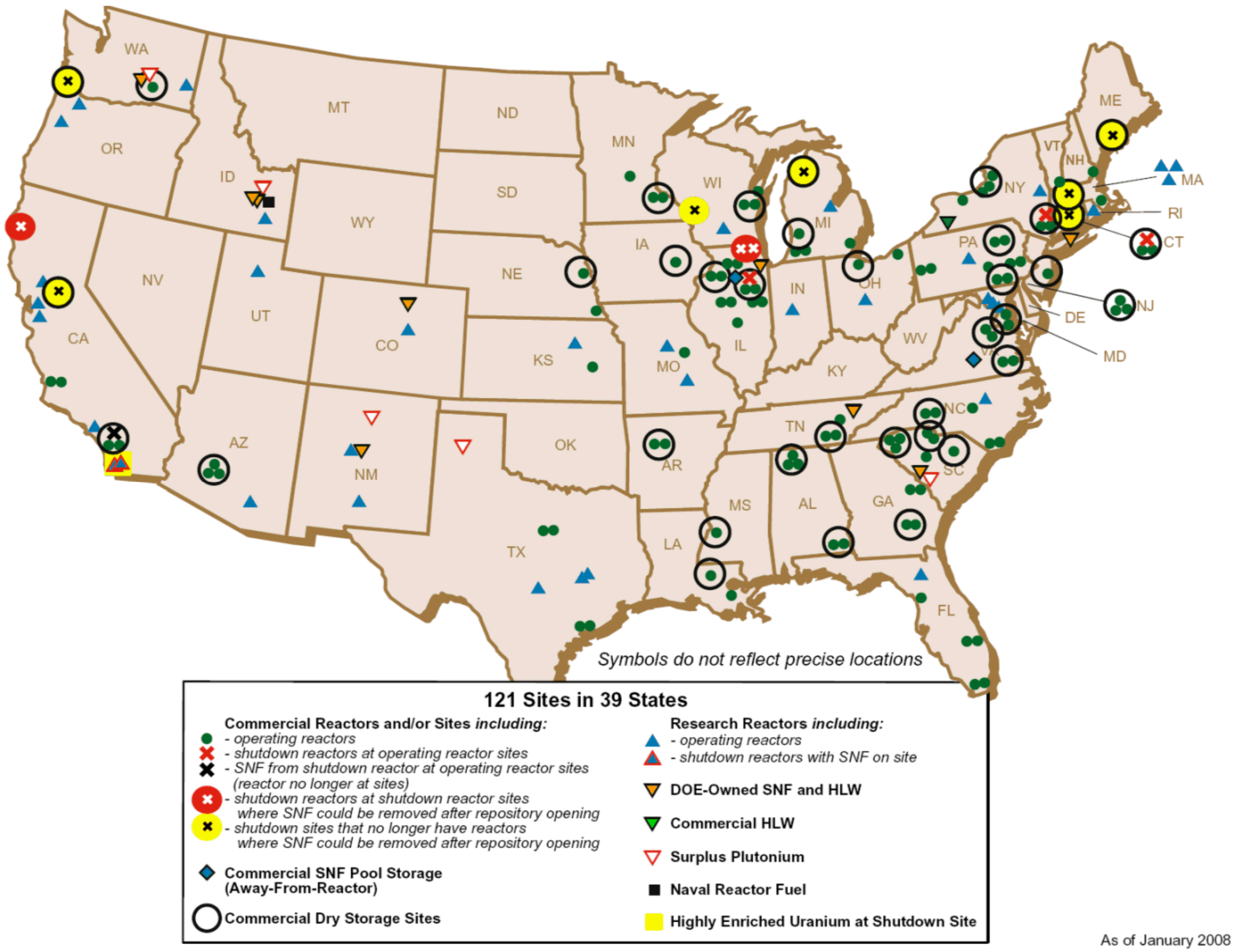
Commercial Nuclear Energy

Wastes from the Production of Nuclear Weapons

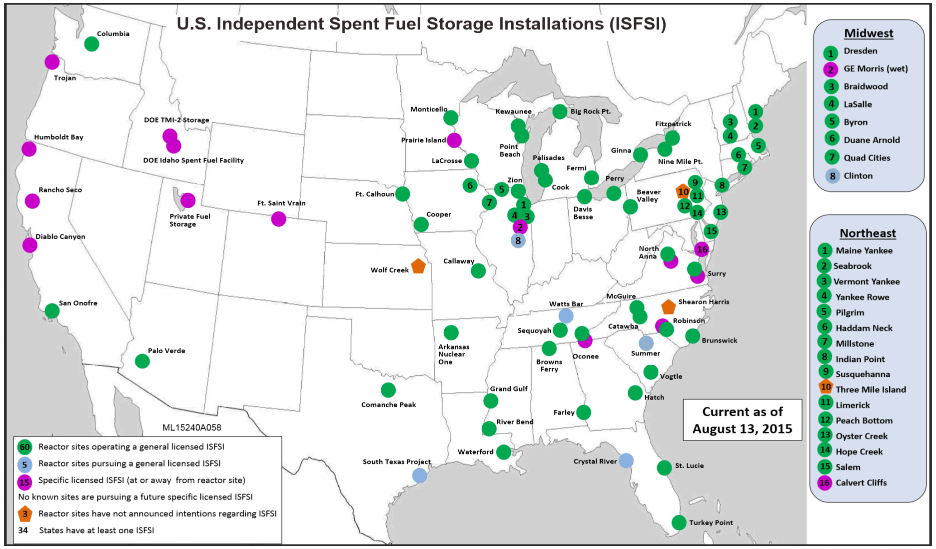
Ongoing Defense Programs

Spent Nuclear Fuel and High-Level Radioactive Waste in the United States

Sandia National Laboratories



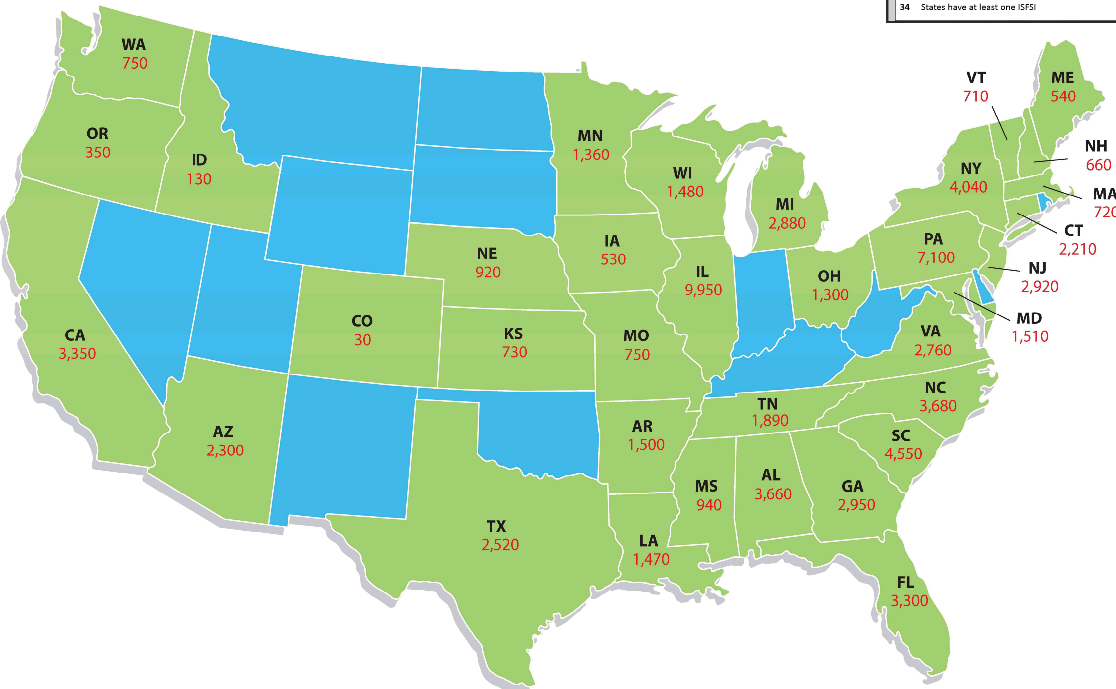
Where Commercial SNF is Stored Today



Source: U.S. NRC website, downloaded 7/10/2016

Used Nuclear Fuel in Storage

(Metric Tons, end of 2015)



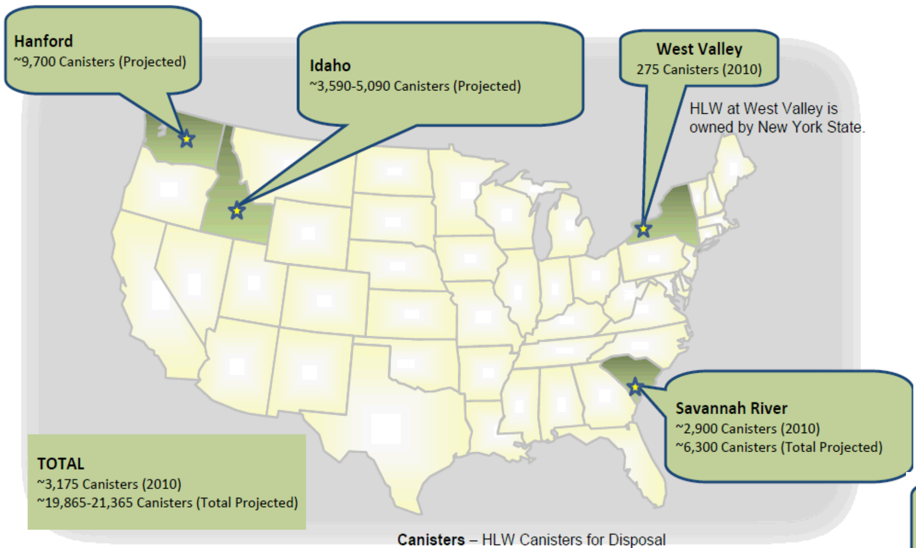
Source: Gutherman Technical Services

http://www.nei.org/CorporateSite/media/Images/Infographics/Used-Fuel-Storage.jpg?width=8261&height=6384&ext=.jpg

NEI
NUCLEAR ENERGY INSTITUTE

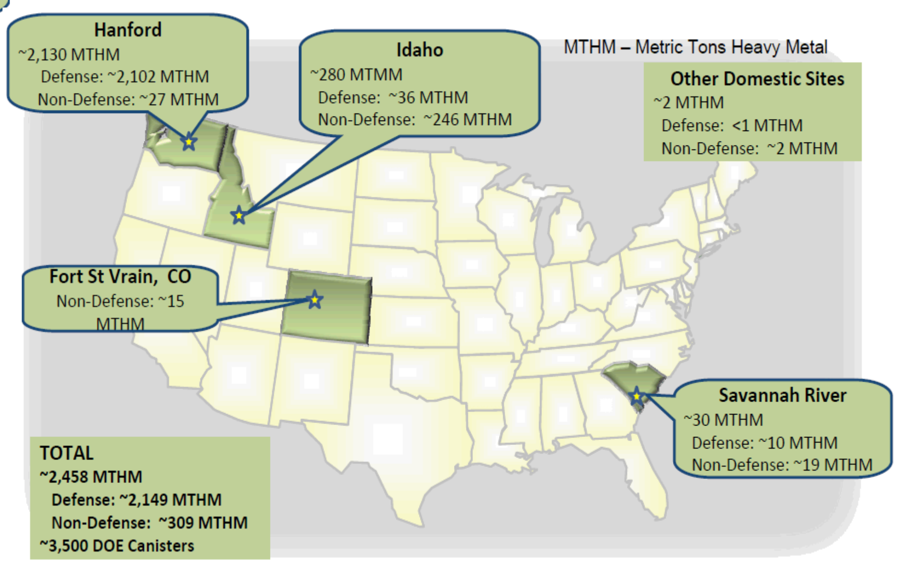
Where DOE-Managed SNF and High-Level Radioactive Waste (HLW) is Stored Today

Sandia National Laboratories



DOE-Owned HLW
~20,000 total canisters
(projected)

DOE-Owned SNF
~2,458 Metric
Tons

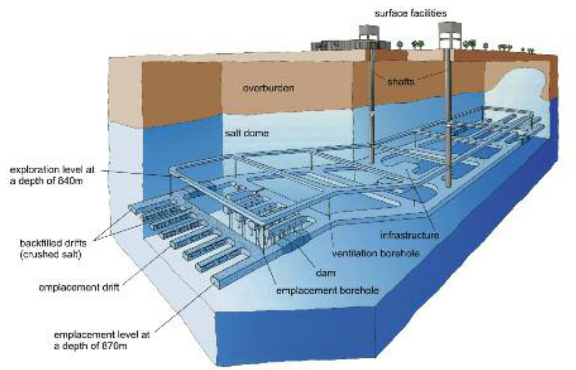


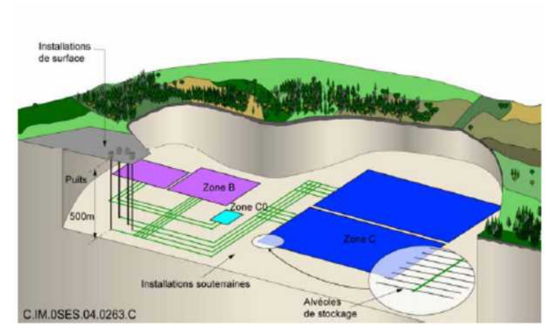
Source: Marcinowski, F., "Overview of DOE's Spent Nuclear Fuel and High-Level Waste," presentation to the Blue Ribbon Commission on America's Nuclear Future, March 25, 2010, Washington DC.

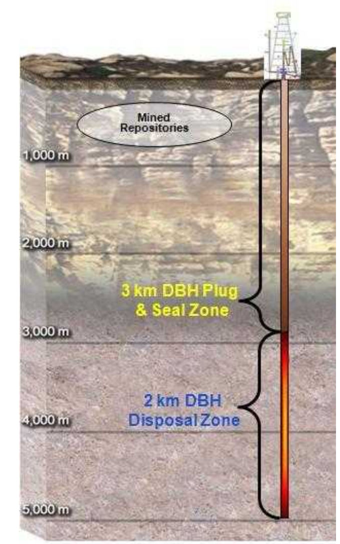
Deep Geologic Disposal Remains the Preferred Approach for Long-Term Isolation of Nuclear Waste

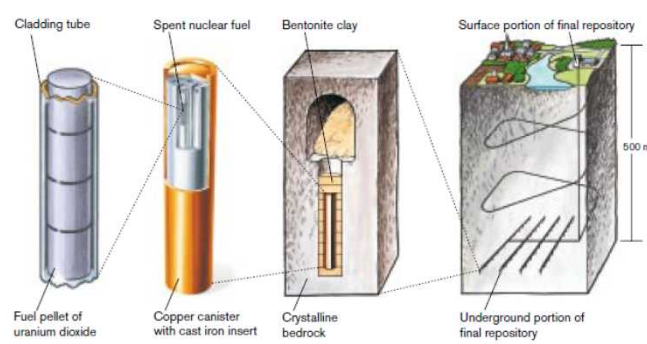
"The conclusion that disposal is needed and that deep geologic disposal is the scientifically preferred approach has been reached by every expert panel that has looked at the issue and by every other country that is pursuing a nuclear waste management program."

Blue Ribbon Commission on America's Nuclear Future, 2012





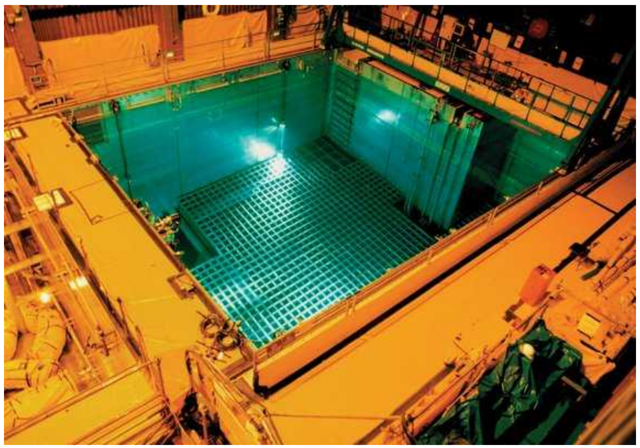




With the abandonment of the Yucca Mountain Project, the U.S. currently has no path forward for repository disposal. Current plans call for development of a repository by 2048. Where is the waste now?

Standard Industry Practice for SNF

On-site storage of spent nuclear fuel is the only option available

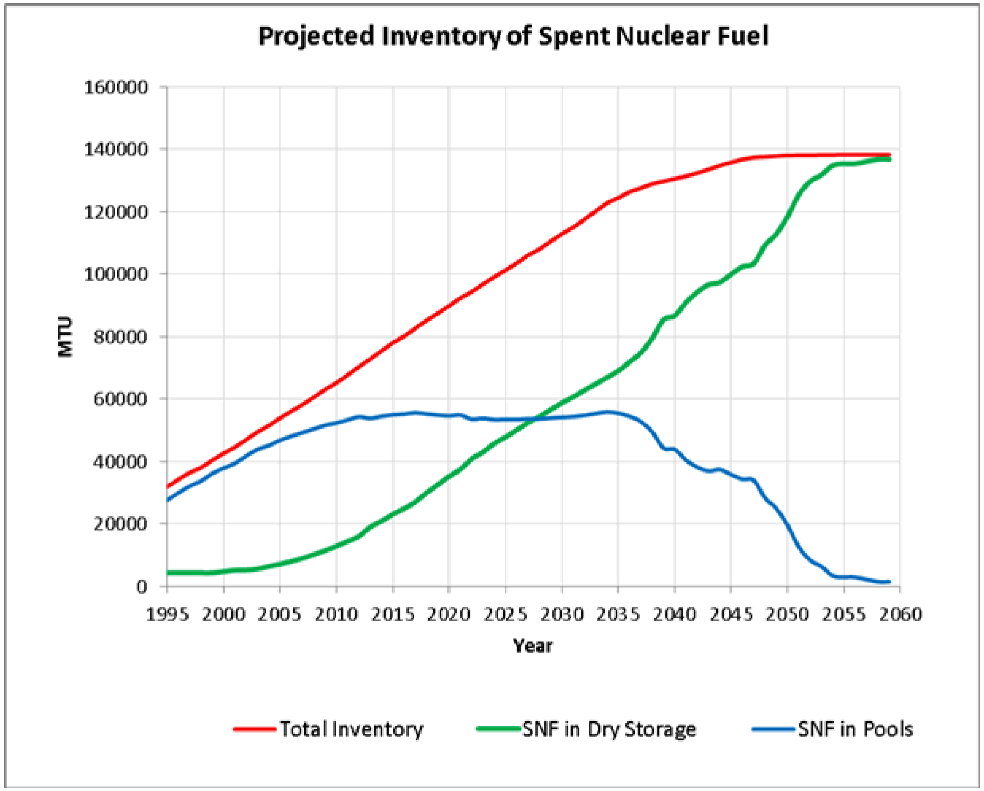


Pool Storage: essential to reactor operations, but nearing capacity, ~ 80% of existing US reactors have dry storage facilities on site

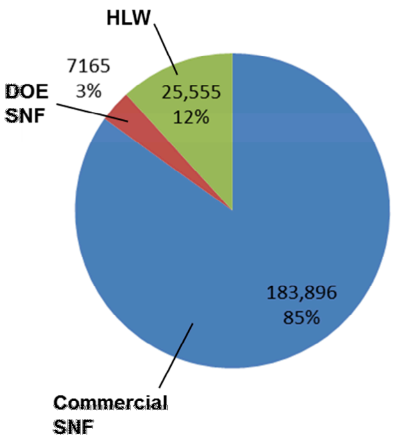
Dry Storage: horizontal and vertical concepts are in use. R&D in progress to support the technical basis for license extensions beyond original 20-yr period

Future Projections

Projection assumes full license renewals and no new reactor construction or disposal



Projected Volumes of SNF and HLW in 2048



Volumes shown in m^3, assuming constant rate of nuclear power generation and packaging of future commercial SNF in existing designs of dual-purpose canisters

Approx. 80,150 MTHM (metric tons heavy metal) of SNF in storage in the US today

- 25,400 MTHM in dry storage at reactor sites, in approximately 2,080 cask/canister systems
- Balance in pools, mainly at reactors

Approx. 2200 MTHM of SNF generated nationwide each year

- Approximately 160 new storage canisters are loaded each year because reactor pools are essentially at capacity

Ongoing Research Specific to Storage and Transportation of SNF

- Spent fuel integrity during extended storage
  - Will the fuel cladding retain its integrity during storage?

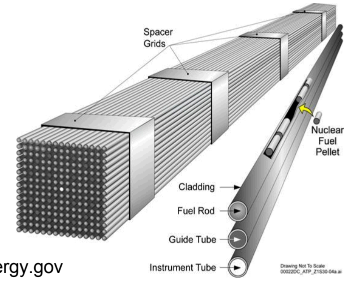


Photo: energy.gov

- Storage system integrity
  - Will the storage canisters retain their integrity?

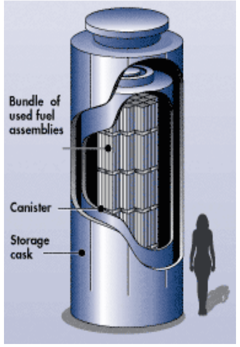
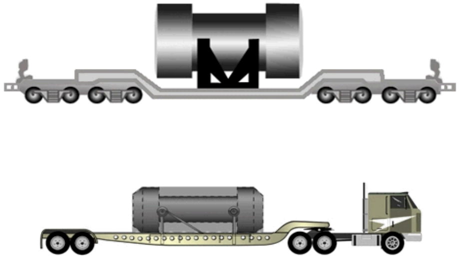


Photo: nrc.gov

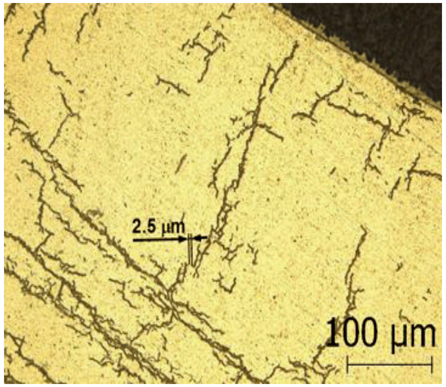
- Spent fuel transportability following extended storage
  - Will stresses associated with normal conditions of transport cause cladding failure?



energy.gov/pictures

Understanding High Burn-up Cladding Performance

- ***Ductile/Brittle Transition Temperatures:*** Tests indicate that cladding is more ductile at cooler temperatures than previously thought. Lower rod internal pressure results in fewer radial hydrides.

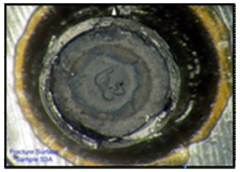


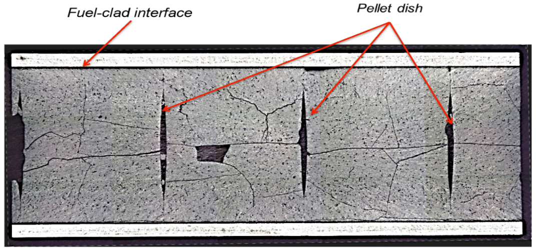
Circumferential and Radial hydrides in High Burn-up ZIRLO cladding subjected to peak temperatures of 350°C and 92 MPa hoop stress. (Billone, 2015. ANL)

- ***Thermal analysis:*** More realistic modeling indicates that peak clad temperatures may be lower than previously thought. This reduces the risk of forming radial hydrides.

	238	247	244	234	
234	257	269	268	256	235
241	268	255	271	269	246
247	268	268	260	269	247
238	255	269	269	257	238
	239	248	246	235	

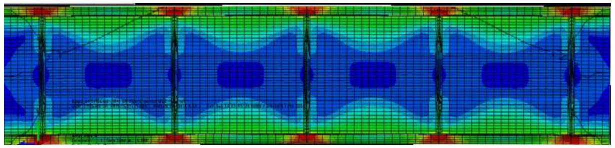
Maximum cladding surface temperature (°C) for each assembly in *one* type of licensed cask. (Hanson, et al, 2016. PNNL)





Fuel rod segment before bend testing (Wang, et al., 2016. ORNL)

- ***Strength and Fatigue:*** Cyclic bending tests of irradiated fuel segments identify increased strength due to pellet/clad and pellet/pellet bonding effects.



Stress distribution in fuel showing the fuel pellets supporting the clad due to cohesive bonding.(Wang, et al., 2014, ORNL)

Obtaining Data on High Burnup Cladding After 10 Years of Storage

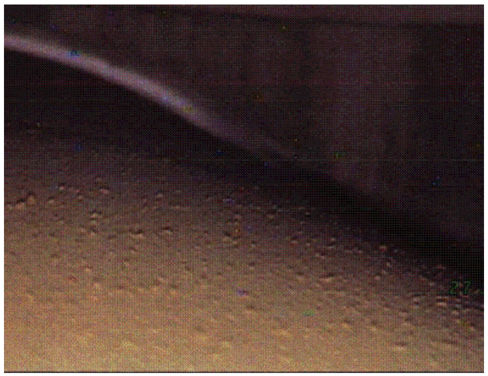
The DOE/EPRI High Burnup Confirmatory Data Project
Goal: To obtain data on physical properties of High Burnup Spent Fuel after 10 years of dry storage.

- Steps:
  1. *Loading* a commercially licensed TN-32B storage cask with high burn-up fuel in a utility storage pool (planned for 2017)
     1. Loading well characterized fuel of four common cladding alloys
     2. Instrumenting cask outfitted with thermocouples. Gas samples taken before going to the pad and periodically during storage.
  2. *Drying* using industry standard practices
  3. *Storing* at the utility's dry cask storage site for 10 years
  4. *Transporting* to a laboratory for opening
  5. *Testing* the rods before ("sister"rods) and after storage to understand their mechanical properties.

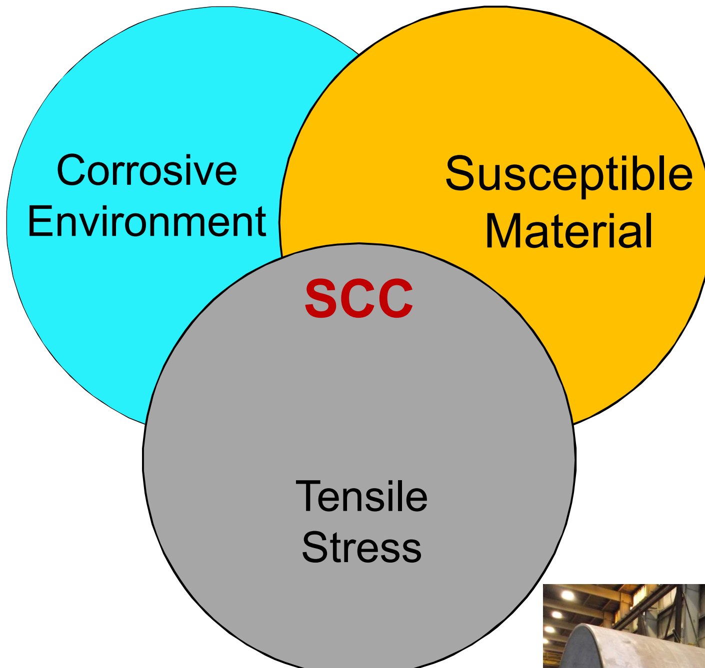

Prairie Island Dry Storage

Understanding Canister Performance:

Primary Concern is Stress Corrosion Cracking (SCC), which requires three concurrent conditions:



Dust on canister surface at Calvert Cliffs (EPRI, 2014)



Weld zone, 304 SS plate.
Photo: Ranor

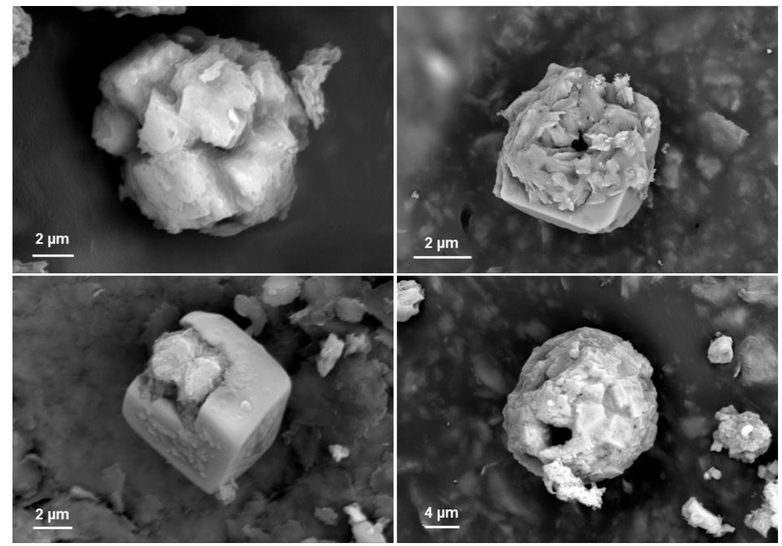
Mock-up Canister
Photo: Enos and Bryan (2016), SNL

Understanding Canister Performance:

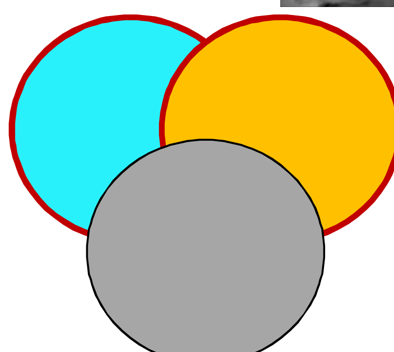
Do We Have a Corrosive Environment?

DOE and EPRI collected limited dust samples at Calvert Cliffs, Hope Creek, and Diablo Canyon. Chloride was found in some areas which could provide the chemistry needed for crack initiation and growth. Need more sampling to determine which areas of the country are at greater risk.

Examples of sea-salt aerosols found on canisters.
Photo: Bryan and Enos (2014), SNL



Photos: Enos, SNL



Conclusion: Need to determine higher risk areas both environmentally and on the canister.

Understanding Canister Performance:

Is there Tensile Stress Through the Canister Wall?

Full-diameter canister mockup undergoing residual stress testing. Preliminary results indicate through-wall tensile residual stresses along welds and exacerbated at weld repairs that could allow for cracks to grow through the canister wall.

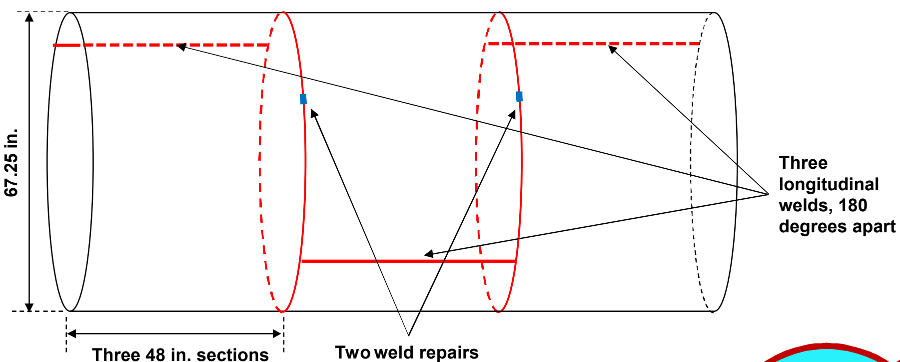
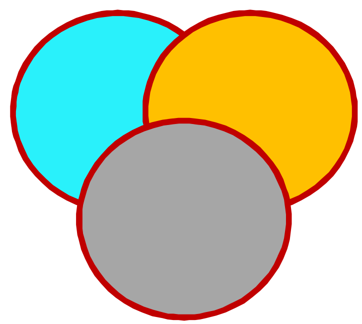
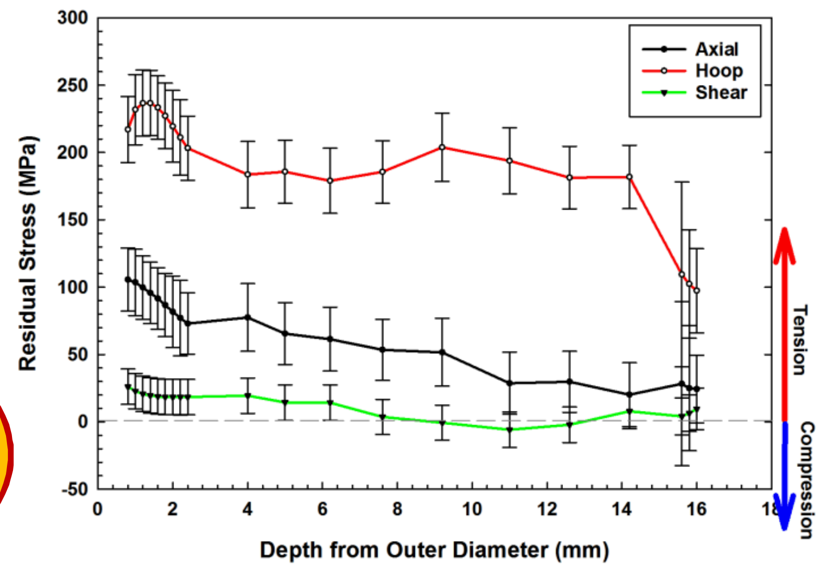
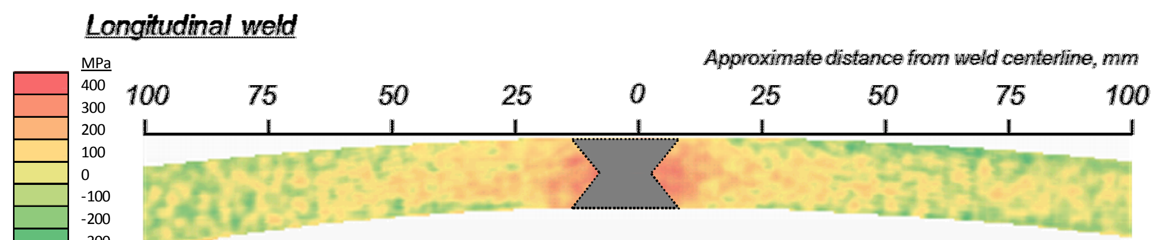


Photo: Enos and Bryan, SNL





Measured Stresses, Circumferential weld HAZ, Sandia Canister Mockup. Enos and Bryan (2016), SNL



Transporting Spent Nuclear Fuel:

How do Stresses on Fuel During Normal Conditions of Transport Compare to Failure Limits?

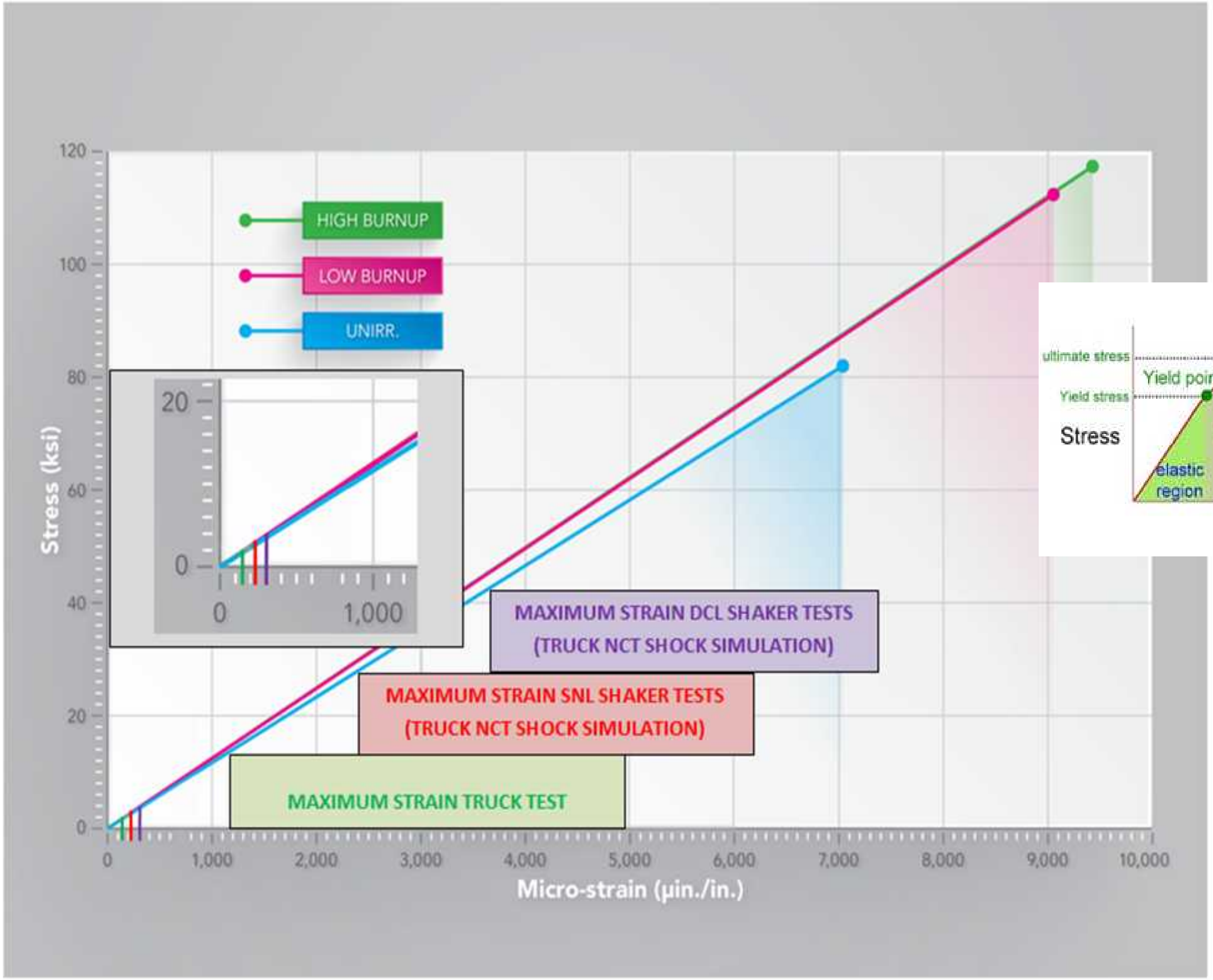
Three series of tests using a surrogate PWR assembly

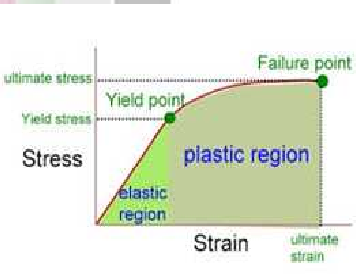
1. Truck data on a vertical acceleration shaker table
2. Over-the-road truck test
3. Truck and rail data on a commercial seismic shaker with six degrees of motion

McConnell et al, 2016, SNL and PNNL

Transporting Spent Nuclear Fuel:

How do Stresses on Fuel During Normal Conditions of Transport Compare to Failure Limits?





McConnell et al, 2016, SNL and PNNL

Stresses during truck transport are small, and are unlikely to damage the fuel.

Stresses relevant to ship and rail transport will be measured in 2017 (Spanish transport cask test carried out by SNL).