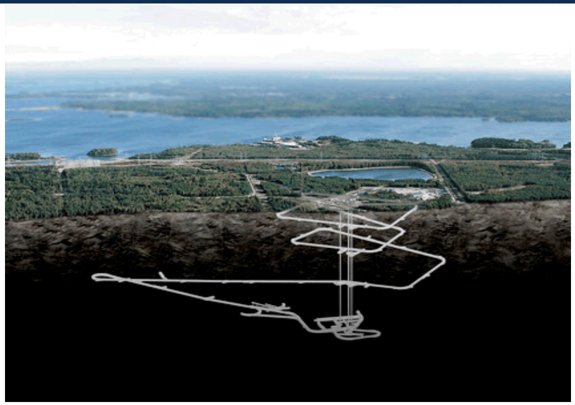
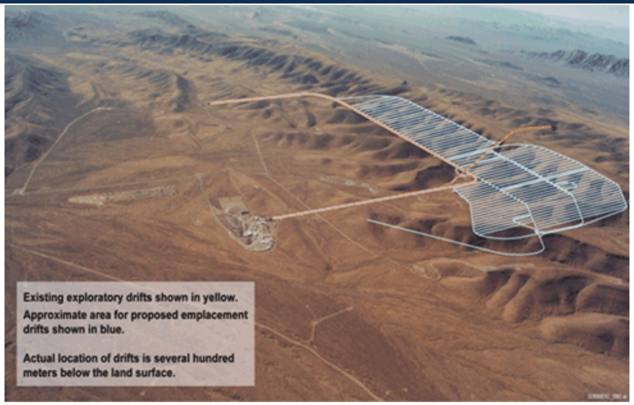
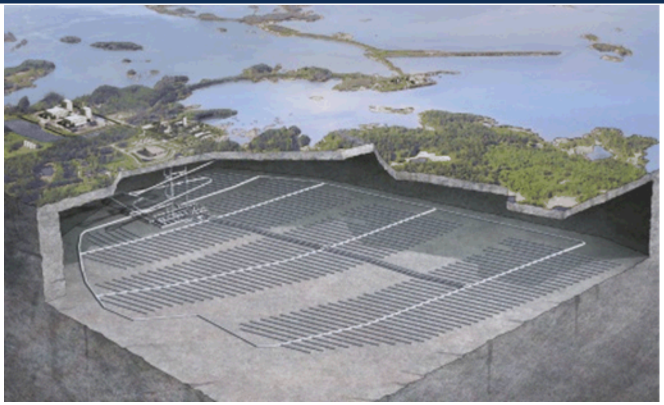
SAND2017-11272PE







The Back-end of the Nuclear Fuel Cycle: Focus on Deep Geologic Disposal of Radioactive Waste

David C. Sassani
Distinguished Member of Technical Staff
Sandia National Laboratories
Washington University Department of Earth and Planetary Sciences
St. Louis, Missouri
October, 19, 2017

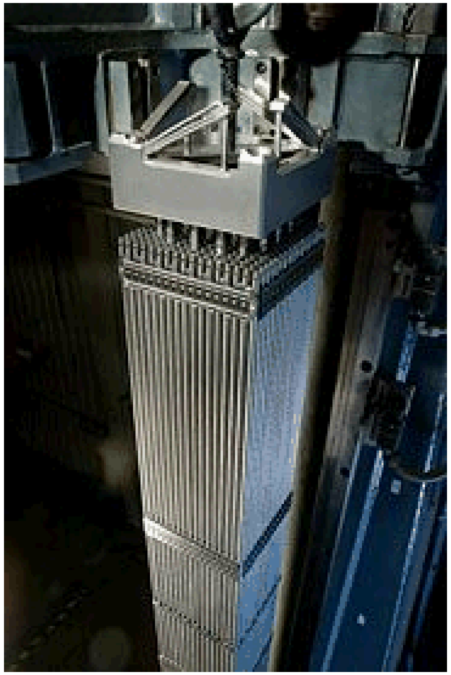
Presentation Overview

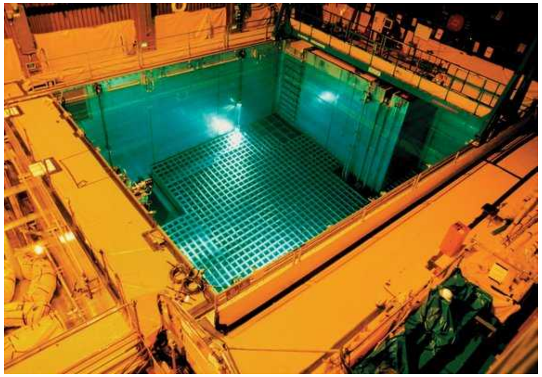
- Background
  - What is nuclear waste?
    - How much and where?
- Overview of the US Program
  - Recent R&D
    - Storage, transportation, disposal
    - Disposal concepts
- Geologic Disposal systems: US and other nations
  - Safety case components
  - Post-closure performance assessments
- Summary and Conclusions

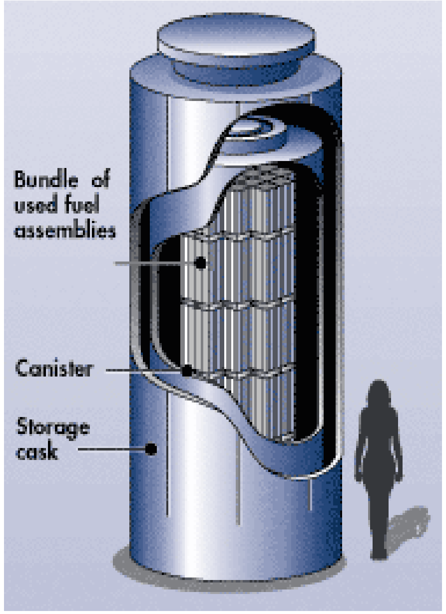
Types of Radioactive Waste

- Spent nuclear fuel
  - Uranium and plutonium fuel that has been irradiated in reactors for electric power generation, research, or defense purposes
- High-Level Radioactive Waste
  - Highly radioactive material derived from the processing of irradiated reactor fuel to extract plutonium
- Transuranic Waste
  - Industrial waste contaminated with plutonium and other long-lived radioactive elements, primarily generated during the fabrication of nuclear weapons
- Low-level Radioactive Waste
  - Wastes with low to moderate levels of radioactivity, generated from multiple sources including nuclear power, defense programs, industry, and medicine
- Uranium mining and milling wastes

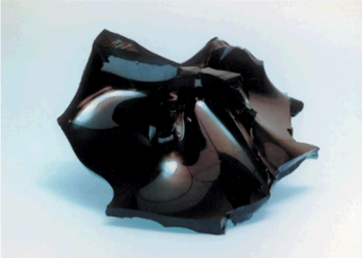
Spent Nuclear Fuel







High-Level Radioactive Waste



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—

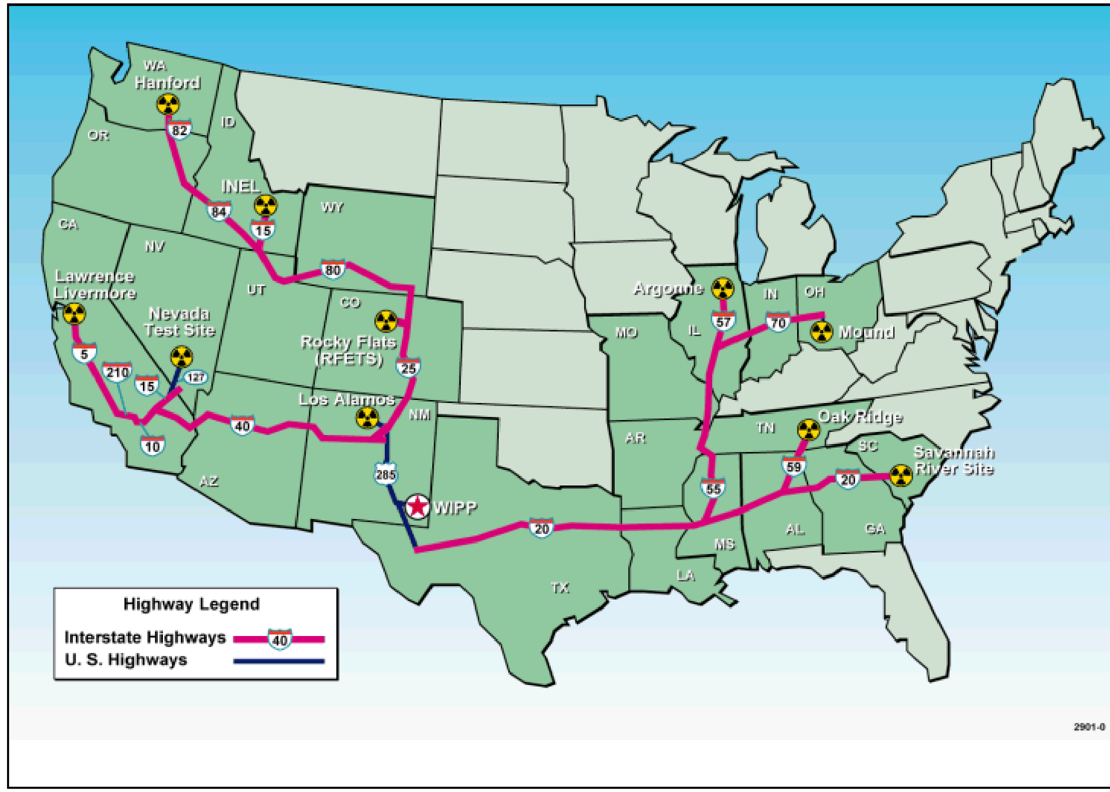
  (A) high-level radioactive waste;

  (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 Transportation

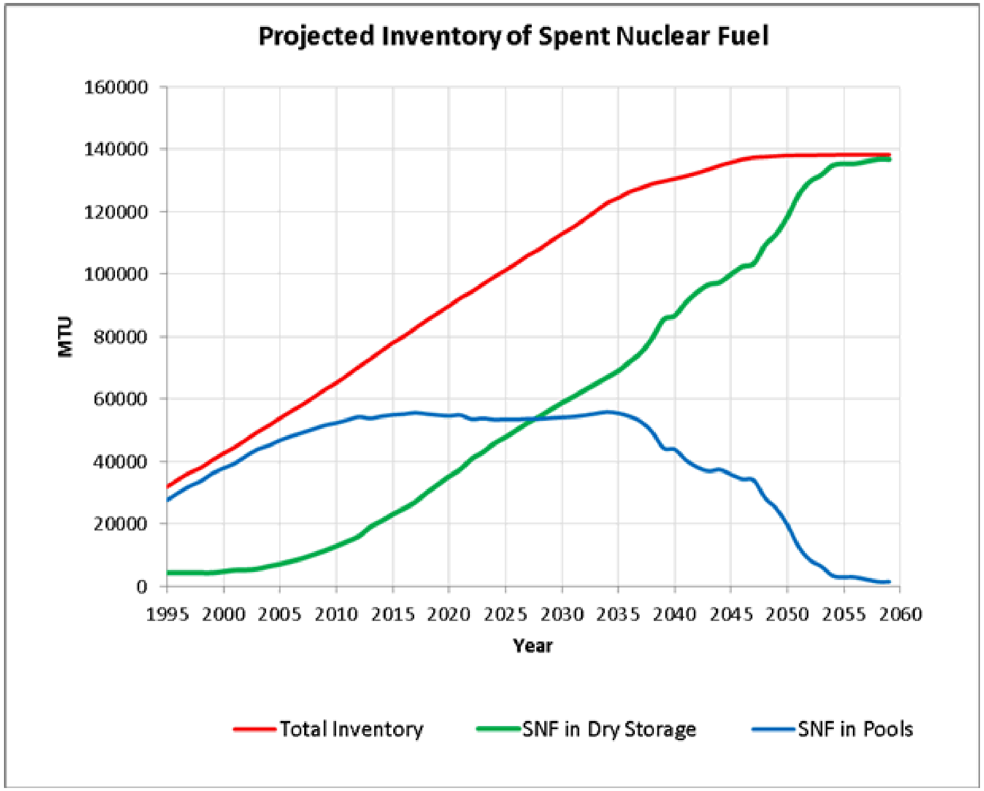
- Ten primary sites ship waste to WIPP
- All shipments by truck



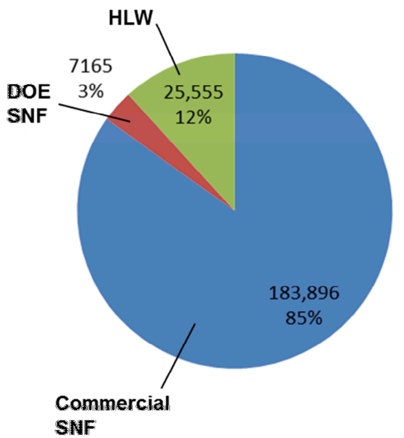
Images from http://www.wipp.energy.gov/Photo_Gallery_Images

US Projections of Spent Nuclear Fuel (SNF) and High-Level Radioactive Waste (HLW)

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

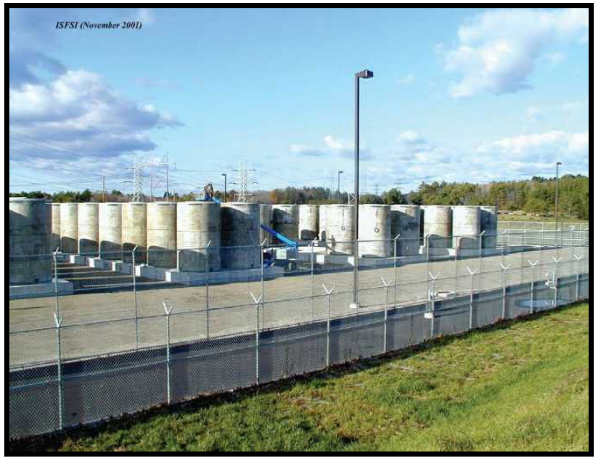
Approx. 80,150 MTHM (metric tons heavy metal) of SNF in storage in the US today

- 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

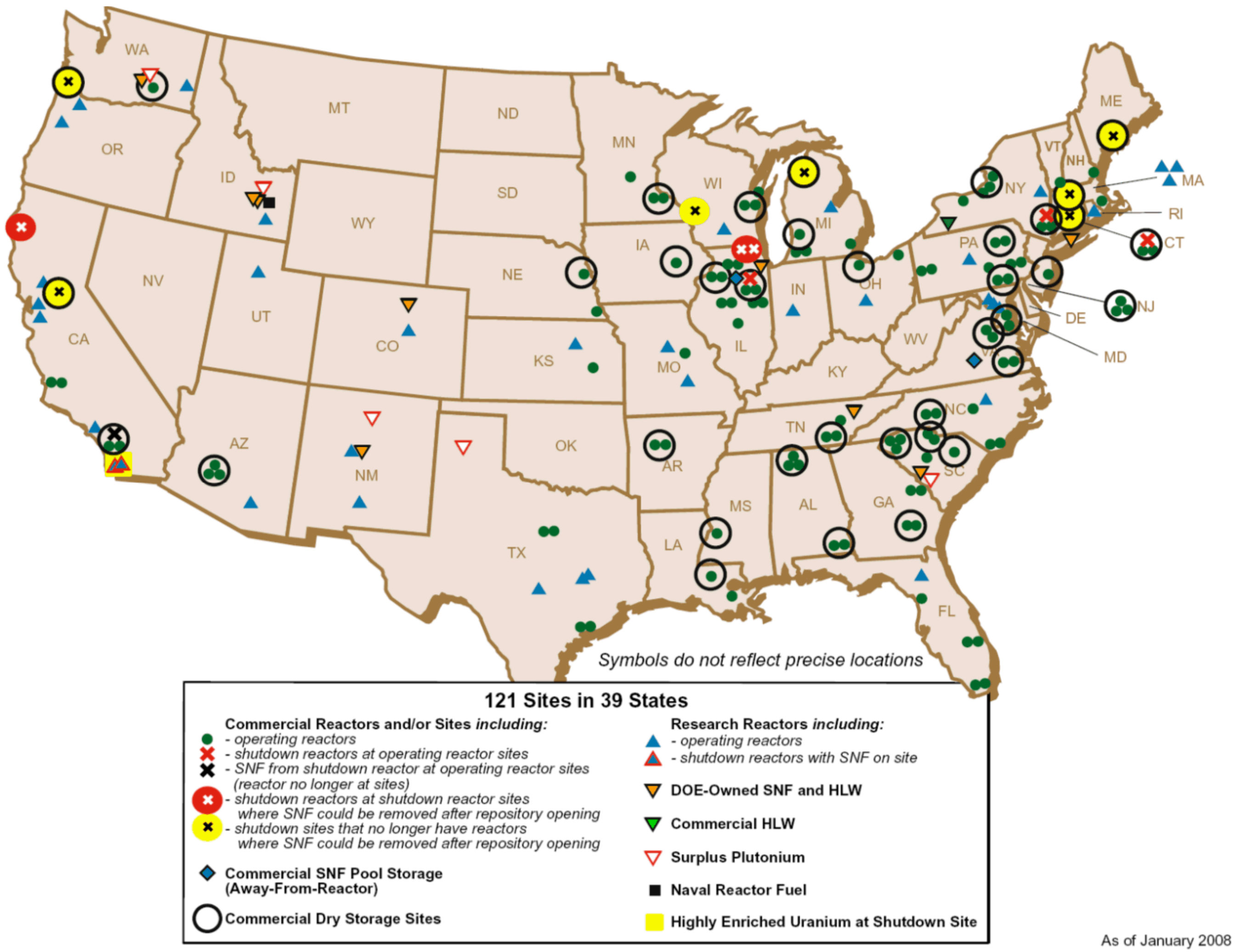
- Approximately 160 new dry storage canisters are loaded each year in the US

What is the U.S. doing without a repository?



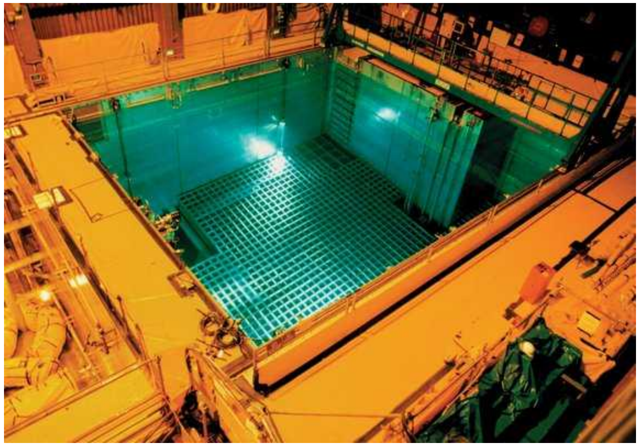
Spent Nuclear Fuel and High-Level Radioactive Waste in the U.S.

Spent Nuclear Fuel and High-Level Radioactive Waste is stored at 129 sites in 39 states



What Comes Next in the US?

Surface storage of spent nuclear fuel will continue



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

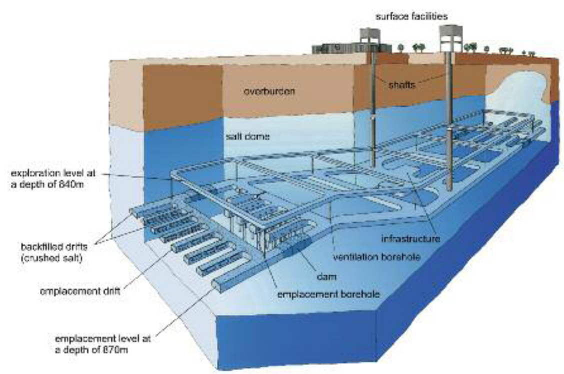
Dry Storage: horizontal and vertical concepts are in use. R&D in progress to support the technical basis for license extensions beyond original 20-yr period

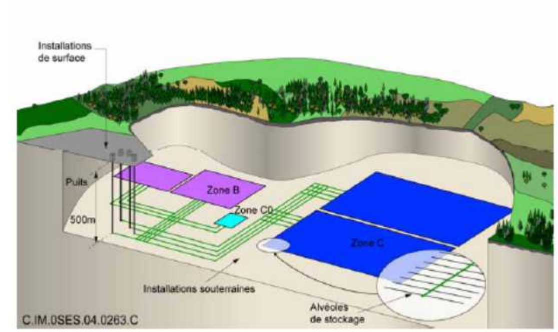
11

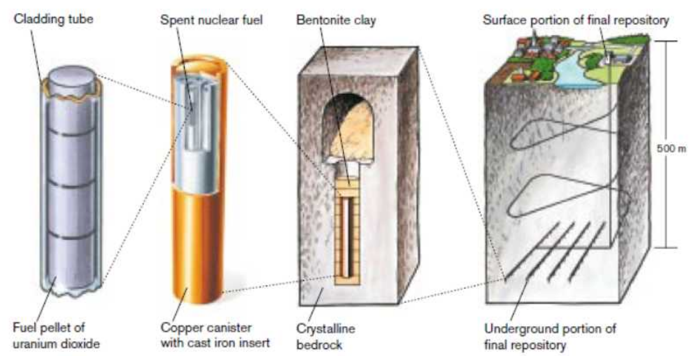
Deep geologic disposal has been planned since the 1950s, and remains an essential element of nuclear waste management

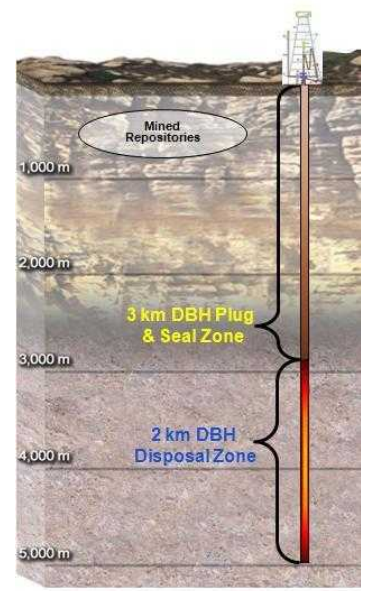
"The conclusion that disposal is needed and that *deep geologic disposal is the scientifically preferred approach* has been reached by every expert panel that has looked at the issue and by every other country that is pursuing a nuclear waste management program."

Blue Ribbon Commission on America's Nuclear Future, 2012 (emphasis added)









Overview of the US Program

History and Current Status of the US Program

- **1982**: ***Nuclear Waste Policy Act*** defines Federal responsibility for permanent disposal of spent fuel and high-level waste, and leaves responsibility for storage at reactor sites with private sector
- **1987**: Congress amends NWPA to focus solely on disposal at ***Yucca Mountain, Nevada***
- **2002:** Congress overrides Nevada's veto of the site and directs the Department of Energy and the Nuclear Regulatory Commission to proceed with the licensing process
- **2008**: Yucca Mountain Repository ***License Application submitted***
- **2009**: Department of Energy (DOE) states Yucca Mountain to be unworkable (defunded after **2010**)
- **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) staff to complete its review and ***Safety Evaluation Report (SER)*** for Yucca Mountain application with remaining funds
- **2013:** DOE proposes to "facilitate the availability of a geologic repository by 2048" and publishes ***Strategy document*** for waste management
- **2015**: NRC staff completes SER for Yucca Mountain, finds that "the DOE has ***demonstrated compliance*** with the NRC regulatory requirements" for both pre-closure and post-closure safety
- **2016**: Private sector applications to the NRC for ***consolidated interim storage of spent fuel***
- **2017**: DOE ***requests FY2018 funding*** from Congress to restart Yucca Mountain licensing process. Approximately 300 technical contentions remain to be heard before a licensing board can reach a decision regarding construction authorization

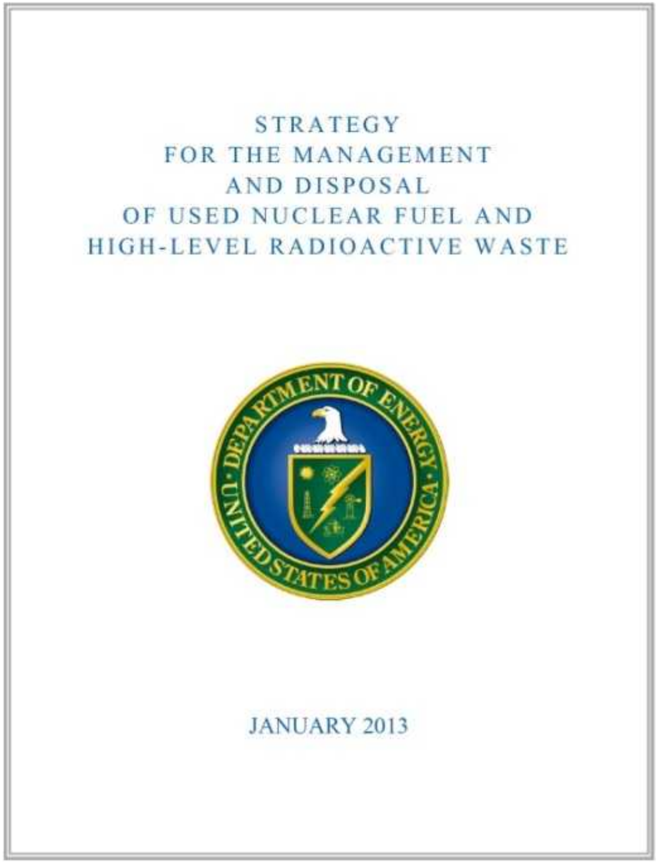
Summary of the Administration's UNF and HLW Strategy

Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste issued January 2013

The Strategy is:

- A statement of Administration policy regarding the importance of addressing the disposition of used nuclear fuel and high-level radioactive waste
- The response to the final report and recommendations made by the *Blue Ribbon Commission on America's Nuclear Future*
- The initial basis for discussions among the Administration, Congress and other stakeholders

- The Strategy outlines a 10-year program of work that:
  - Sites, designs, licenses, constructs and begins operations of a *pilot interim storage facility*
  - Advances toward the siting and licensing of a *larger interim storage facility*
  - Makes demonstrable progress on the siting and characterization of *repository* sites

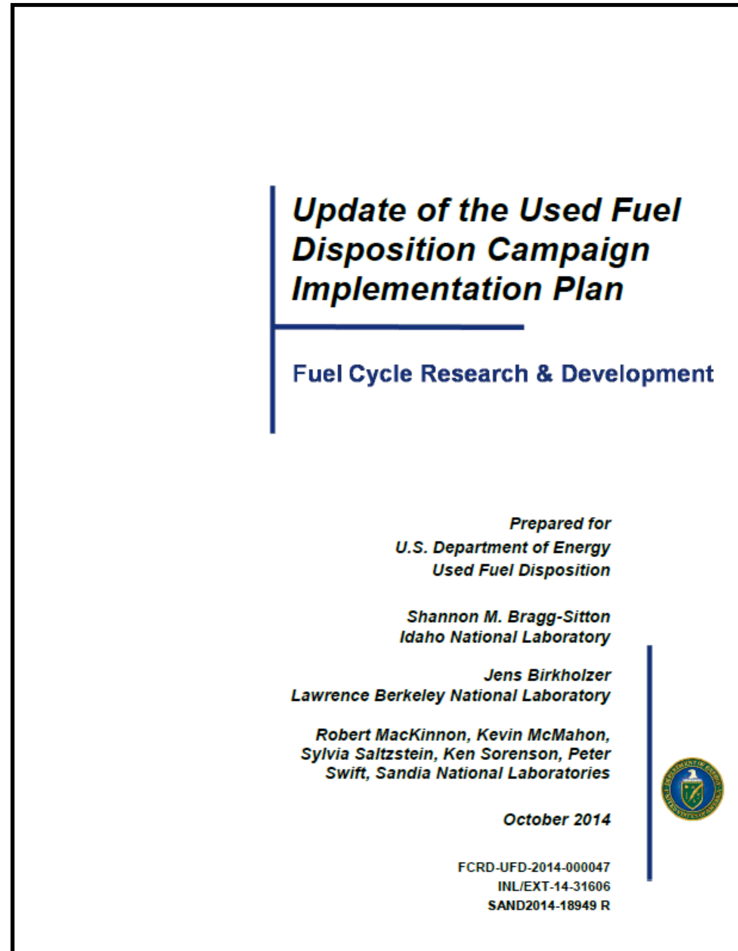


Used Fuel Disposition Campaign (UFDC) R&D Mission

The MISSION of the Used Fuel Disposition Campaign is to identify alternatives and conduct scientific research and technology development to *enable* ***storage, transportation and disposal*** *of used nuclear fuel and wastes generated by existing and future nuclear fuel cycles*.

Update of the Used Fuel Disposition Campaign Implementation Plan

FCRD-UFD-2014-000047, October 2014



Update of the Used Fuel Disposition Campaign Implementation Plan

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Fuel Disposition

Shannon M. Bragg-Sitton
Idaho National Laboratory

Jens Birkholzer
Lawrence Berkeley National Laboratory

Robert MacKinnon, Kevin McMahon, Sylvia Saltzstein, Ken Sorenson, Peter Swift, Sandia National Laboratories

October 2014

FCRD-UFD-2014-000047
INL/EXT-14-31606
SAND2014-18949 R

Storage and Transportation R&D Objectives

1. **Support the development of the technical bases to demonstrate used fuel integrity for extended storage periods**
2. **Support the development of the technical bases for fuel retrievability and transportation after long-term storage**
3. **Support the development of the technical bases for transportation of high burnup fuel**

Obtaining Data on High Burnup Cladding After 10 Years of Dry Storage

- DOE/EPRI High Burnup Confirmatory Data Project Goal:

  To provide confirmatory data for models, future SNF dry storage cask design, and to support license renewals/new licenses for interim storage facilities

- Steps

  1) Loading a commercially licensed TN-32B storage cask with high burn-up fuel in a utility storage pool

     Loading well characterized fuel of 4 common cladding alloys

     - Instrumenting cask outfitted with thermocouples
     - Gas samples taken before going to pad and periodically during storage

  2) Drying using industry standard practices
  3) Storing at utility dry cask storage site – 10 years
  4) Transporting to lab to open
  5) Testing rods to understand mechanical properties
  6) Baseline data: 25 fuel rods with similar histories to those in the cask will be tested to document pre-storage properties ("Sister Rods")

Prairie Island Dry Storage

Understanding Canister Performance:

Primary Concern – Stress Corrosion Cracking (SCC) Requiring 3 Concurrent Conditions

Dust on canister surface at Calvert Cliffs (EPRI 2014)

Photo of dry canister weld. Photo: SNL

Mock-up Canister Photo: Enos, SNL

Understanding Canister Performance:

Can a Corrosive Environment Form?

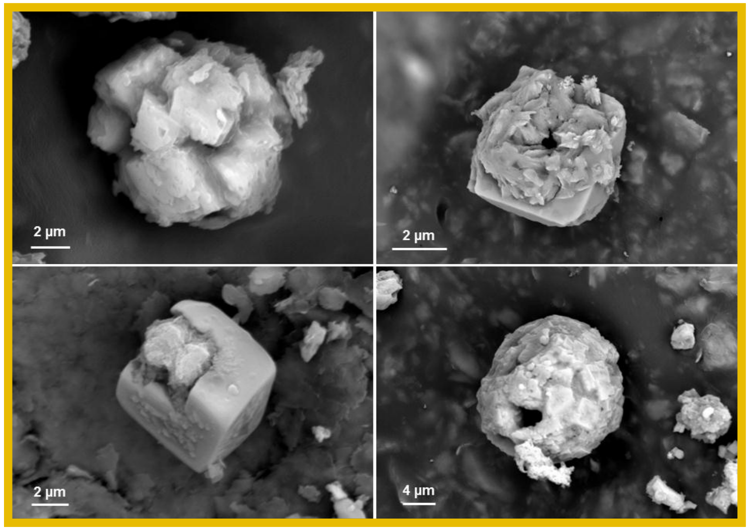
DOE/EPRI sampling efforts at Calvert Cliffs, Hope Creek, Diablo Canyon, and Maine Yankee.
Potentially corrosive chloride salts found in some areas. Need additional sampling to determine:

(1) deposited salt compositions as a function of geographical location;

(2) salt loads and compositions as a function of canister surface location and surface temperatures.

Dust Sampling at the Diablo Canyon ISFSI

Sea-salt aerosols found in canister surface dusts.



Photos: Bryan, SNL

Are deliquescent brines stable on the heated canister surface?

PREVIOUS WORK Ammonium- and chloride-containing brines are not stable on heated surfaces, rapidly degassing until one or the other component is consumed. This makes presence of chloride-rich brines at inland sites with ammonium-rich continental salts unlikely.

CURRENT WORK Evaluating the stability of brines formed by sea-salt deliquescence at elevated temperatures.

Transporting Spent Nuclear Fuel:

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

THREE SERIES OF TESTS USING 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

21

So, DOE is Performing a More Realistic Test with Spain (ENSA, ENRESA) and South Korea (KORAD, KAERI)

- Equipos Nucleares (ENSA) and ENRESA provided an ENUN 32P rail cask, basket, and cradle for international test program
    - ENUN 32P is similar to existing NRC-licensed cask currently in use in USA
    - Surrogate assemblies from Spain, Korea, and US
- Testing to be conducted by US National Labs
- Tests significantly different than previous tests
    - Instrumented surrogate assemblies will be
        - within a rail-cask basket
        - within an actual rail cask on
            - *a heavy-haul truck*
            - *two different ships*
            - *a railcar*

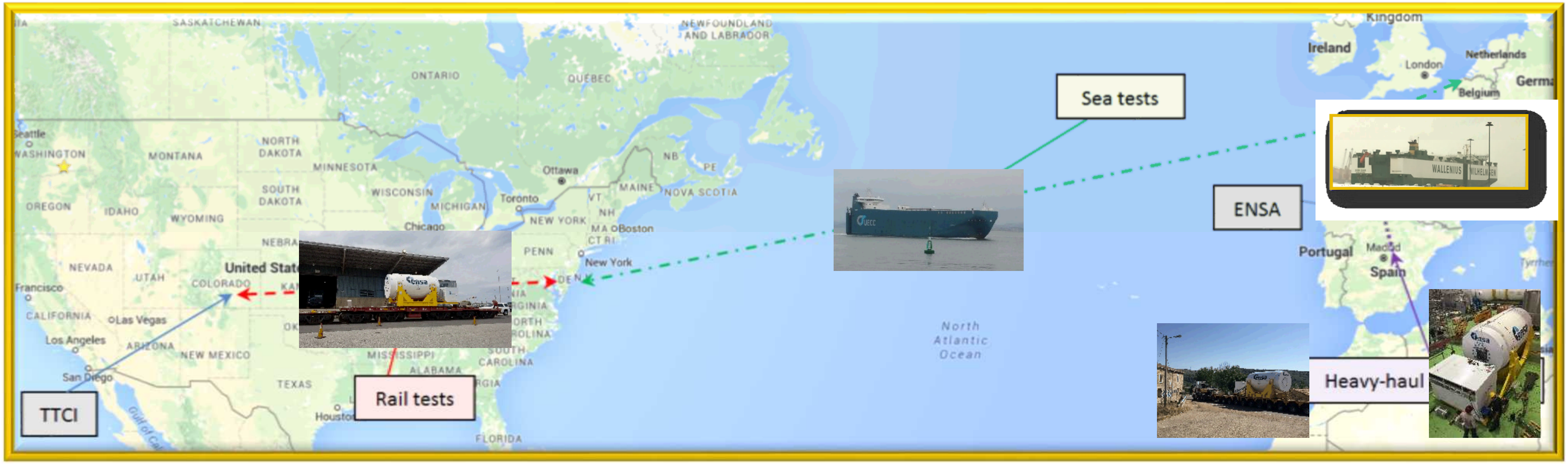
ENUN 32P basket. Photo curtesy of ENSA

ENUN 32P Cask. Photo curtesy of ENSA

Barge from Spain to Belgium. Photo: McConnell, SNL

22

Routing of Cask



Photos provided by Steve Ross, PNNL

1) **Heavy-haul truck from within Spain** ~ June 14, 2017
2) **Coastal sea shipment from Santander to large northern European port** ~ June 27, 2017
3) **Ocean transport from Europe to eastern U.S. port** (e.g., Baltimore)
4) **Commercial rail shipment from East Coast to Pueblo, Colorado** ~ Aug 3, 2017
5) **Testing at the Transportation Technology Center, Inc.**
6) **Return trip to ENSA will be the same**

Data will be collected throughout all legs of the transport as well as the transfers between legs.

Current Storage and Transportation R&D

Sandia National Laboratories

Spent fuel integrity

- Current tests and analyses indicate that spent fuel is ***more*** robust than was previously thought
- The *DOE/EPRI High Burnup Confirmatory Data Project* will obtain data after 10 years of dry storage to confirm current test and analysis results from parallel hot cell testing of "sister rods"

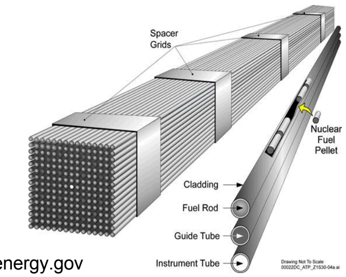


Image: energy.gov

Storage system integrity

- *Stress corrosion cracking* of canisters may be a concern in some parts of the country, and more work is needed in *analysis and detection*
- *Monitoring and Aging Management* practices at storage sites will be important to confirm storage system performance during extended service

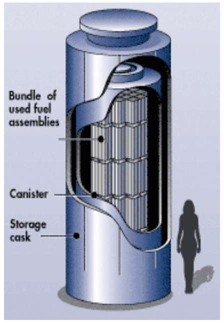
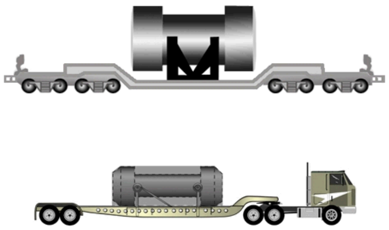


Image: nrc.gov

Spent fuel transportability following extended storage

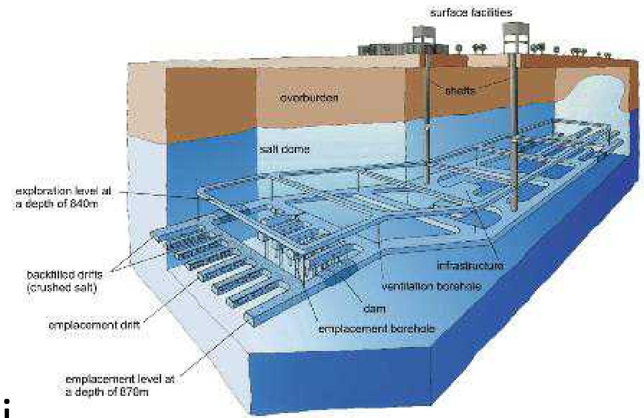
- The *realistic stresses* fuel experiences due to vibration and shock during normal transportation are *far below yield and fatigue limits* for cladding

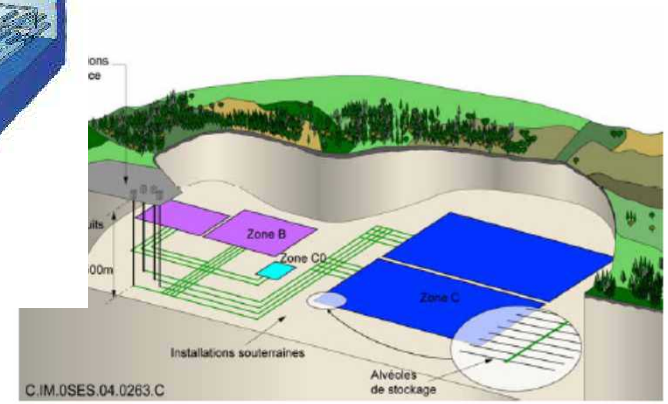


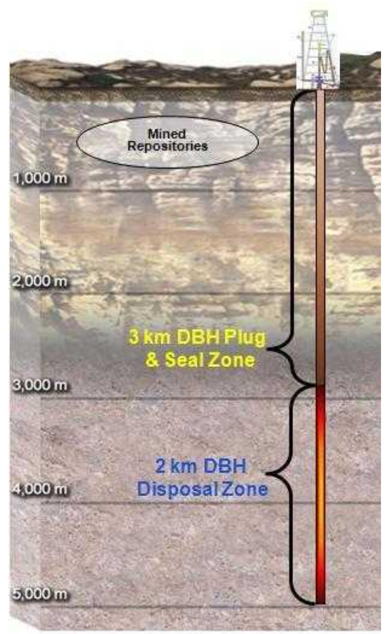
Energy.gov/pictures

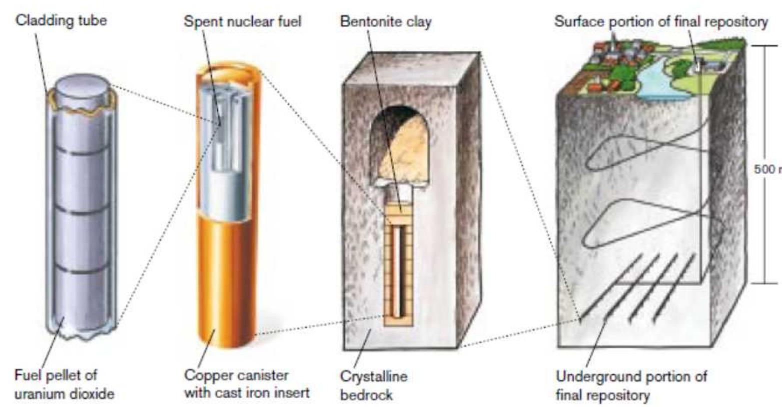
UFDC R&D Focus for Spent Fuel and HLW Geologic Disposal

- Provide a sound technical basis for multiple viable disposal options in the US
- Increase confidence in the robustness of generic disposal concepts
- Develop the science and engineering tools needed to support disposal concept implementation





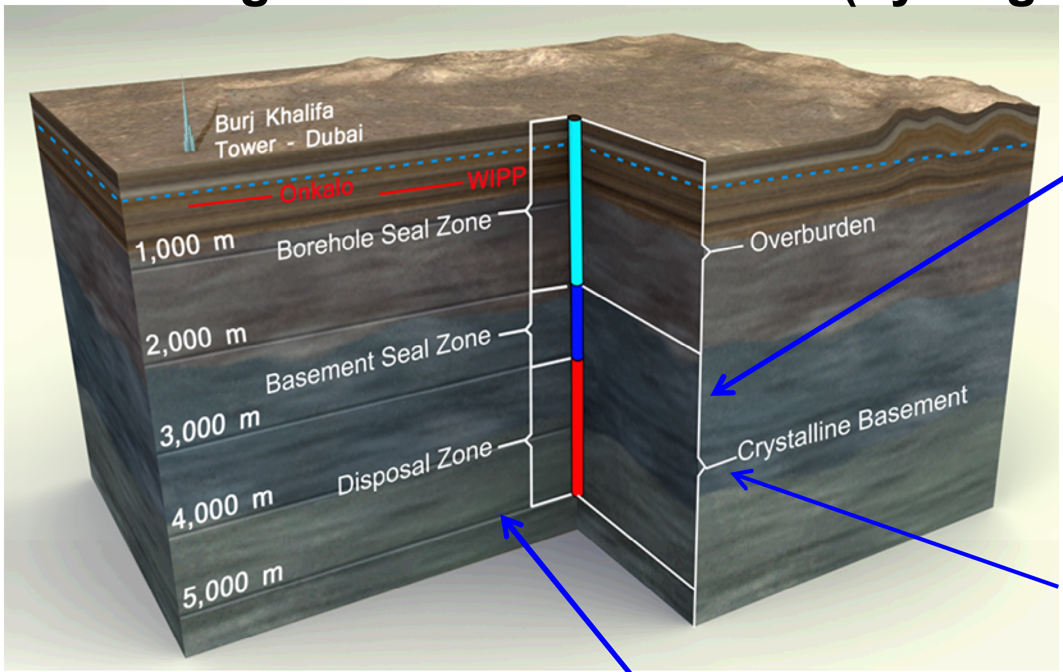




Deep Borehole Disposal Concept –

Safety and Feasibility Considerations (ended summer 2017)

Long-Term Waste Isolation (hydrogeochemical characteristics)



Waste emplacement is deep in crystalline basement

- At least 1,000 m of crystalline rock (seal zone) overlying the waste disposal zone
- Crystalline basement within 2,000 m of the surface is common in many stable continental regions

Crystalline basement can have very low permeability

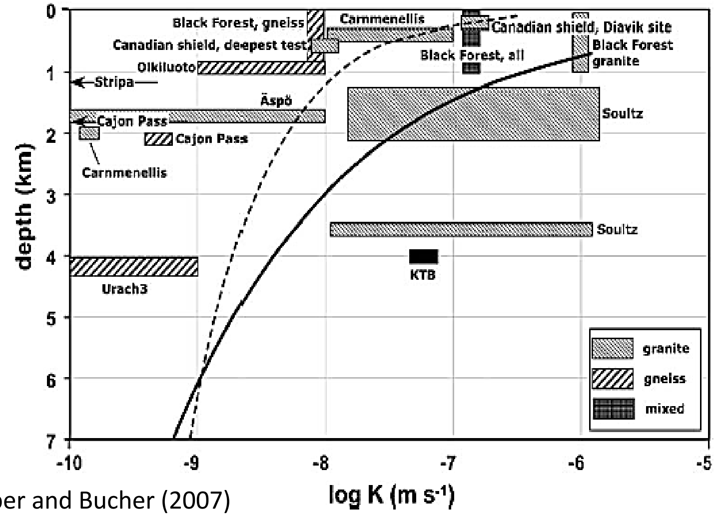
- limits flow and transport

Deep groundwater in the crystalline basement:

- Can have very long residence times – isolated from shallow groundwater
- Can be highly saline and geochemically reducing – enhances the sorption and limits solubility of many radionuclides
- Can have density stratification (saline groundwater underlying fresh groundwater) – opposes thermally-induced upward groundwater convection

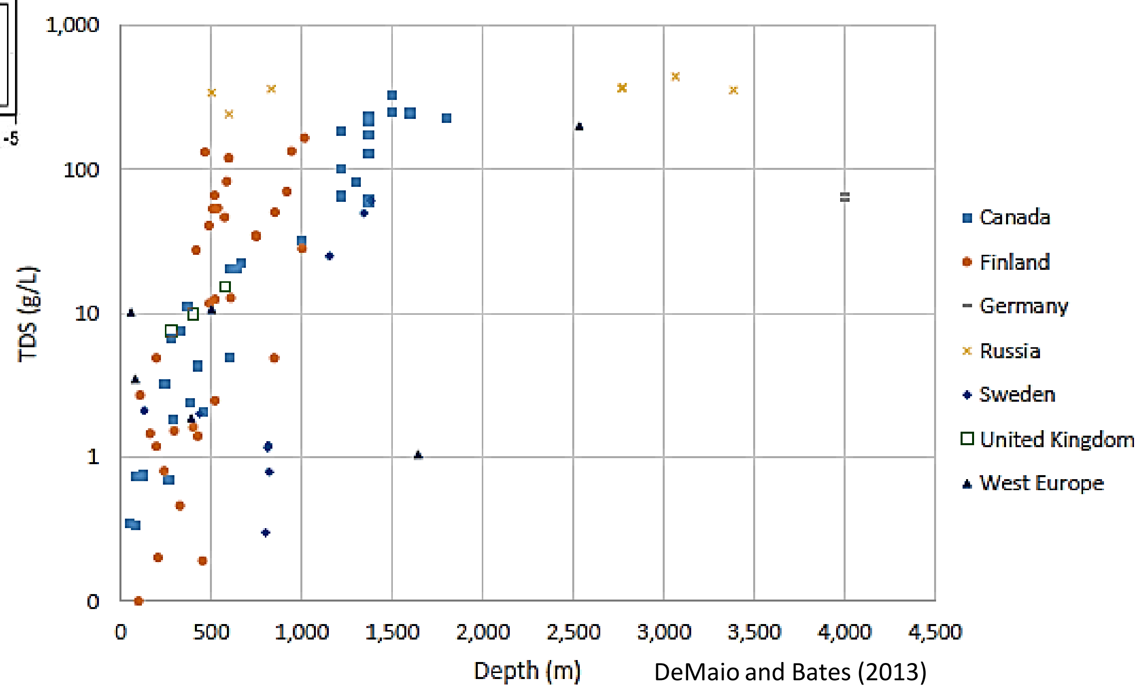
Observed Profiles

Bulk Permeability Decreases with Depth



Stober and Bucher (2007)

Salinity Increases with Depth



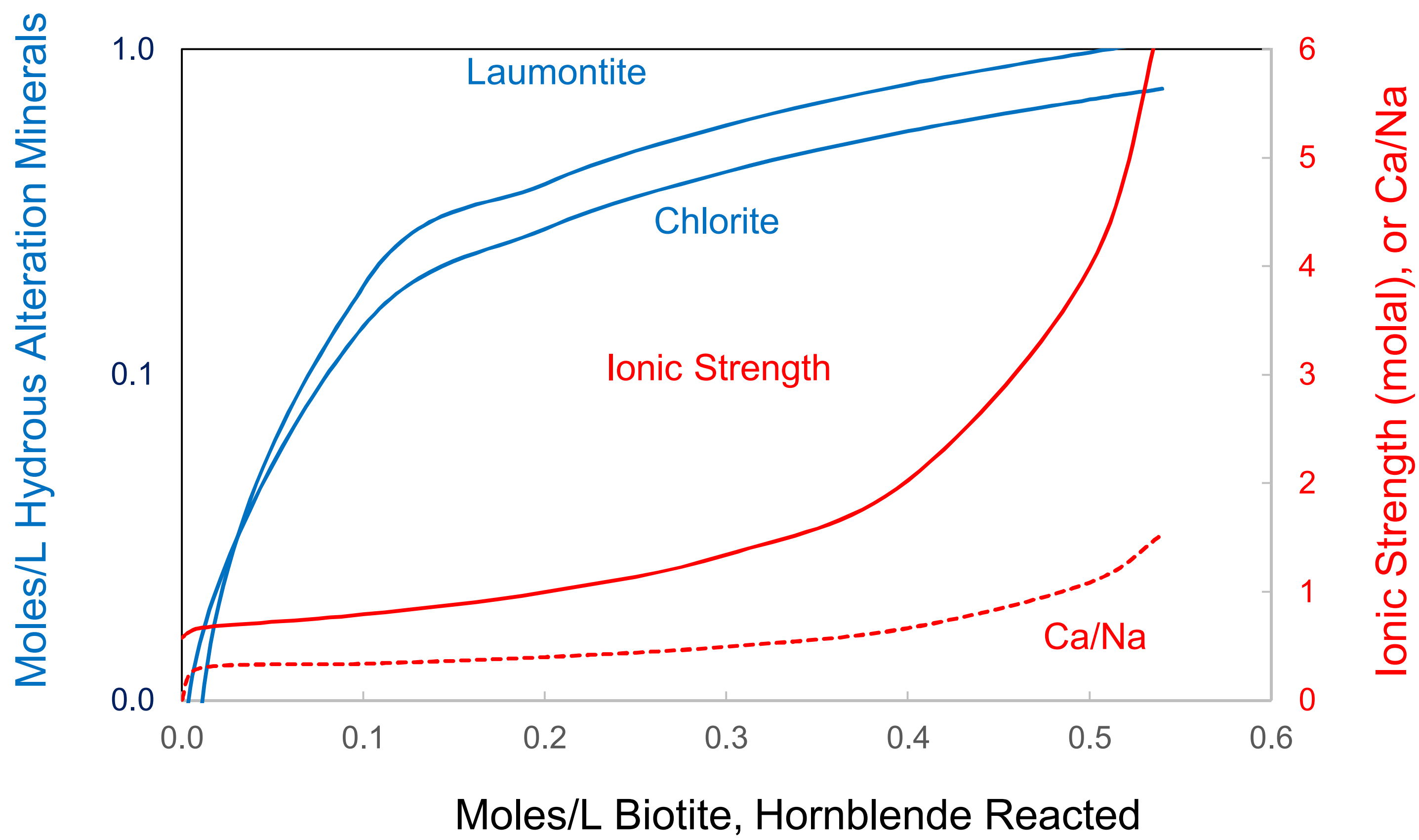
DeMaio and Bates (2013)

How Much of a Role Does Fluid-Rock Reaction Play in Driving Increased Salinity?

General Observations

- Calculated Generic Granite Hydrologic Alteration Results
  - Reaction creates Albite + K-feldspar + Chlorite + Laumontite + Brine
    - Minor amounts (< 0.02 moles) of epidote, calcite, and gypsum form
    - Albite and K-feldspar masses increase substantially
    - Almost all of the quartz is dissolved.
  - Produces a residual Ca-Na-Cl brine at pH of 6.8
    - Net Loss of water causes the ionic strength of the solution to increase
      - From an initial ionic strength of 0.6 upwards to > 5 molal
      - The Ca/Na calculated for brine is 1.55
      - Low Mg concentration
  - End-member Canadian Shield brines from Frape et al. (1984) with highest salt contents of ~240 – 325 g/L
    - Have ionic strengths of 4.5 - 6.2
    - 0.7 < Ca/Na < 3
    - Low Mg concentration

Solution and Mineralogic Evolution



Geologic Disposal Systems:
US and Other Nations - Existing Safety Cases

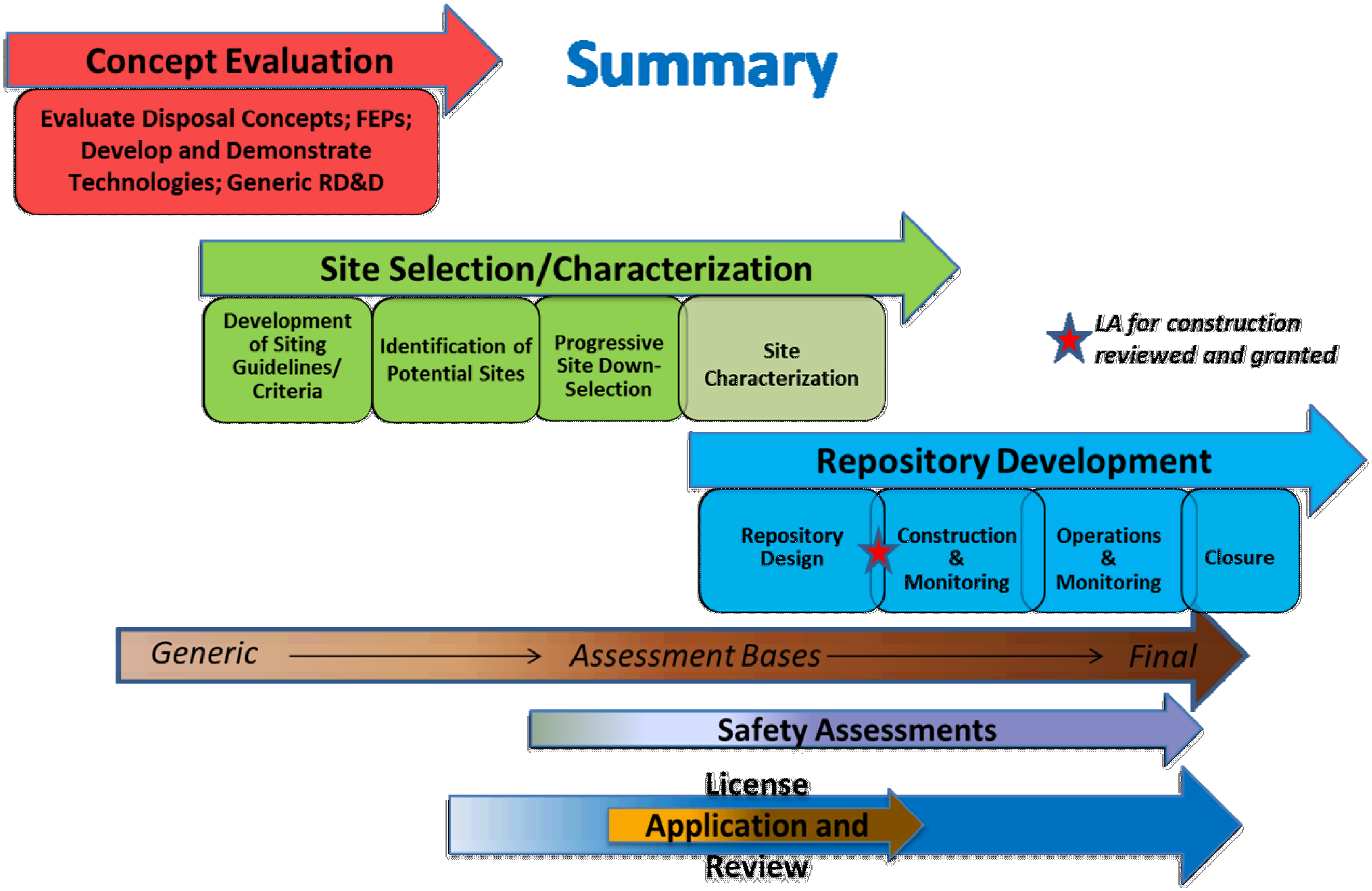
Mined Deep Geologic Disposal Concepts World-Wide

Nation	Host Rock	Status
Finland	Granitic Gneiss	Construction license granted 2015
Sweden	Granite	License application submitted 2011
France	Argillite	Disposal operations planned for 2025
Canada	Granite, sedimentary rock	Candidate sites being identified
China	Granite	Repository proposed in 2050
Russia	Granite, gneiss	Licensing planned for 2029
Germany	Salt, other	Uncertain
USA	Salt (transuranic waste at the Waste Isolation Pilot Plant) Volcanic Tuff (Yucca Mountain)	WIPP: operating Yucca Mountain: suspended

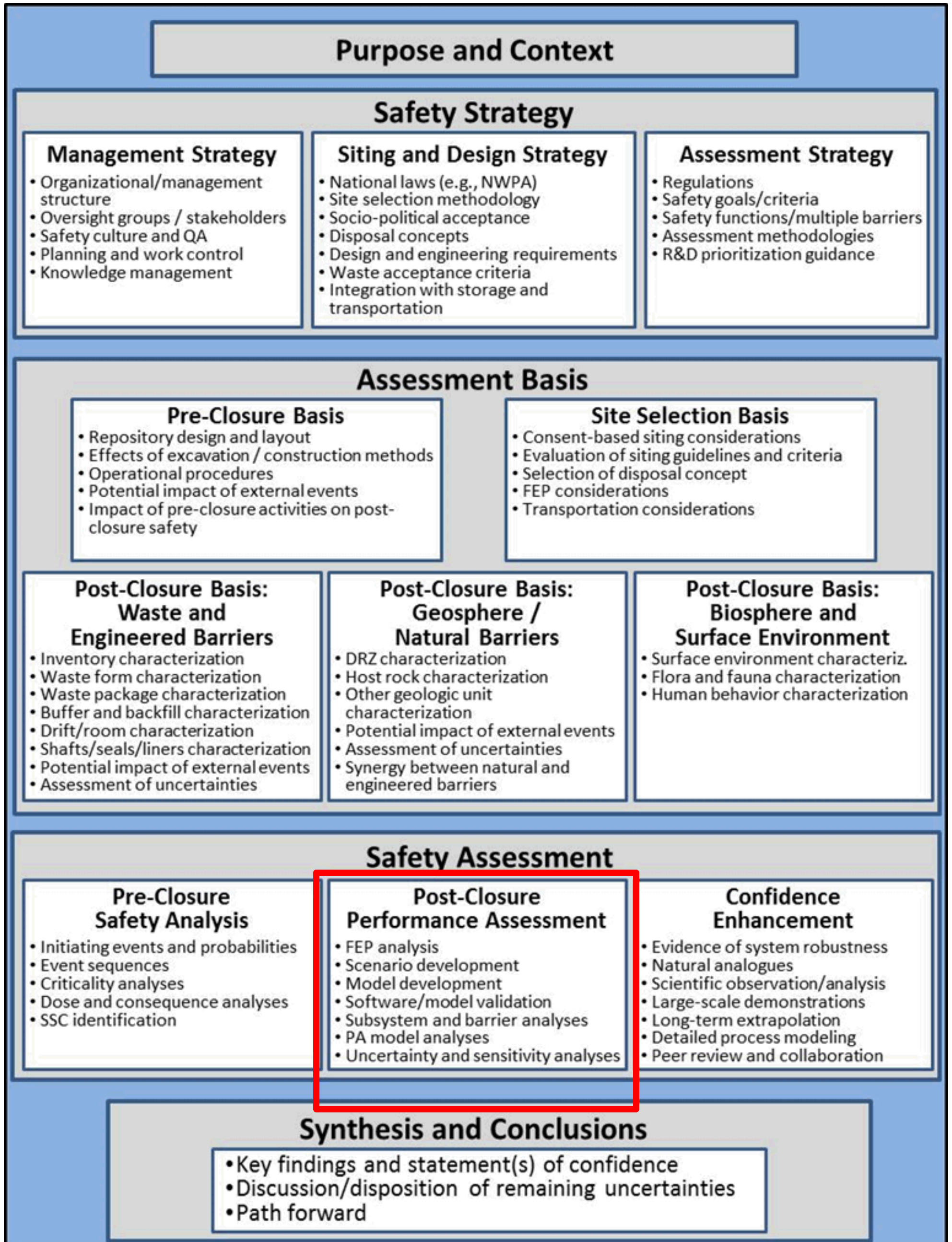
Others: Belgium (clay), Korea (granite), Japan (sedimentary rock, granite), UK (uncertain), Spain (uncertain), Switzerland (clay), Czech Republic (granitic rock), others including all nations with nuclear power.

Source: Information from Faybishenko et al., 2016

Safety Case Summary



Detailed Elements of the Safety Case:



Safety case includes comprehensive consideration of all relevant aspects of the repository system, applicable regulatory aspects, and relevant data/observations

Post-closure performance assessment evaluates quantitatively the behavior of the repository system over geologic time for comparison to regulatory limits, including evaluation of uncertainties and variability of the system

How does Deep Geologic Disposal Achieve Safe Isolation?

Sandia National Laboratories

Overall performance relies on multiple components; different disposal concepts emphasize different barriers (natural and engineered)

Natural barriers prevent or delay water from reaching waste form

Engineered barriers prevent or delay water from reaching waste form

Slow degradation of waste form limits exposure to water

Near Field: water chemistry limits aqueous concentrations

Natural and engineered barriers prevent or delay transport of radionuclides to the human environment

Time (radioactive decay)

Isolation mechanisms may differ for different nuclides in different disposal concepts

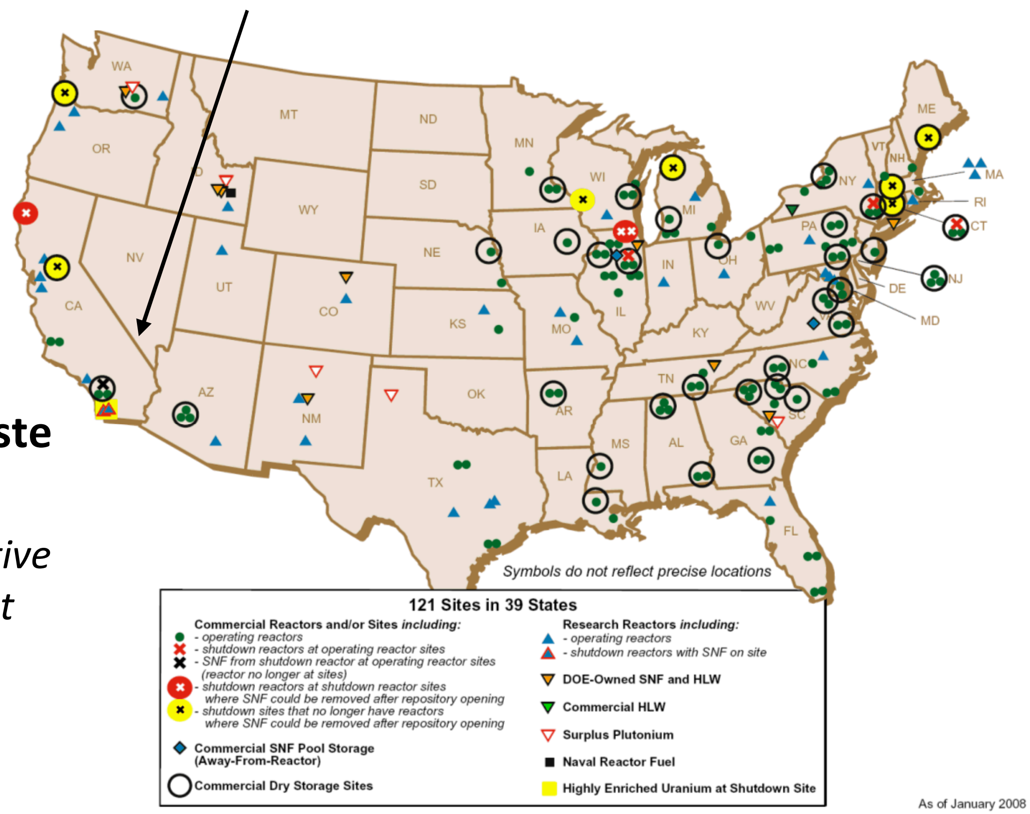
Examples from the Proposed Yucca Mountain Repository

The Yucca Mountain Mission

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

[121 sites in 39 states](#)

Proposed Yucca Mountain Repository



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

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

Waste for Yucca Mountain

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

DOE & Naval Spent Nuclear Fuel:
2,333 MTHM
(~400 naval waste packages)
(DSNF packaged with HLW)

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

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

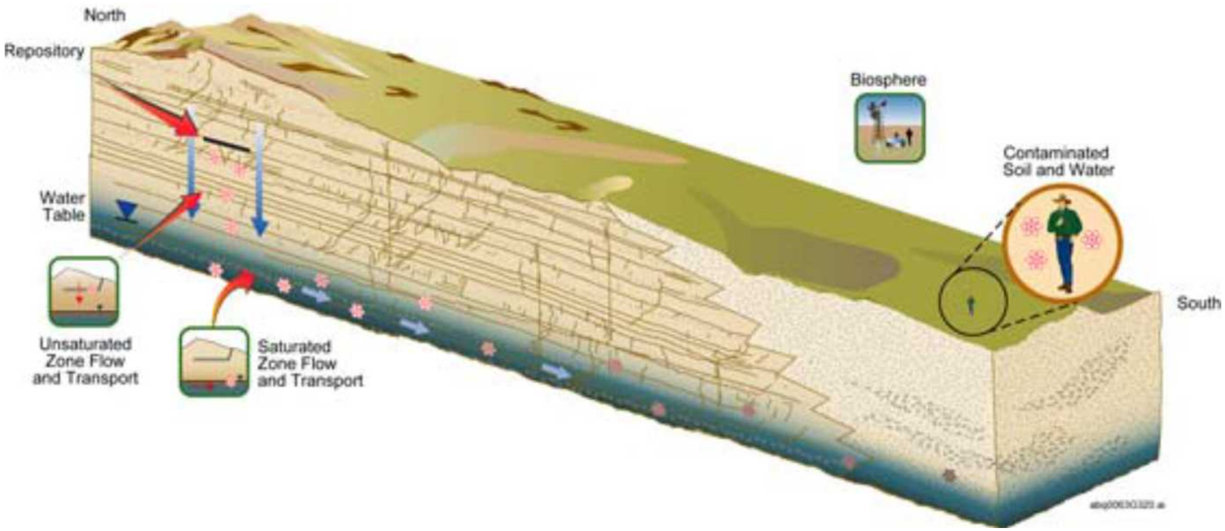
Major Elements of the Yucca Mountain Repository Concept

- 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

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

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

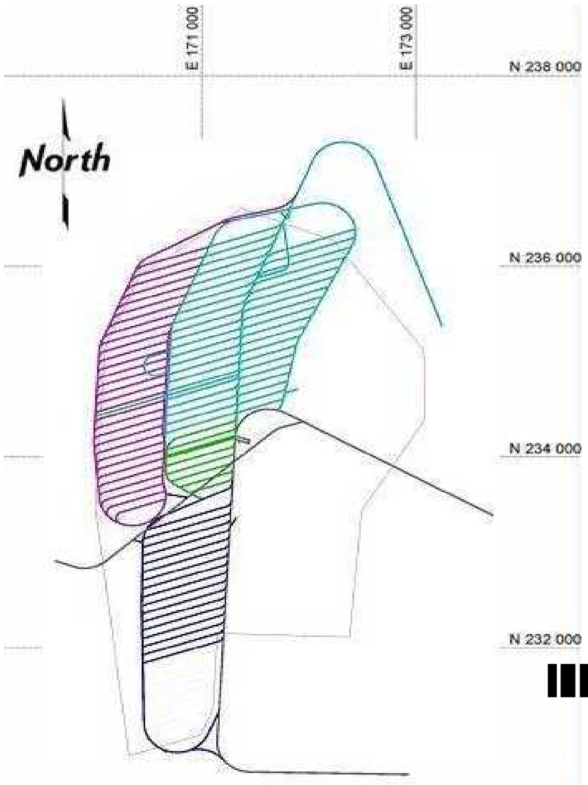
outer layer 2.5 cm Alloy 22 (Ni-Cr-Mo-V)

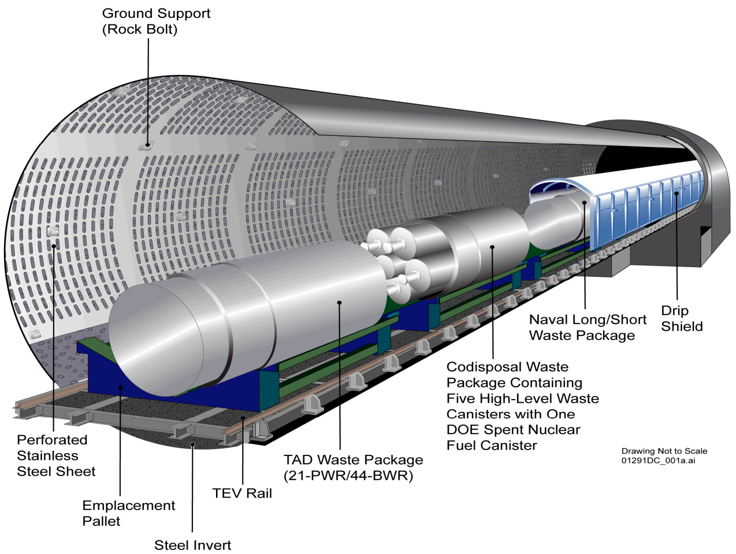
inner layer 5 cm stainless steel

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

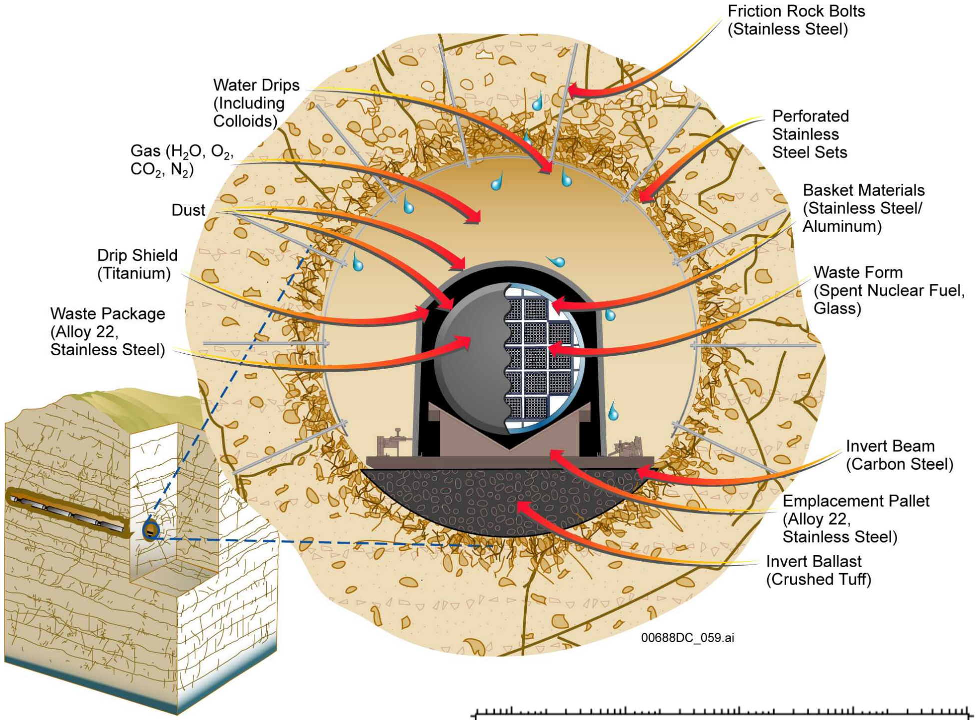
Drip shields

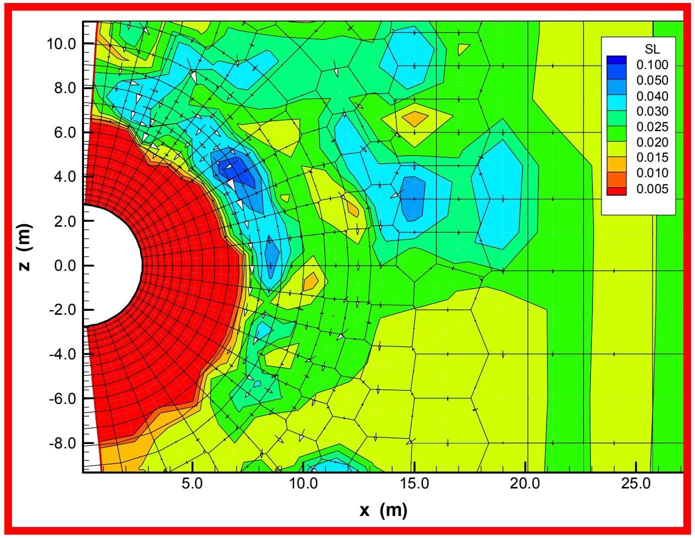
free-standing 1.5 cm Ti shell



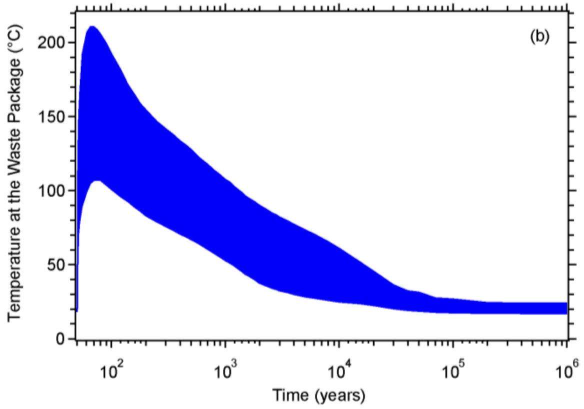


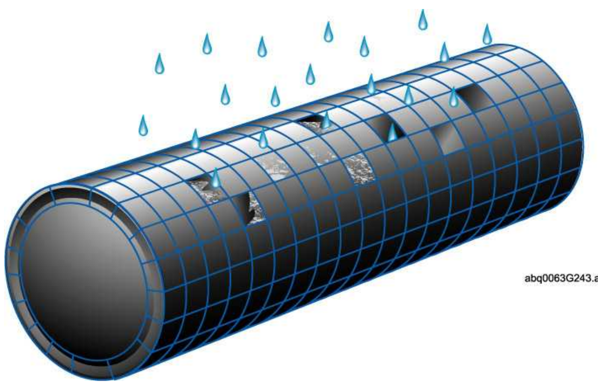
The Emplacement Environment at Yucca Mountain



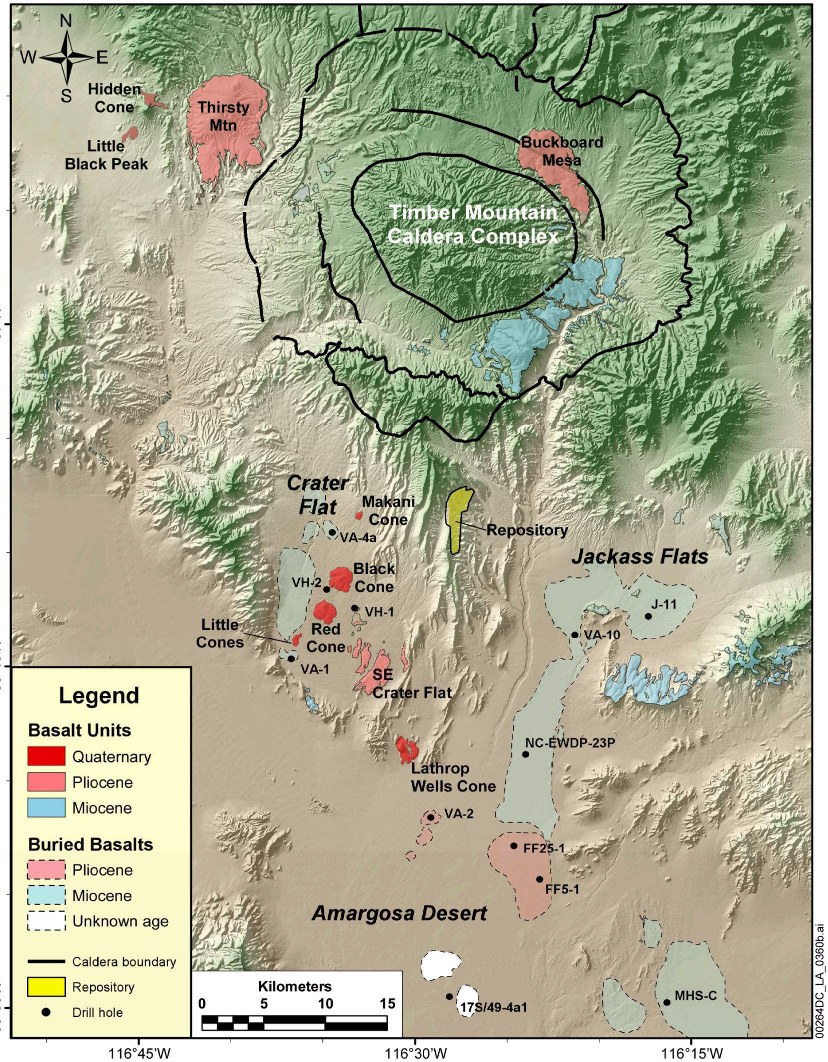


Material testing and models characterize performance of the engineered barriers

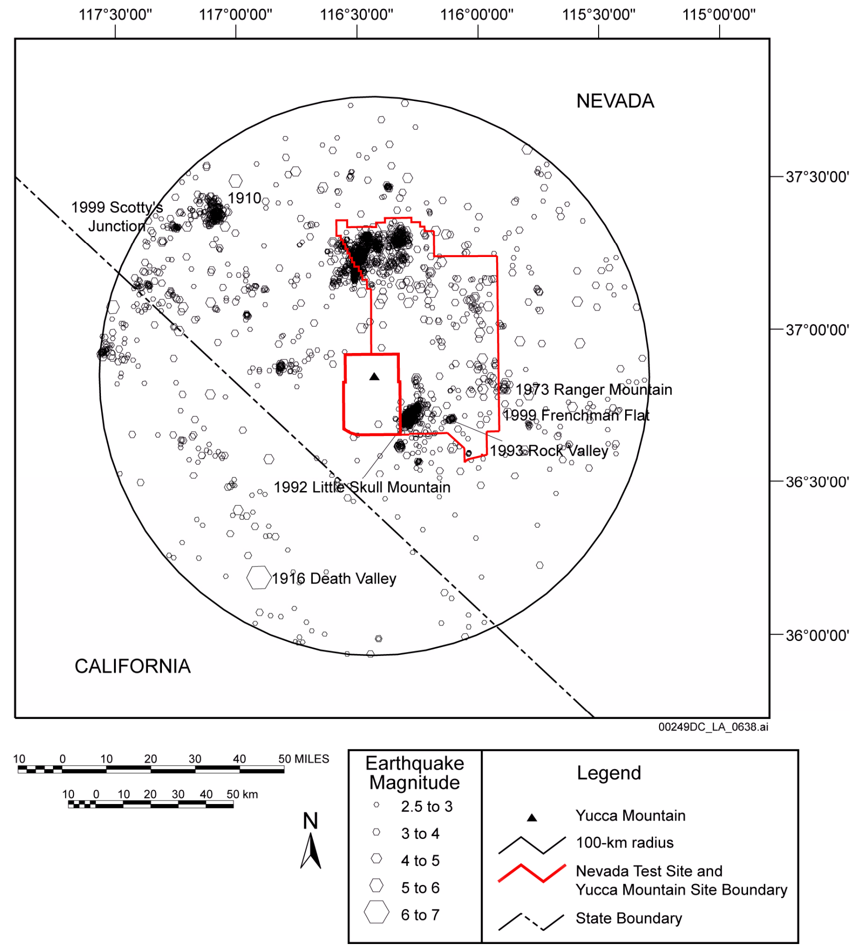




Igneous and Seismic Activity in the Yucca Mountain Region

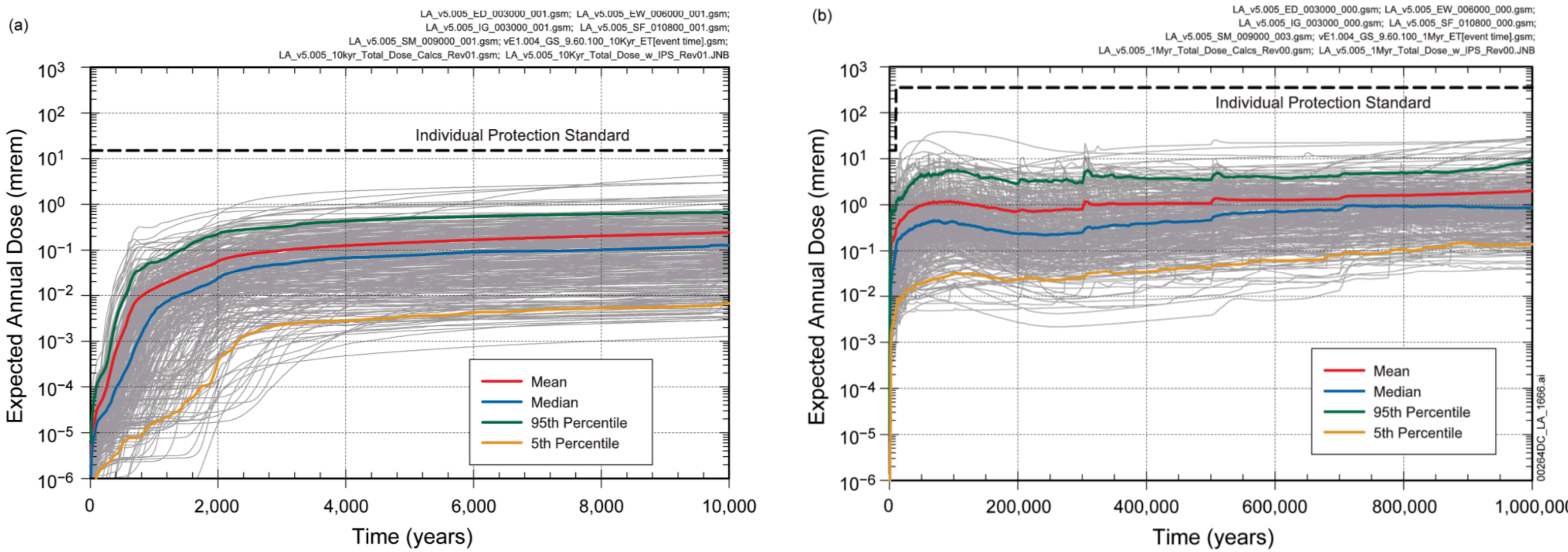


Distribution of Miocene and younger (< 5.3 Ma) Basaltic Rocks in the Yucca Mountain Region (DOE/RW-0573 Rev. 1, Figure GI 5-39)



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

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)

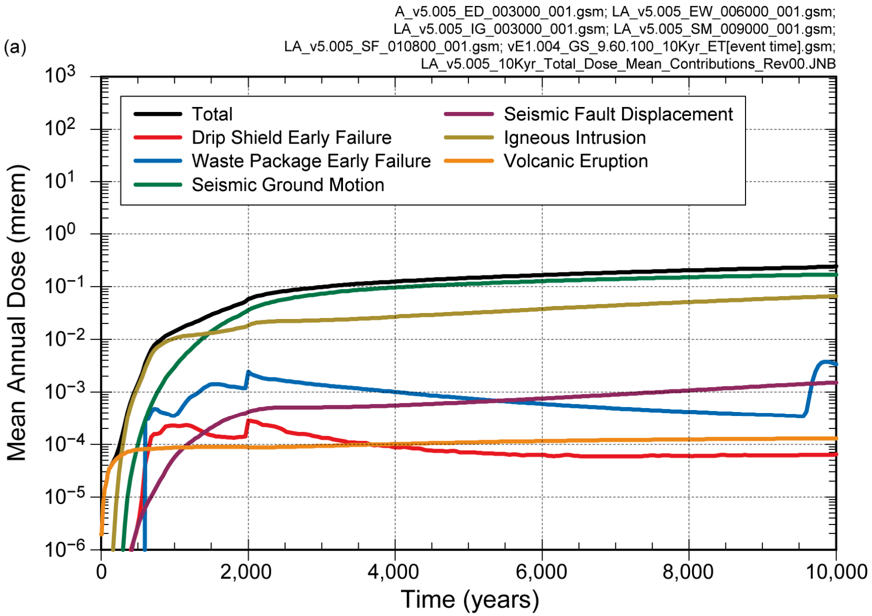
TSPA-LA estimated 10,000 yr maximum mean annual dose: 0.0024 mSv (0.24 mrem)

1,000,000 years

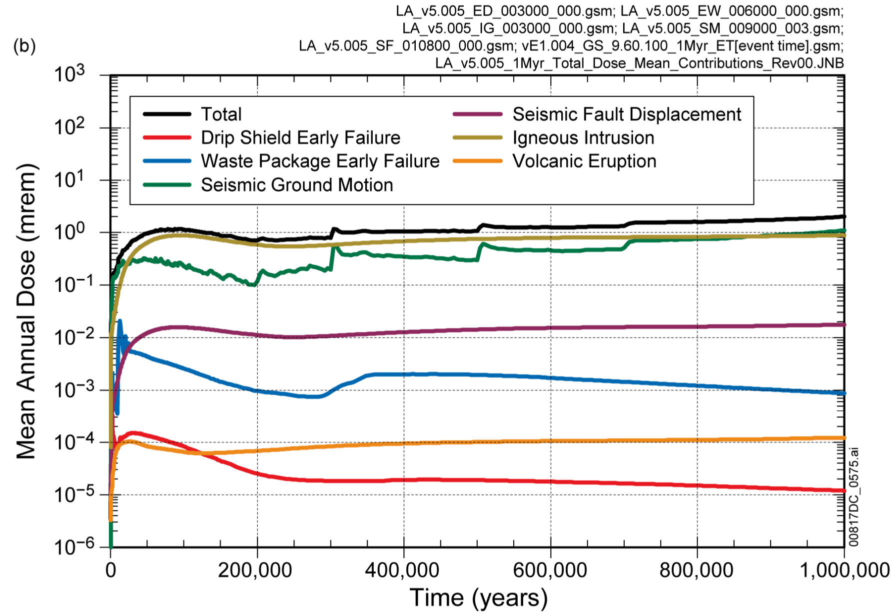
1,000,000-year Standard:
Mean annual dose no more than 1 mSv (100 mrem)

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



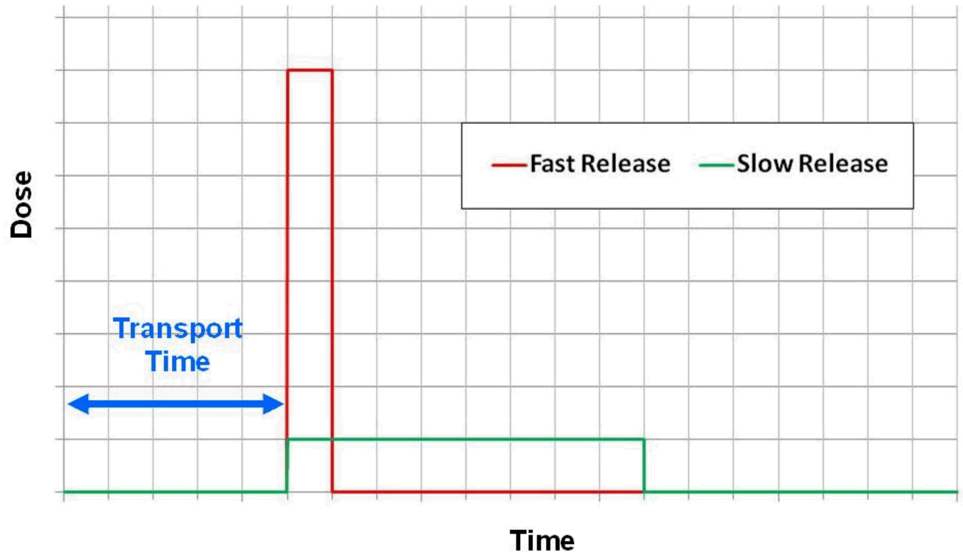
1,000,000 years

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

Simplistic Insights from Safety Assessments

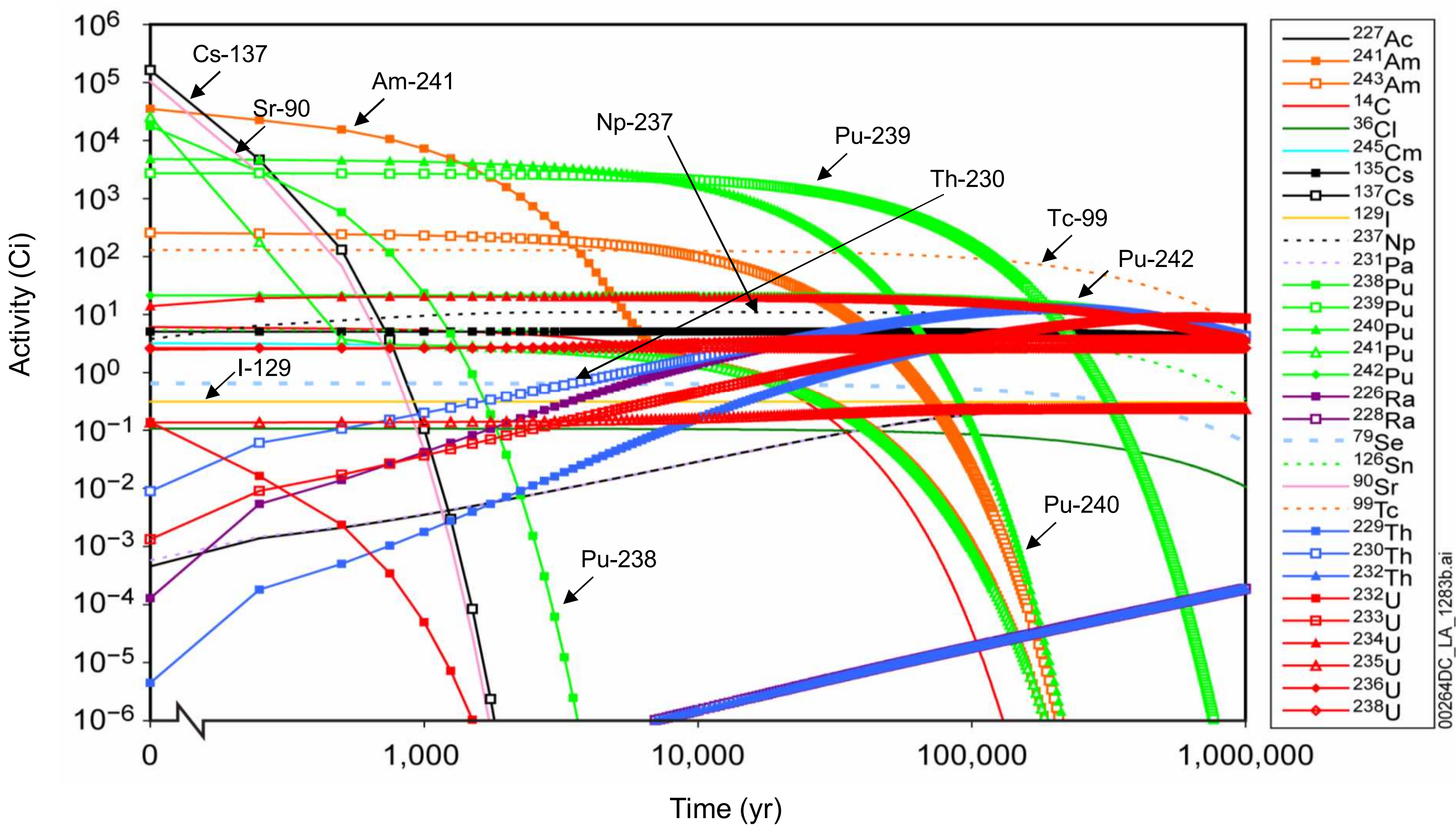
What matters for long-term performance?

- Initial mass (inventory) of dose-contributing radionuclides (or parents)
- Rate of radionuclide releases from waste packages (fast vs. slow)
  - Waste form and waste package degradation rates, radionuclide solubility
- Transport processes/residence time in the engineered barrier system and in the natural system / geosphere
  - Mass spreading: advection, dispersion, diffusion
  - Mass retention/loss: sorption, decay



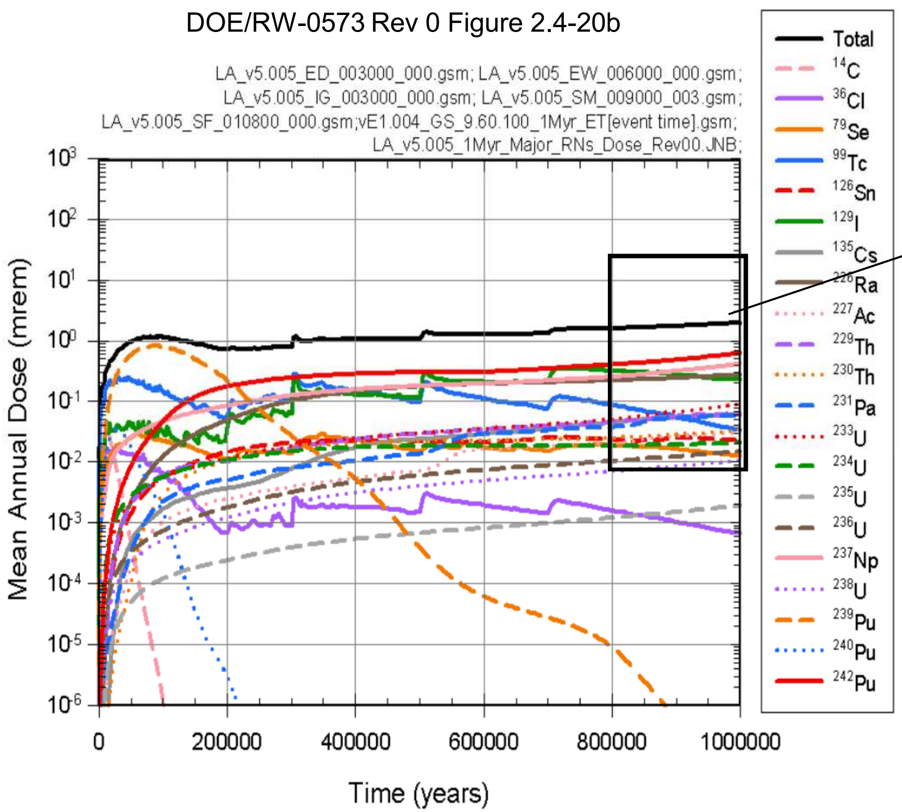
Freeze and Lee, 2011, Proceedings of the 2011 International High-Level Radioactive Waste Management Conference

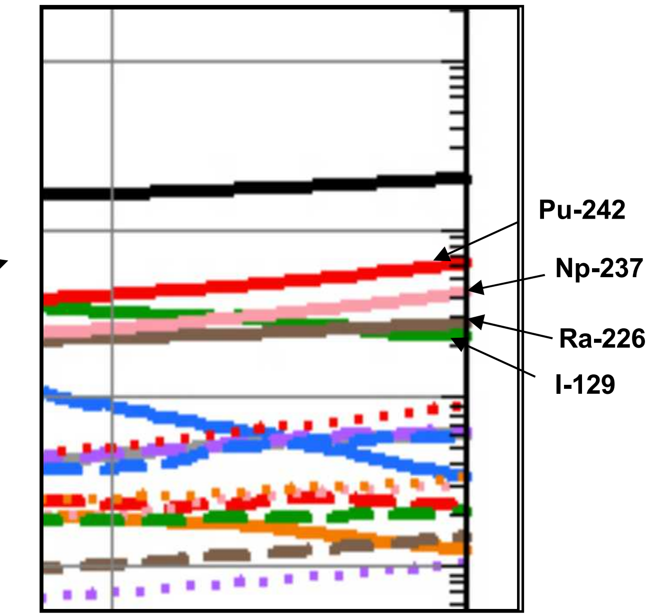
Commercial Used Nuclear Fuel Decay



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.

Contributors to Total Dose: Yucca Mountain

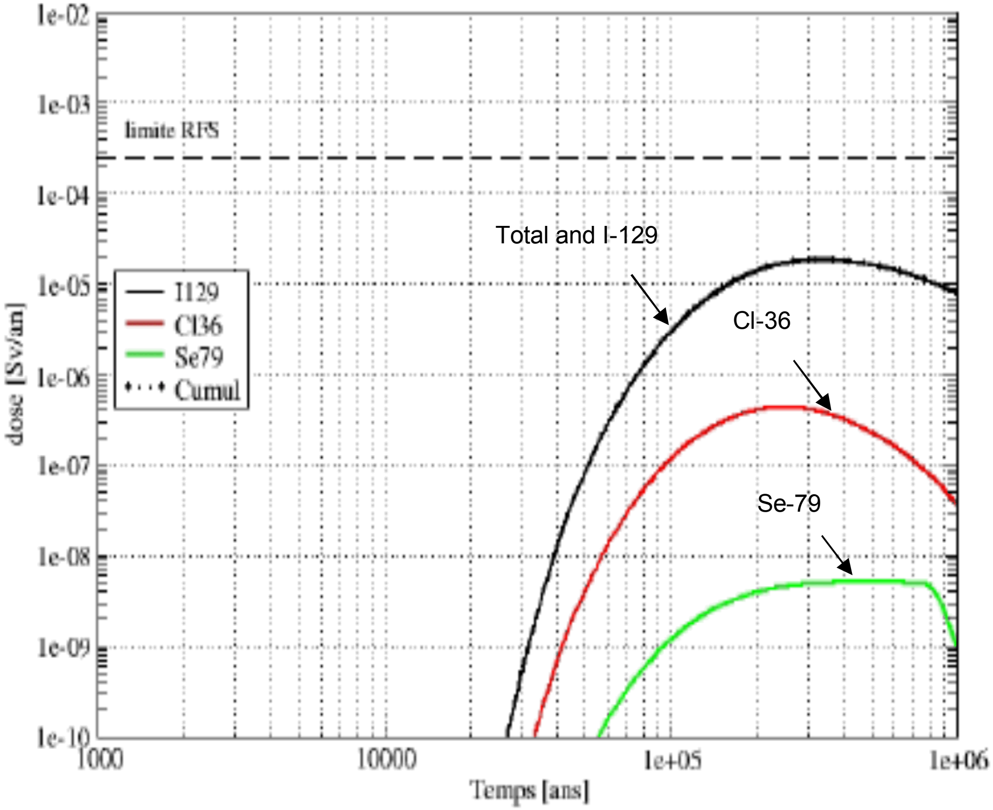




Disposal concept with an oxidizing environment and advective transport in the far-field: Fractured Tuff

Actinides are significant contributors to dose; I-129 is approx. 1/10th of total

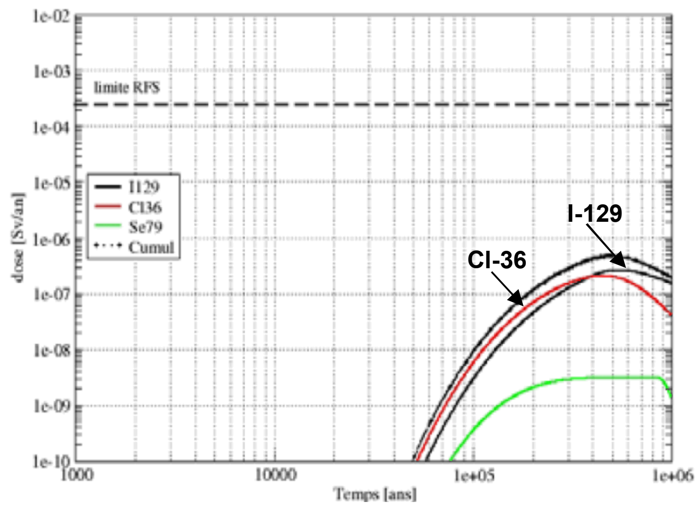
Contributors to Total Dose: Meuse / Haute Marne Site (France)



Diffusion-dominated disposal concept: Argillite

I-129 is the dominant contributor at peak dose

Examples shown for direct disposal of spent fuel (left) and vitrified waste (below)



ANDRA 2005, *Dossier 2005: Argile. Tome: Evaluation of the Feasibility of a Geological Repository in an Argillaceous Formation*, Figure 5.5-18, SEN million year model, CU1 spent nuclear fuel and Figure 5.5-22, SEN million year model, C1+C2 vitrified waste

Contributors to Total Dose: Forsmark site (Sweden)

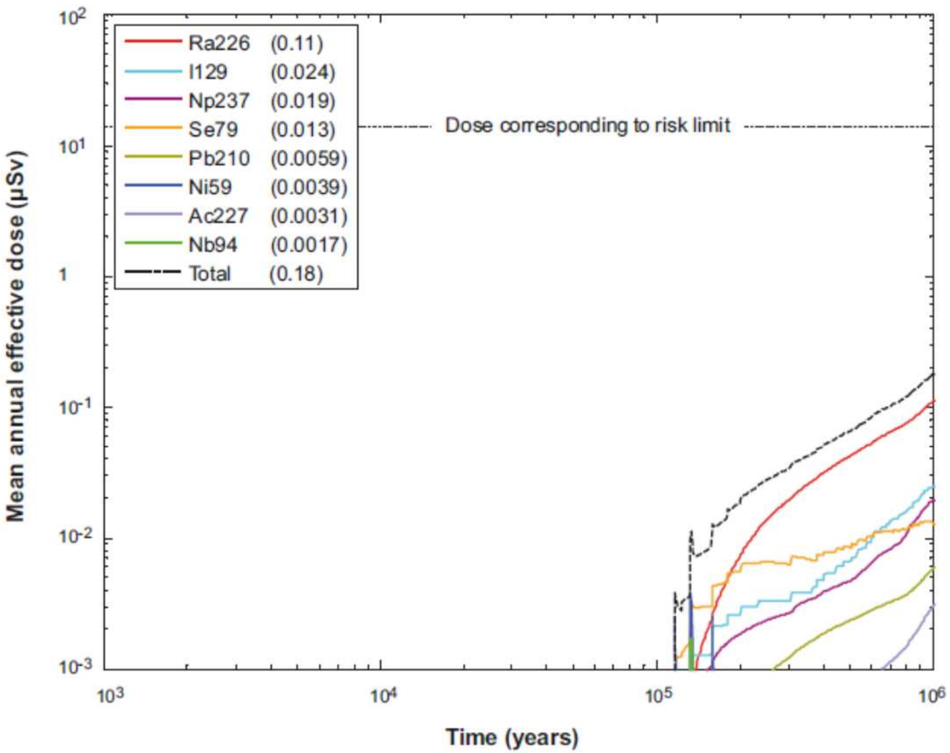


Figure 13-18. Far-field mean annual effective dose for the same case as in Figure 13-17. The legends are sorted according to descending peak mean annual effective dose over one million years (given in brackets in µSv).

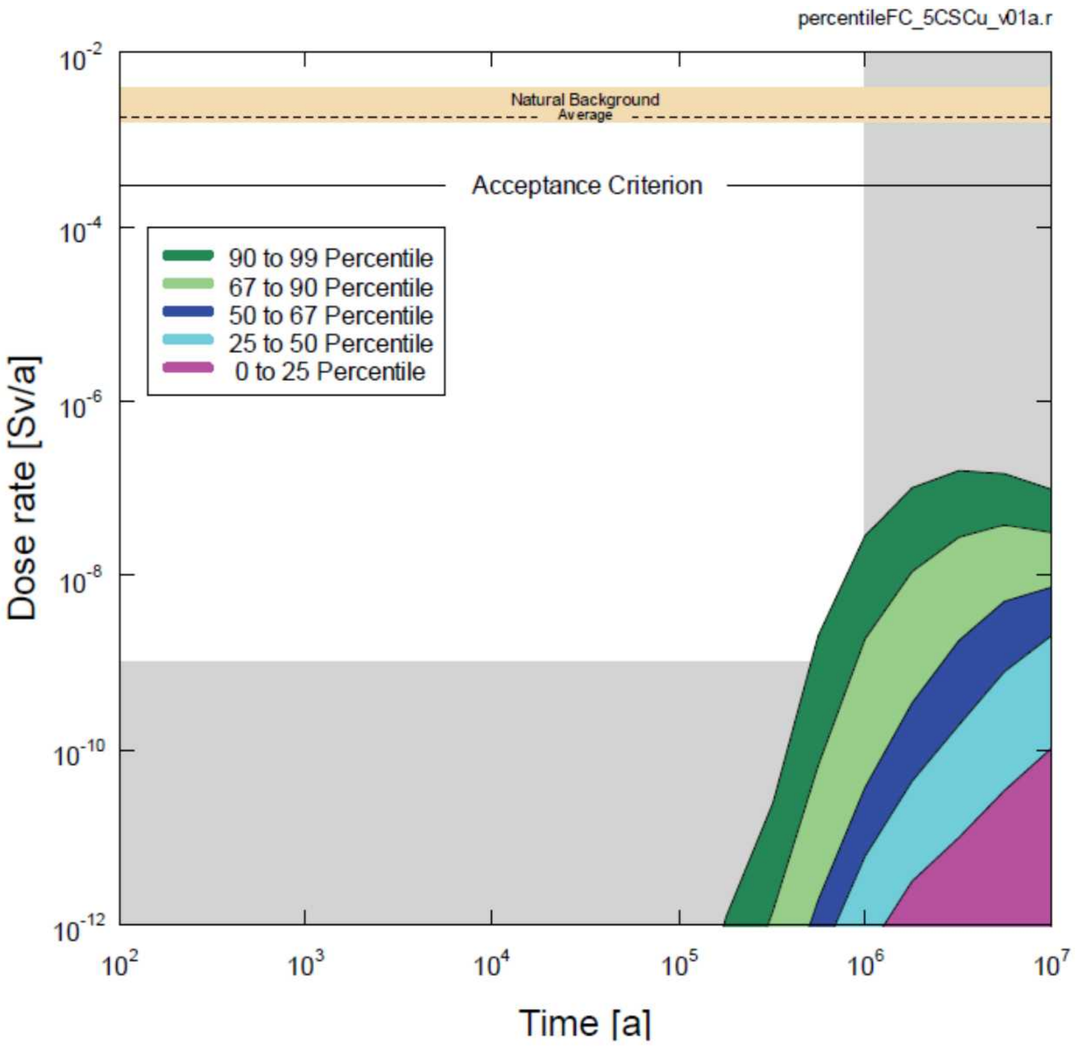
SKB 2011, Long-term safety for the final repository for spent nuclear fuel at Forsmark, Technical Report TR-11-01

Disposal concept with advective transport in the far-field: Fractured Granite

Long-term peak dose dominated by Ra-226

Once corrosion failure occurs, dose is primarily controlled by fuel dissolution and diffusion through buffer rather than far-field retardation

Long-term Dose Estimates: Canada



Diffusion-dominated disposal concept: spent fuel disposal in carbonate host rock

Long-lived copper waste packages and long diffusive transport path

Major contributor to peak dose is I-129

NWMO 2013, Adaptive Phased Management: Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock, NWMO TR-2013-07, Figure 7-87.

Summary and Conclusions

Summary and Conclusions

- All nations with significant quantities of spent nuclear fuel and/or high-level radioactive waste are investigating options for deep geologic disposal
  - Variety of geology available within U.S.
  - UFDC R&D on various geologic systems for
    - Mined repositories
    - Deep Boreholes (ended in Summer 2017)
- Published analyses of deep geologic disposal of spent nuclear fuel and high-level radioactive waste indicate that multiple disposal concepts in a range of geology have the potential for excellent long-term performance
  - Isolation can be achieved by various combinations of natural (i.e., geologic) barriers and engineered barriers working together
  - Estimates of peak dose may be dominated by different radionuclides in different disposal concepts

Backup Materials

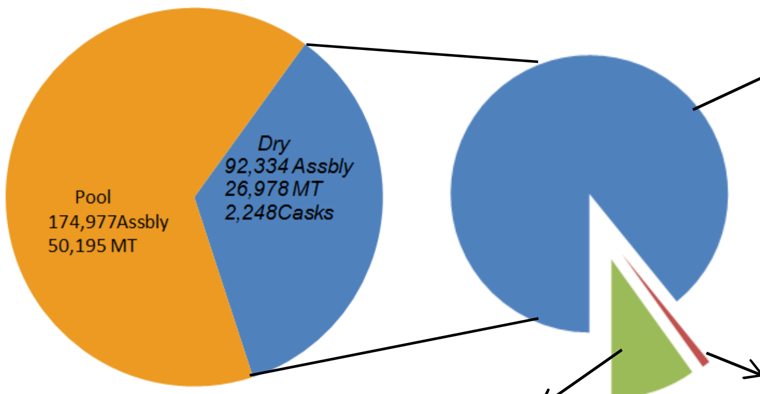
Brief History of the US Program

- **1982**: Nuclear Waste Policy Act defines Federal responsibility for permanent disposal of spent fuel and high-level waste, and leaves responsibility for storage at reactor sites with private sector
- **1987**: Congress amends NWPA to focus solely on disposal at Yucca Mountain, Nevada
- **2002:** Congress overrides Nevada's veto of the site and directs the Department of Energy and the Nuclear Regulatory Commission to proceed with the licensing process
- **2008:** DOE submits Yucca Mountain license application to the NRC
- **2010**: DOE determines Yucca Mountain is "unworkable" and Congress terminates funding for the project
- **2013:** DOE proposes to "facilitate the availability of a geologic repository by 2048"
- **2015:** NRC staff completes its Safety Evaluation Report for Yucca Mountain, concluding that "DOE has met the applicable regulatory requirements" related to safety
- **2016**: Private sector applications to the NRC for consolidated interim storage of spent fuel
- **2017**: DOE requests FY2018 funding from Congress to restart Yucca Mountain licensing process. Approximately 300 technical contentions remain to be heard before a licensing board can reach a decision regarding construction authorization

Storage and Transportation R&D

Commercial Dry Storage System Inventory is Diverse and Growing

Reactor Discharges at Dec 2016, Dry Inventory as of May, 2016



2,032 Welded Metal Canisters In Vented Concrete Overpacks 82,318 Assemblies, 89.2% of Dry

Transnuclear (35.2%)
Holtec (49.7%)
NAC (12.9%)

204 Bare Fuel Casks 9,150 Assemblies, 9.9% of Dry

12 Welded Metal Canisters in Transport Overpacks 866 Assemblies, 0.9% of Dry

- *Majority is in Large Welded Canisters*
- *Current dry storage inventory is diverse*
- *Trend toward higher capacities*

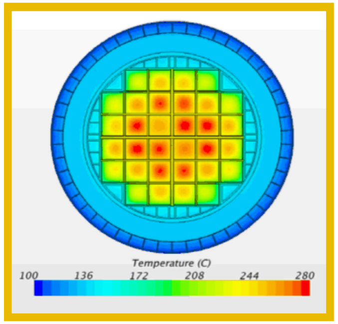
Transnuclear TN-32

Holtec Hi-Star 100

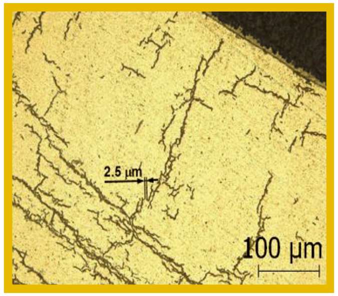
Source: Derived from Data in "Commercial Spent Nuclear Fuel and High-Level Radioactive Waste Inventory Report", FCRD-NFST-2013, Rev. 4, June 30, 2016 and Data contained in ""Dry Storage Cask Inventory Assessment", FCRD-NFST-2014-000602, Rev 2, August 30, 2016

Understanding High Burn-up Cladding Performance

- **Thermal Analysis**
  - More detailed modeling shows considerable margin between design basis loading and actual loading resulting in lower temperatures than previously thought

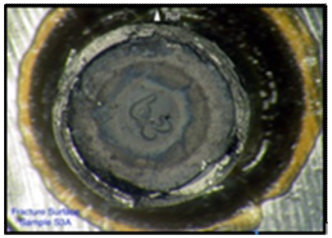


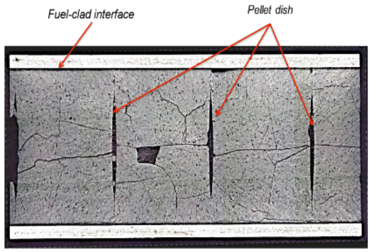
Maximum cladding surface temp. (°C) for each assembly in *one* type of licensed cask. (Fort, et al, 2016. PNNL)



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)

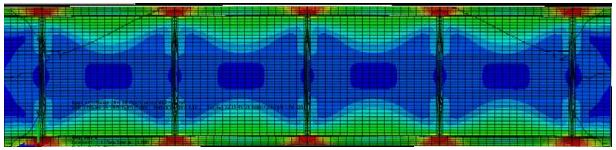
- **Ductile/Brittle Transition Temperatures**
  - Lower temperatures and lower rod internal pressures than previously assumed results in fewer radial hydrides
  - Temperature where cladding loses significant ductility is thus lower than previously thought





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

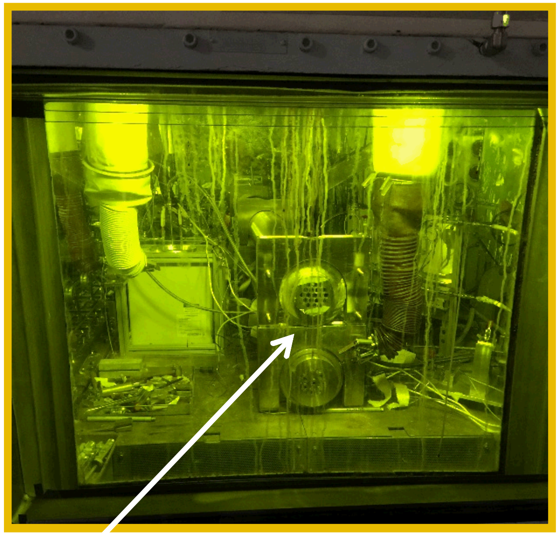
- **Strength and Fatigue**
  - Cyclic bending tests of irradiated fuel segments identify increased strength due to pellet/clad and pellet/pellet bonding effects.



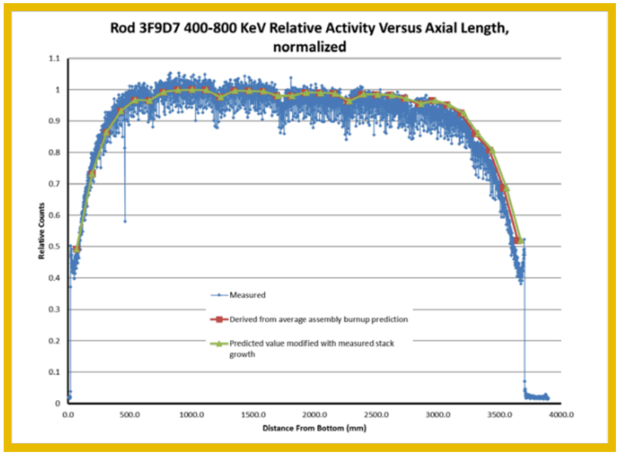
Stress distribution in fuel showing the fuel pellets supporting the clad due to cohesive bonding.(Wang, et al., 2014, ORNL)

High Burnup Confirmatory Data Project – Obtaining *Baseline* Data

- 25 fuel rods with similar histories to those in the cask will be tested to document pre-storage properties ("Sister Rods")
  - Areva and Westinghouse rods pulled in June and January 2015 from different assemblies
    - 9 AREVA M5® rods
    - 12 Westinghouse Zirlo® rods
    - 4 Westinghouse Zircaloy-4 (2 Low-tin; 2 Standard)
  - All 25 sister rods currently at Oak Ridge National Laboratory undergoing nondestructive analysis
  - Non-destructive tests began in FY17; destructive tests planned to begin in FY18
    - 14.5 rods at ORNL
    - 10 rod equivalents at PNNL
    - 0.5 rod equivalents at ANL



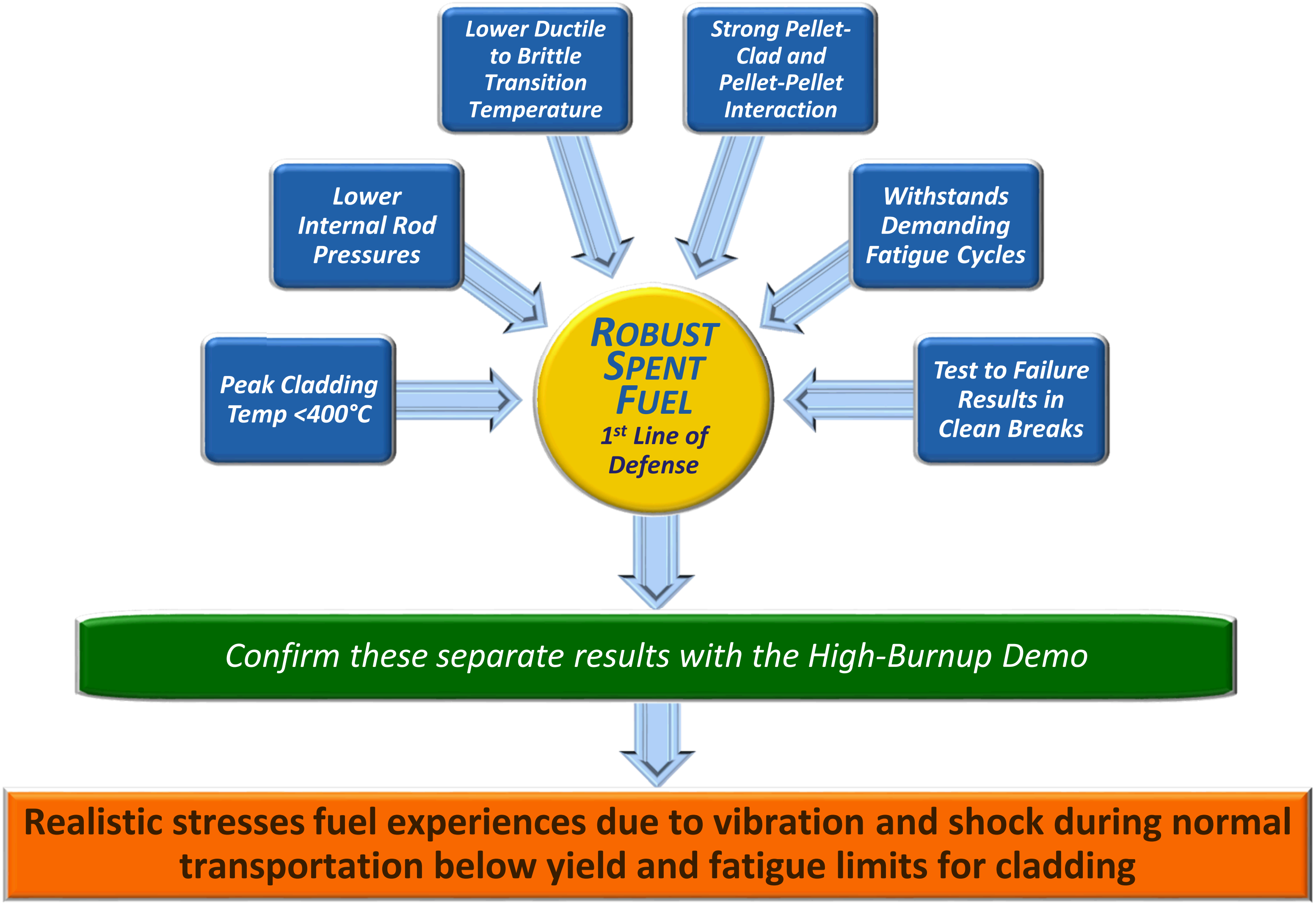
25 Sister Rods in ORNL Hot Cell
Photo: Saltzstein, SNL



Sister Rod gamma scan results to determine the axial burnup profile and identify pellet locations (Montgomery R, 2016).

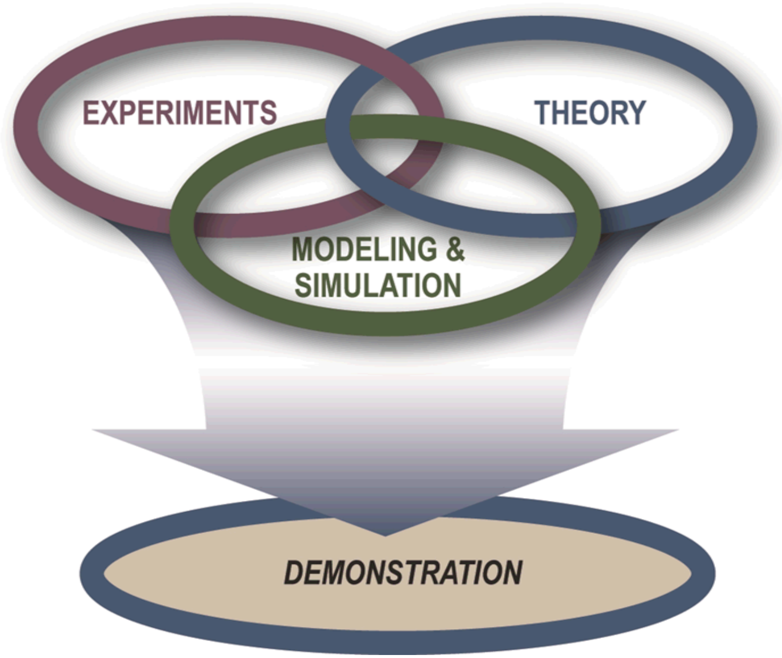
Current R&D Indicates SNF is Robust:

Expected Handling/Transport Loads Less Than Previously Thought



Commercial Spent Fuel Summary of Activities

Technical Direction



Partnerships

- **Industry**
  - Utilities – NEI, EPRI
  - Cask manufacturers
  - Fuel suppliers
  - Rail and trucking companies
- **National Laboratories**
  - 11 National Labs
  - Specialized personnel, facilities and equipment are available
- **Small Businesses**
  - $5.2 million and 13 contracts awarded
- **Universities**
  - More than 18 universities, numerous students and professors are involved ($27M)
- **Nuclear Regulatory Commission**
  - Jointly fund research when appropriate
  - Continue some testing NRC began
- **International – ESCP**
  - Extended Storage Collaboration Program

Observations from Current Storage and Transportation R&D

Sandia National Laboratories

1. Spent fuel integrity

- Current test and analyses indicate that spent fuel is ***more*** robust than was previously thought.
- The *DOE/EPRI High Burnup Confirmatory Data Project* will obtain data after 10 years of dry storage to confirm current test and analysis results.

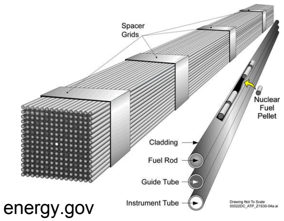


Photo: energy.gov

2. Storage system integrity

- *Stress corrosion cracking of canisters may be a concern in some parts of the country. More work is needed in analysis and detection.*
- *Monitoring and Aging Management practices at storage sites will be important to confirm storage system performance during extended service.*

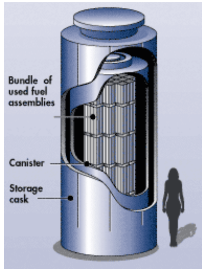
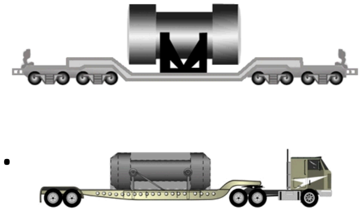


Photo: nrc.gov

3. Spent fuel transportability following extended storage

- *The realistic stresses fuel experiences due to vibration and shock during normal transportation are far below yield and fatigue limits for cladding.*

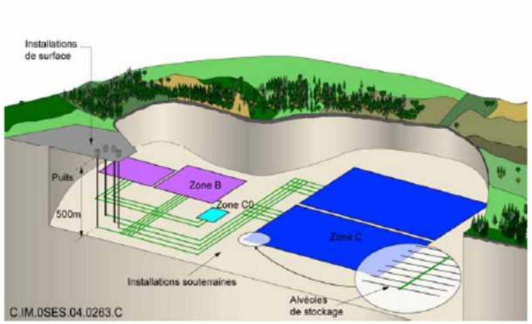

Energy.gov/pictures

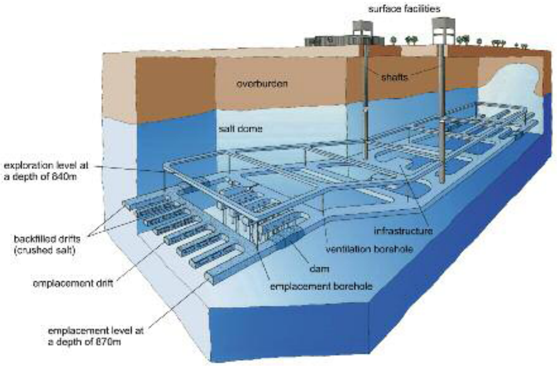
Disposal R&D

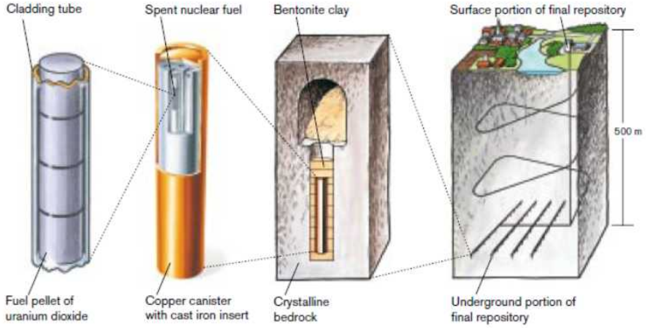
Deep Geologic Disposal Remains an Essential Element of Nuclear Waste Management

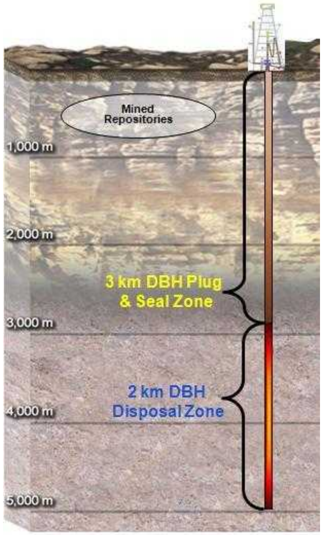
"The conclusion that disposal is needed and that deep geologic disposal is the scientifically preferred approach has been reached by every expert panel that has looked at the issue and by every other country that is pursuing a nuclear waste management program."

Blue Ribbon Commission on America's Nuclear Future, 2012





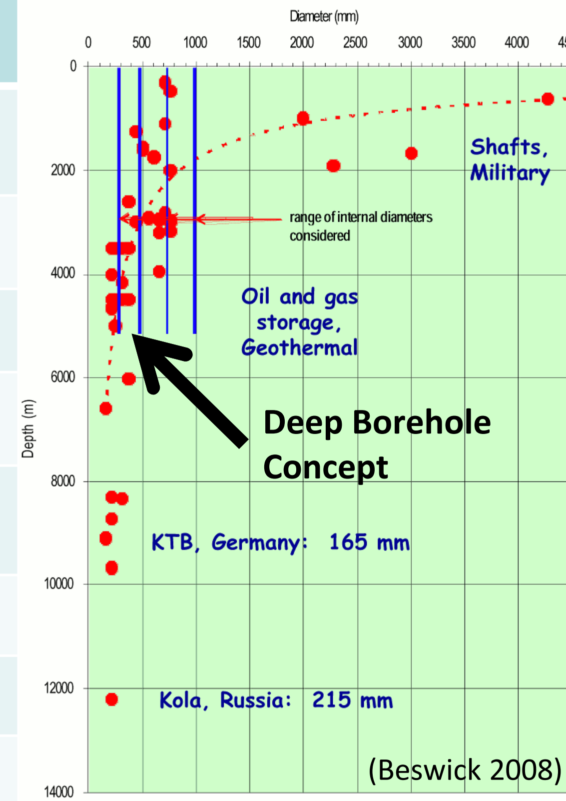


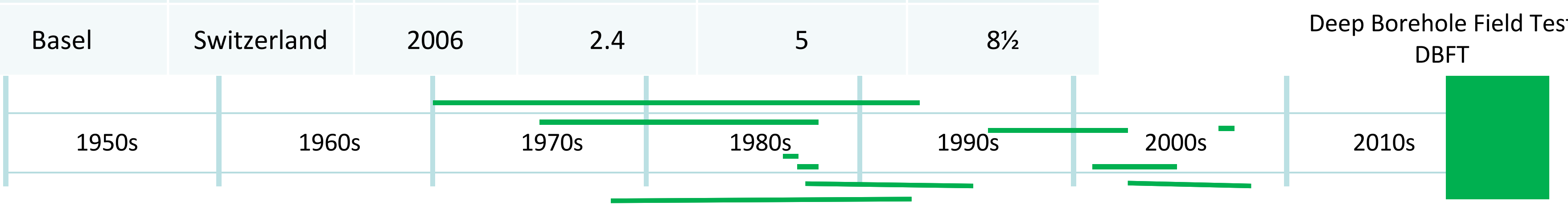


Deep Borehole Conditions: Crystalline Basement Reaction Controls

Deep Crystalline Drilling

Site	Location	Years	Depth to Crystalline [km]	Total Depth [km]	Diam. at TD [inch]
Kola	NW USSR	1970-1992	0	12.2	8½
Fenton Hill	New Mexico	1975-1987	0.7	2.9, 3.1, 4.0, 4.4	8¾, 9⅞
Urach	SW Germany	1978-1992	1.6	4.4	5½
Gravberg	Central Sweden	1986-1987	0	6.6	6½
Cajon Pass	Southern California	1987-1988	0.5	3.5	6¼
KTB	SE Germany	1987-1994	0	4, 9.1	6, 6½
Soultz	NE France	1995-2003	1.4	5.1, 5.1, 5.3	9⅝
CCSD	E China	2001-2005	0	2, 5.2	6
SAFOD	Central California	2002-2007	0.8	2.2, 4	8½, 8¾
Basel	Switzerland	2006	2.4	5	8½





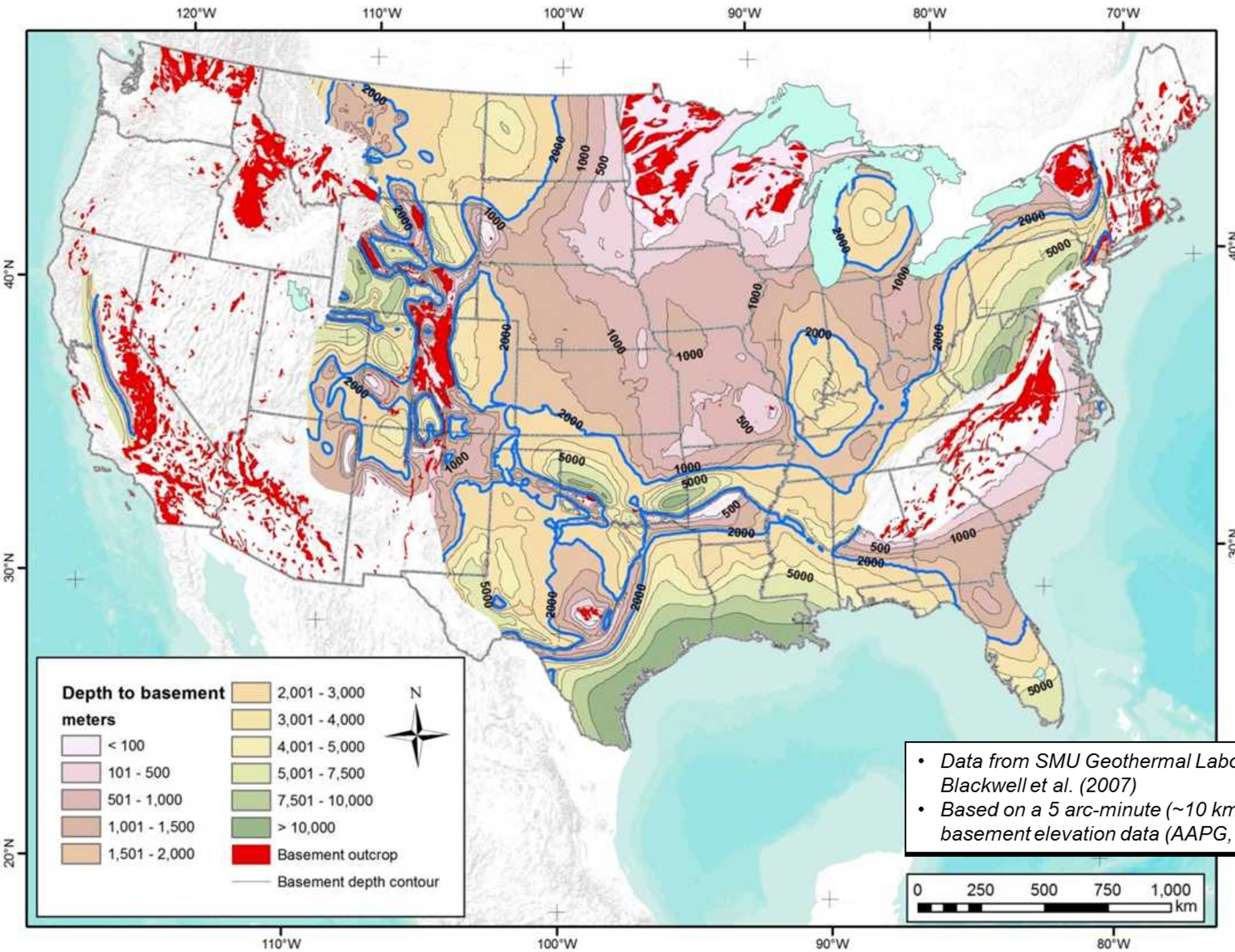
Preferred Geologic Conditions

- Geohydrological Considerations
  - No large-scale connected pathways from depth to aquifer systems
    - No through going fracture/fault/shear zones that provide fast paths
    - No structural features that provide potential connective pathways
  - Low permeability of crystalline basement at depth
    - Urach 3: (Stober and Bucher, 2000; 2004)
      - ~10^{-19} m^2 (intact rock); ~10^{-14} to 10^{-17} m^2 (bulk: parallel to or across shears)
      - Decreasing with Depth
  - Evidence of ancient, isolated nature of groundwater
    - Salinity gradient increasing downward to brine at depth (Park et al., 2009)
      - Limited recharge/connectivity with surface waters/aquifers
      - Provides density resistance to upward flow
    - Major element and isotopic indication of compositional equilibration with rock
      - Crystalline basement reacting with water (Stober and Bucher, 2004)
      - Ancient/isolated groundwater
        - » Ages – isotopes, paleoseawater (Stober and Bucher, 2000)
        - » Radiogenic isotopes from atmosphere lacking: ^{81}Kr, ^{129}I, ^{36}Cl
        - » Radiogenic isotopes/ratios from rock: ^{81}Kr, $^{87}Sr/^{86}Sr$; $^{238}U/^{234}U$
        - » Noble gases (^{4}He, Ne) & stable isotopes (^{2}H, ^{18}O) compositions from deep water: (e.g., Gascoyne and Kamineni, 1993)

Preferred Geologic Conditions (Continued)

- Geochemical Considerations
  - Reduced, or reducing, conditions in the geosphere (rock and water system)
    - Crystalline basement mineralogical (and material) controls
    - Magnetite-hematite buffer low oxygen potential
      - Oxides equilibria => T-low fO_2 paths (e.g., Sassani and Pasteris, 1988; Sassani, 1992)
    - Biotite common Fe^{+2} phase (Bucher and Stober, 2000)
      - Rock-reacted fluid compositions – water sink (Stober and Bucher, 2004)
      - More rock dominated at depth (Gascoyne and Kamineni, 1993)
  - Stratification of salinity – increasing to brine deep in crystalline basement
    - Canadian Shield salinity increases with depth to ~350 g/L TDS; (Gascoyne and Kamineni, 1993; Park et al., 2009)
      - More Ca-rich brines with further reaction with deeper rock
    - Urach 3, Germany, ~70- g/L TDS NaCl brine (Stober and Bucher, 1999; 2004)
  - Subset of waste forms and radionuclides are redox sensitive
    - Lower degradation rates
    - Lower solubility-limited concentrations
    - Increased sorption coefficients
  - Higher salinity
    - Density gradient opposes upward flow
    - Reduces/eliminates colloidal transport

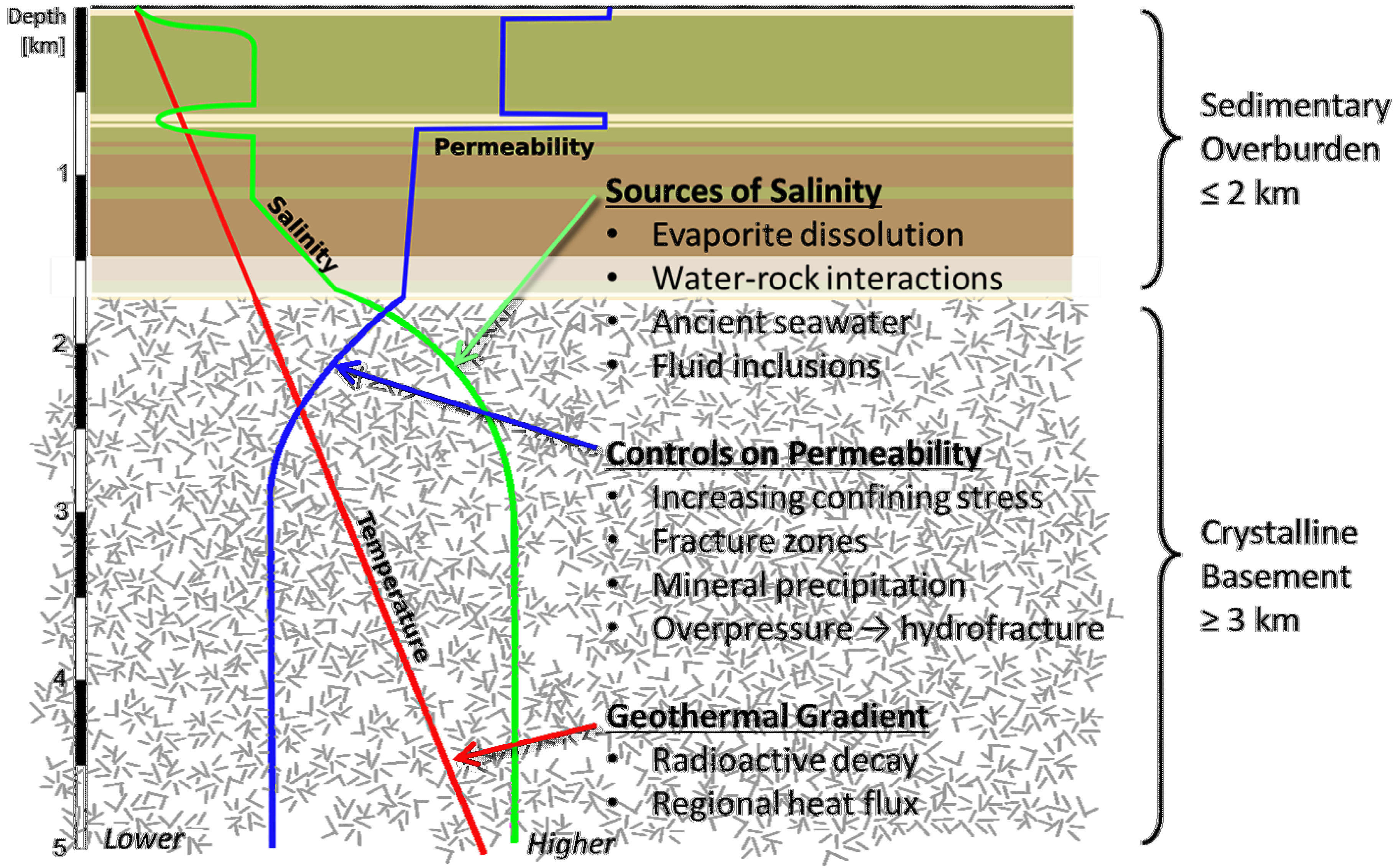
Depth to Basement – National Scale



- *Data from SMU Geothermal Laboratory - Blackwell et al. (2007)*
- *Based on a 5 arc-minute (~10 km) grid spacing of basement elevation data (AAPG, 1978)*

Distribution of crystalline basement at a depth of less than 2 km (tan shading) and granitic outcrop (red) in the contiguous US (from Figure 3-2 in Perry et al., 2015)

Deep Borehole Conceptual Profiles



Fluid-Rock Reaction Evaluations

- Analyses for generic fluid-rock reaction systems in crystalline basement
  - Evaluate mechanisms in the crystalline basement to form deep, isolated brines
    - Reaction path models for granite mineral reactions with seawater
      - Alteration mineralogy – hydrous phases (H_2O sinks)
      - Evolved brine compositions (major elements, Cl, Br)
    - Fluid inclusion contributions (soluble salts) considered
    - Calculating leachate compositions from Black Forest crystalline basement rocks
  - Conditions Comparable to ~ 5 km depth
    - Generic Granite Composition(s)
    - Seawater Starting Brine Composition
    - ~100 – 150^{o}C, P_{sat}
    - PHREEQC Reaction Path Calculations

Hypothetical Granite

- 20% Quartz; 40% K-feldspar; 15% Plagioclase (Albite); 9% Muscovite; 8% Biotite; and 8% Hornblende (volume %)
- Represented as a 10 kg (3.8 L) block having a molar mixture of
  - 33.3 moles Quartz: 14.4 moles K-feldspar: 5.7 moles Albite: 2.2 moles Muscovite: 1.8 moles Biotite: 0.9 moles Hornblende
- Granite is “reacted” with 0.1 liter of seawater at 100^{o}C.
  - This is a 38:1 rock:fluid ratio by volume, equivalent to a rock with a fluid-filled porosity of ~ 3%

Progress in Deep Geologic Disposal

- Three examples out of many

	2006 Plans	2016 Actions
Finland	Submit license application in 2012	License application submitted 28 December 2012 Construction License granted 12 November 2015
Sweden	Select a site by 2008	Forsmark site selected 3 June 2009 License application submitted 16 March 2011
Canada	Adaptive Phased Management recommended as an approach	More than 20 communities have expressed interest Eight areas currently being studied as potential candidates for further consideration

GDSA Framework

GDSA = Geologic Disposal Safety Assessment

Input Parameters

- Parameter database

DAKOTA

- Interface Control
- Uncertainty Sampling and Quantification
- Sensitivity Analysis

Computational Support

- Processing (Python, etc.)
- Mesh generation
- Visualization: ParaView (Parallel Visualization Application), VisIt

PFLOTRAN

Multi-Physics Simulation and Process Integration

Source Term and EBS Evolution Model

- Inventory (decay/ingrowth)
- WF degradation
- WP degradation
- Radionuclide release
- Thermal, mechanical
- Gas generation

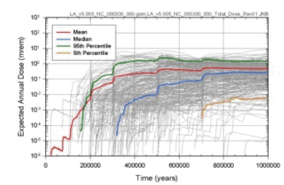
Flow and Transport Model

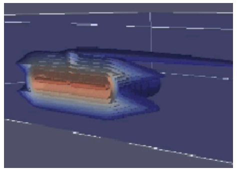
- Advection, diffusion, dispersion
- Sorption
- Precipitation, dissolution
- Decay, ingrowth
- Colloids
- Chemical reactions
- Heat transport

Biosphere Model

- Exposure pathways
- Uptake/ transfer
- Dose calculations

Output





Visit us at pa.sandia.gov

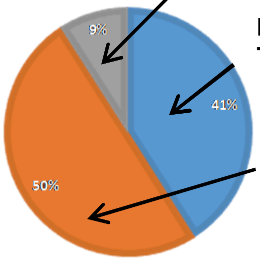
WIPP

Relative Amounts of Transuranic Waste

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

TRU volume is comparable to SNF and HLW

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



SNF and HLW data from SNL 2014, Table ES-1

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

TRANSURANIC WASTE LIMITATIONS.—

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

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

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

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

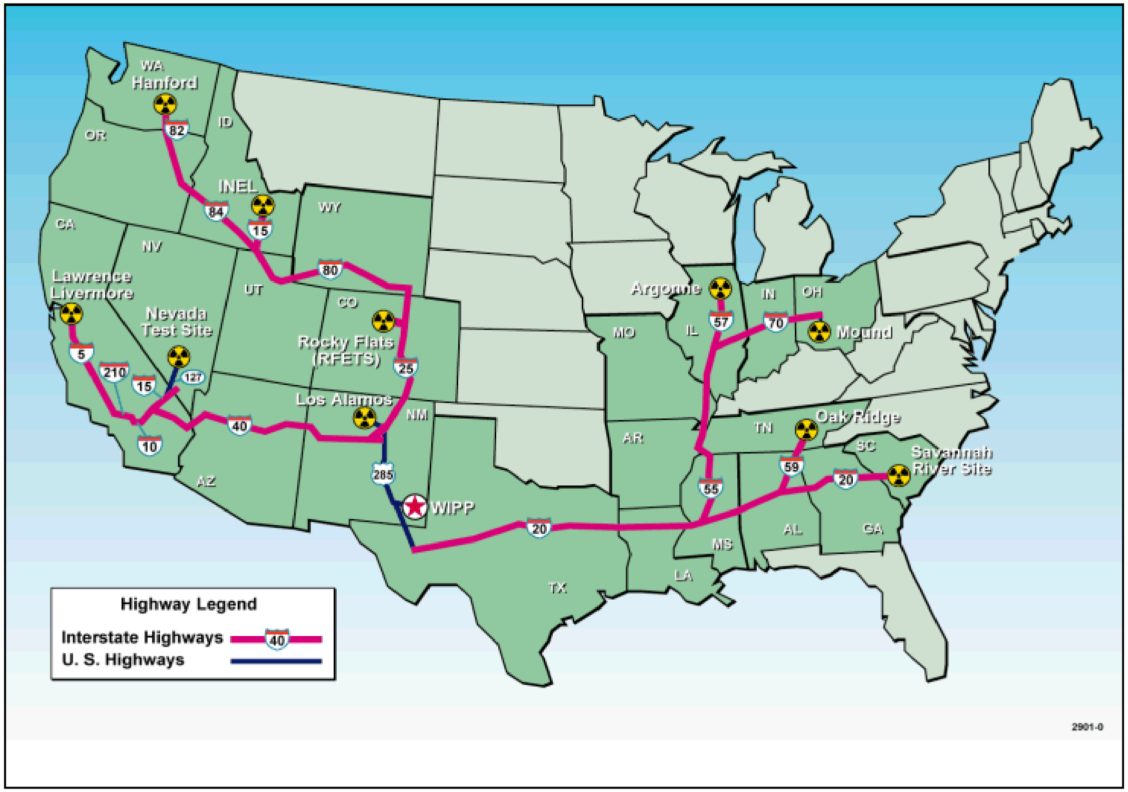
(A) CURIES PER LITER.— Remote-handled transuranic waste received at WIPP shall not exceed 23 curies per liter maximum activity level (averaged over the volume of the canister).

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

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

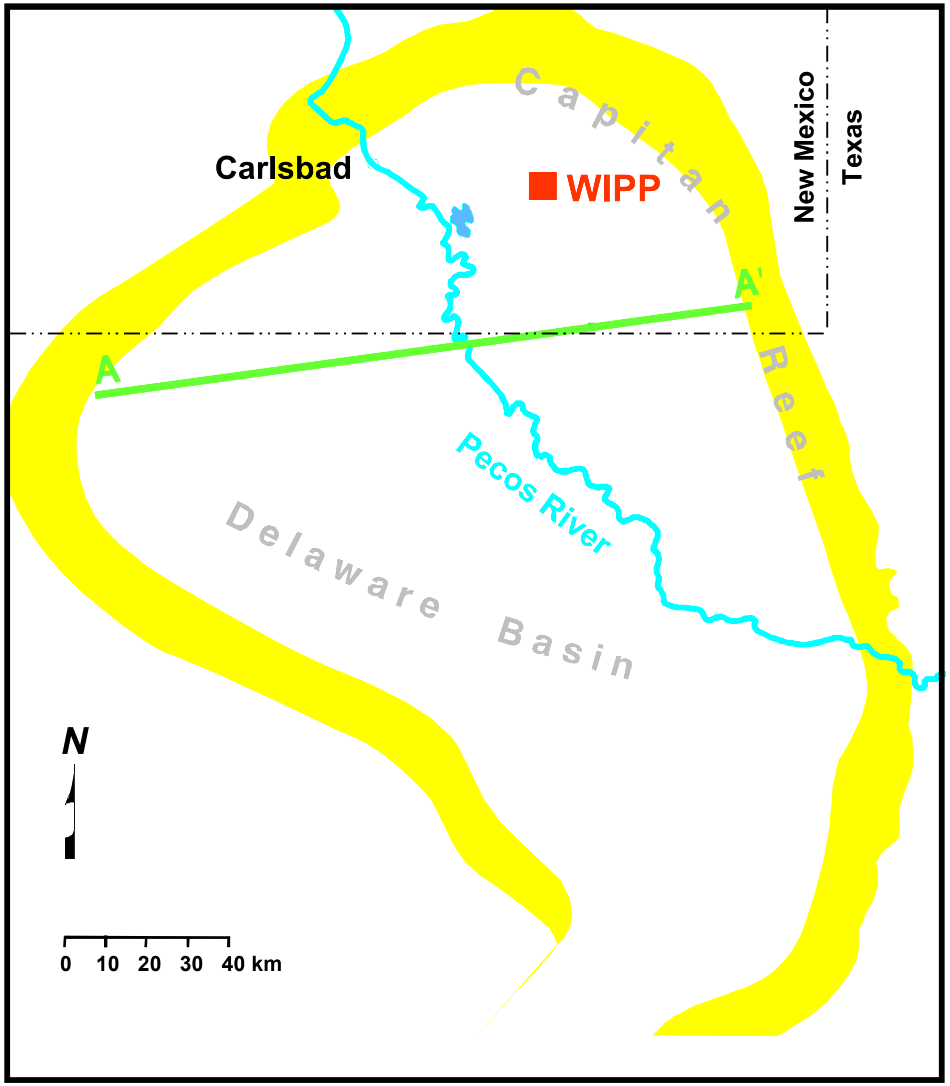
WIPP Transuranic Waste Transportation

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



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

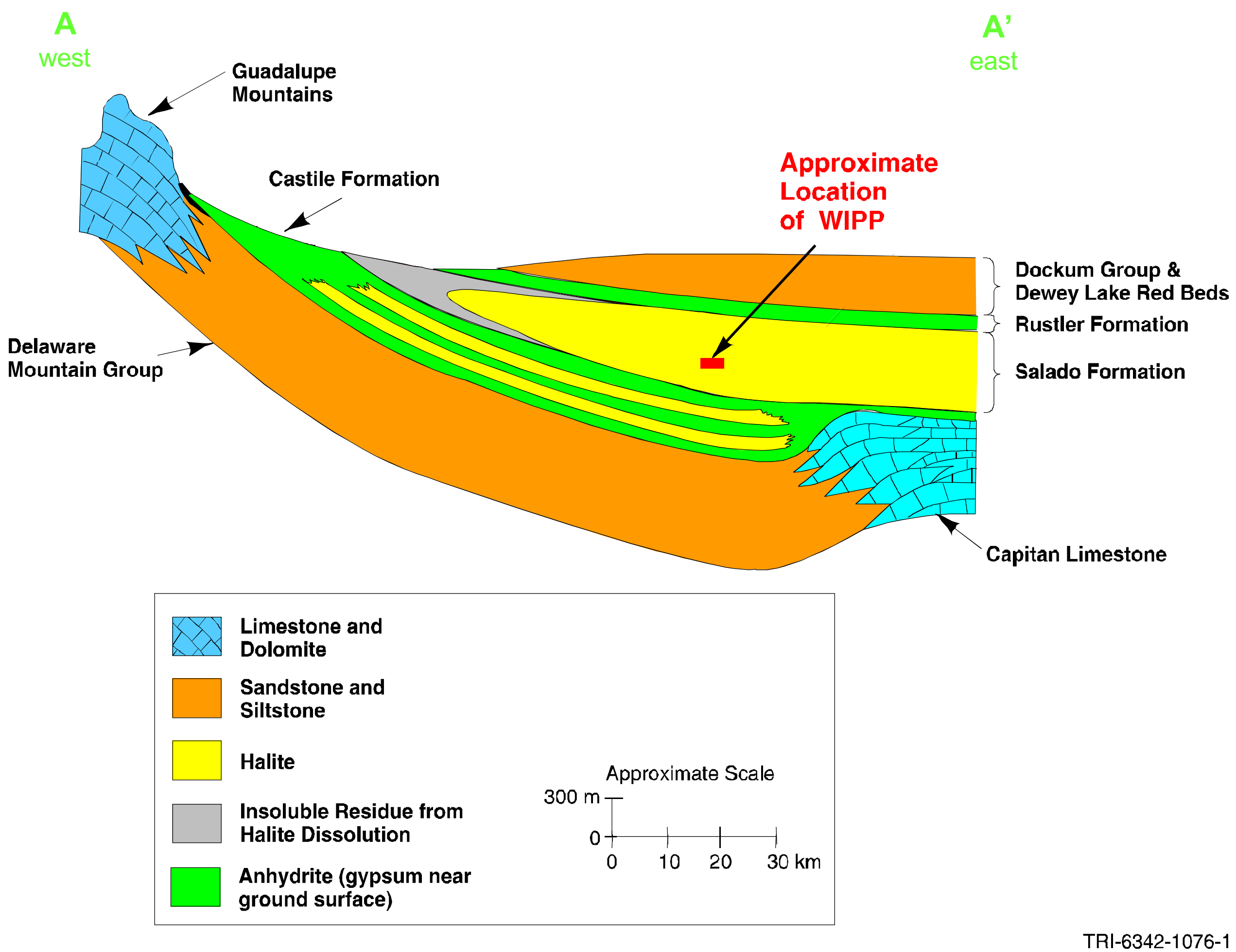
Site Geology



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

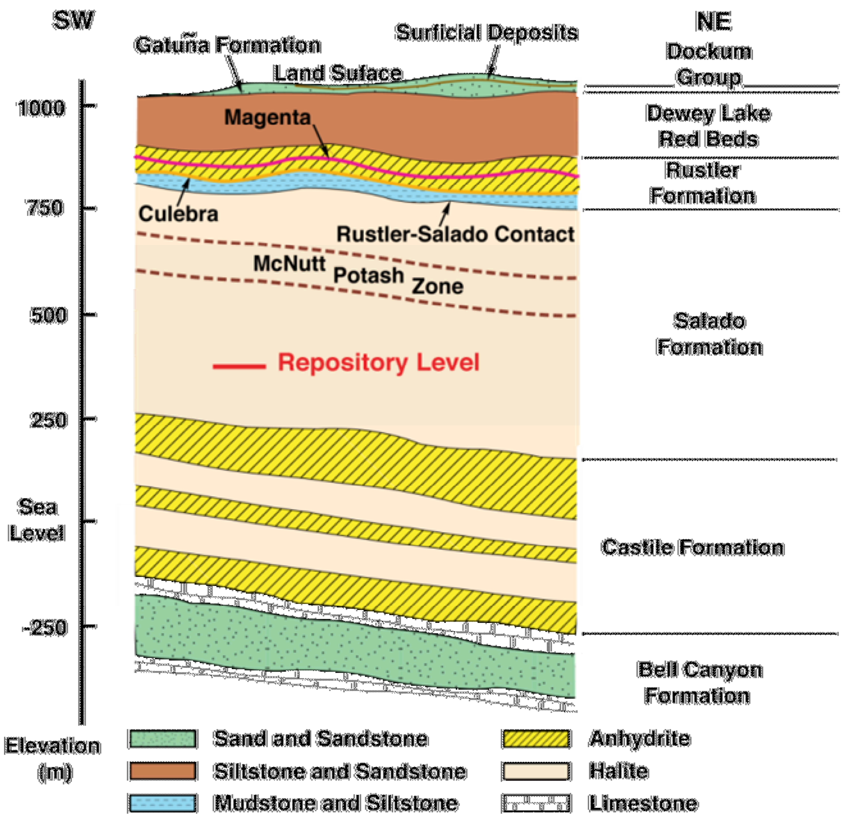
Site Geology (cont.)



Schematic West-East Geologic Cross Section of Delaware Basin

Note extreme vertical exaggeration

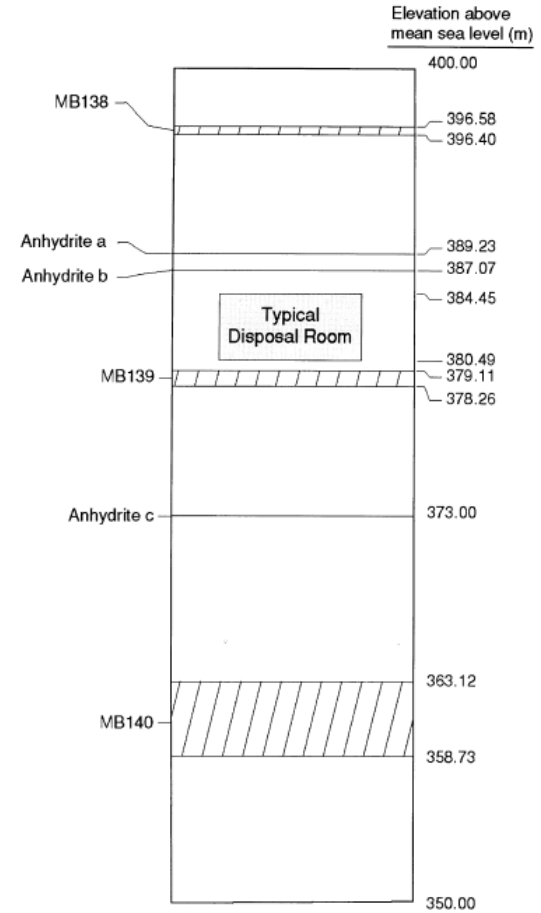
Local Stratigraphy at WIPP



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

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

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



References

AAPG, 1978, Basement map of North America: Am. Assoc. Petroleum Geologists, scale: 1:5,000,000

Blackwell, D.D., P. Negraru, and M. Richards, 2007. Assessment of the enhanced geothermal system resource base of the United States, Natural Resources Research, DOI 10:1007/s11053-007-9028-7.

Bucher K, and Stober I (2000) Hydrochemistry of water in the crystalline basement. In: Hydrogeology of Crystalline Rocks (eds Stober I, Bucher K), pp. 141-75. Kluwer Academic Publishers, Dordrecht.

Bucher, K. and Stober, I. (2002) Water-rock reaction experiments with Black Forest gneiss and granite, Water-Rock Interaction. Springer, pp. 61-95.

Bucher, K. and Stober, I. (2010) Fluids in the upper continental crust. Geofluids 10, 241-253.

DeMaio, W., and Bates, E. (2013). Salinity and Density in Deep Boreholes. Massachusetts Institute of Technology. UROP REPORT: October 29, 2013. 14 p.

Frape, S., Fritz, P. and McNutt, R.t. (1984) Water-rock interaction and chemistry of groundwaters from the Canadian Shield. Geochimica et Cosmochimica Acta 48, 1617-1627.

Gascoyne, M. and Kamineni, D. C. (1993) The hydrogeochemistry of fractured plutonic rocks in the canadian shield. In: Hydrogeology of Hard Rocks, 440- 449. Banks, S. B. and Banks, D. (editors) Geol. Survey of Norway: Trondheim.

Park, Y.-J., E.A. Sudicky, and J.F. Sykes (2009), Effects of shield brine on the safe disposal of waste in deep geologic environments, Advances in Water Resources 32: 1352-1358.

Perry, F., Kelley, R., Houseworth, J., and Dobson, P., 2015. A GIS Database to Support the Application of Technical Siting Guidelines to a Deep Borehole Field Test. FCRD-UFD-2015-000603. LA-UR-15-22397. Los Alamos , NM: US Department of Energy Used Fuel Disposition Campaign.

Sassani, D.C., 1992. Petrologic and Thermodynamic Investigation of the Aqueous Transport of Platinum-Group Elements During Alteration of Mafic Intrusive Rocks, Ph.D. Dissertation, Washington University, St. Louis, University Microfilms.

Sassani, D.C., and Pasteris, J.D., 1988. Preliminary investigation of alteration in a basal section of the southern Duluth Complex, Minnesota, and the effects on the sulfide and oxide mineralization, in G. Kisvarzanyi and S.K. Grant, eds., North American Conference on Tectonic Control of Ore Deposits and the Vertical and Horizontal Extent of Ore Systems, Proceedings Volume, University of Missouri-Rolla, 280-291.

SNL (Sandia National Laboratories), 2014. Evaluation of Options for Permanent Geologic Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste in Support of a Comprehensive National Nuclear Fuel Cycle Strategy (2 Volumes). FCRD-UFD-2013-000371. Albuquerque, NM: US Department of Energy Used Fuel Disposition Campaign.

Stober I, and Bucher K.,1999, Origin of salinity of deep groundwater in crystalline rocks, Terra Nova, 11, p. 181-189.

Stober I, and Bucher K (2000) Hydraulic Properties of the upper Continental Crust: data from the Urach 3 geothermal well. In: Hydrogeology of Crystalline Rocks (eds Stober I, Bucher K), pp. 53-78. Kluwer Academic Publishers, Dordrecht.

Stober I and Bucher K (2004) Fluid sinks within the earth's crust. Geofluids 4(2): 143–151.

Stober, I. & K. Bucher, 2007. Hydraulic properties of the crystalline basement. Hydrogeology Journal, 15:213 224.

References and selected bibliography

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).

Blue Ribbon Commission on America's Nuclear Future, 2012. *Report to the Secretary of Energy,* 158 p.

Carter LJ, 1987. *Nuclear imperatives and public trust: dealing with radioactive waste*, Resources for the Future, Inc. Baltimore, MD: John Hopkins University Press.

Faybishenko, B., Birkholzer, J., Persoff, P., Budnitz, R., Sassani, D., and Swift, P., 2016. International Approaches for Deep Geological Disposal of Nuclear Waste: Geological Challenges in Radioactive Waste Isolation, Fifth Worldwide Review, LBNL-1006984, Lawrence Berkeley National Laboratory.

Freeze, G.A., and J.H. Lee, 2011, *A Simplified Performance Assessment (PA) Model for Radioactive Waste Disposal Alternatives*, proceedings of the 2011 International High-Level Radioactive Waste Management Conference, April 10-14, 2011, Albuquerque, NM.

Helton, JC and Marietta, MG (eds.), 2000. "The 1996 Performance Assessment for the Waste Isolation Pilot Plant," special issue of *Reliability Engineering and System Safety* v. 69, p. 1-454.

Helton, JC, Hansen, CW, and Swift, PN (eds.), 2014, "Performance Assessment for the Proposed High-Level Radioactive Waste Repository at Yucca Mountain, NV," special issue of *Reliability Engineering and System Safety,* v. 122,p. 1-456.

National Academies/National Research Council (NA/NRC), 1957. *The disposal of radioactive waste on land*. Publication 519. Washington, DC: National Academy Press. National Academies/National Research Council; 1957

NWMO (Nuclear Waste Management Organization), 2013. Adaptive Phased Management: Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock, NWMO TR-2013-07.

References and selected bibliography (cont.)

SKB (Svensk Kämbränslehantering AB [Swedish Nuclear Fuel and Waste Management Co.]), 2011. *Long-Term Safety for the Final Repository for Spent Nuclear Fuel at Forsmark: Main Report of the SR-Site Project,* Technical Report TR-11-01.

US DOE (United States Department of Energy) 2008. *Yucca Mountain Repository License Application*, DOE/RW-0573, Rev. 1.

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.

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

Yardley, BWD, Ewing, RC, and Whittleston, RA (eds.), 2016. "Deep-mined Geological Disposal of Radioactive Waste," *Elements* v 12, n. 4.

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

Key Websites for the Waste Isolation Pilot Plant: http://www.wipp.energy.gov/library/caolib.htm and http://www.wipp.energy.gov/wipprecovery/recovery.html

References

- ANDRA Agence nationale pour la gestion des déchets radioactifs), *Dossier 2005: Argile. Tome: Safety Evaluation of a Geological Repository* (English translation: original documentation written in French remains ultimately the reference documentation); 2005
- Carter LJ. Nuclear imperatives and public trust: dealing with radioactive waste, resources for the Future, Inc. Baltimore, MD: John Hopkins University Press; 1987
- Ekren, E.B., Dinwiddie, G.A., Mytton, J.W., Thordarson, W., Weir, J.E., Jr., Hinrichs, E.N., and Schroder, L.J., Geologic and Hydrologic Considerations for Various Concepts of High-Level Radioactive Waste Disposal in Conterminous United States, U.S. Geologic Survey Open-File Report 74-158
- McKelvey V. Major assets and liabilities of the Nevada Test Site as a high- level radioactive waste repository. Letter from Dr. V. McKelvey (USGS) to R. W. Roberts (US Energy Research and Development Administration), July 9, 1976
- National Academies/National Research Council (NA/NRC). The disposal of radioactive waste on land. Publication 519. Washington, DC: National Academy Press. National Academies/National Research Council; 1957
- Rechard RP, Cotton TA, Voegele M. Site selection and regulatory basis for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste. Reliability Engineering and System Safety v. 122, p. 7-31; 2014
- Roseboom EH. Disposal of high-level nuclear waste above the water table in arid regions. Circular 903. Denver, CO: US Department of the Interior, Geological Survey; 1983.
- SKB (Svensk Kärnbränslehantering AB). Long-term safety for the final repository for spent nuclear fuel at Forsmark, Technical Report TR-11-01; 2011.
- Spengler RW, Muller DC, Livermore RB. Preliminary report on the geology and geophysics of drill hole UE25a-1, Yucca Mountain, Nevada Test Site. Denver, CO: US Geological Survey; 1979 Open-File Report 79-926
- Schneider KJ, Platt AM. High-level radioactive waste management alternatives. Washington, DC: Atomic Energy Commission; 1974 WASH-1297
- SNL (Sandia National Laboratories). Total system performance assessment model/analysis for the license application. MDL-WIS-PA-000005 Rev00, AD 01. Las Vegas, NV: U.S. Department of Energy Office of Civilian Radioactive Waste Management; 2008.

References (cont.)

- U.S. Department of Energy (DOE). Final environmental impact statement, management of commercially generated radioactive waste. DOE/EIS-0046F. Washington, DC: US Department of Energy; 1980
- U.S. Department of Energy (DOE). Site characterization plan: Yucca Mountain Site, Nevada research and development area, Nevada: Consultation draft, Nuclear Waste Policy Act. DOE/RW-0160-vol.1–vol. 9. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 1988
- U.S. DOE (US Department of Energy). Viability assessment of a repository at Yucca Mountain. DOE/RW-0508. Washington, DC: Office of Civilian Radioactive Waste Management, US Department of Energy; 1998
- U.S. DOE (U.S. Department of Energy). Yucca Mountain site suitability evaluation. DOE/RW-0549. Las Vegas, NV: U.S. Department of Energy; 2002.
- U.S.DOE (U.S. Department of Energy).Final environmental impact statement for a geologic repository for the disposal of spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nye County, Nevada. DOE/EIS-0250F. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management; 2002
- U.S. DOE (U.S. Department of Energy). Yucca Mountain repository license application safety analysis report. DOE/RW-0573, Update no. 1. Las Vegas, NV: U.S. Department of Energy; 2008
- U.S. DOE (United States Department of Energy), "U.S. Department of Energy's Motion to Withdraw," filed March 3, 2010 with the United States of America Nuclear Regulatory Commission Atomic Safety and Licensing Board, Docket no. 63.001, ASLBP no. 09-892-HLW-CAB04; 2010
- U.S. Nuclear Regulatory Commission (NRC). *Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 3, Repository Safety after Permanent Closure.* NUREG-1949, Vol. 3; 2014.
- U.S. Nuclear Regulatory Commission (NRC). *Safety Evaluation Report Related to Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada; Volume 2, Repository Safety Before Permanent Closure,* and *Volume 5, Proposed Conditions on the Construction Authorization and Probable Subjects of License Specifications*. NUREG-1949, Vol. 2 and Vol. 5, 2015
- Walker JS. The road to Yucca Mountain. Berkeley, CA: University of California Press; 2009

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

References

- Carter LJ. Nuclear imperatives and public trust: dealing with radioactive waste, resources for the Future, Inc. Baltimore, MD: John Hopkins University Press; 1987
- Helton, JC, Anderson, DR, Basabilvazo, G., Jow, H.N., and Marietta, M.G., Conceptual Structure of the 1996 performance assessment for the Waste Isolation Pilot Plant, special issue of *Reliability Engineering and System Safety* v. 69, p. 151-165; 2000
- Helton, JC and Marietta, MG, "The 1996 Performance Assessment for the Waste Isolation Pilot Plant," special issue of *Reliability Engineering and System Safety* v. 69, p. 1-454; 2000
- INEEL (Idaho National Engineering and Environmental Laboratory). *INEEL Subregional Conceptual Model Report Volume 3: Summary of Existing Knowledge of Natural and Anthropogenic Influences on the Release of Contaminants to the Subsurface Environment from Waste Source Terms at the INEEL.* INEEL/EXT-03-01169, Rev. 2; 2003
- Matalucci, RV. *In Situ Testing at the Waste Isolation Pilot Plant,* SAND87-2382, Sandia National Laboratories, 1987.
- McCutcheon, C. *Nuclear reactions: the politics of opening a radioactive waste disposal site.* University of New Mexico Press, Albuquerque, NM; 2002
- National Academies/National Research Council (NA/NRC). The disposal of radioactive waste on land. Publication 519. Washington, DC: National Academy Press. National Academies/National Research Council; 1957
- Rechard RP. Historical background on performance assessment for the Waste Isolation Pilot Plant. *Reliability Engineering and System Safety* v. 69, p. 5-46; 2000
- SNL (Sandia National Laboratories), Evaluation of Options for Permanent Geologic Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste, Revision 1. Two Volumes, SAND2014-0187P and SAND2014-0189P; 2014.
- SRNL (Savannah River National Laboratory), Waste Isolation Pilot Plant Technical Assessment Team Report, SNRL-RP-2014-01198 Revision 0, March 17, 2015.
- U.S. DOE (US Department of Energy), Title 40 CFR Part 191, Compliance Certification Application for the Waste Isolation Pilot Plant, DOE/CAO 1996-2184; 1996
- U.S. DOE (US Department of Energy, Title 40 CFR Part 191 Subparts B and C Compliance Recertification Application 2014 for the Waste Isolation Pilot Plant; 2014
- U.S. DOE (US Department of Energy, Waste Isolation Pilot Plant Recovery Plan, Revision 0, September 30, 2014.

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

References

- 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.
- Bryan, C. and Enos, D. (2014). Results of Stainless Steel Canister Corrosion Studies and Environmental Sample Investigations. FCRD-UFD-2014-000055, U.S. Department of Energy, 102 p.