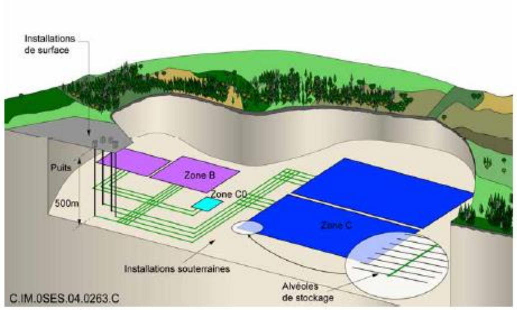
SAND2016-11313PE

Exceptional service in the national interest

Sandia National Laboratories

?

?



Current Status of Spent Nuclear Fuel and High-Level Radioactive Waste Management in the United States

Peter Swift
Sandia National Laboratories

Presentation to ChNE 439/539
University of New Mexico
November 9, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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.. SAND2016-xxxxx

Outline

- Where We Are Today
  - The waste
  - Status of the disposal program
  - Extended surface storage
- What it takes to license a repository
  - The formerly proposed Yucca Mountain Repository as an example

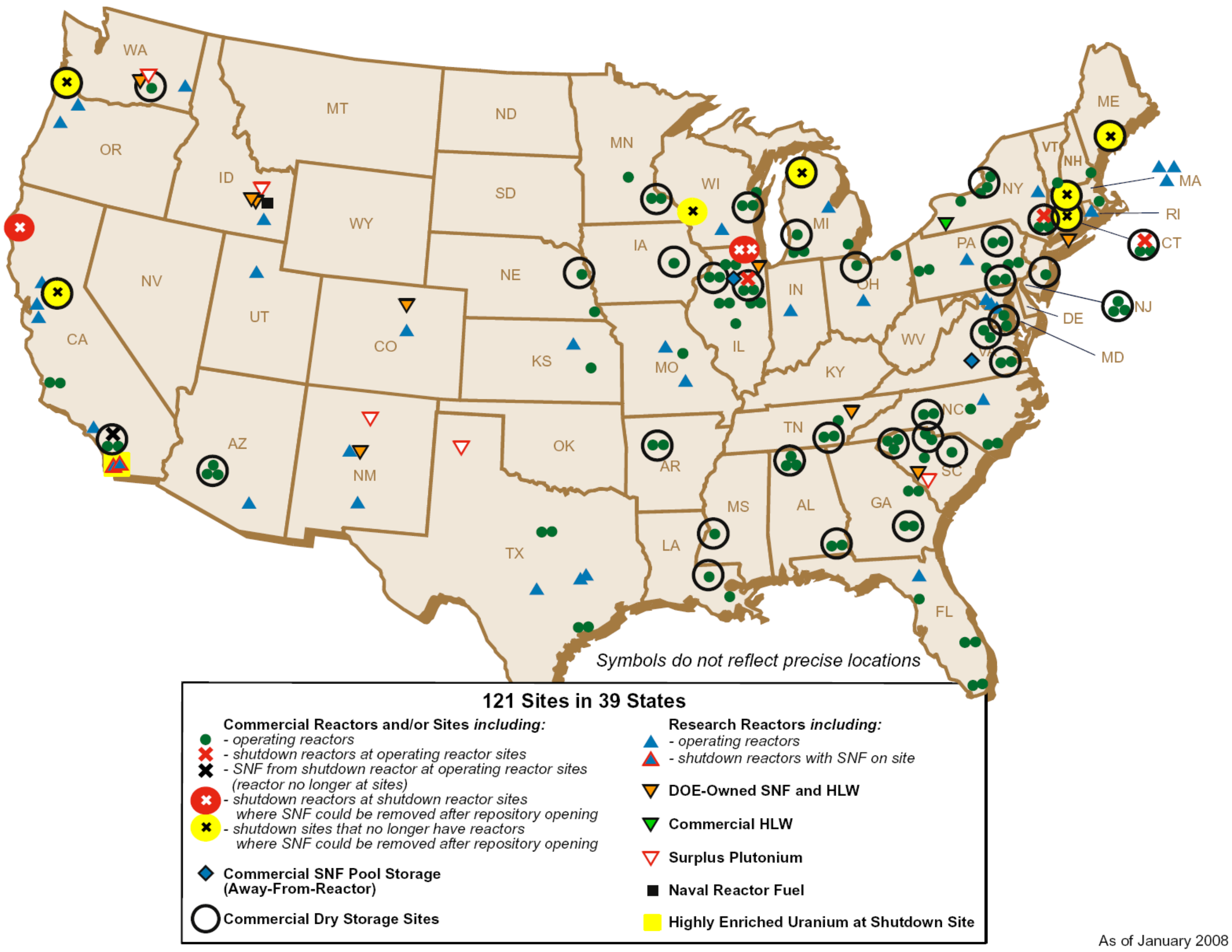
Spent nuclear fuel and high-level radioactive waste comes from three major sources

Commercial Nuclear Energy

Ongoing Defense Programs

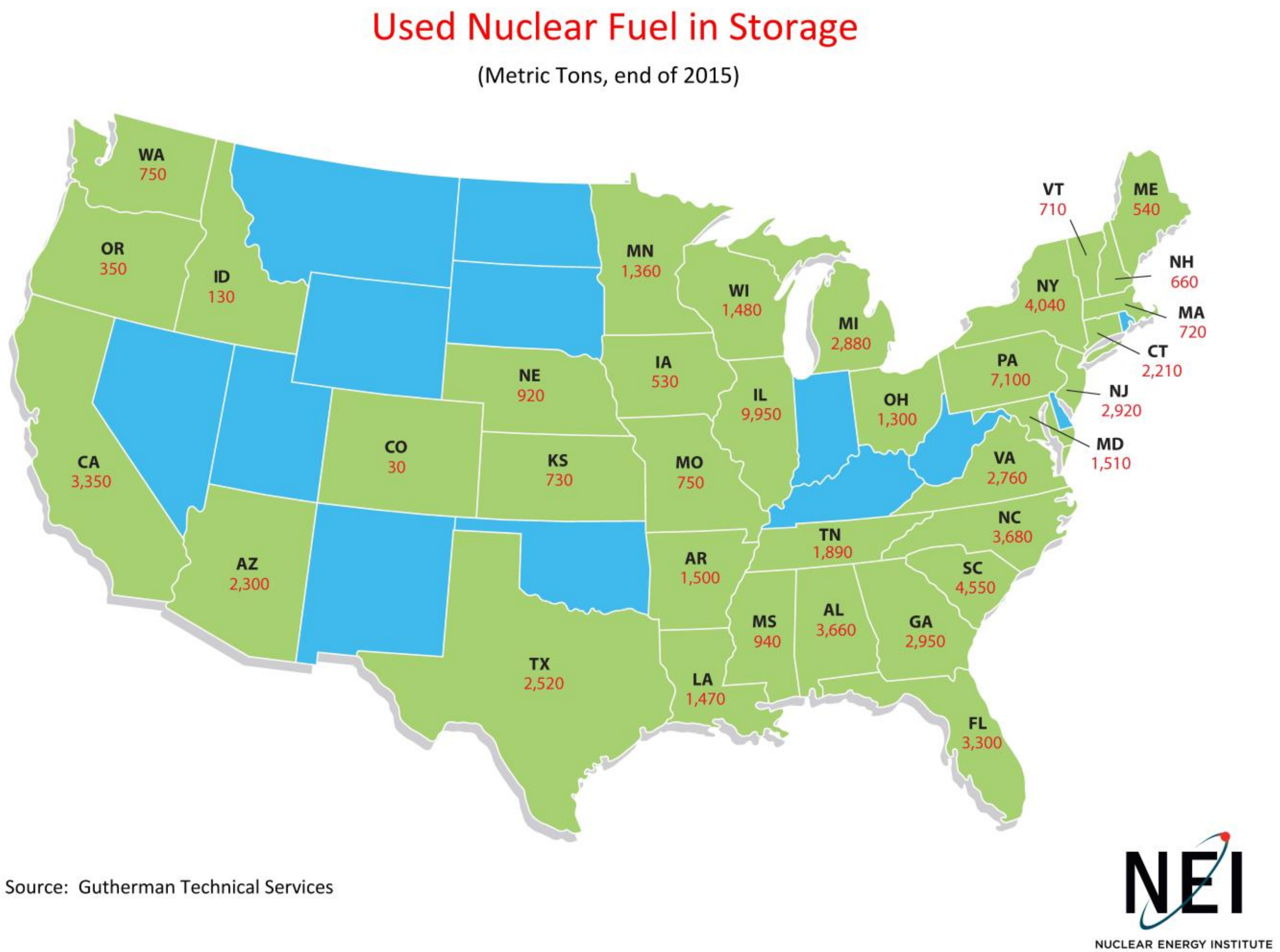
Wastes from the Production of Nuclear Weapons

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



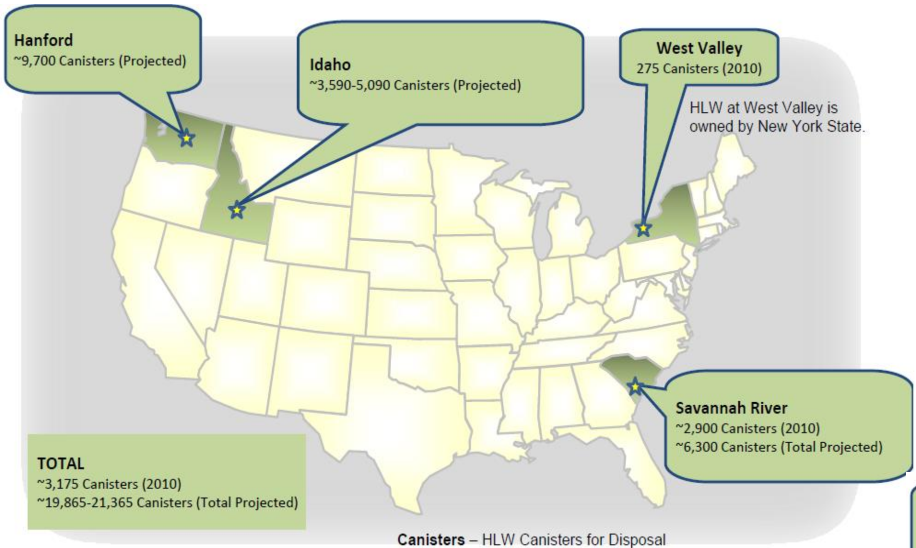
As of January 2008

Where Commercial SNF is Stored Today



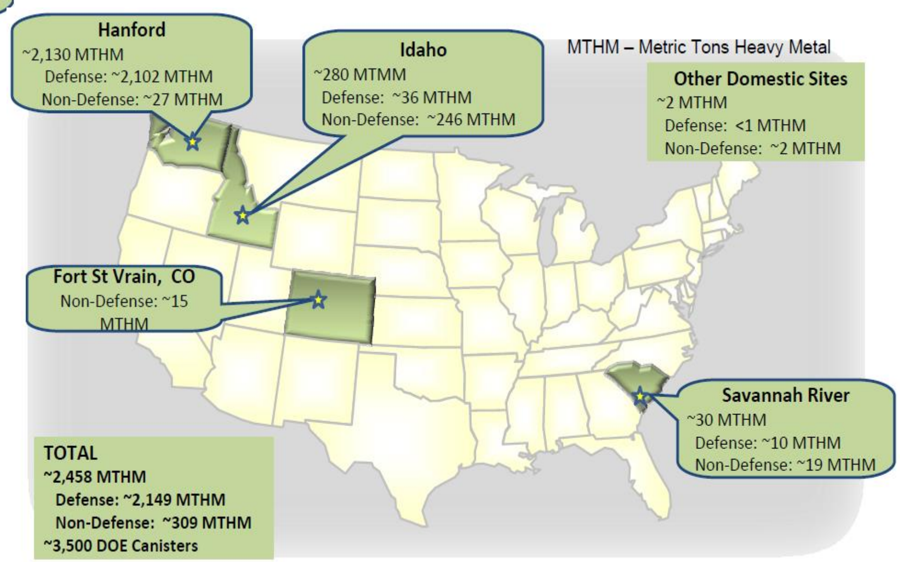
http://www.nei.org/CorporateSite/media/Images/Infographics/Used-Fuel-Storage.jpg?width=8261&height=6384&ext=.jpg

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



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

DOE-Owned SNF
~2,458 Metric
Tons

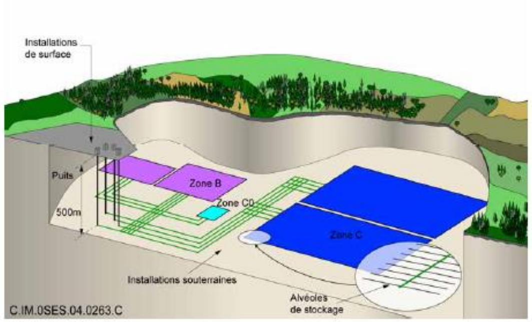


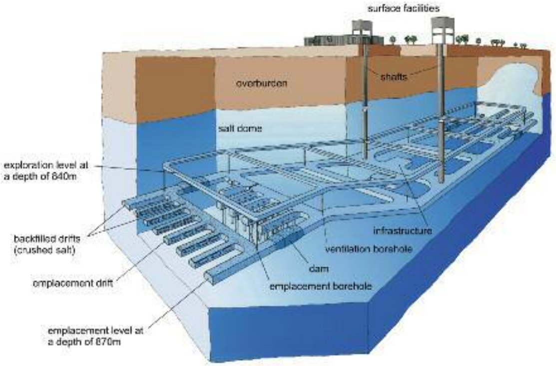
Source: Marcinowski, F., "Overview of DOE's Spent Nuclear Fuel and High-Level Waste," presentation to the Blue Ribbon Commission on America's Nuclear Future, March 25, 2010, Washington DC.

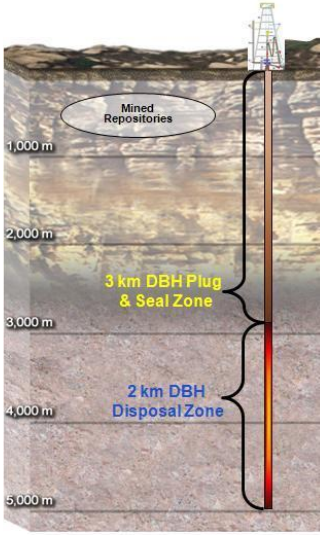
Deep Geologic Disposal Remains the Preferred Approach for Long-Term Isolation of Nuclear Waste

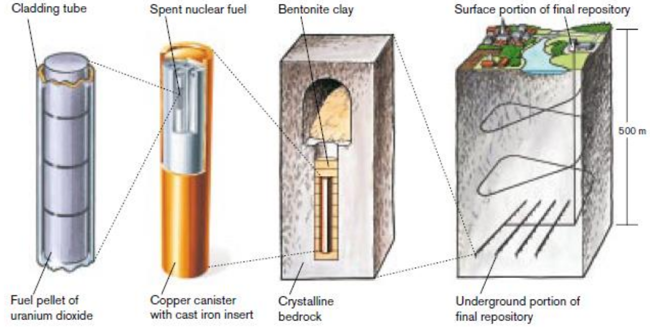
“The conclusion that disposal is needed and that deep geologic disposal is the scientifically preferred approach has been reached by every expert panel that has looked at the issue and by every other country that is pursuing a nuclear waste management program.”

Blue Ribbon Commission on America’s Nuclear Future, 2012







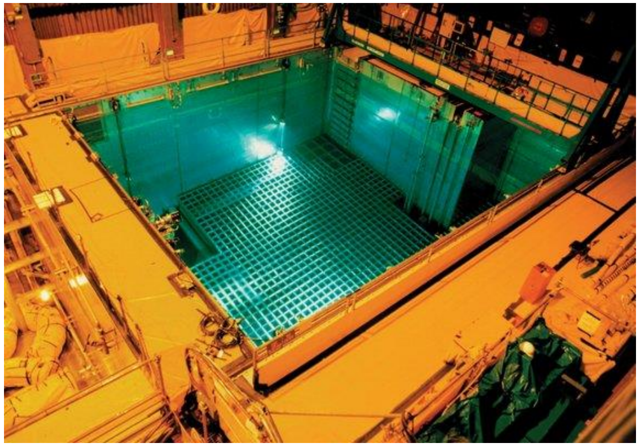


Current Status of the US Program

- **2008**: Yucca Mountain Repository License Application submitted
- **2009**: Department of Energy (DOE) determines Yucca Mountain to be unworkable
- **2010**: Last year of funding for Yucca Mountain project
- **2012**: Blue Ribbon Commission on America's Nuclear Future completes its recommendations, including a call for a consent-based process to identify alternative storage and disposal sites
- **2013**: Federal Court of Appeals orders Nuclear Regulatory Commission (NRC) to complete its staff review of the Yucca Mountain application with remaining funds
- **2014**: Transuranic waste disposal operations at the Waste Isolation Pilot Plant cease after an underground fire and radiological release
- **2015**: NRC staff completes Yucca Mountain review, finds that "the DOE has demonstrated compliance with the NRC regulatory requirements" for both preclosure and postclosure safety
- **2015**: DOE begins consideration of a separate repository for defense high-level wastes
- **2015**: DOE initiates first phase of public interactions planning for a consent-based siting process for both storage and disposal facilities
- **2016**: Yucca Mountain licensing process remains suspended, and approximately 300 technical contentions remain to be heard before a licensing board can reach a decision
- **2016**: Private sector applications to the NRC for consolidated interim storage (1 submitted, 1 anticipated)

Standard Industry Practice for SNF

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

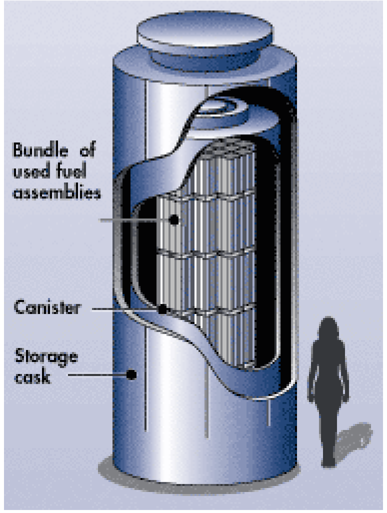


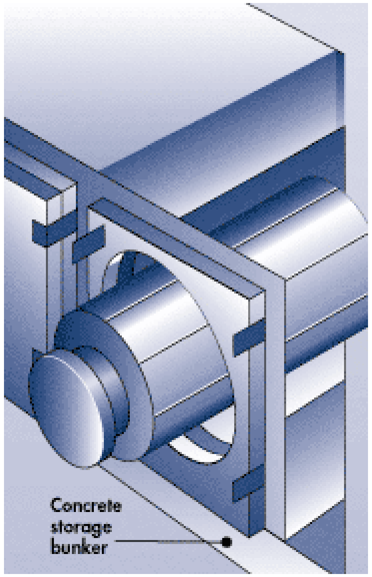
Pool Storage: essential to reactor operations, but nearing capacity, ~ 80% of existing US reactors have dry storage facilities on site

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

Storage Terminology

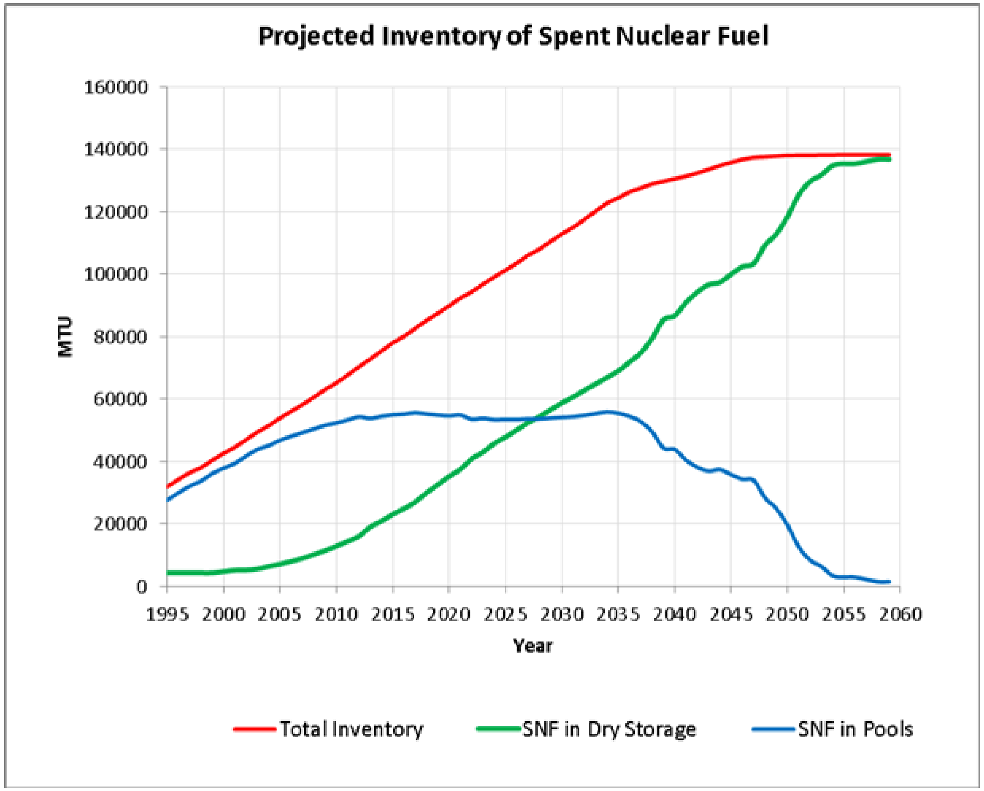
- Dual purpose canister (DPC)
  - A canister that is certified for both storage and transportation of spent nuclear fuel
- Dry cask/canister storage systems
  - The most common type of dry storage cask system is the vertical cask/canister system shown above, in which the inner stainless steel canister is removed from the storage overpack before being placed in a shielded transportation cask for transport
    - Can be constructed both above and below grade
  - Horizontal bunker-type systems and vaults are also in use
  - Some older fuel is also stored as “bare fuel” in casks with bolted lids; few sites continue to load these systems
- Multiple vendors provide NRC-certified dry storage systems to utilities



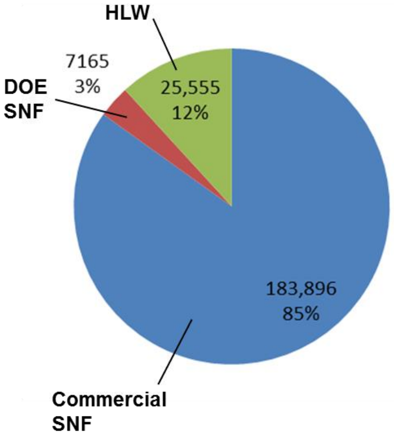


Future Projections

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 DPCs are loaded each year because reactor pools are essentially at capacity

Observations on Current Practice

- Current practice is safe and secure
  - Extending current practice raises data needs; e.g., canister integrity, fuel integrity, aging management practices
- Current practice is optimized for reactor site operations
  - Occupational dose
  - Operational efficiency of the reactor
  - Cost effective on-site safety
- Current practice is not optimized for transportation or disposal
  - Thermal load, package size, and package design

Placing spent fuel in dry storage in dual purpose canisters (DPCs) commits the US to some combination of three options

1) Repackaging spent fuel in the future
2) Constructing one or more repositories that can accommodate DPCs
3) Storing spent fuel at surface facilities indefinitely, repackaging as needed

Each option is technically feasible, but none is what was originally planned

Ongoing Research Specific to Storage and Transportation of SNF

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

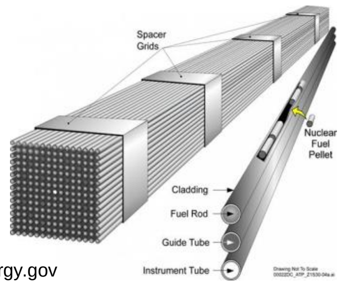


Photo: energy.gov

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

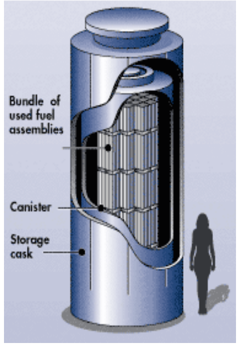
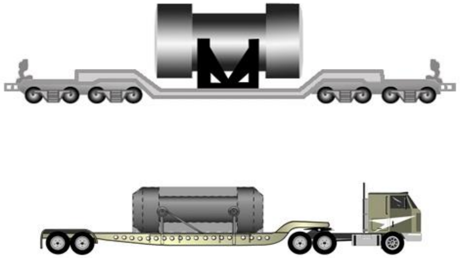


Photo: nrc.gov

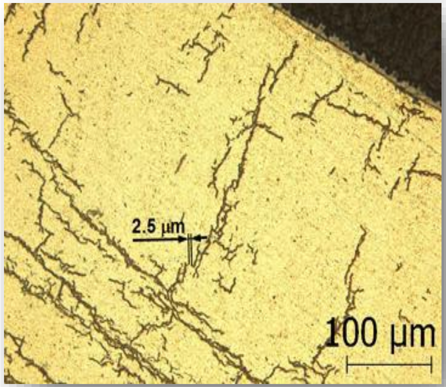
- Spent fuel transportability following extended storage
  - Will stresses associated with normal conditions of transport cause cladding failure?



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.

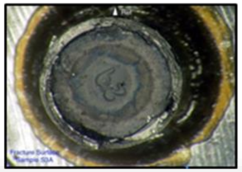


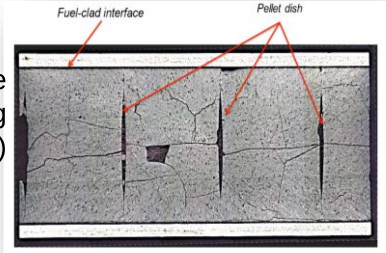
Circumferential and Radial hydrides in High Burn-up ZIRLO cladding subjected to peak temperatures of 350°C and 92 MPa hoop stress. (Billone, 2015. ANL)

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

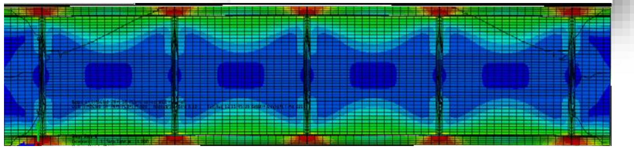
	238	247	244	234	
234	257	269	268	256	235
241	268	255	271	269	246
247	268	268	260	269	247
238	255	269	269	257	238
	239	248	246	235	

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)



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

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

Obtaining Data on High Burnup Cladding After 10 Years of Storage

Sandia National Laboratories

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 to understand their mechanical properties.
- License Amendment request submitted to the NRC by Dominion in August, 2015, for lid design and additional heat load
- Draft Safety Evaluation Report anticipated from the NRC in summer of 2016

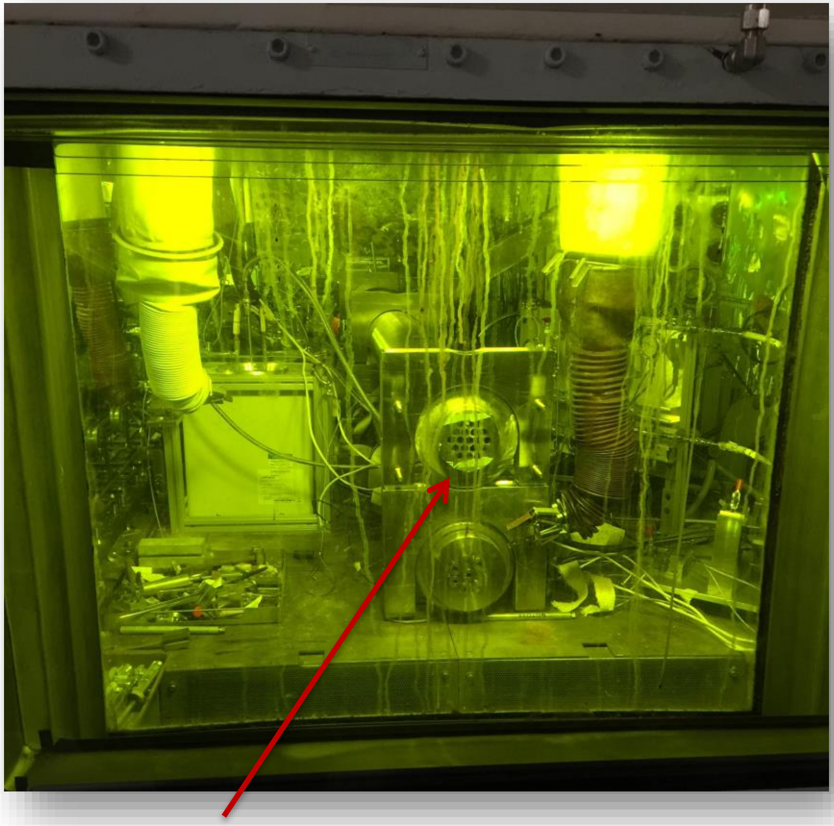
Prairie Island Dry Storage

High Burnup Confirmatory Data Project – Obtaining ***Baseline*** Data

25 fuel rods with similar histories will be tested now to document properties before 10 years of storage.

"Sister Rod" Acquisition and Testing

- Areva and Westinghouse rods pulled in June and January 2015 from different assemblies
  - AREVA M5™ rods
  - Westinghouse Zirlo™ rods
  - Westinghouse low-tin Zircaloy-4 rods
  - Westinghouse standard Zircaloy-4 rods
- All 25 sister rods currently at Oak Ridge National Laboratory
- Draft Sister Rod Test Plan in peer review
  - Cladding mechanical properties
  - Hydride distribution
  - Pellet cladding bonding

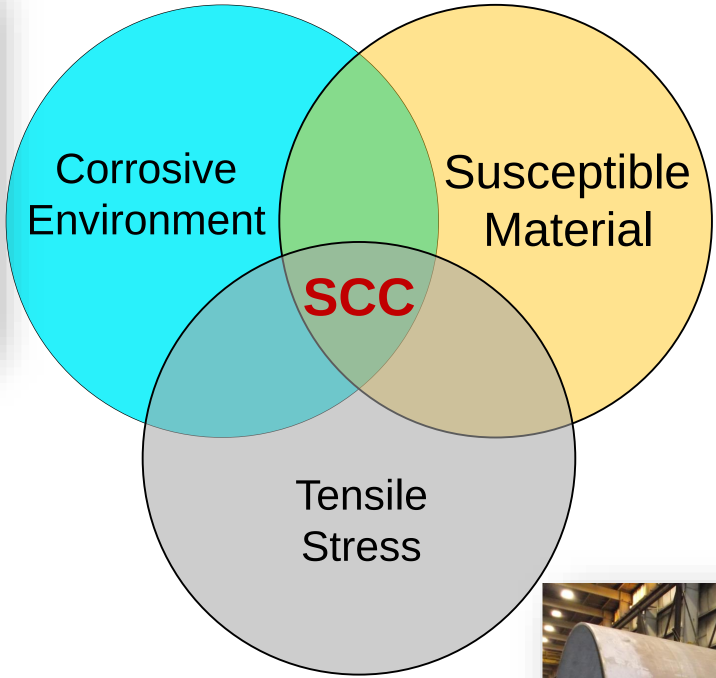


25 Sister Rods in ORNL Hot Cell.
Photo: Saltzstein, SNL

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, SNL

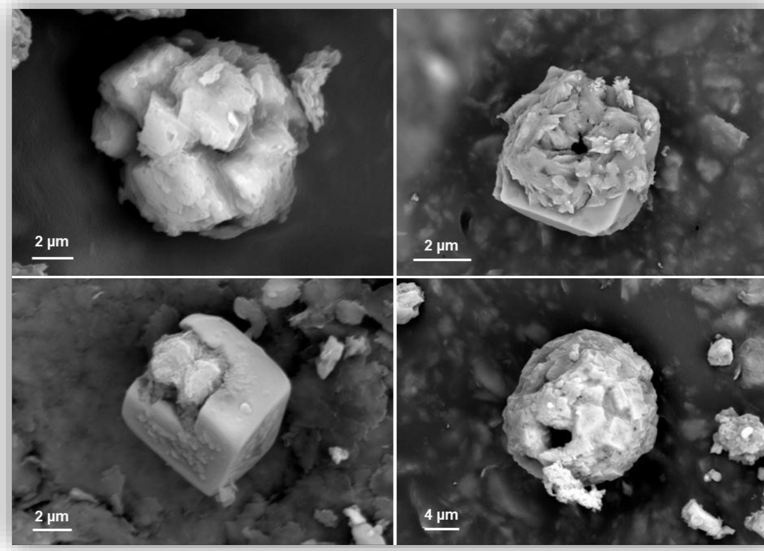
Understanding Canister Performance:

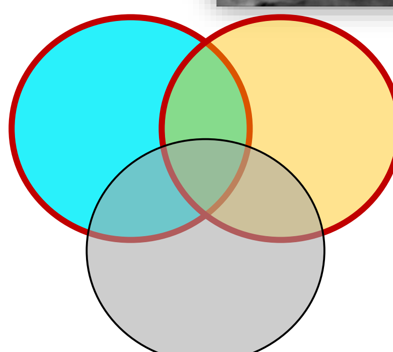
Do We Have a Corrosive Environment?

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.

Photos: Enos, SNL

Examples of sea-salt aerosols found on canisters. Photo: Bryan, 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.

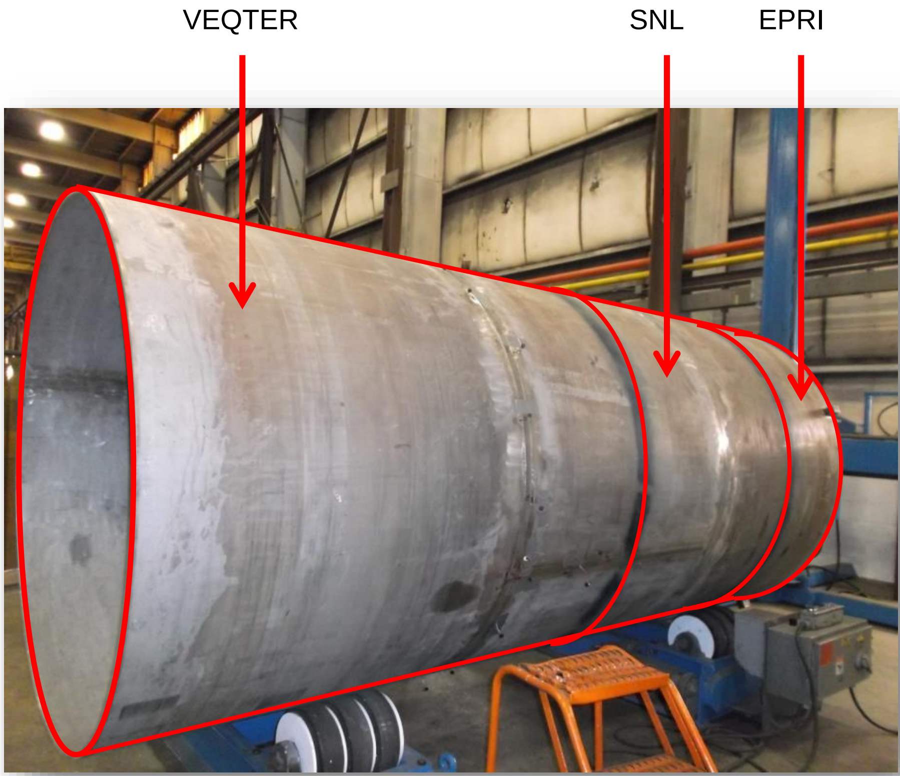
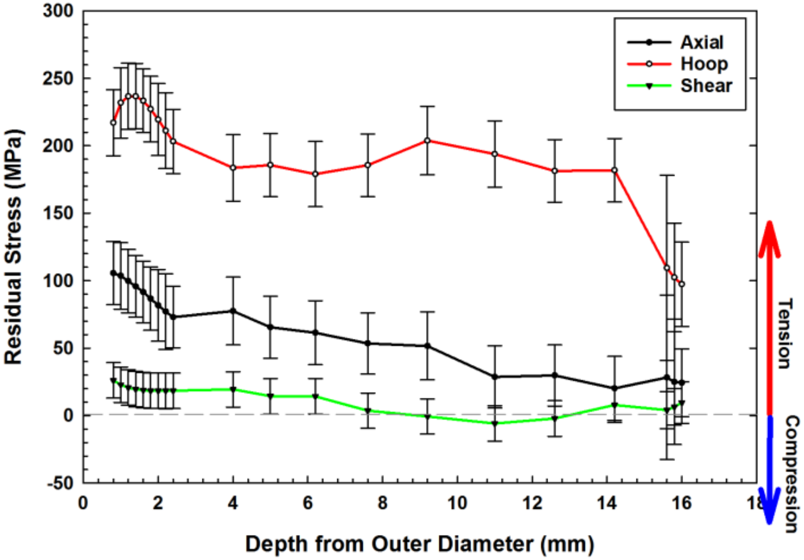
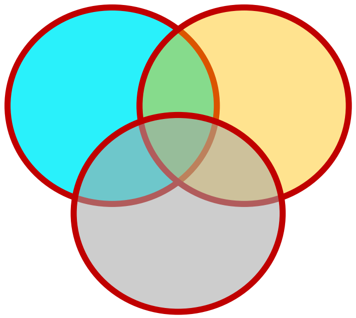


Photo: Enos, SNL



Measured Stresses, Circumferential weld HAZ, Sandia Canister Mockup. Enos, SNL



Transporting Spent Nuclear Fuel:

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

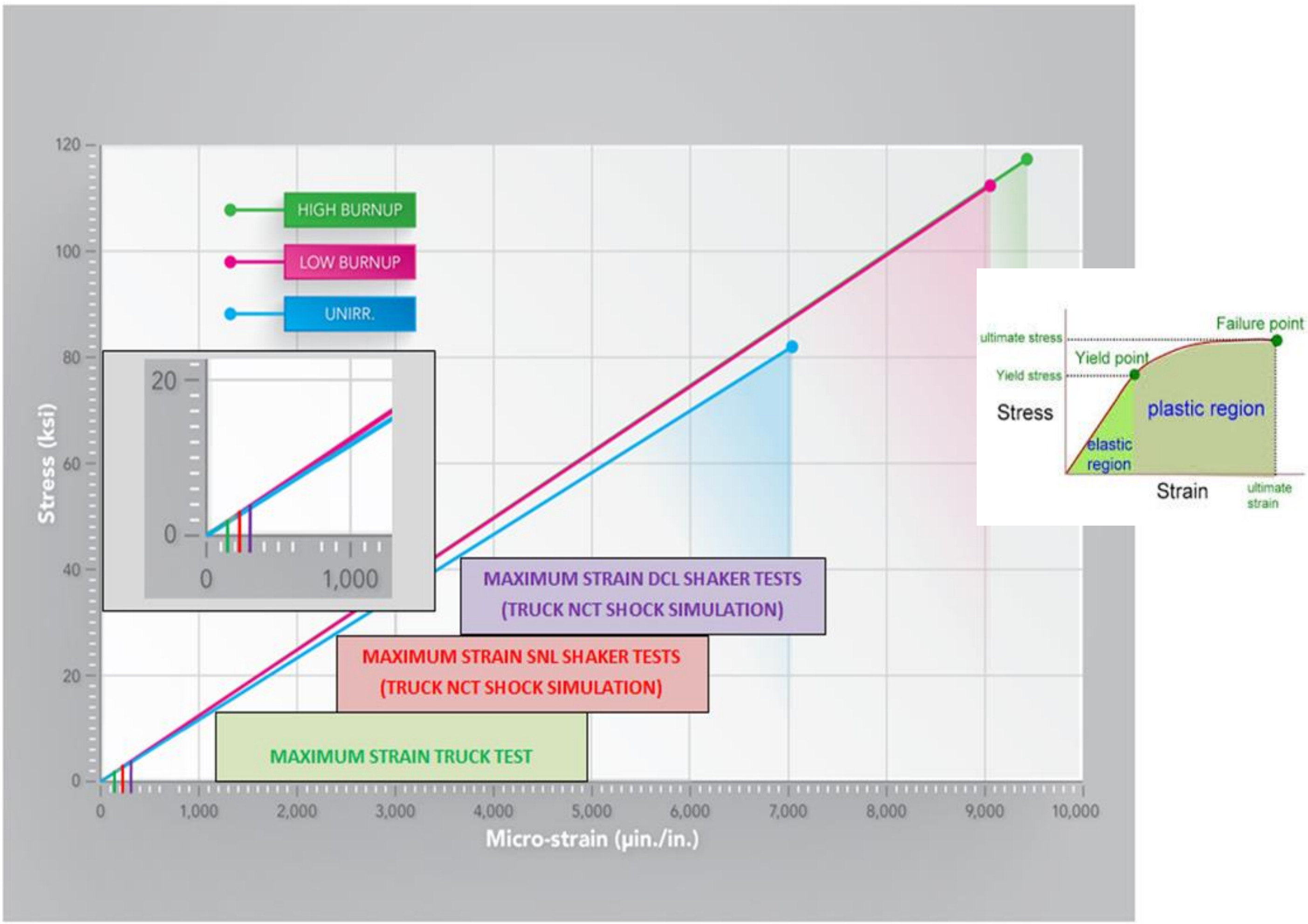
Three series of tests using a surrogate PWR assembly

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:

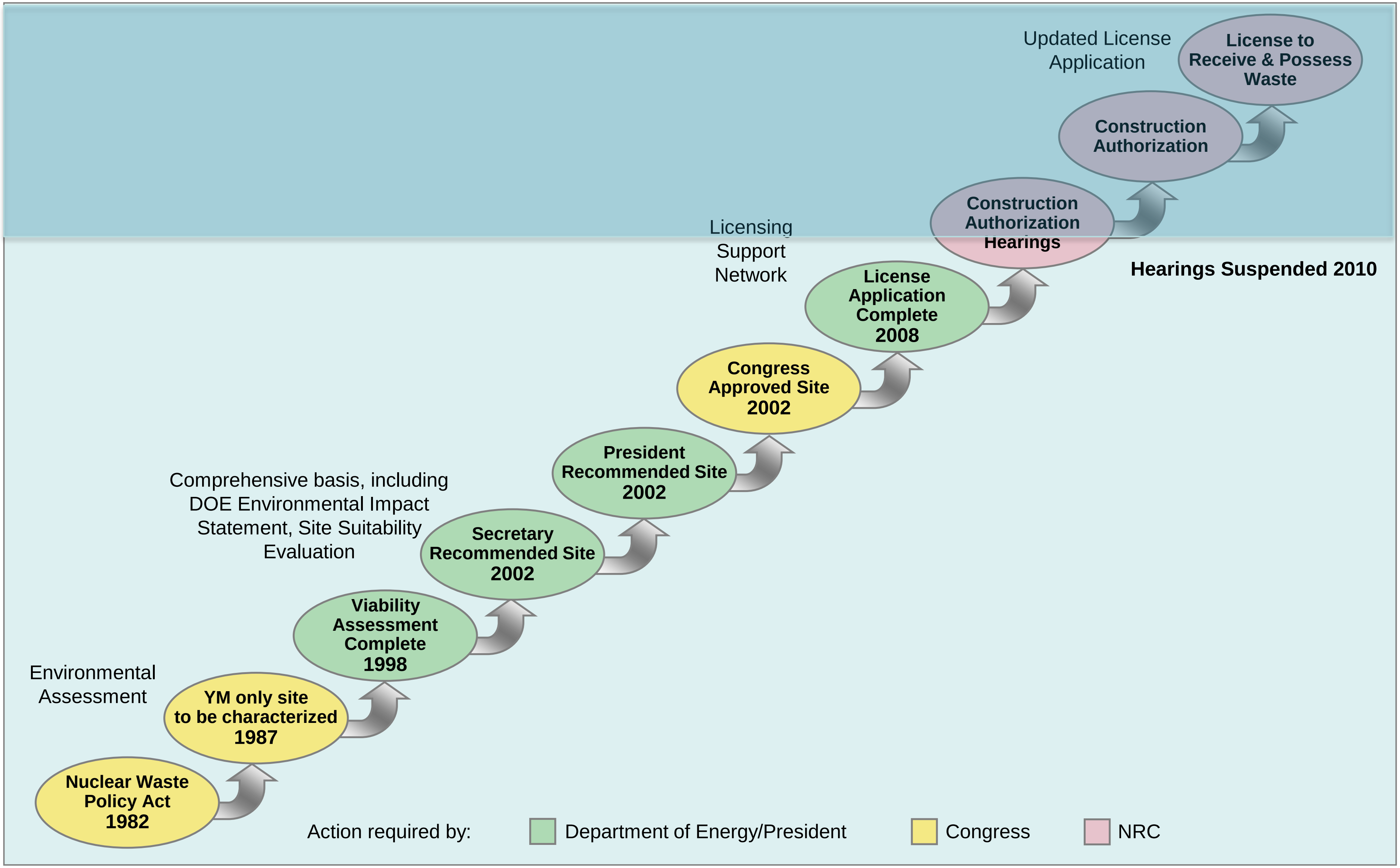
How do Stresses on Fuel During Normal Conditions of Transport Compare to Failure Limits?



McConnell et al, 2016, SNL and PNNL

What it may take to License a Repository

A Short History of Yucca Mountain



What does a Repository License Application Look Like?

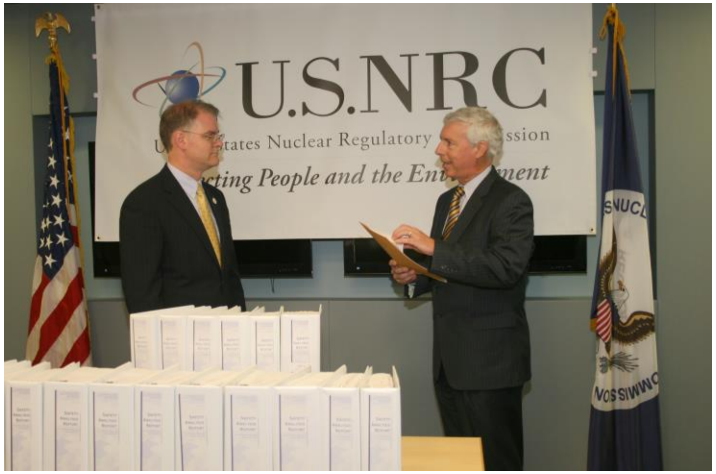
The 2008 Yucca Mountain License Application (LA) included

- 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)

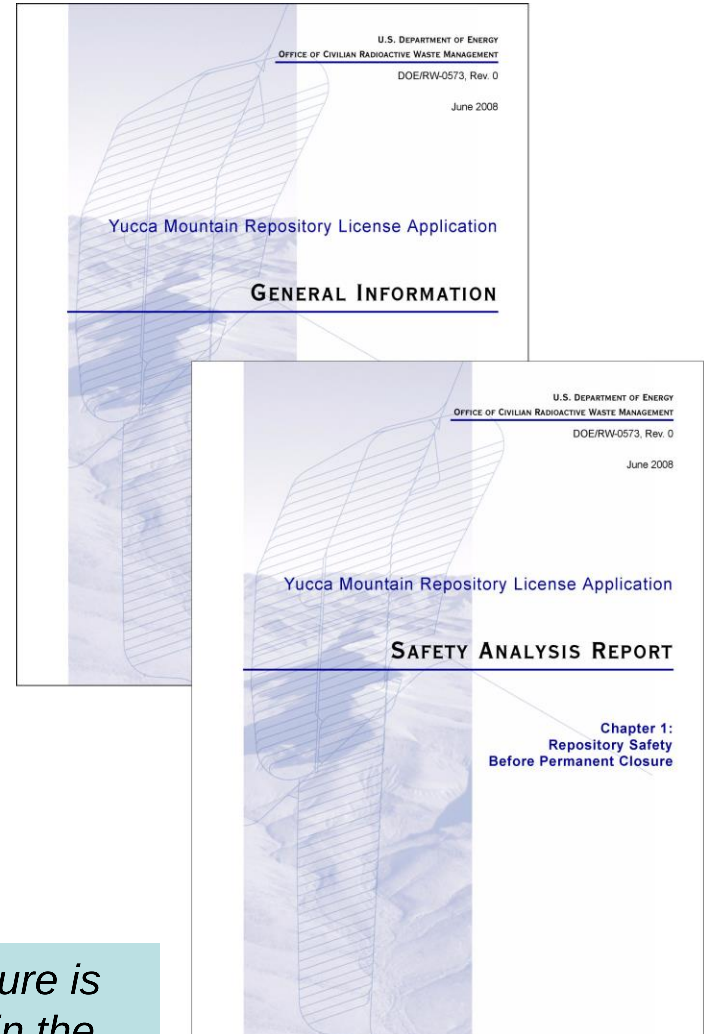
NRC Licensing process originally anticipated to take 3-4 years for a decision on construction authorization



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

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

Postclosure Safety Requirements

- For Yucca Mountain, EPA standards and NRC regulations define:
  - A requirement for a probabilistic “performance assessment”
  - Compliance limits for estimated mean annual dose and groundwater concentrations for
    - Individual protection
    - Individual protection following human intrusion
    - Groundwater protection
  - The scope of the total system performance assessment (TSPA) model
    - Criteria for identifying the features, events, and processes (FEPs) that must be considered in the TSPA
    - Characteristics of the “Reasonably Maximally Exposed Individual” (RMEI)
  - A requirement for the identification and description of multiple barriers that contribute to waste isolation

Defining the Scope of the Performance Assessment

The EPA defines "Performance Assessment" (40 CFR 197.12; restated by the NRC at 10 CFR 63.2)

- *"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."

Defining the Scope of the Performance Assessment

The EPA defines "Probability" and "Consequence" criteria that determine what must be included in performance assessment (40 CFR 197.36, restated by the NRC at 10 CFR 63.342)

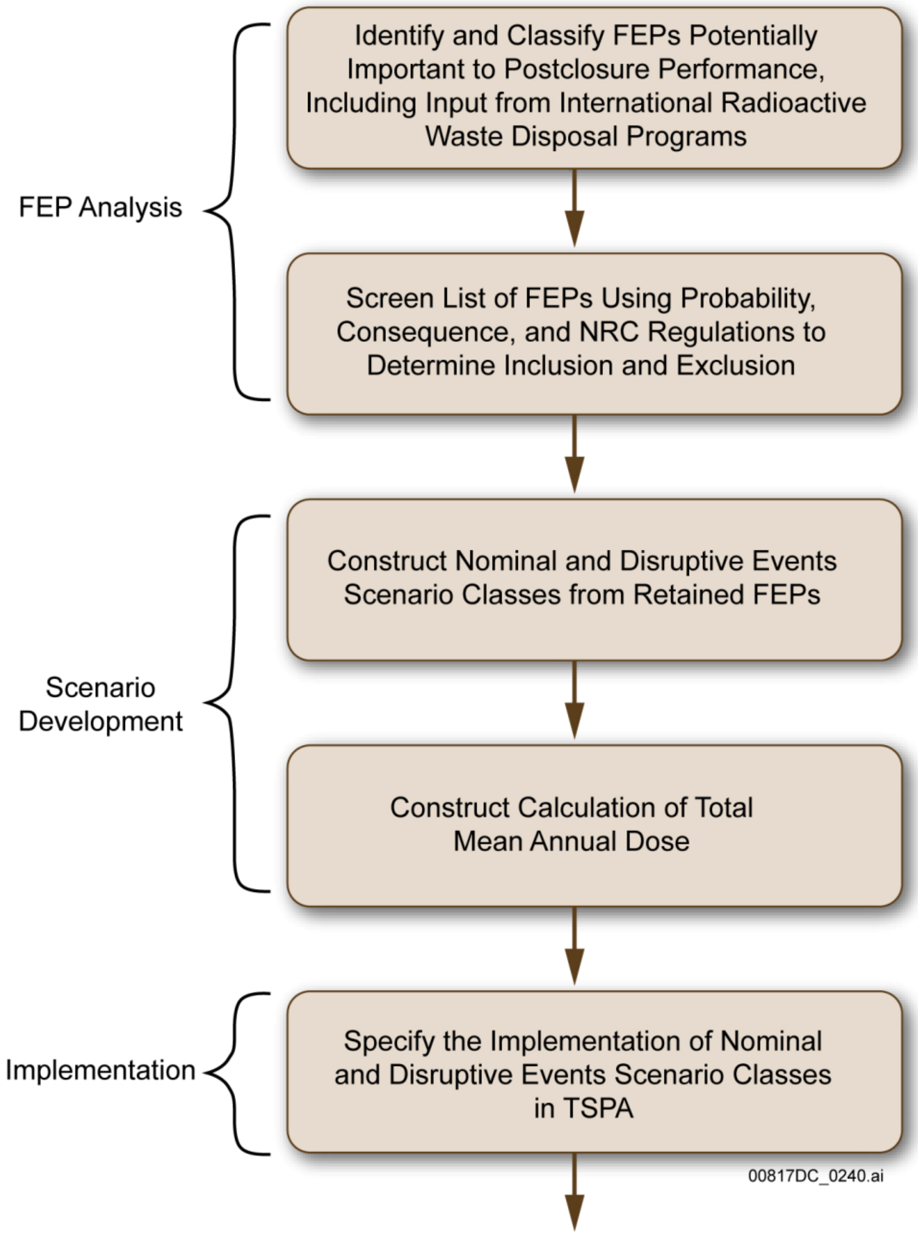
> "The DOE's performance assessments…shall not include consideration of very unlikely features, events, or processes, i.e., those that are estimated to have less than one chance in 100,000,000 per year of occurring"
>
> …
>
> "DOE's performance assessments need not evaluate the impacts resulting from features, events, and processes or sequences of events and processes with a higher chance of occurring if the results of the performance assessments would not be changed significantly in the initial 10,000-year period after disposal."

How Much Can a Performance Assessment Reasonably Include?

- 374 FEPs evaluated for the YM LA (SNL 2008a,b)
  - 222 excluded from the TSPA
  - 152 included in the TSPA
  - Full documentation provided with the LA
- Four scenario classes defined for TSPA analysis

Formal proof of completeness is not possible for an analysis of the future

Rigorous and iterative review can provide confidence that the chosen scenarios are representative and include the necessary FEPs



TSPA-LA Scenarios

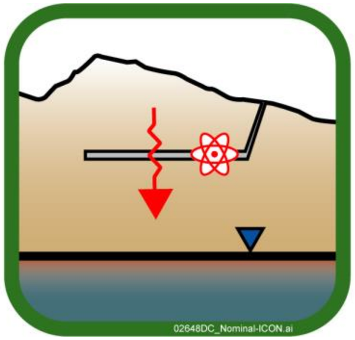
Four scenario classes divided into seven modeling cases

Nominal Scenario Class

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

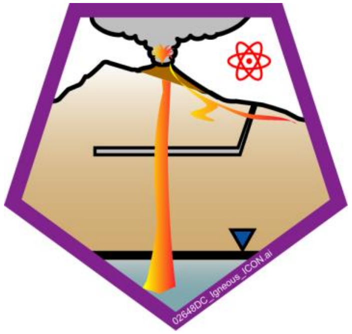
Early Failure Scenario Class

- Waste Package Modeling Case
- Drip Shield Modeling Case



Igneous Scenario Class

- Intrusion Modeling Case
- Eruption Modeling Case



Seismic Scenario Class

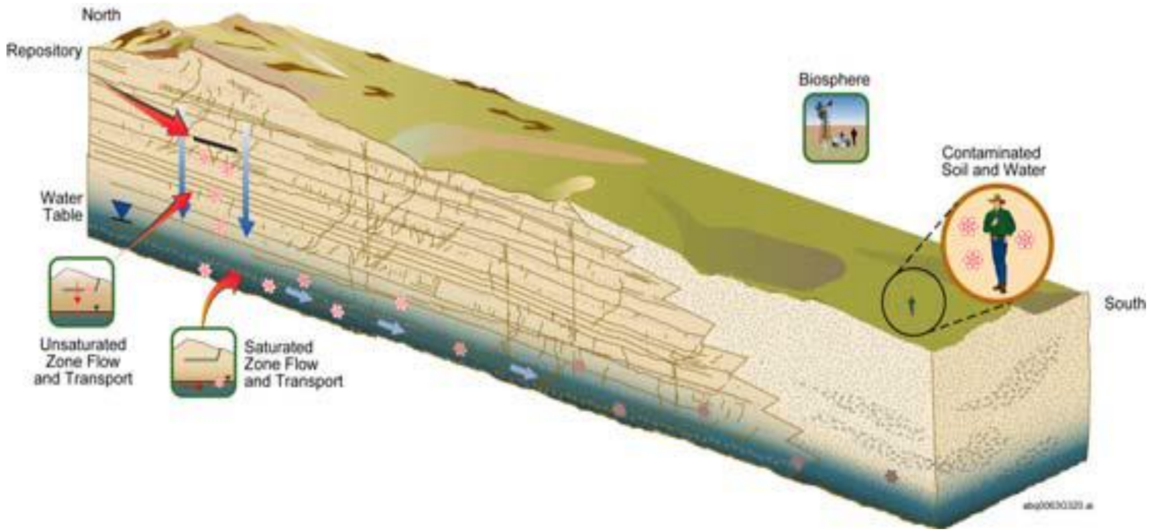
- Ground Motion Modeling Case
- Fault Displacement Modeling Cas

Regulatory Basis for Uncertainty Analysis

- "The NRC will determine compliance, based upon the arithmetic mean of the projected doses from DOE's performance assessments for the period within 1 million years after disposal" (EPA 40 CFR 197.13(a), restated by the NRC at 10 CFR 63.303)
- "The DOE must demonstrate, using performance assessment, that there is a reasonable expectation that … " [estimated doses will be below specified limits] (EPA 40 CFR 197.20(a), restated by the NRC at 10 CFR 63.111(a))
- "Reasonable expectation means that NRC is satisfied that compliance will be achieved based upon the full record before it. Characteristics of reasonable expectation include that it:
  - (a) Requires less than absolute proof because absolute proof is impossible to attain for disposal due to the uncertainty of projecting long-term performance;
  - (b) Accounts for the inherently greater uncertainties in making long-term projections of the performance of the Yucca Mountain disposal system;
  - (c) Does not exclude important parameters from assessments and analyses simply because they are difficult to precisely quantify to a high degree of confidence; and
  - (d) Focuses performance assessments and analyses upon the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values." (EPA 40 CFR 197.14, restated by the NRC at 10 CFR 63.304)

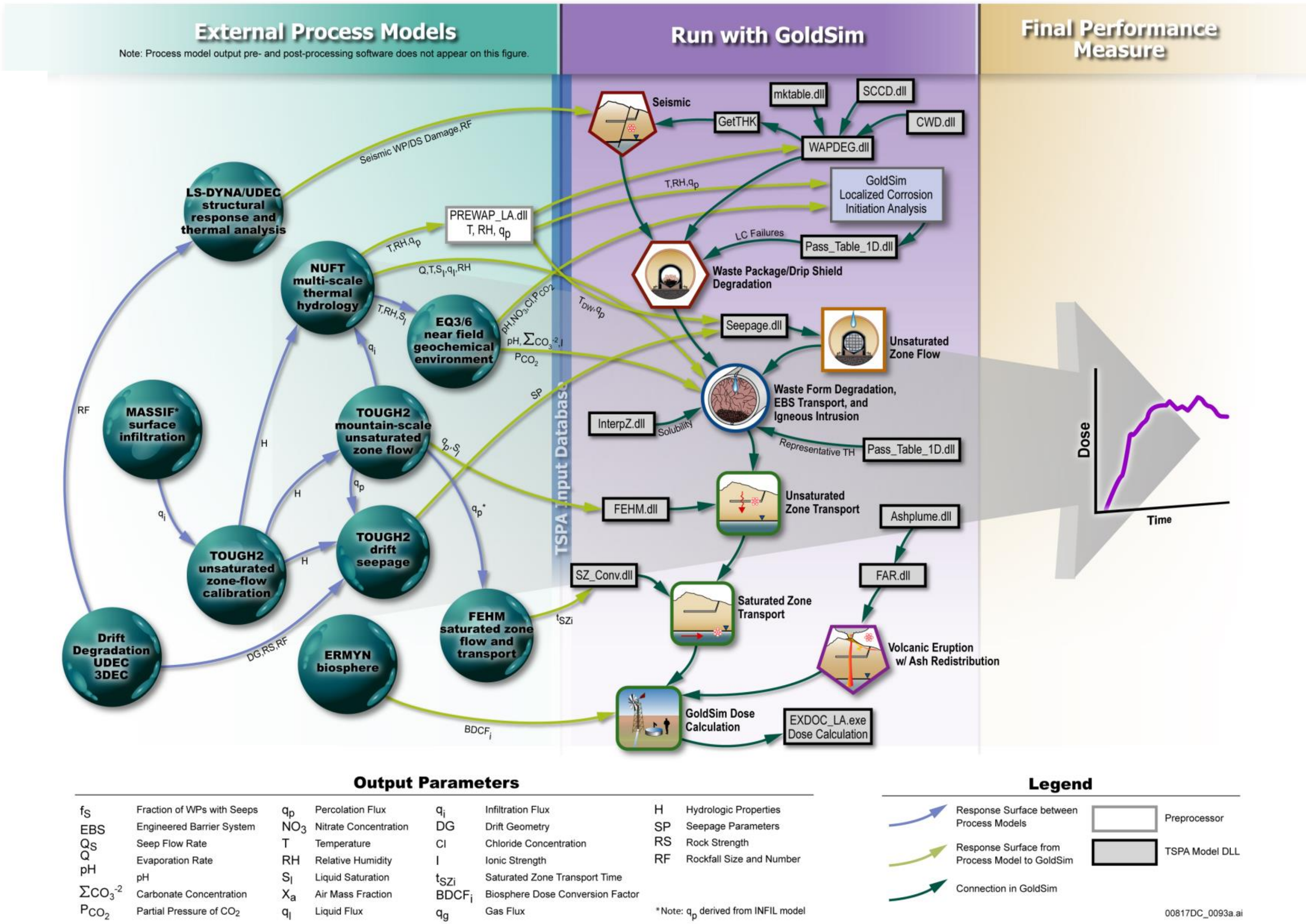
Major Long-Term Processes Active at Yucca Mountain

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

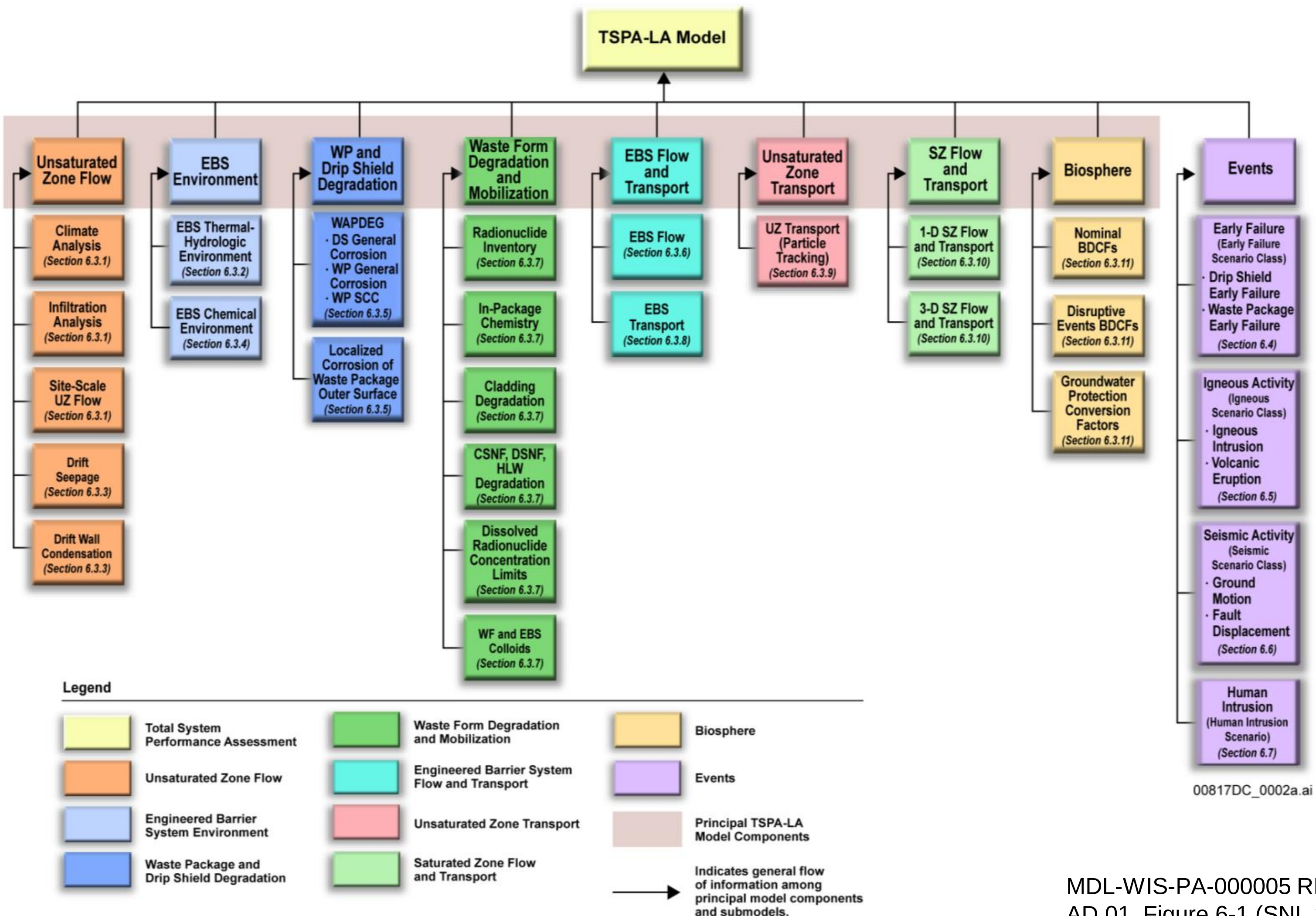


  - Radionuclides are mobilized by seepage water and percolate downward to the water table
  - Lateral transport in the saturated zone leads to biosphere exposure at springs or withdrawal wells
  - Seismicity and volcanism may disrupt the system over geologic time

Total System Performance Assessment Architecture



Postclosure Science Supporting the TSPA



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

Uncertainty in Yucca Mountain TSPA

Sandia National Laboratories

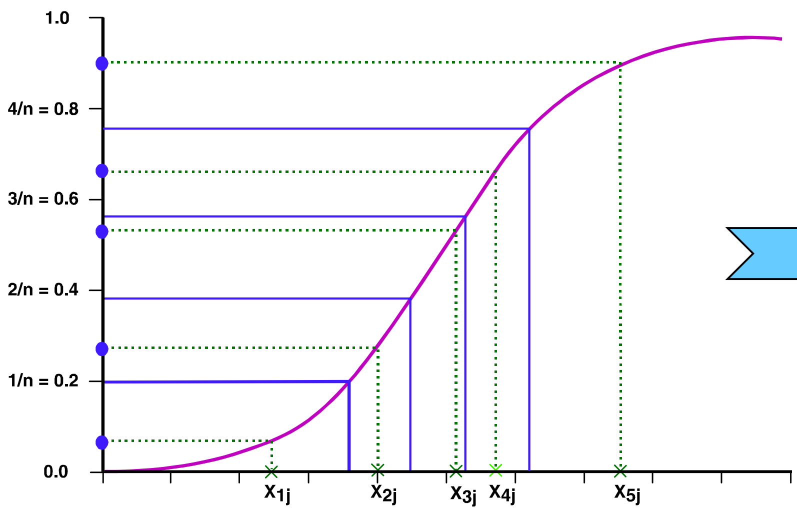
Aleatory Uncertainty
− Inherent randomness in events that could occur in the future − Alternative descriptors: irreducible, stochastic, intrinsic, type A − Examples: ➢ *Time and size of an igneous event* ➢ *Time and size of a seismic event*

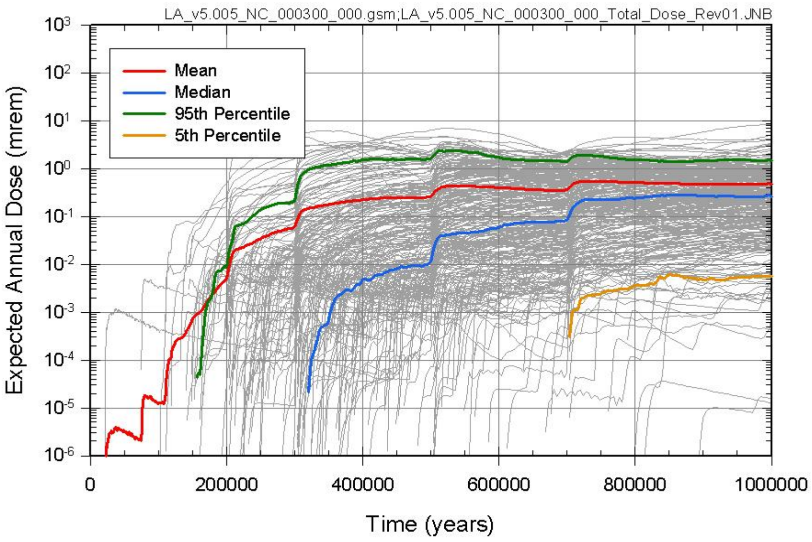
Epistemic uncertainty
− Lack of knowledge about appropriate value to use for a quantity assumed to have a fixed value − Alternative descriptors: reducible, subjective, state of knowledge, type B − Examples: ➢ *Spatially averaged permeabilities, porosities, sorption coefficients, …* ➢ *Rates defining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

Uncertainty in YM TSPA (cont.)

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

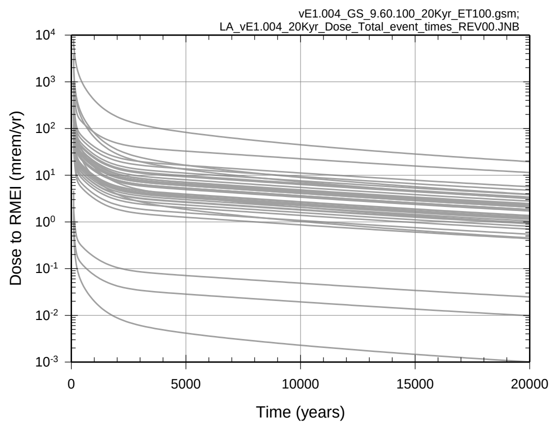
(approx. 400 uncertain epistemic parameters in TSPA-LA)



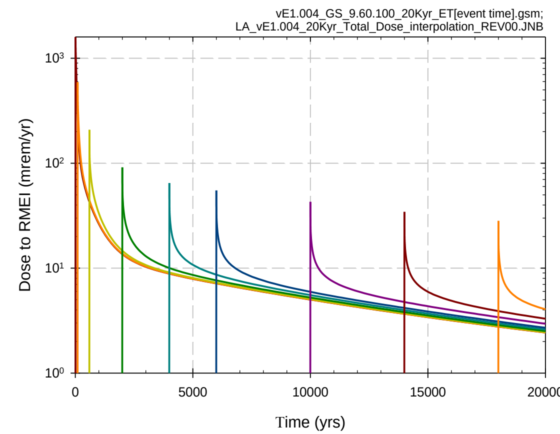


Aleatory uncertainty incorporated through the design of the analysis

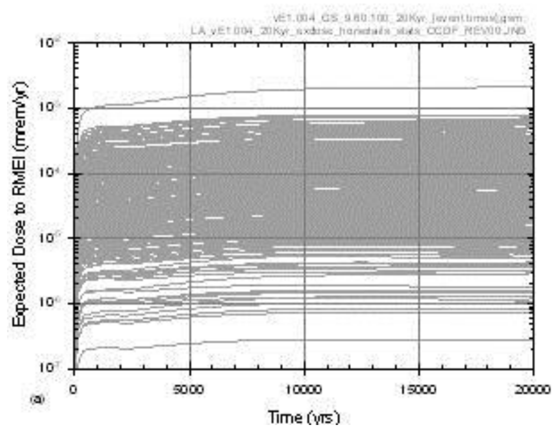
Example: Calculation of Expected Eruptive Dose



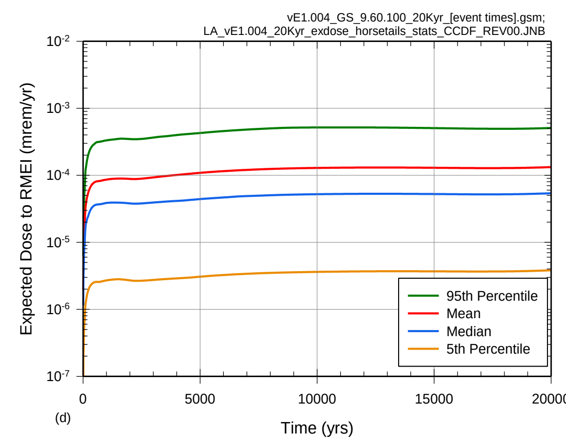
Eruptive dose: 40 realizations of aleatory uncertainty conditional on a single eruption of 1 waste package at time zero



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



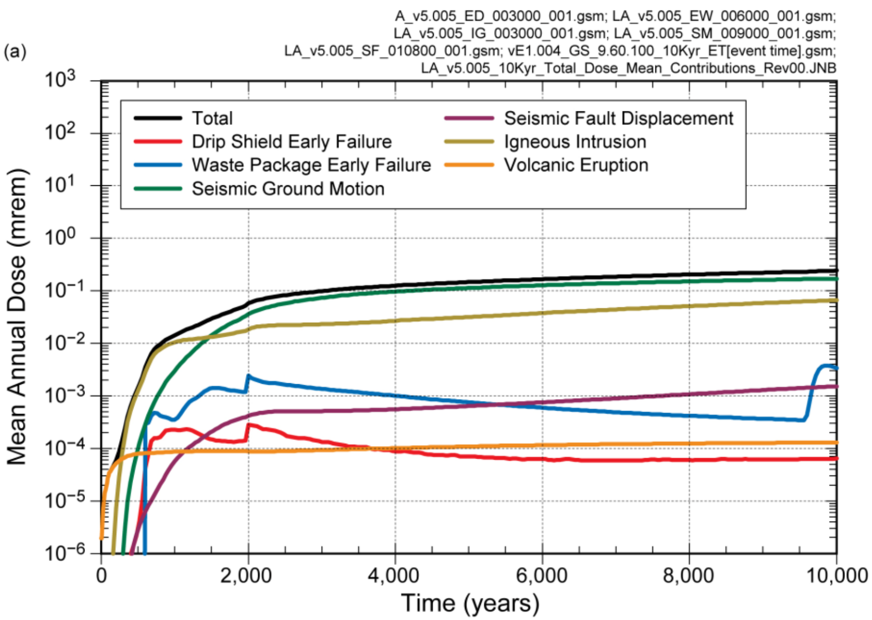
Expected eruptive dose; 300 realizations, each showing expected dose from a single sampling of epistemic uncertainty with events at all times



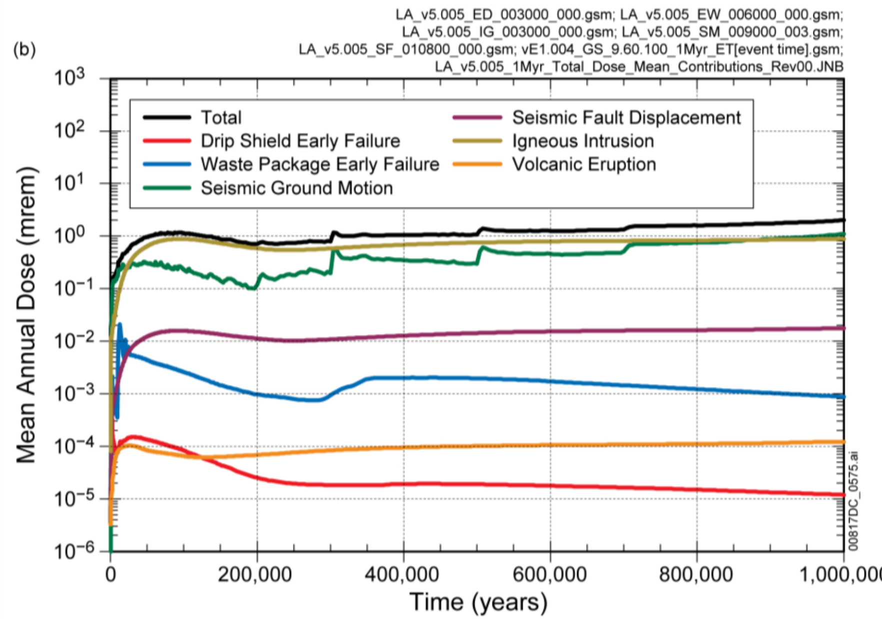
Summary curves showing overall mean dose from eruption

MDL-WIS-PA-000005 Rev 00, Figures J7.3-1, 2,&4 (SNL 2008c)

Modeling Cases Contributing to Total Mean Annual Dose



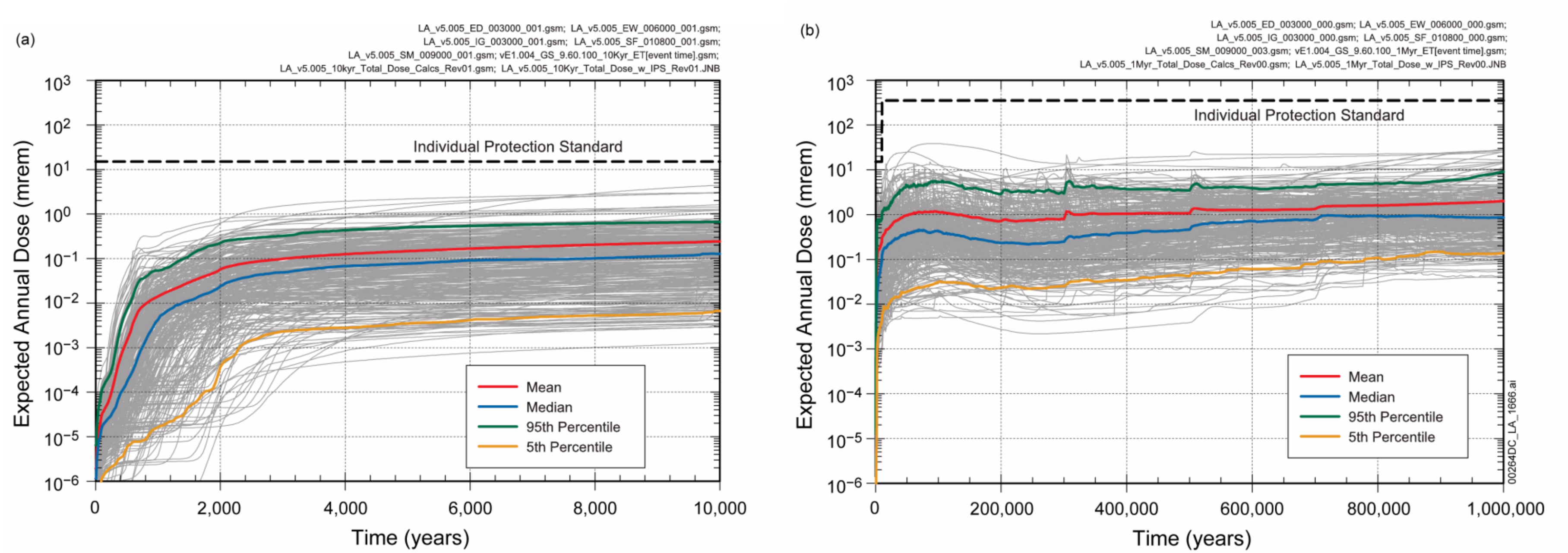
10,000 years



1,000,000 years

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

Long-Term Performance of Yucca Mountain



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

10,000 years

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

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

1,000,000 years

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

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

Closing thoughts regarding Repository Licensing

40 CFR 191 (EPA 1985)

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

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

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

Discussion

References for Yucca Mountain

- SNL (Sandia National Laboratories), 2008a. Features, Events, and Processes for the Total System Performance Assessment: Methods. ANL-WIS-MD-000026, Rev 00. Las Vegas, NV: U.S. Department of Energy Office of Civilian Radioactive Waste Management
- SNL (Sandia National Laboratories), 2008b. Features, Events, and Processes for the Total System Performance Assessment: Analyses. ANL-WIS-MD-000026, Rev 00. Las Vegas, NV: U.S. Department of Energy Office of Civilian Radioactive Waste Management
- SNL (Sandia National Laboratories), 2008c. Total system performance assessment model/analysis for the license application. MDL-WIS-PA-000005 Rev00, AD 01. Las Vegas, NV: U.S. Department of Energy Office of Civilian Radioactive Waste Management
- Swift, P.N., C.W. Hansen, J.C. Helton, R.L. Howard, M. K. Knowles, R.J. MacKinnon, J.A. McNeish, S.D. Sevougian, 2014. "Summary discussion of the 2008 performance assessment for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada," in Helton, J.C., C.W. Hansen, and P.N. Swift, eds., "Special Issue: Performance Assessment for the Proposed High-Level Radioactive Waste Repository at Yucca Mountain", *Reliability Engineering and System Safety* v. 122, pages 449-456.
- U.S. DOE (U.S. Department of Energy), 1996. Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO-1996-2184, Carlsbad, NM, U.S. Department of Energy Carlsbad Area Office
- U.S. DOE (U.S. Department of Energy), 2008. Yucca Mountain repository license application safety analysis report. DOE/RW-0573, Update no. 1. Las Vegas, NV: U.S. Department of Energy
- U.S. Nuclear Regulatory Commission (NRC), 2014. Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 3, Repository Safety after Permanent Closure. NUREG-1949, Vol. 3
- U.S. Nuclear Regulatory Commission (NRC), 2015. Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 2, Repository Safety Before Permanent Closure, and Volume 5, Proposed Conditions on the Construction Authorization and Probable Subjects of License Specifications. NUREG-1949, Vol. 2 and Vol. 5

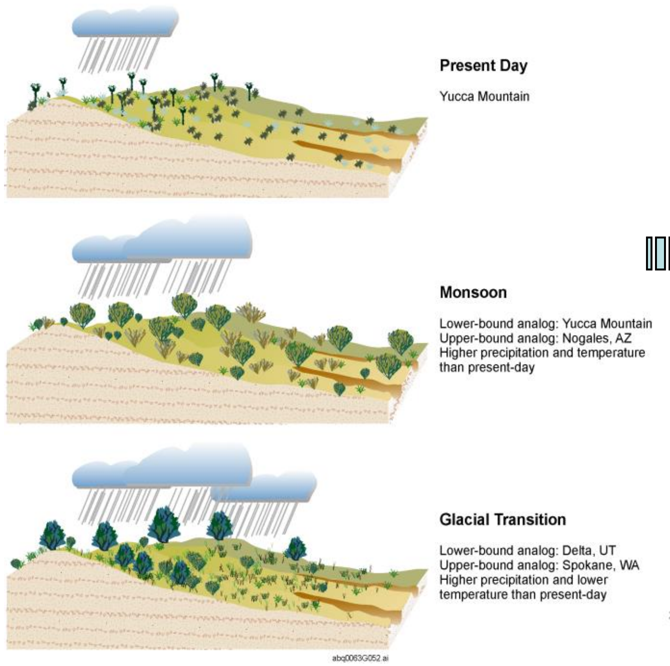
Key Websites for Yucca Mountain and WIPP: http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app.html; http://www.wipp.energy.gov/library/caolib.htm

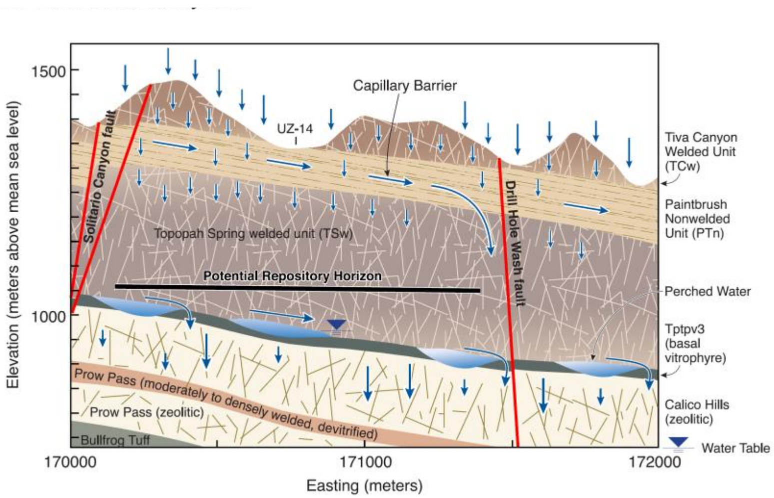
References for Storage and Transportation R&D

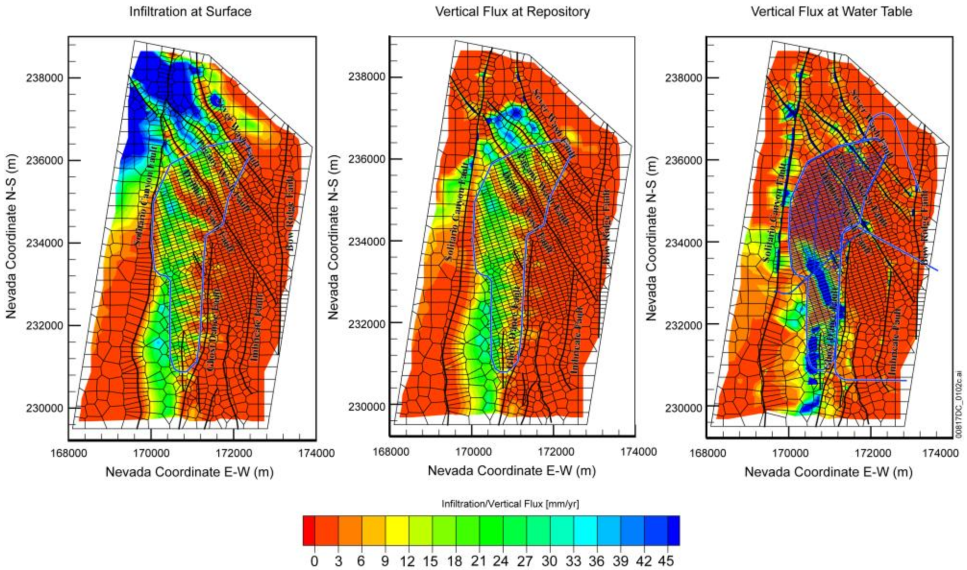
- Billone, M., "Effects of Lower Drying-Storage Temperatures on the DBTT of High-Burnup PWR Cladding," *FCRD-UFD-2015-000008*. U. S. Department of Energy, Office of Used Nuclear Fuel Disposition, August 2015.
- Hanson, B., "High Burnup Fuel, Associated Data Gaps, and Integrated Approach for Addressing the Gaps," presentation to the U.S. Nuclear Waste Technical Review Board, February 17, 2016, Knoxville, TN.
- Wang, J.-A., Wang, H., Jiang, H., Bevard, B., Howard, R., "FY14 Status Report: CIRFT Testing Results on High Burnup UNF " *FCRD-UFD-2014-000053.* U. S. Department of Energy, Office of Used Nuclear Fuel Disposition, September 2014.
- Enos, D.G. , Bryan, C.R., Norman, K.M , "Data Report on Corrosion Testing of Stainless Steel SNF Storage Canisters," *FCRD-UFD-2013-000324, SAND2013-8314*. U. S. Department of Energy, Office of Used Nuclear Fuel Disposition. September 2013.
- McConnell, P., "Sandia Shaker Table and Over-the-Road Vibration Studies," presentation to the U.S. Nuclear Waste Technical Review Board, February 17, 2016, Knoxville, TN.
- Wang, J.-A., H. Wang, H. Jian, Y. Yan, B. Bevard, "CIRFT Testing of High Burnup used Nuclear Fuel from PWR and BWRs," presentation to the U.S. Nuclear Waste Technical Review Board, February 17, 2016, Knoxville, TN.
- Enos, D.G., and Bryan, C.R. , 2016. "Understanding the Risk of Chloride Induced Stress Corrosion Cracking of Interim Storage Containers for the Dry Storage of Spent Nuclear Fuel: Residual Stresses in Typical Welded Containers." *SAND2015-8668 C*. Conference Paper, NACE 2016, Vancouver, BC.

Backup material

Groundwater Flow at Yucca Mountain

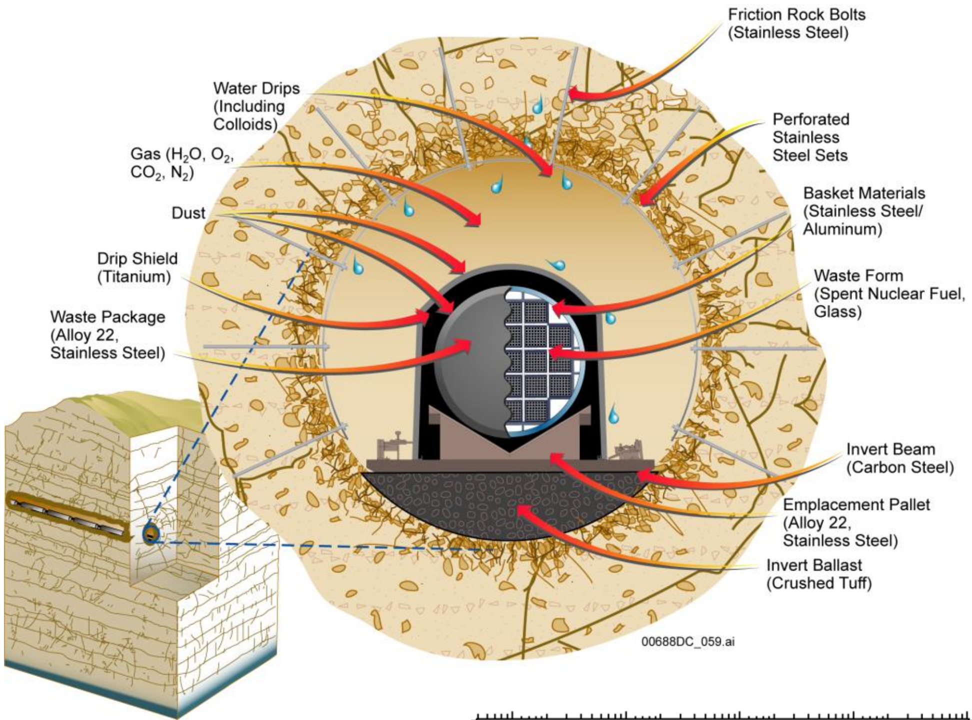


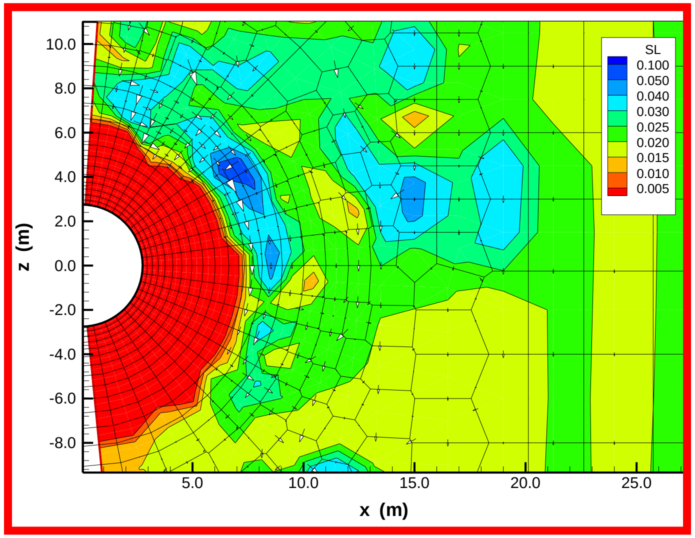




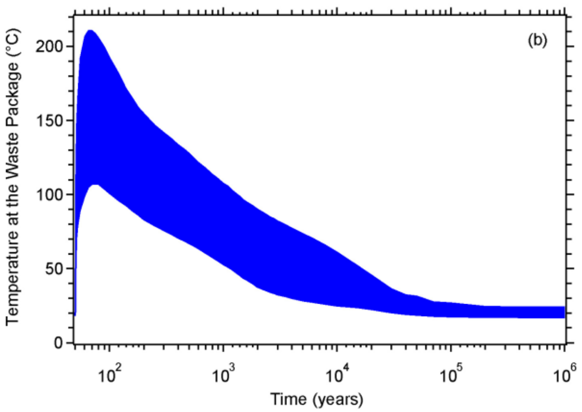
Field tests and models provide basis for understanding infiltration and flow in unsaturated rocks at Yucca Mountain

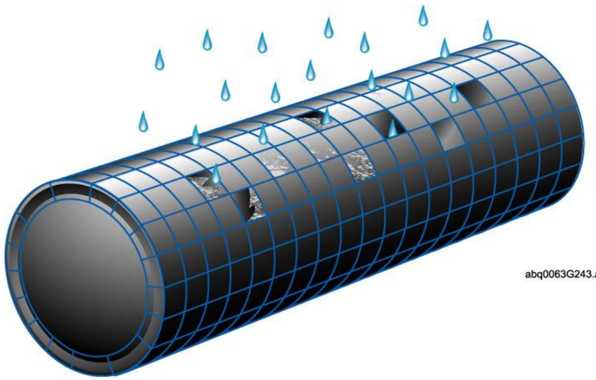
The Emplacement Environment at Yucca Mountain





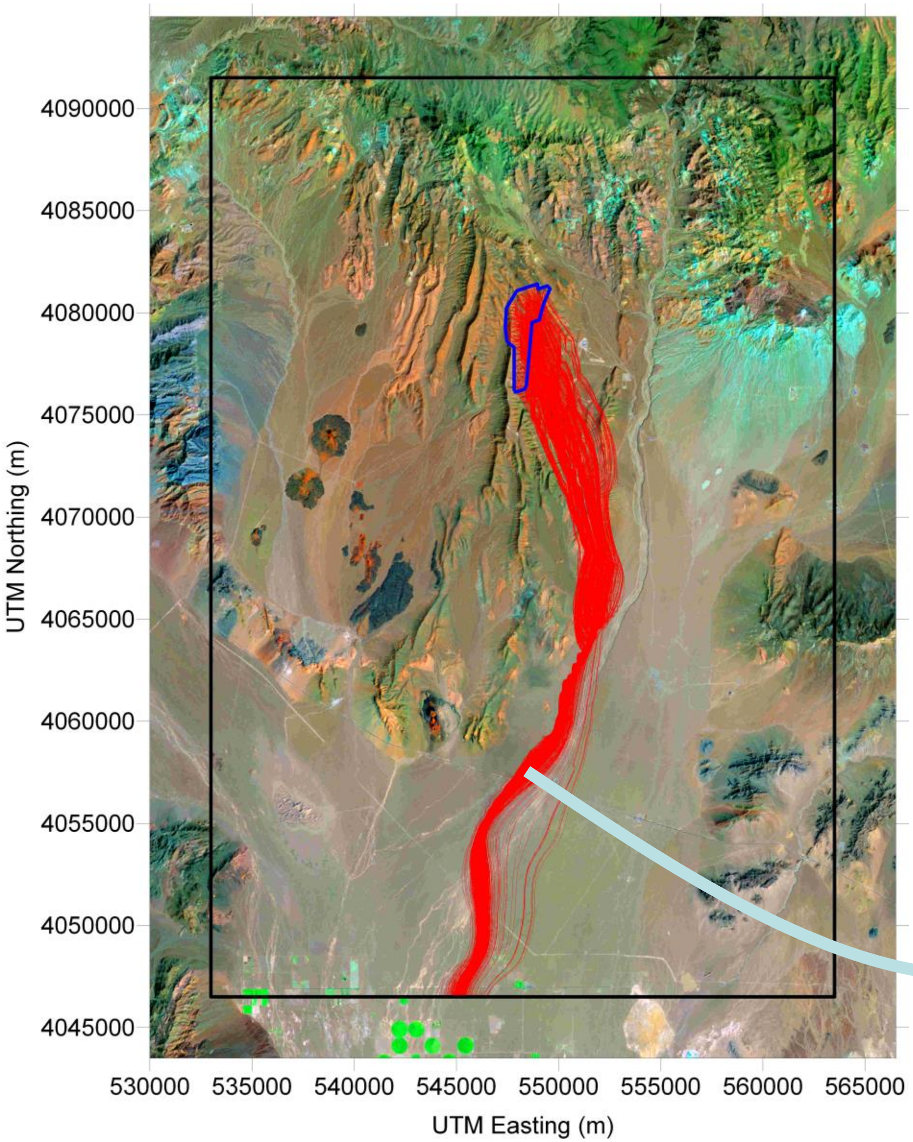
Material testing and models characterize performance of the engineered barriers

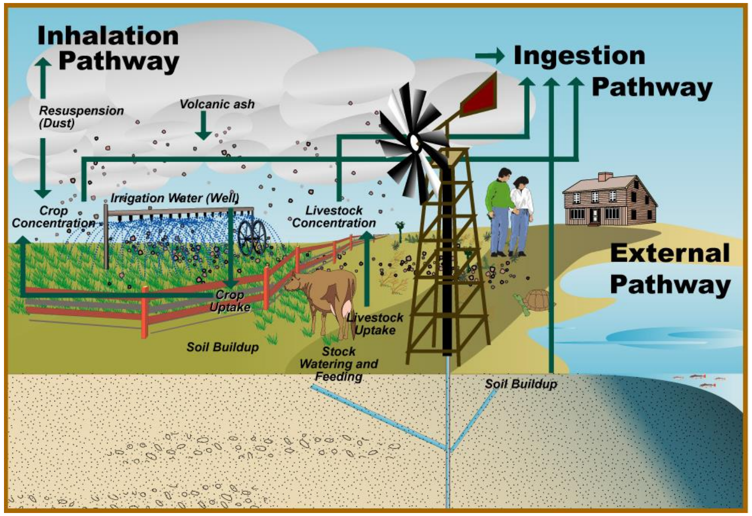




Estimating Dose to Hypothetical Future Humans

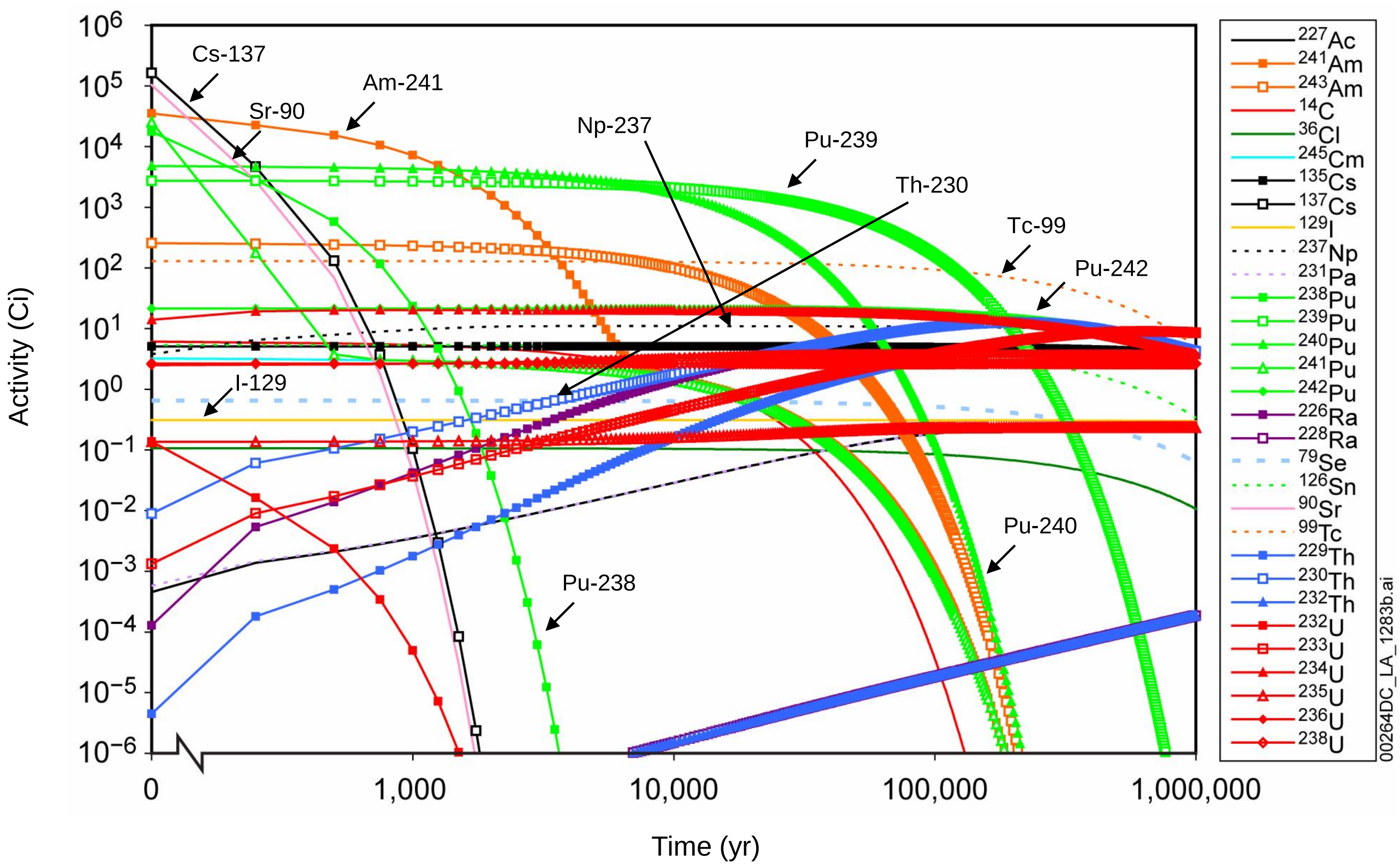
Sandia National Laboratories





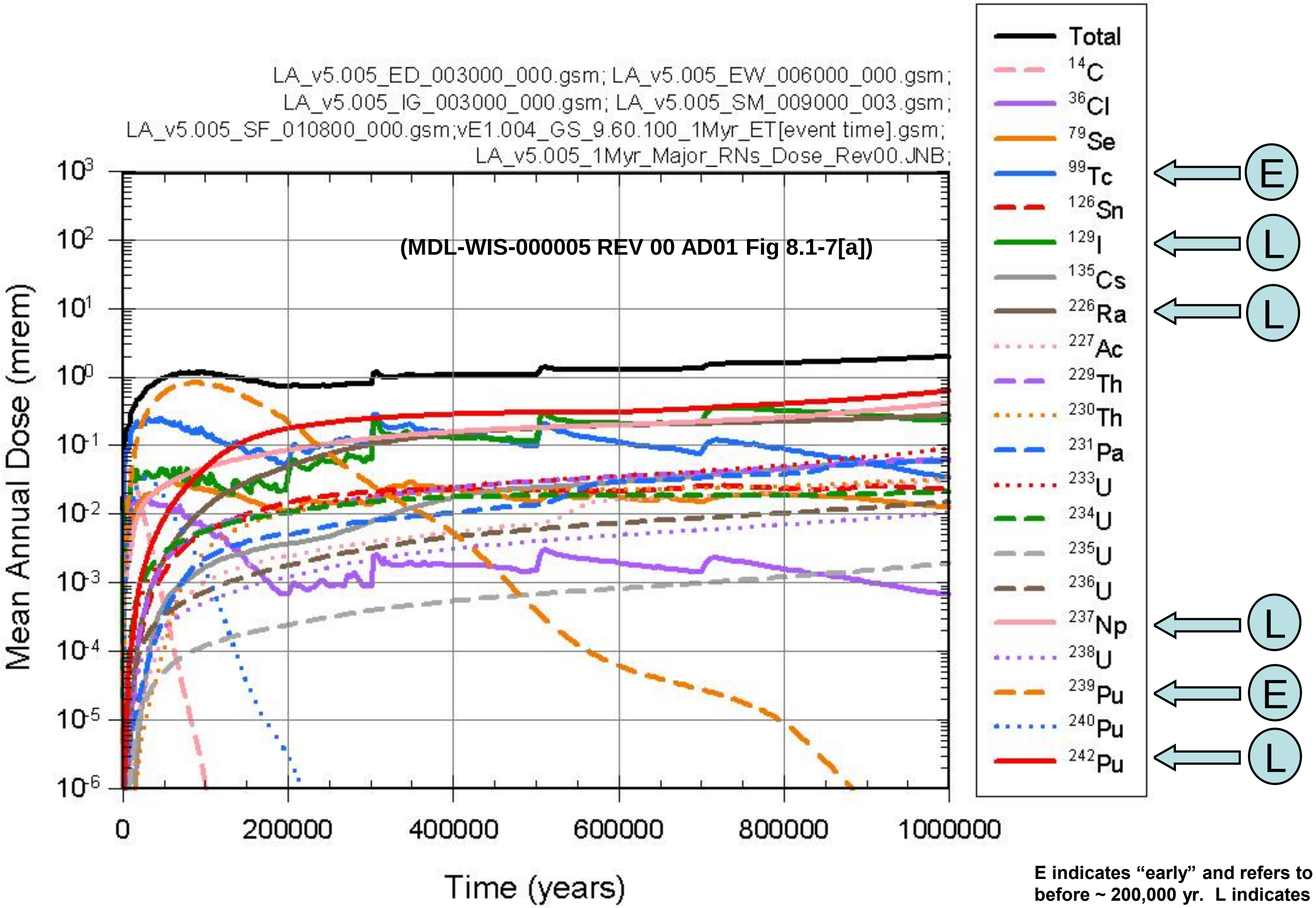
Modeled groundwater flow paths and hypothetical exposure pathways

Commercial Used Nuclear Fuel Decay



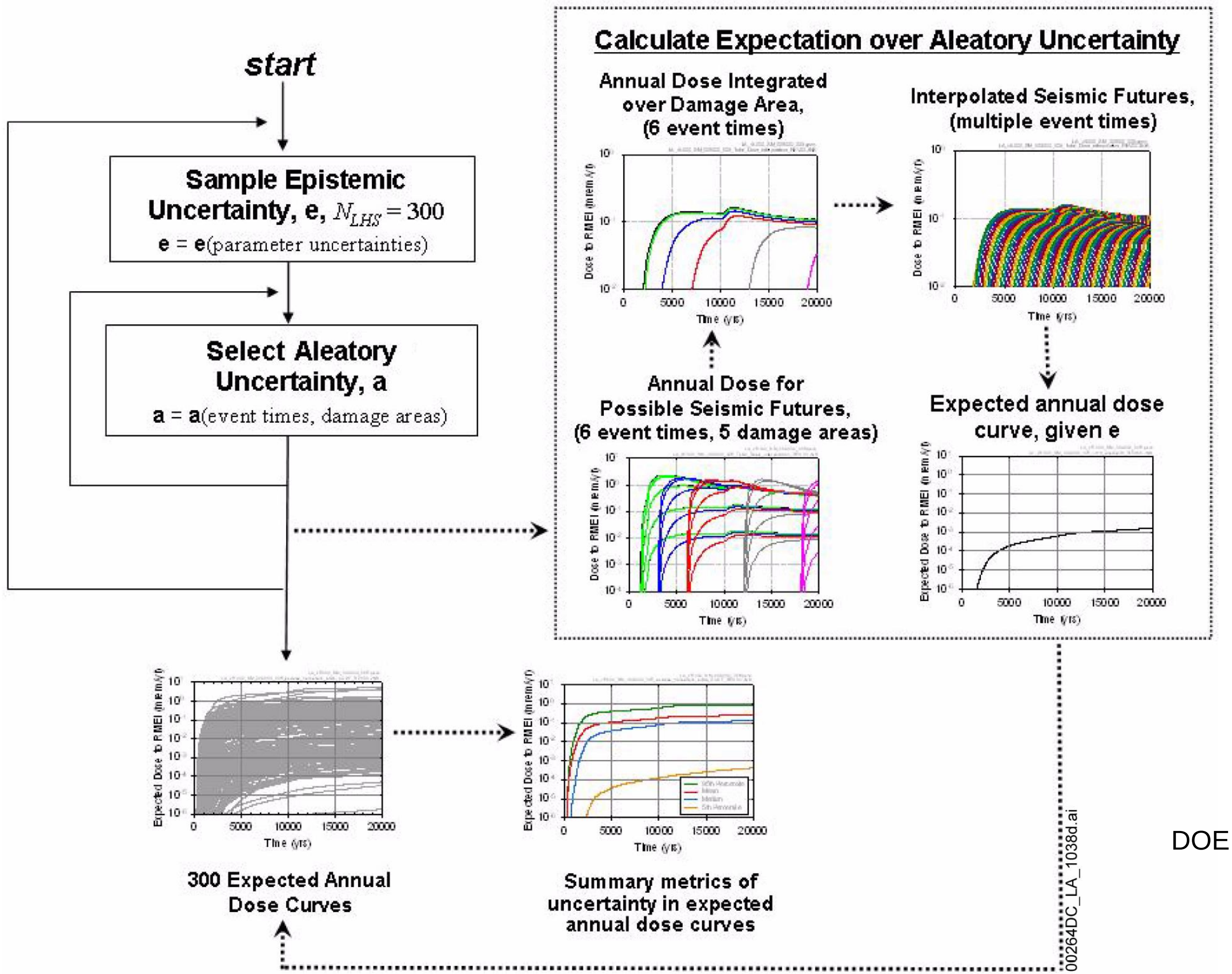
DOE/RW-0573 Rev 0, Figure 2.3.7-11, inventory decay shown for an single representative Yucca Mountain used fuel waste package, as used in the Yucca Mountain License Application, time shown in years after 2117.

Radionuclides Important to Mean Dose at Yucca Mountain



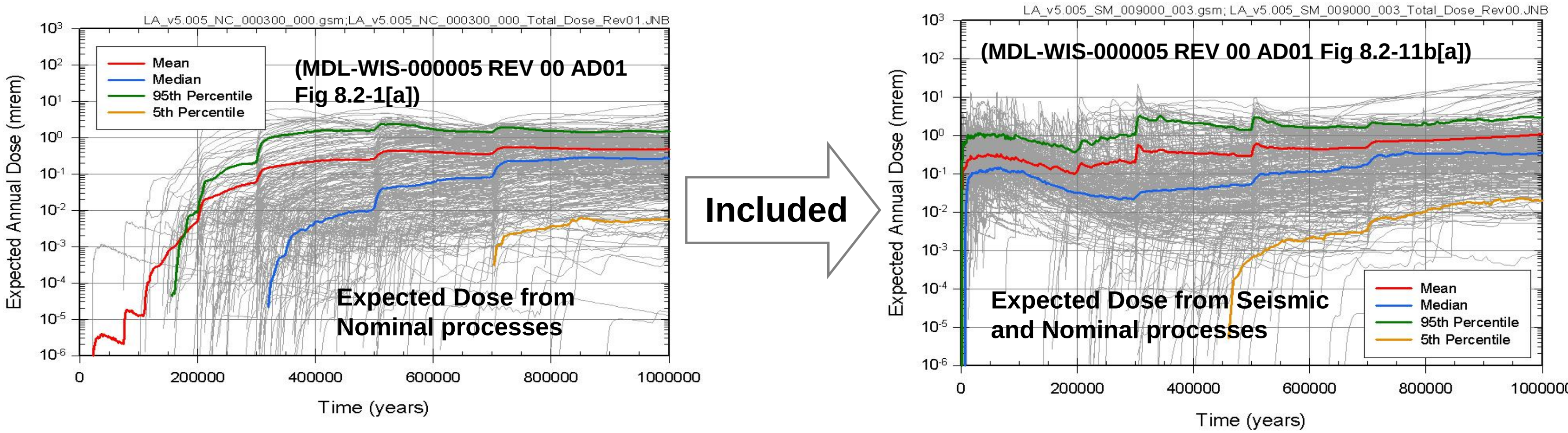
E indicates “early” and refers to the time period before ~ 200,000 yr. L indicates “late” and refers to the time period after ~ 200,000 yr

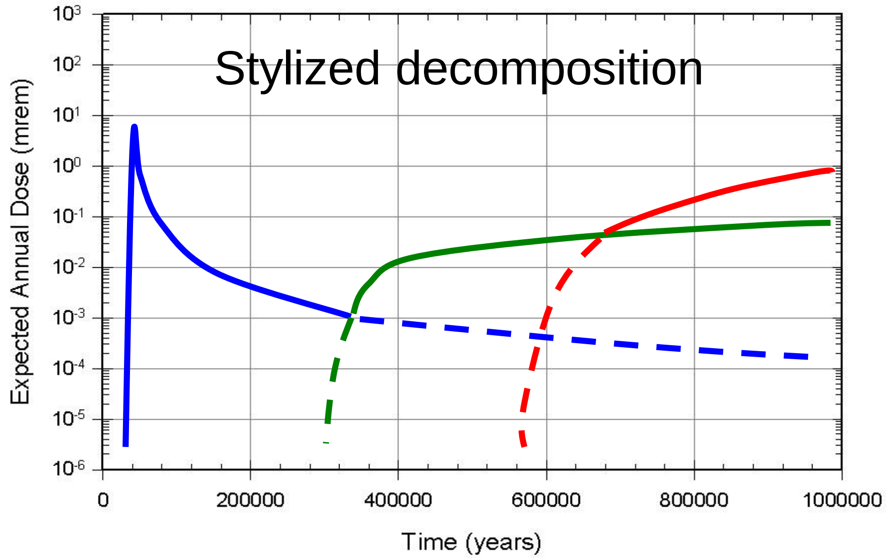
Example: Calculation of Expected Seismic Dose



DOE 2008 Figure 2.4-8

Composition of Seismic Ground Motion Dose

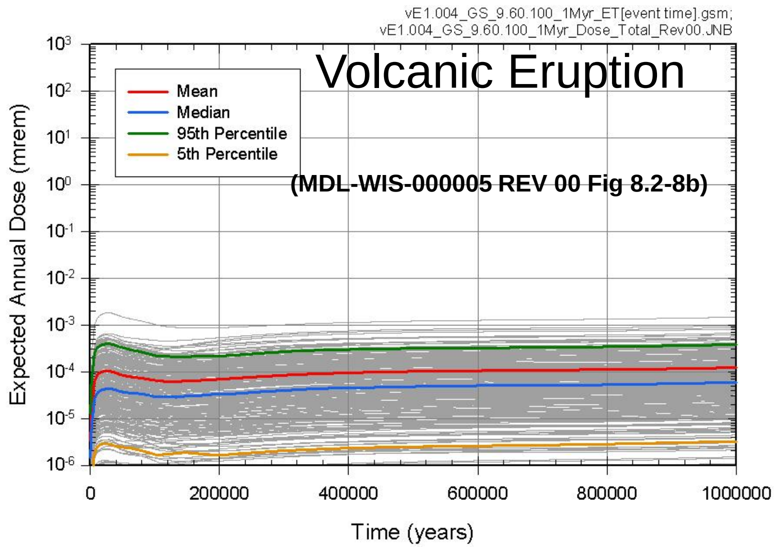




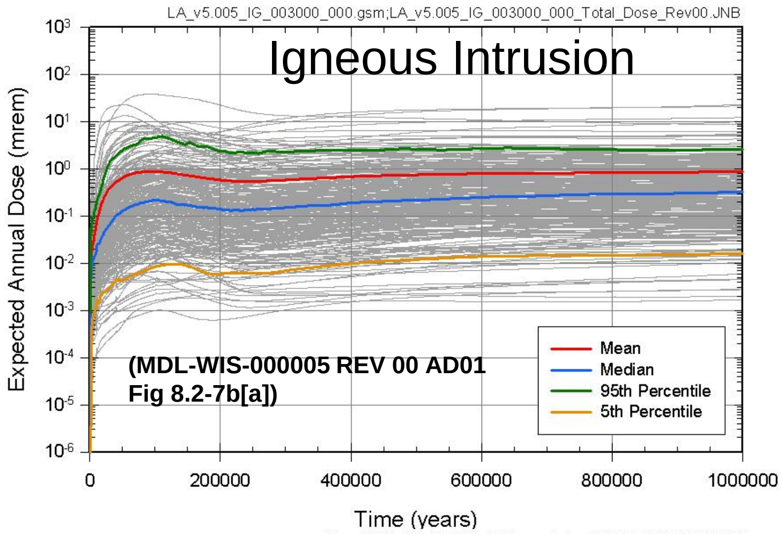
- From seismic damage to co-disposal waste packages (diffusion)
- From stress corrosion cracking failure failure of commercial SNF waste packages (diffusion)
- From general corrosion failure of both types of waste packages (advection)

Construction of Total Dose

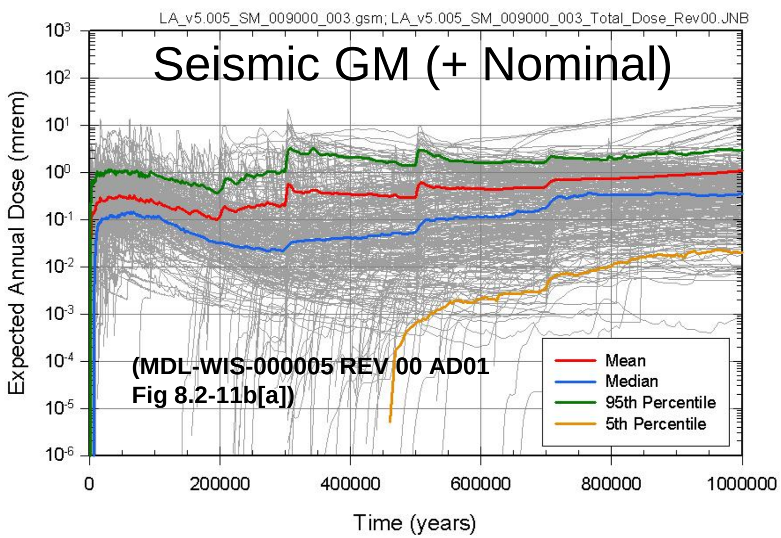
Sandia National Laboratories

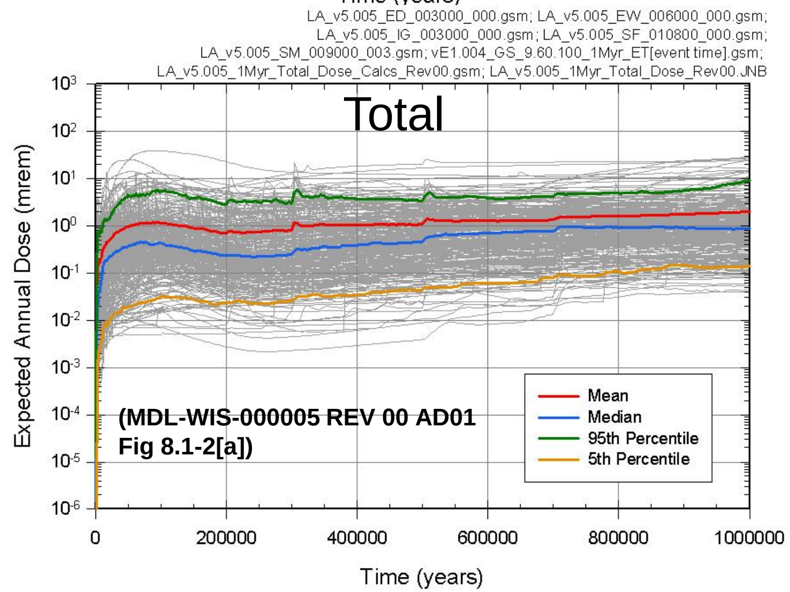


+



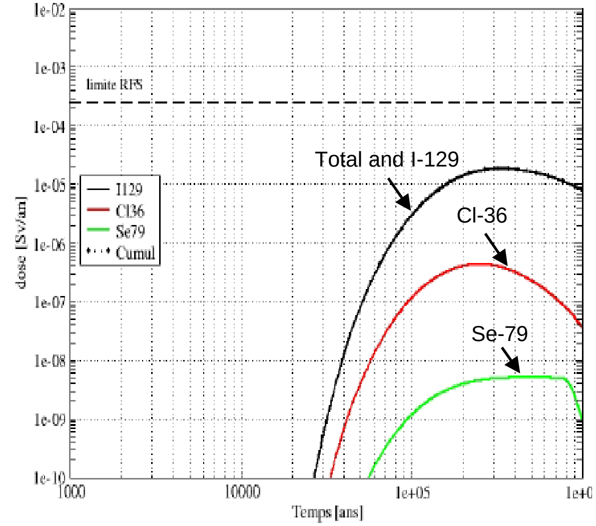
+



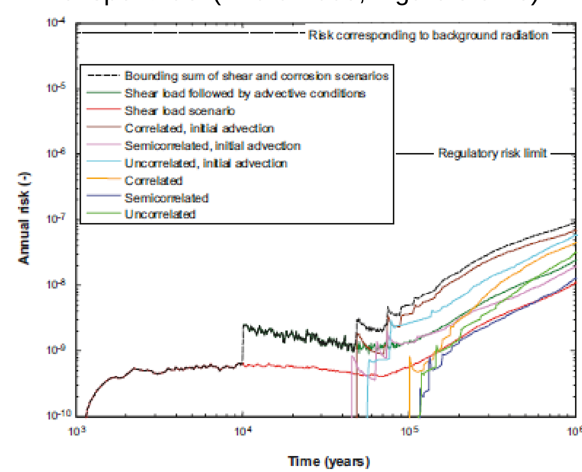


How Does Yucca Mountain Compare to Other Proposed Repositories?

- 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)



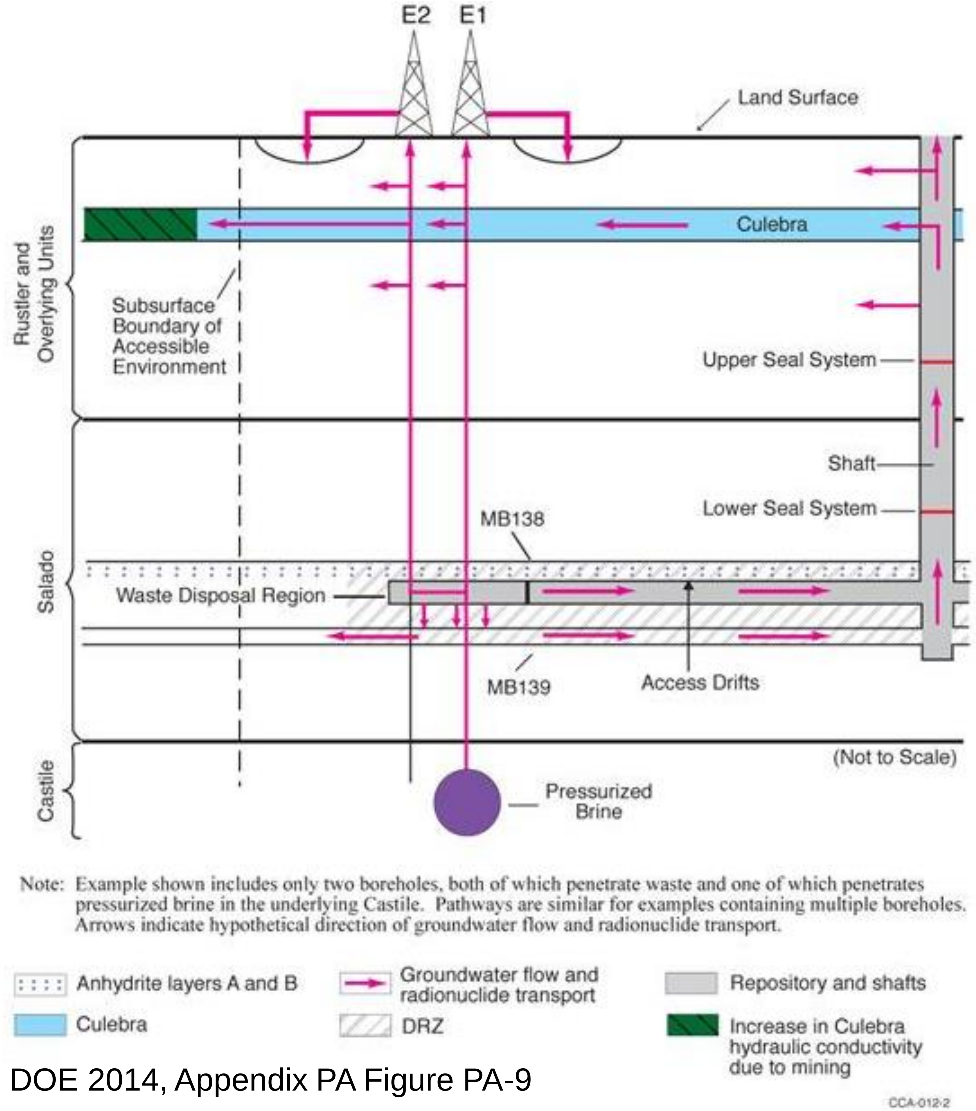
Estimated risk for the Swedish Forsmark site (SKB 2011 Figure 13-69, assumes dose-to-risk conversion of $0.073 Sv^{-1}$)

WIPP Examples

Scenarios for WIPP Performance Assessment: *Disturbed Performance*

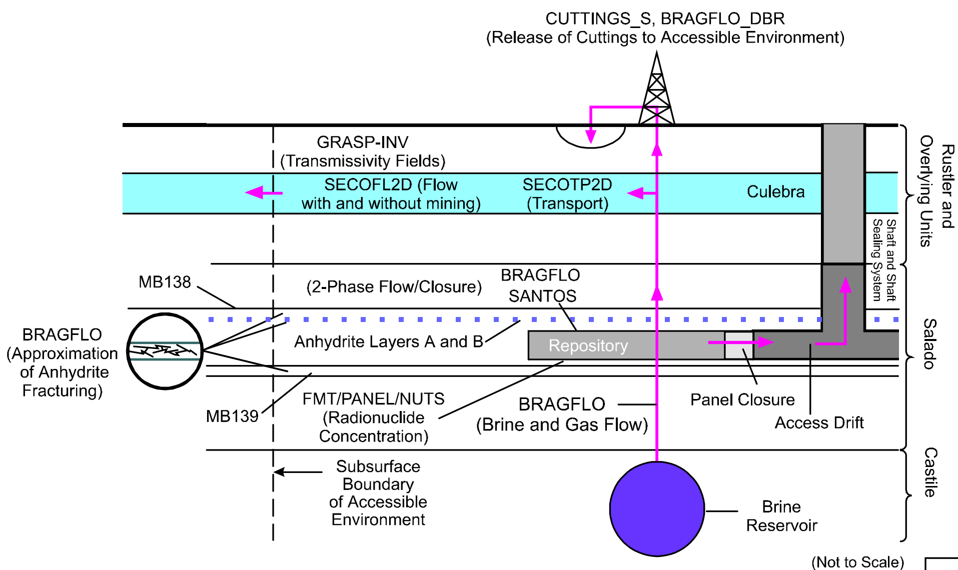
This example shows two intrusion boreholes into the same disposal panel.

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



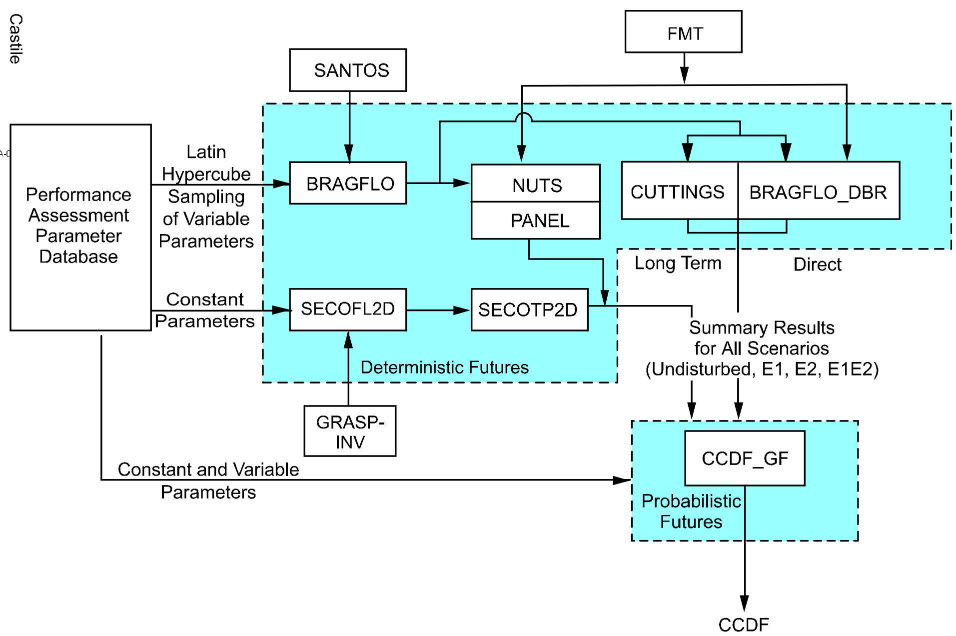
DOE 2014, Appendix PA Figure PA-9

WIPP Performance Assessment Models



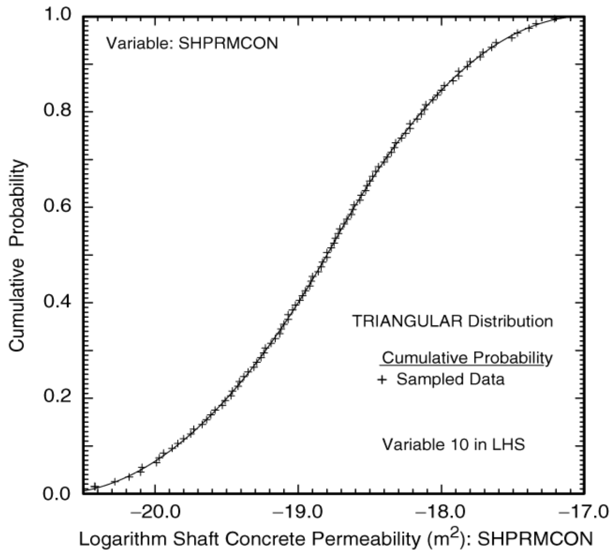
Models simulate major processes for each scenario

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



Perform Uncertainty Analysis Using Monte Carlo Simulations

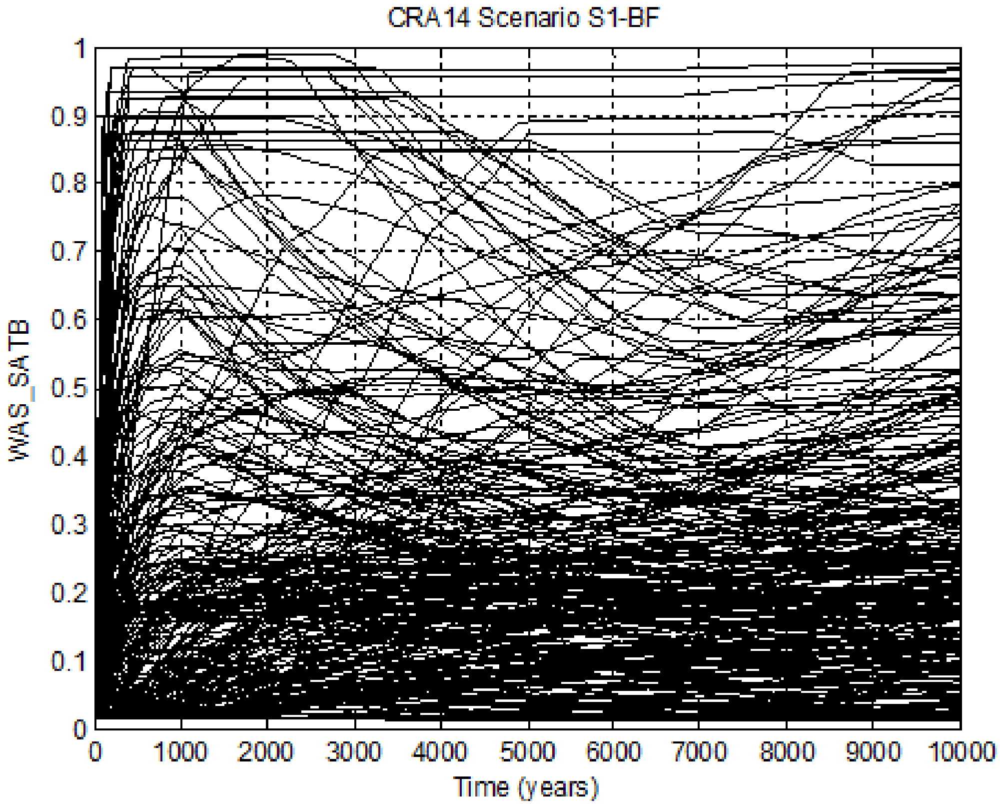
- Estimate the number of simulations needed (n)
- Draw n samples from distributions characterizing uncertainty in input parameters
  - Each simulation requires a different set of input values
- Perform a complete system simulation for each set of sampled input parameter values
  - Fixed-value parameters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

10,000-year Undisturbed Performance



n = 100

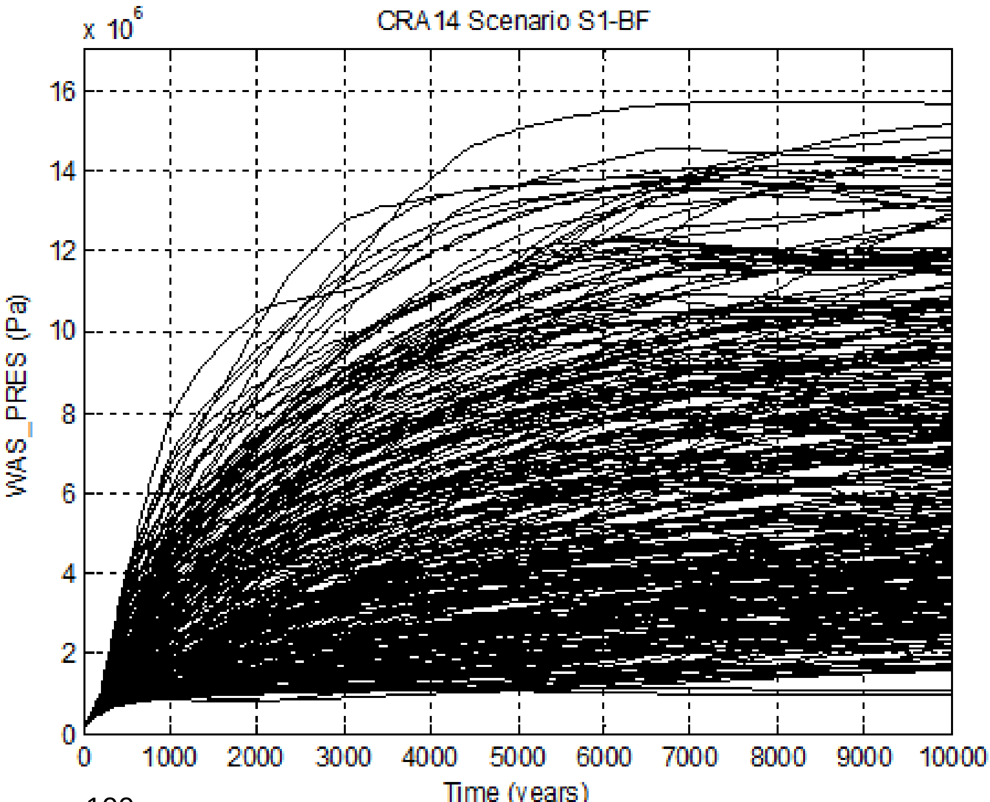
DOE 2014, Appendix PA, Figure PA-41

Saturation in the waste depends on multiple coupled processes

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

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

10,000-year Undisturbed Performance



n = 100

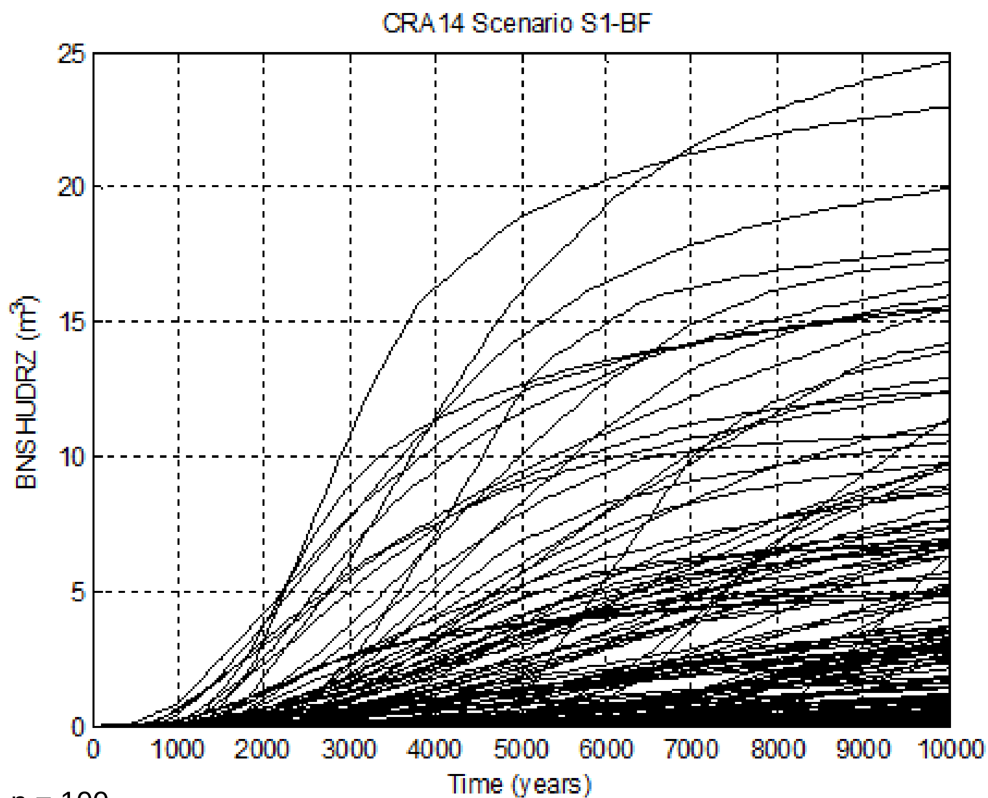
DOE 2014, Appendix PA, Figure PA-35

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 Flow upward through Shaft Seals

10,000-year Undisturbed Performance



n = 100

DOE 2014, Appendix PA, Figure PA-47

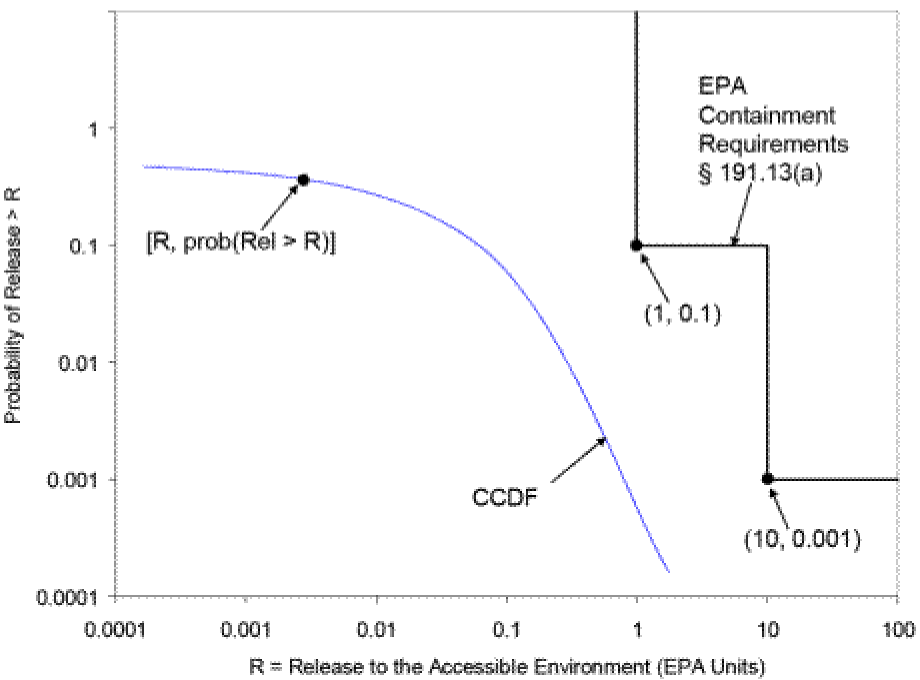
Brine flow upward in the shaft seals is a function of

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

Quantitative Compliance Estimates (WIPP example)

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:

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

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

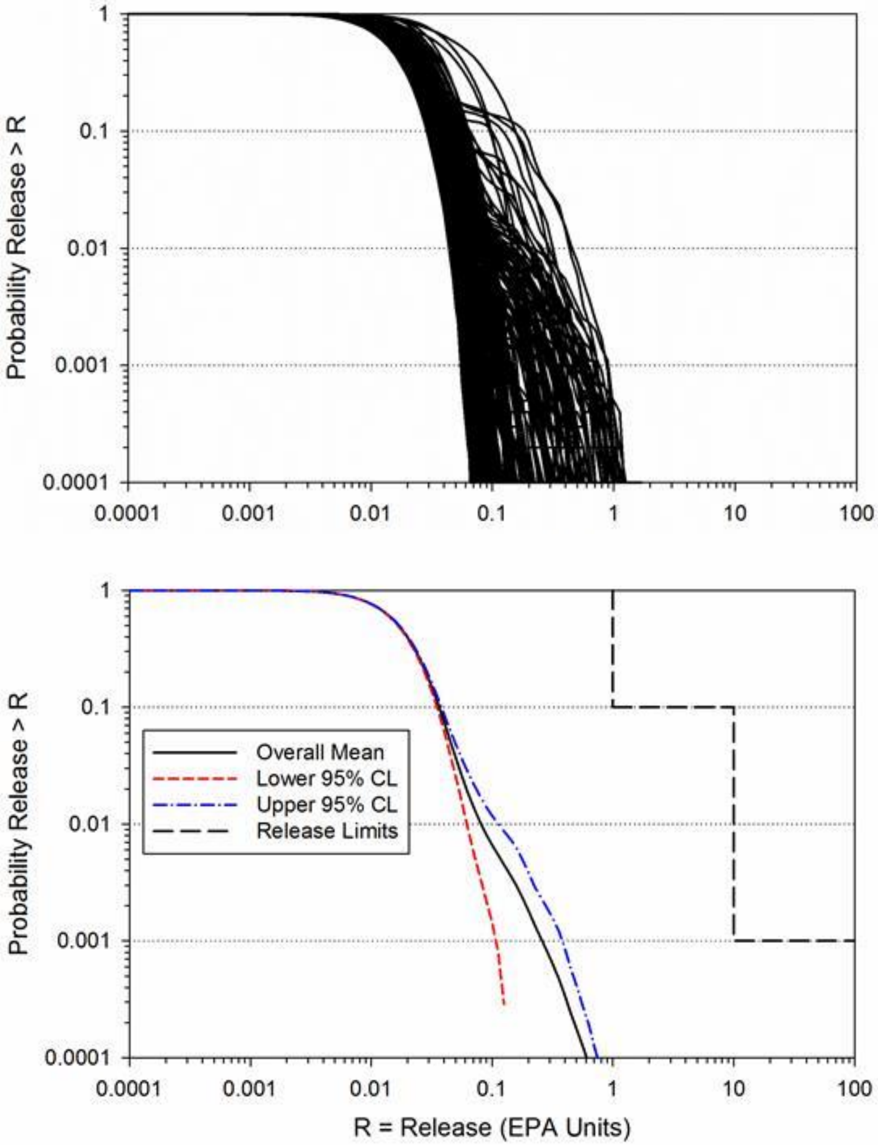
Radionuclide	Release limit L_i per 1000 MTHM* or other unit of waste (10^6 curies of TRU for WIPP)
Americium-241 or –243	100
Carbon-14	100
Cesium-135 or –137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium-238, -239,-240, or –242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium-230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

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

CCDF of Total Normalized Releases From All Scenarios (WIPP)

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

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



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

Release Mechanisms Contributing to the Overall Mean CCDF

Sandia National Laboratories

Undisturbed performance results in zero release

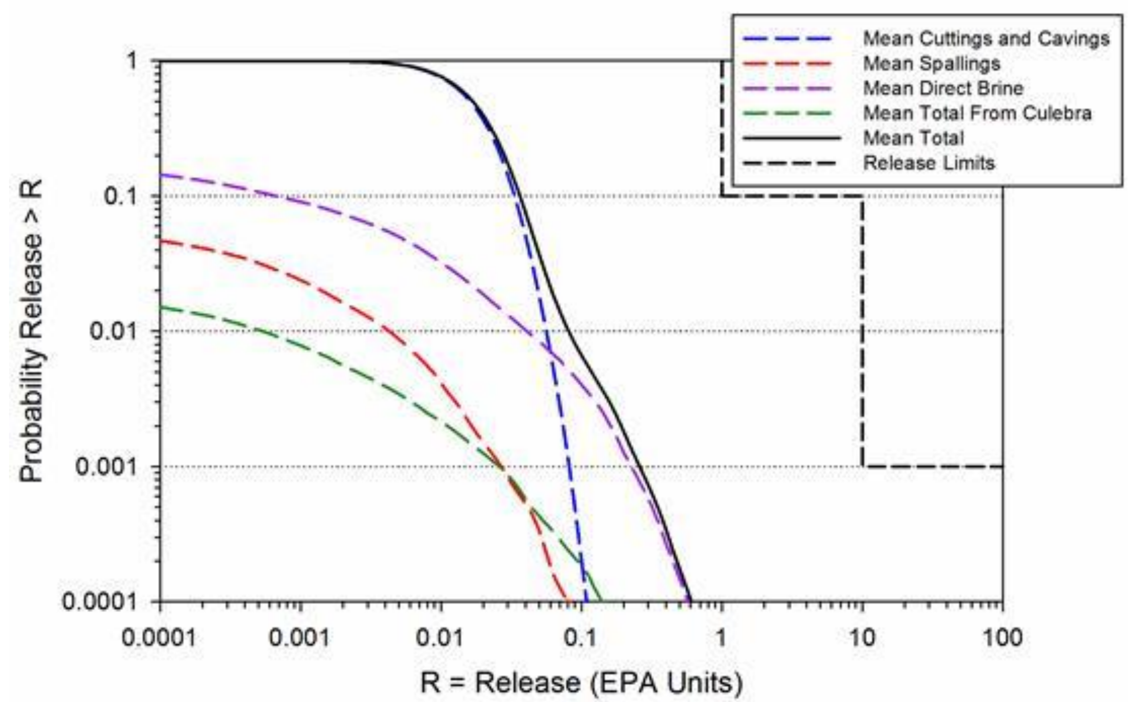
All releases are due to drilling intrusions

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

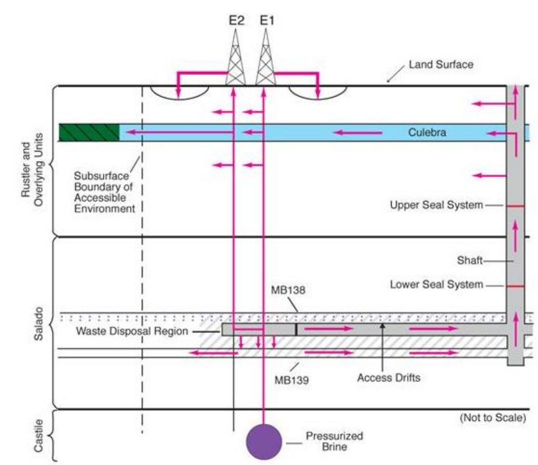
"**Spallings**" are solid material that is transported into the hole during depressurization and brought to the surface during drilling

"**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)



Additional References

- ANDRA Agence nationale pour la gestion des déchets radioactifs), 2005. *Dossier 2005: Argile. Tome: Safety Evaluation of a Geological Repository* (English translation: original documentation written in French remains ultimately the reference documentation)
- SKB (Svensk Kärnbränslehantering AB), 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark, Technical Report TR-11-01
- U.S. DOE (US Department of Energy), 2014. Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2014 for the Waste Isolation Pilot Plant

- Key Website for WIPP documents: http://www.wipp.energy.gov/library/caolib.htm