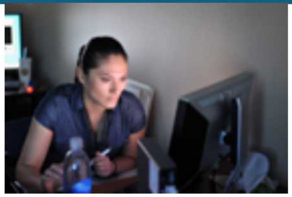
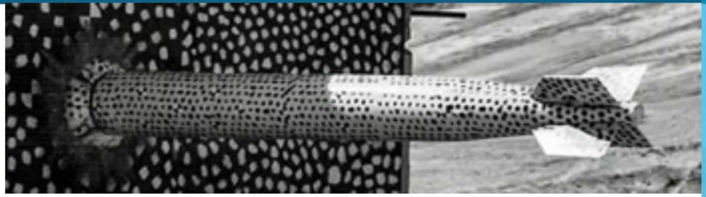
SAND2019-5252PE

# L3: Basic Strategies for Long-term Geological Disposal of HLW






*PRESENTED BY*

Edward N. Matteo



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# Outline

Repository Science Basics

- Natural System
- Engineered Barrier System
- Waste Isolation and the Safety Case

Generic Repository Design Considerations

- Examples from Generic Preliminary Designs in Crystalline and Salt

Site Specific Repository Designs and Long-term Performance Evaluation (from US Programs)

- Yucca Mountain Project (YMP)
- Waste Isolation Pilot Plant (WIPP)

# Repository Science Basics, the Repository System

**The Repository System = the Engineered System + the Natural System**

**Engineered system = Engineered Barriers System (EBS) = near field**

- Waste form, e.g. vitrified glass, spent nuclear fuel, to name a few
- Waste container = Waste Package (WP)
  - material, corrosion resistant or corrosion allowance
  - Size, pour canister vs. dual purpose canister
- Buffer, Backfill, and Seals
  includes excavation disturbed zone (EDZ) = disturbed rock zone (DRZ)
  - fill excavations in disposal drifts, access drifts, and shafts = buffer, backfill, and seals

**The Engineered Barrier System contains redundant sub-systems (waste form, waste package, buffer/backfill, seals), for the purpose of long-term waste isolation.**

# Repository Science Basics, the Repository System

**Natural System = repository horizon + rest of the geologic stratigraphy = far field**

- Repository horizon host lithology
  - Saturated vs. unsaturated
  - permeability/porosity, including fractures, faults, etc.
  - Chemical and mechanical environment = Response to repository-related disturbances
    - Excavations (including the Engineered disturbed zone (EDZ) = disturbed rock zone (DRZ)
    - thermal load of heat generating waste
    - weight of waste packages

# Repository Science Basics, Waste Isolation

The main function of the the repository system is to achieve "**waste isolation**" during the operational (pre-closure) period and especially during the post-closure period.

Isolation is "achieved" when the **predicted** radionuclide concentration in the far field stays below a pre-determined threshold.

- release threshold vs. dose threshold

Of course, far-field predictions can be strongly influenced by the near field processes.

Multi-scale, coupled processes play a significant role in repository performance predictions.

- Thermal, hydrologic, mechanical, chemical

And there are MANY processes and scenarios to consider, such that assumptions must be made.

There is a framework for considering processes and scenarios:

- Features, Events, and Processes (FEP's), which are part of the **Safety Case**

# What is a deep geologic repository?

***An engineered facility for safe handling and disposal of nuclear waste that includes disposal rooms or tunnels excavated sufficiently deep beneath the surface to ensure isolation of the waste from external changes or events. The underground facility typically comprises engineered and geologic barriers that act together to contain the waste within the facility and to limit and delay the release of radionuclides to the surrounding geosphere subsequent to loss of containment. Typical engineered barrier systems include the following components - waste form (and inventory), waste package, buffer/backfill, and engineered seals.***

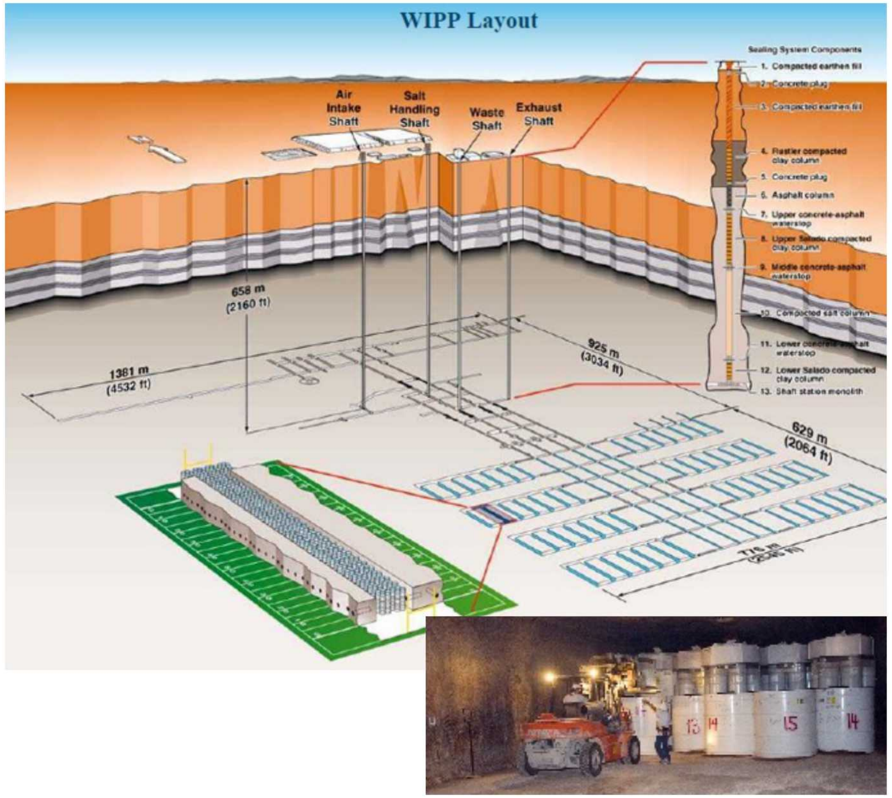
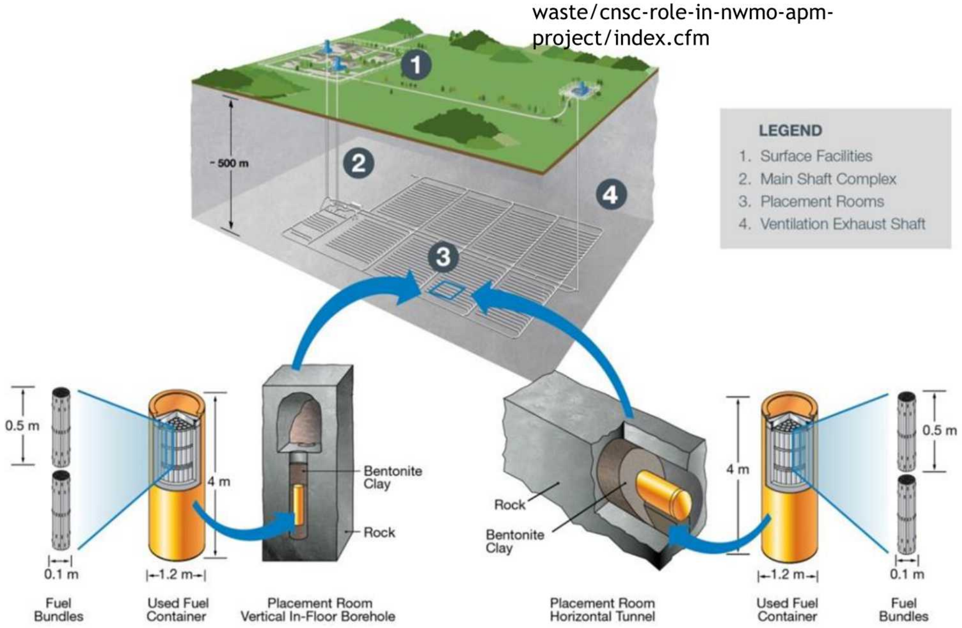



Figure Source: https://www.cnsc-ccsn.gc.ca/eng/waste/high-level-waste/cnsc-role-in-nwmo-apm-project/index.cfm



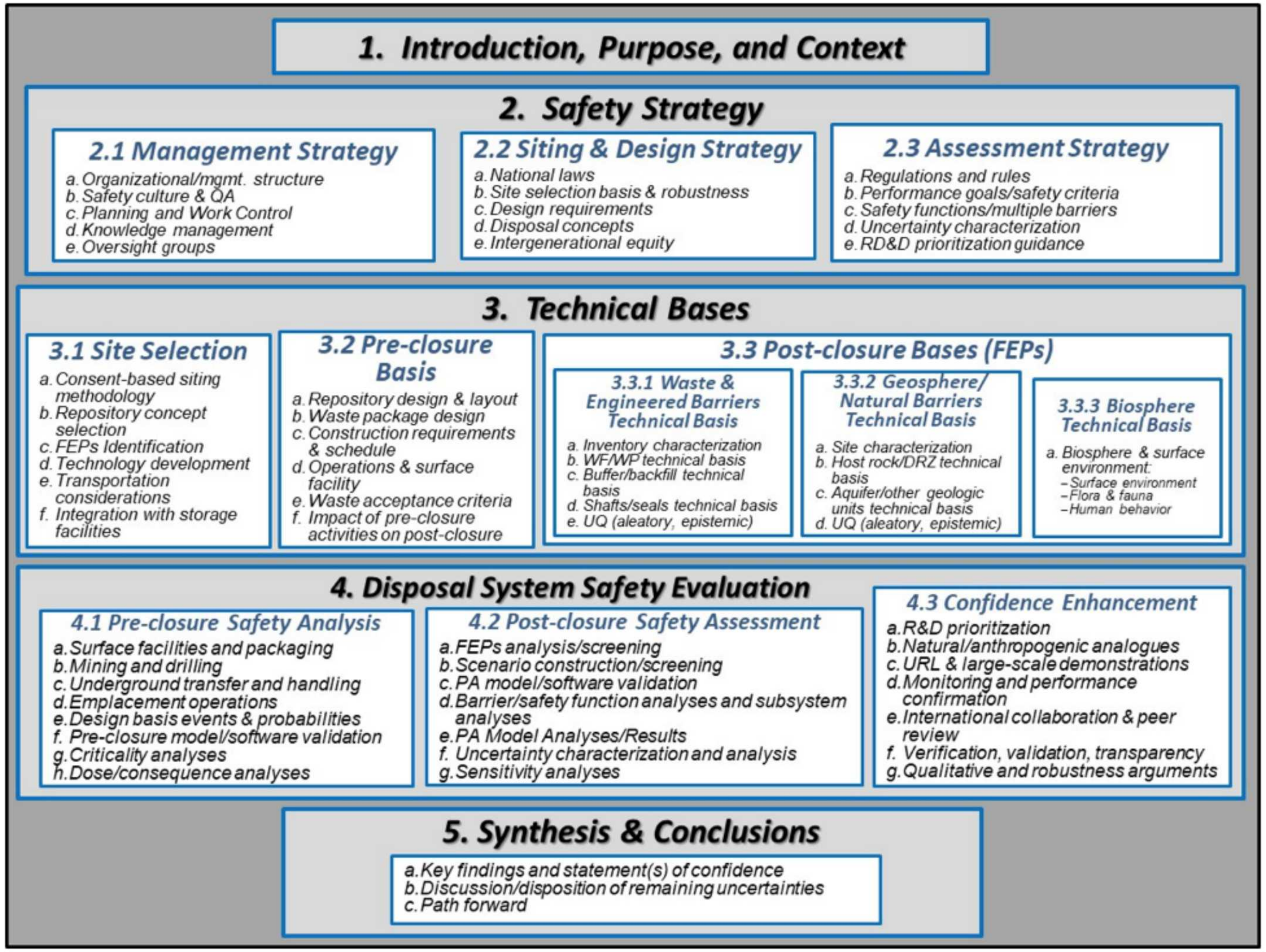
# Repository Science Basics, the Safety Case

Waste Isolation is “measured” by the Safety Case.

The **Performance Assessment** is a key outcome of the Safety Case.

-Predicts long-term repository performance

**Elements of the Safety Case**

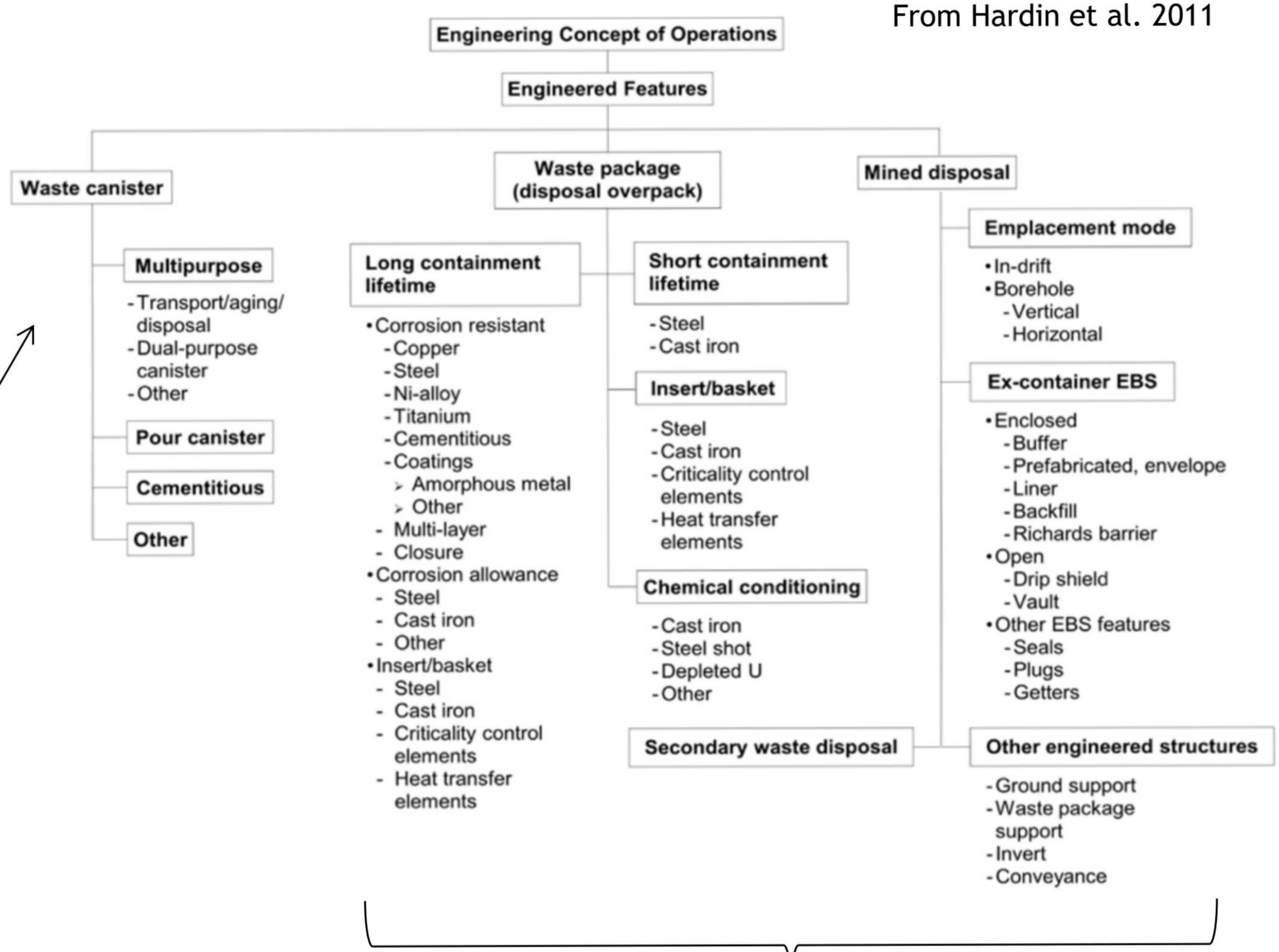


# The Design Concept, is a product of Inventory and the Natural System

From Hardin et al. 2011

Inventory
- Dimensions
- Quantity
- Thermal output

Design Concepts
- Packaging and repository layout




Disposal Media

# Generic Design

<u>**The design concept originates with the Inventory**</u>:

-waste form, quantity, dimensions of waste package (WP)

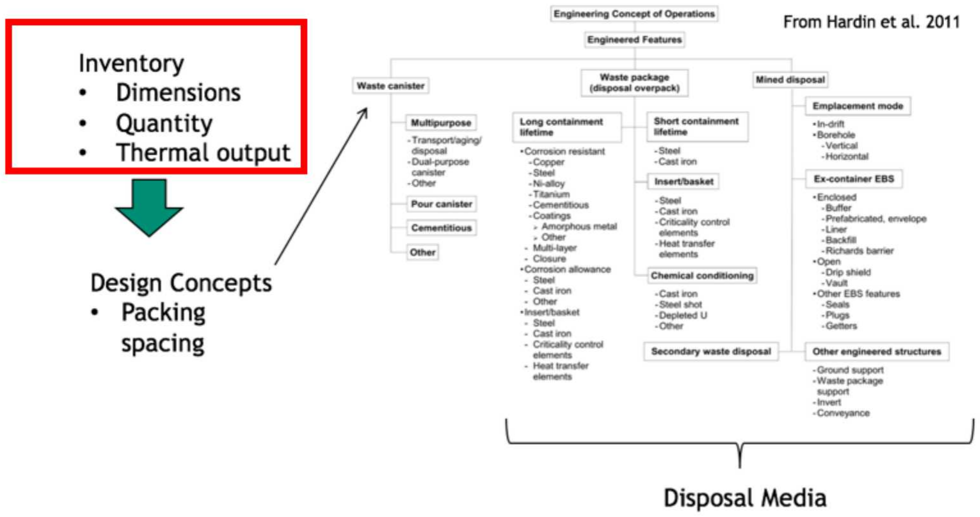
<u>**Ratio of WP to thermal output**</u>

-determines WP spacing -> repository footprint -> site selection?

e.g., in the US domal salt formations are well-suited to a co-mingled US repository, but were in consideration for a defense waste only repository

-determines WP spacing -> repository footprint -> impact on EBS/PA

Minimizing excavation volumes can be a design consideration, esp. in low permeability host media, where release scenarios may be driven by release along excavation pathways



# Generic Crystalline Rock Design Considerations

- Host Rock Constructability
  - Excavation method, ground support, DRZ
  - Construction and sealing cost
- Saturated Zone, Fractured-Rock
  - Low-permeability backfill and seals needed
- Nominal and Disturbed Performance
  - Uncertainty in fractured-rock hydrology
  - Possible future glaciation
- Natural Barrier
  - Potentially old groundwater, small head gradients (nominal)
- Engineered Barriers
  - Clay-based buffer
  - Corrosion-resistant packaging (>>$10^5$ yr containment within buffer)
  - Extensive precedence in international R&D

# Generic Crystalline-Rock Disposal Concept

- Multi-Container Overpack Strategy for HLW
  - Fewer (<5,000) less costly, corrosion-resistant overpacks
  - Unshielded
- In-Drift Axial Emplacement
  - Minimize excavated volume, facilitate handling of heavy packages
  - Small package-package spacing (e.g., 2 m)
  - Backfilling strategy: Packages placed on plinths of compacted clay, then backfilled with pelletized clay
  - Pre-constructed buffer strategy: Each package location prepared with compacted clay blocks and a steel liner; packages slide into liner (e.g., NUHOMS)
- Clay-Based Backfill and Sealing of Accesses
- Constructability Challenges
  - Remote operation in unshielded environments
  - Keeping buffer blocks dry
  - Handling large, heavy packages (up to 2 m OD × 5 m L)

# Generic Salt Design Considerations

- Bedded or Domal Salt Constructability
  - Opening stability
  - Salt backfill
- Superior Heat Dissipation
- Nominal and Disturbed Performance
  - Releases dominated by human intrusion
- Natural Barrier
  - Insignificant groundwater abundance and mobility (nominal)
  - Brine saturation (esp. human intrusion)
- Engineered Barriers
  - Backfill and seals
  - Robust containment during operations
  - Emplacement borehole behavior (e.g., heavy liners)

# Generic Salt Disposal Concept

- Direct Disposal of Pour Canisters
  - HLW glass stability in operational environment
- Robust Overpacking of Other Waste Forms
  - Carbon steel overpack (e.g., DSNF)
- Just-in-Time Drift Construction
  - Minimize handling of crushed salt
- In-Drift Emplacement (axial or transverse)
  - Relatively small, lightweight canisters (e.g., 6 MT HLW)
  - Immediate backfilling with crushed salt
- Constructability Challenges
  - Remote operation in unshielded environments

# Major Elements of the WIPP Disposal Concept

# The Premise for Isolation in Salt

Intact salt is essentially impermeable

Intact salt does not contain flowing groundwater

- Water that is present in salt formations is salt-saturated brine, and incapable of further dissolution

Salt creep will

- Close fractures
- Consolidate crushed salt backfill, and allow shaft seals to function like intact rock
- Close disposal panels and eventually surround waste with salt

Little reliance on waste packages for isolation

- For WIPP, no long-term post-closure function whatsoever is assumed for packages
- Waste is assumed to be exposed to the host rock environment as soon as the repository is closed

# WIPP Transuranic Waste

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

  The term "transuranic waste" means waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years, except for—

  (A) high-level radioactive waste;

  (B) waste that the Secretary has determined, with the concurrence of the Administrator, does not need the degree of isolation required by the disposal regulations; or

  (C) waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with part 61 of title 10, Code of Federal Regulations. (WIPP Land Withdrawal Act of 1992, Section 2)

# WIPP Transuranic Waste (cont.)

Most WIPP waste is "Contact-Handled TRU" (CH-TRU), and requires no additional shielding beyond that provided by drums and liners

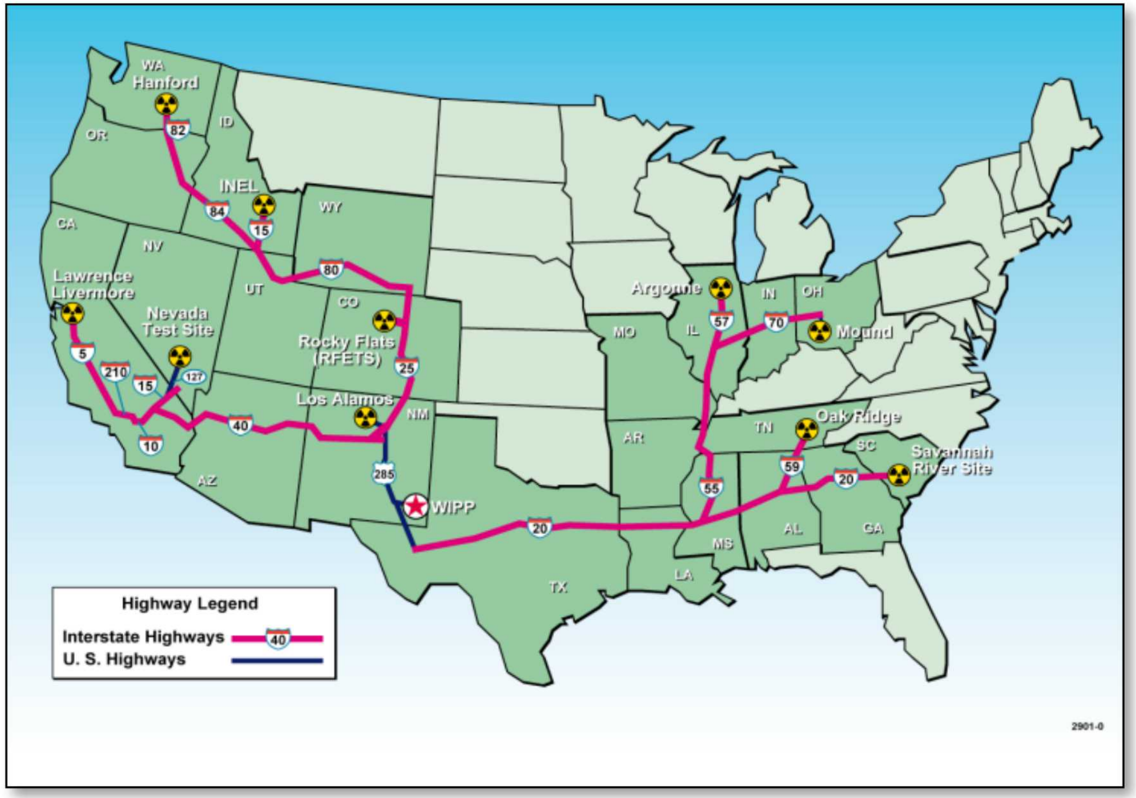
Some WIPP waste is "Remote-Handled TRU" (RH-TRU), with surface gamma radiation dose rates that require shielding

- Defined by WIPP Land Withdrawal Act Section 2 as "transuranic waste with a surface dose rate of 200 millirem per hour or greater"


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

# WIPP Transuranic Waste Transportation

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



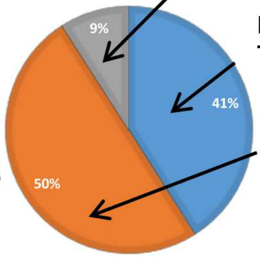

Images from http://www.wipp.energy.gov/Photo_Gallery_Images

# Relative Amounts of Transuranic Waste

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

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.

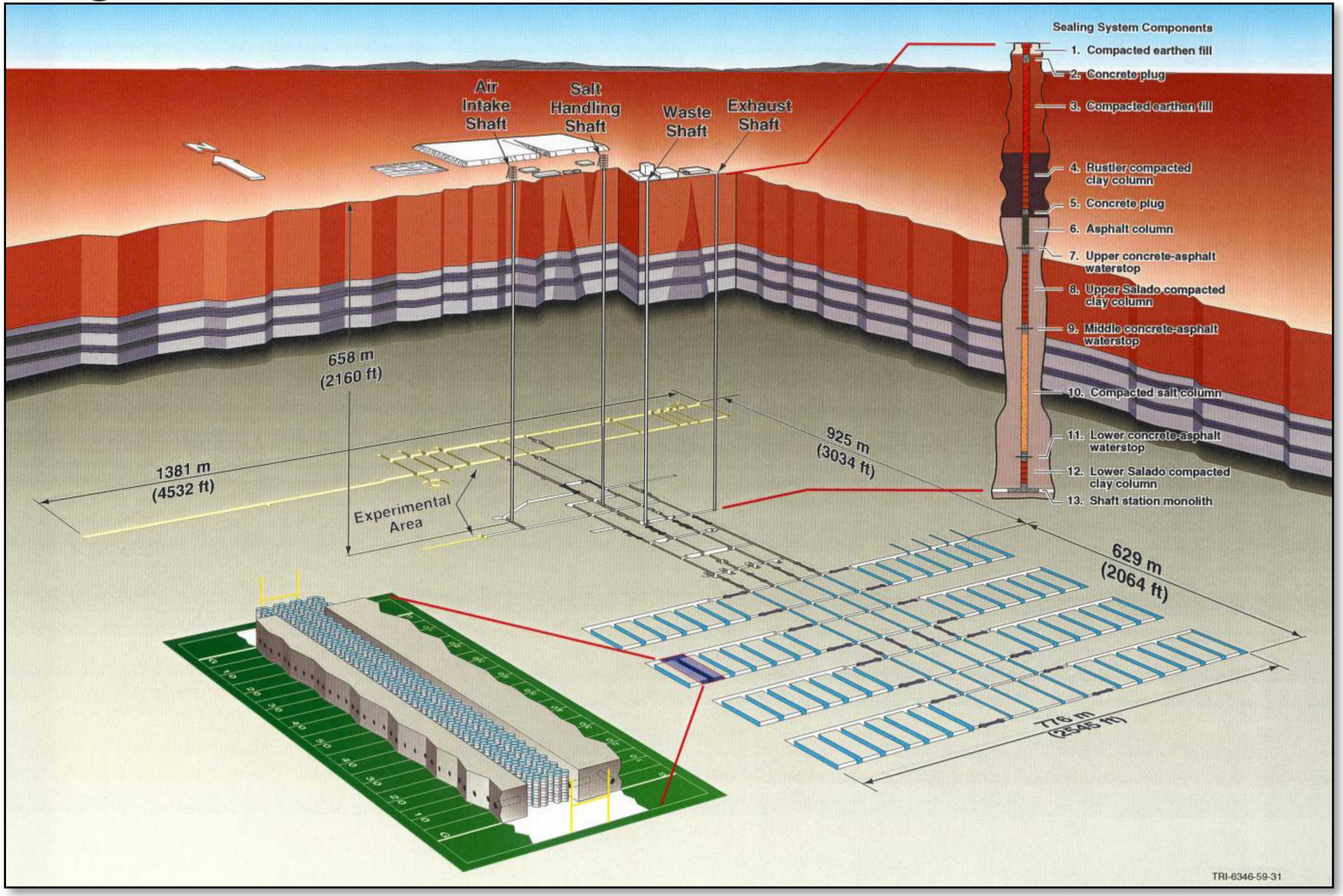
(2) CURIE LIMITS FOR REMOTE-HANDED TRANSURANIC WASTE.—

(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).

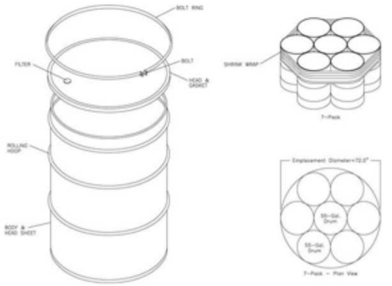
(B) TOTAL CURIES.— The total curies of the remote-handled transuranic waste received at WIPP shall not exceed 5,100,000 curies.

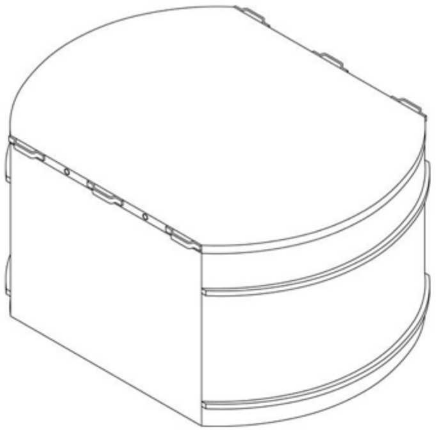
(3) CAPACITY OF WIPP.— The total capacity of WIPP by volume is 6.2 million cubic feet of transuranic waste.

# WIPP Design


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

# WIPP Design (cont.)



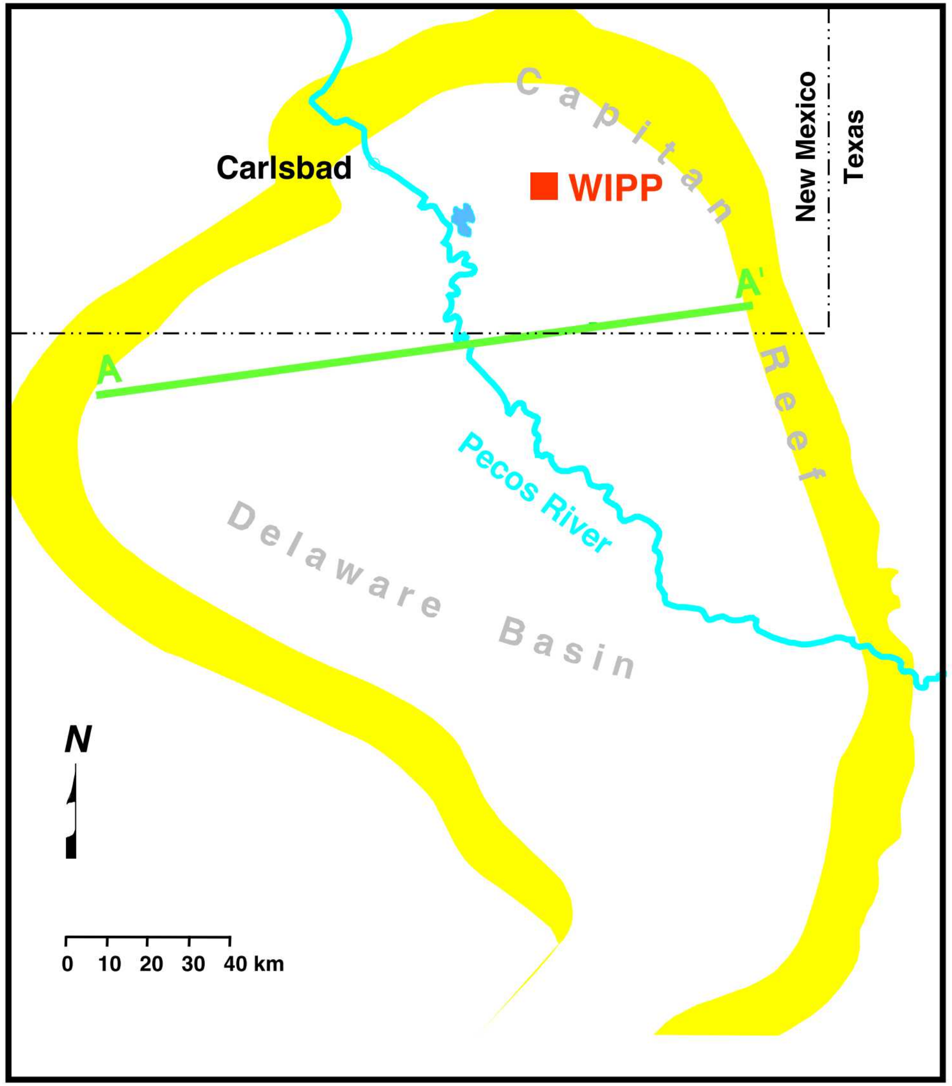


CH-TRU waste shipped and emplaced in drums (55, 85, and 100 gal) and “standard waste boxes”

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

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

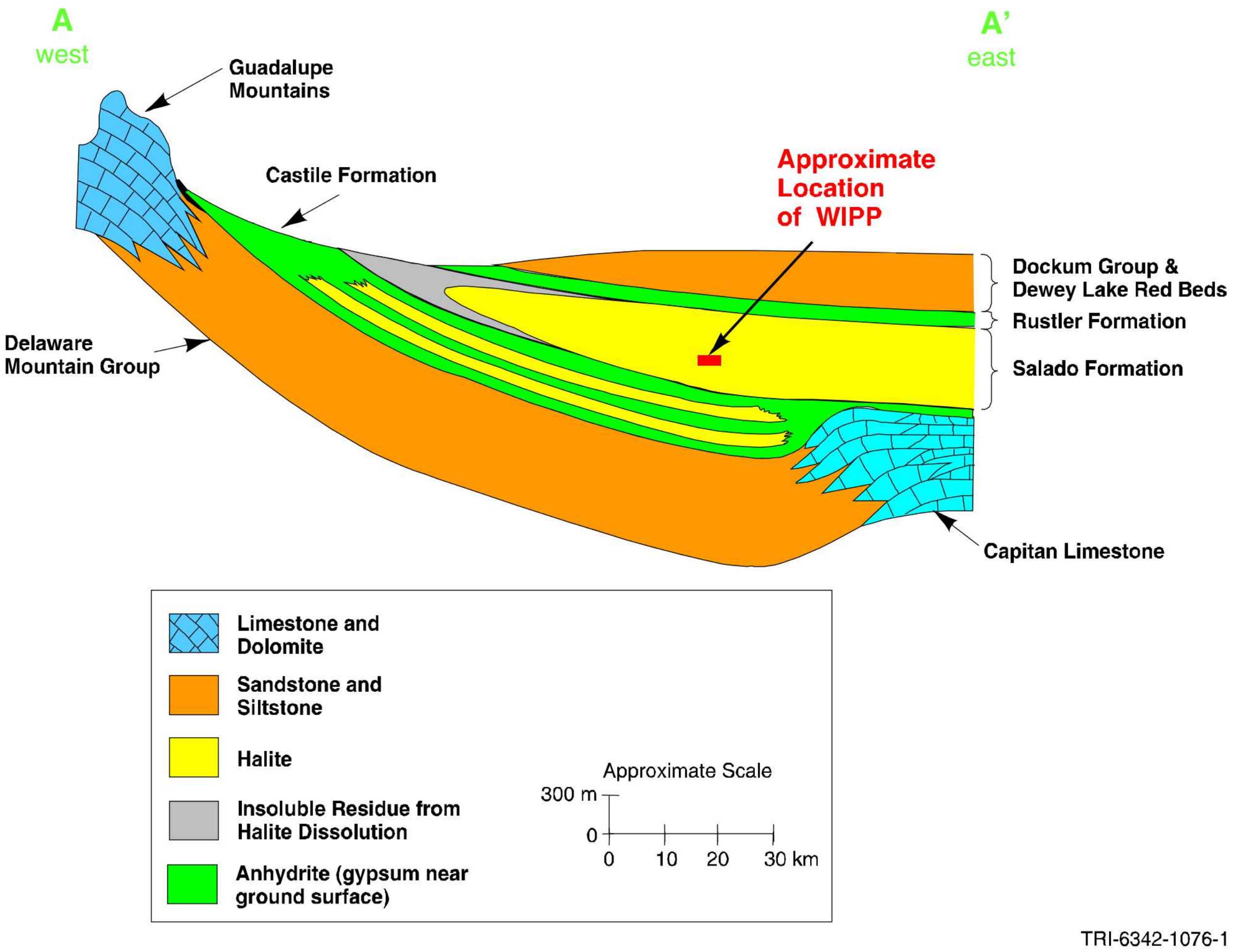
# Site Geology




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

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

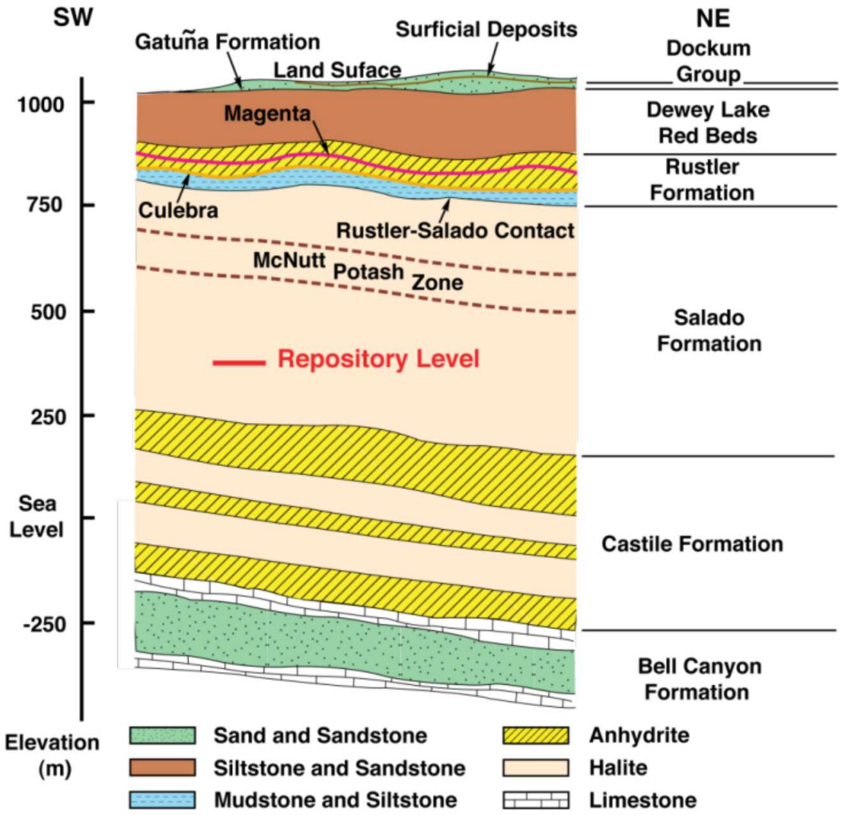
# Site Geology (cont.)




*Schematic West-East Geologic Cross Section of Delaware Basin*

Note extreme vertical exaggeration

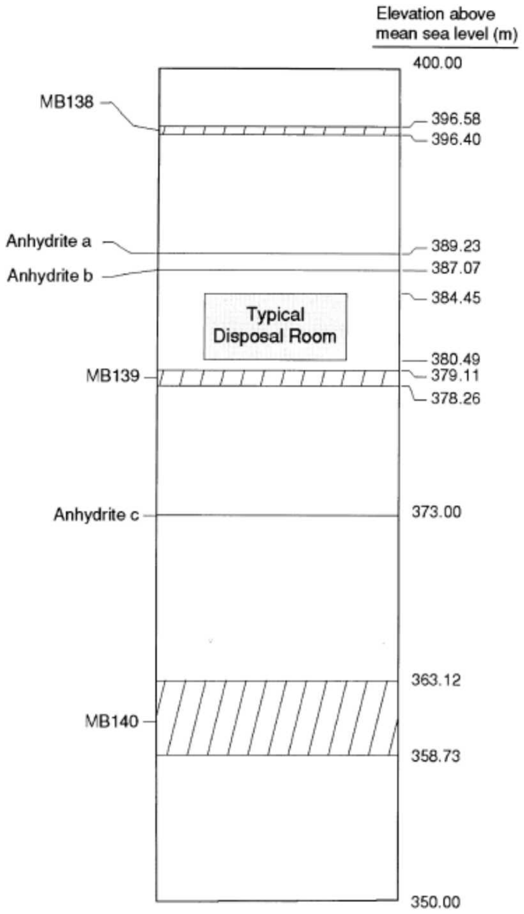
# Local Stratigraphy at WIPP



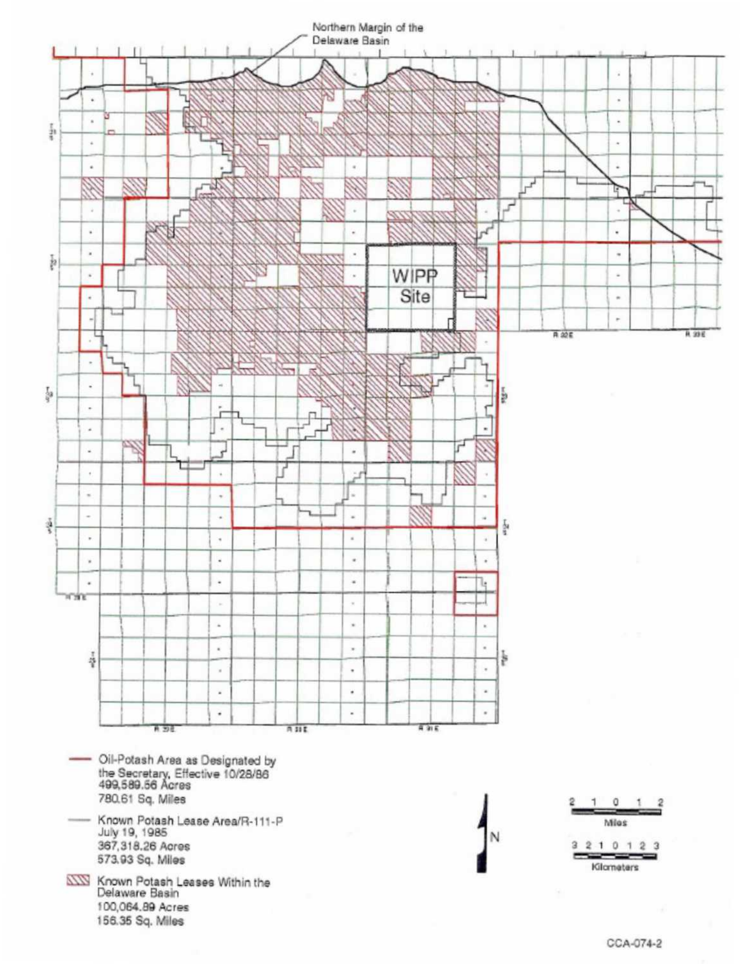

*Within the Salado Formation, halite units are separated by laterally persistent interbeds of anhydrite, clay, and polyhalite.*

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

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



# Natural Resources at WIPP




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

Oil and gas exploration in the WIPP region, image from Google Maps 16 January 2017

# Estimating Long-Term Performance

# EPA's Regulatory Requirements

40 CFR part 191.13: Containment requirements

"(a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:

- (1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (appendix A); and
- (2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (appendix A)."

40 CFR part 191.15: Individual protection requirements

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

40 CFR part 191.24: Groundwater protection standards

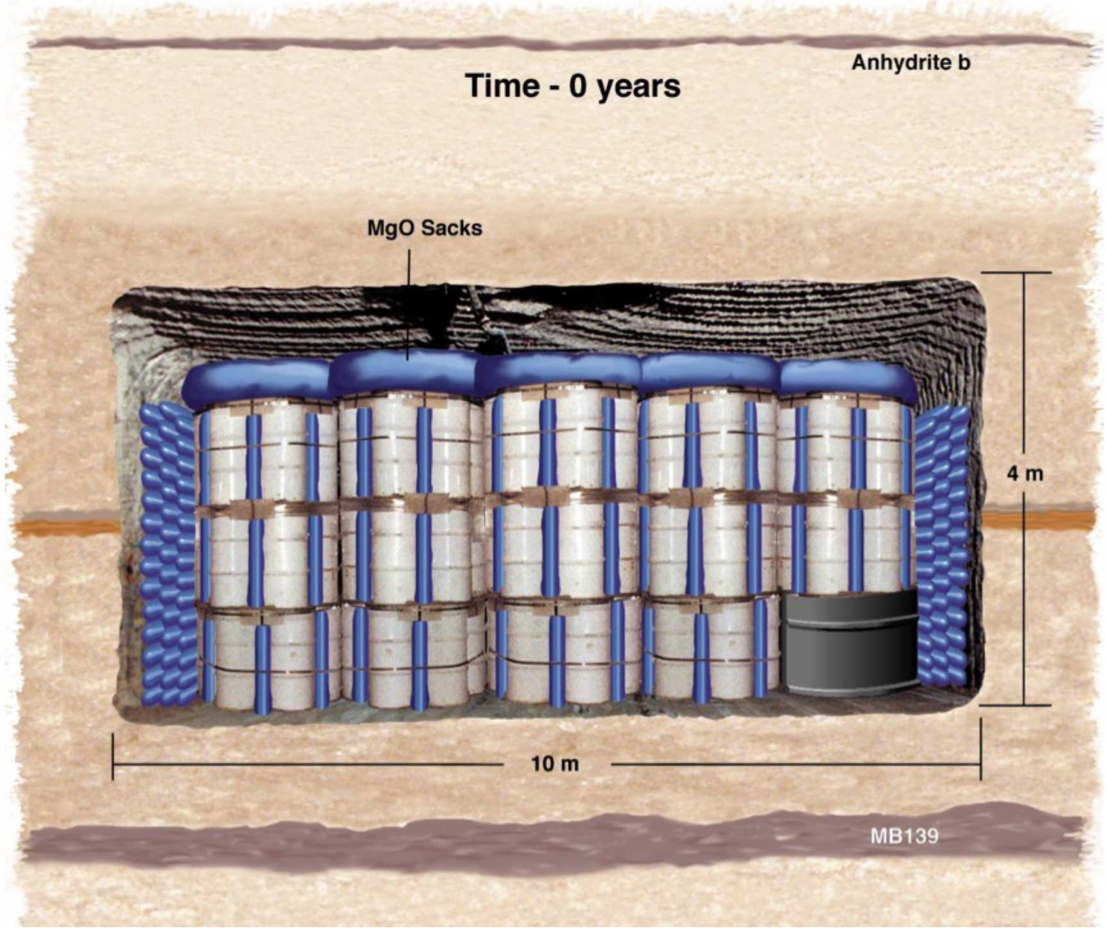
"(a) Disposal systems for waste and any associated radioactive material shall be designed to provide a reasonable expectation that 10,000 years of undisturbed performance after disposal shall not cause the levels of radioactivity in any underground source of drinking water, in the accessible environment,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

(emphasis added)

# Conceptual Model for Long-term Performance: Initial Conditions

## *Sealed Waste and Dry Backfill*

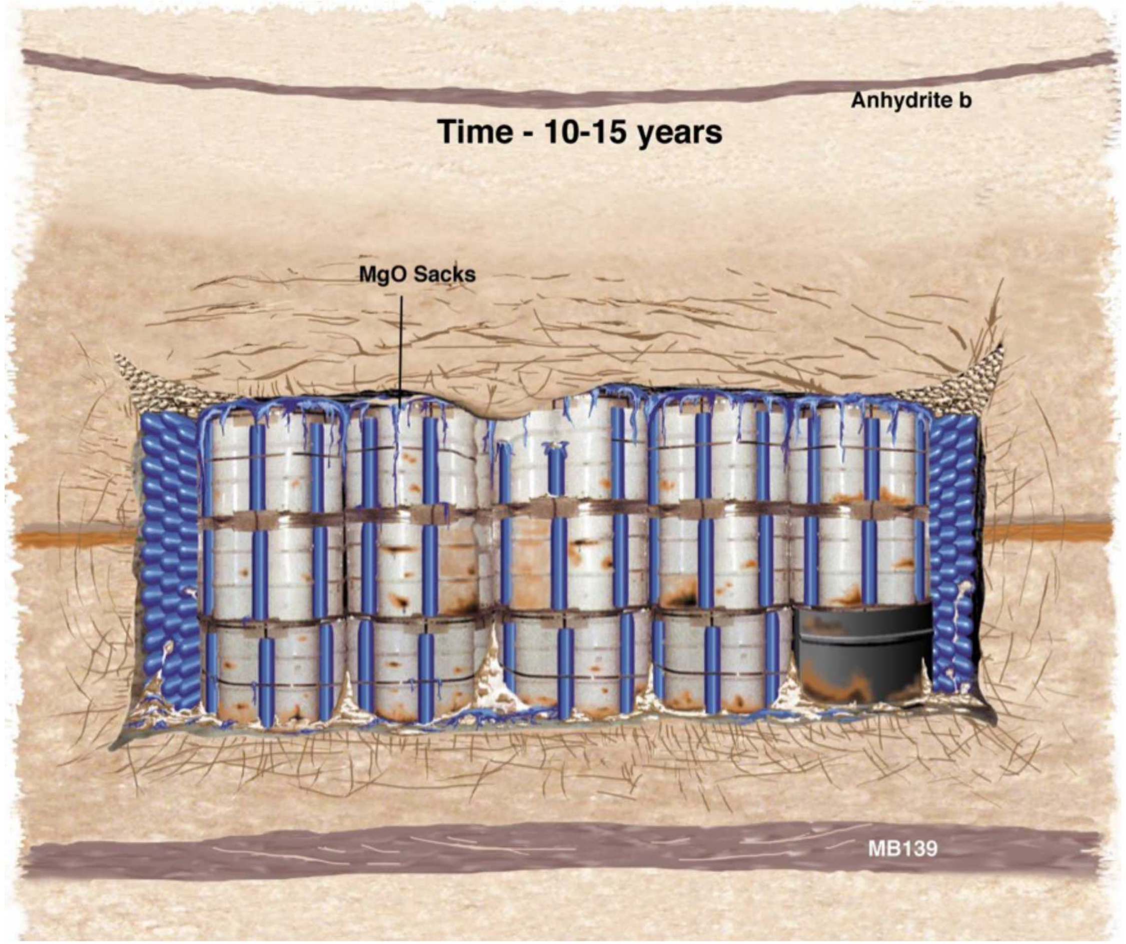
- Introduced components
  - Iron waste drums, boxes
  - MgO backfill
  - Cellulosic, plastic, rubber waste
  - Metallic waste
  - Solidified waste
  - Actinide solids
- Geologic components
  - Salado salt
  - Argillaceous anhydrite interbeds ("marker beds")
- Processes
  - Ground support
  - Ventilation



# Conceptual Model for Long-term Performance: The Near Future

***Rapid Salt Creep Partially Encapsulates Waste***

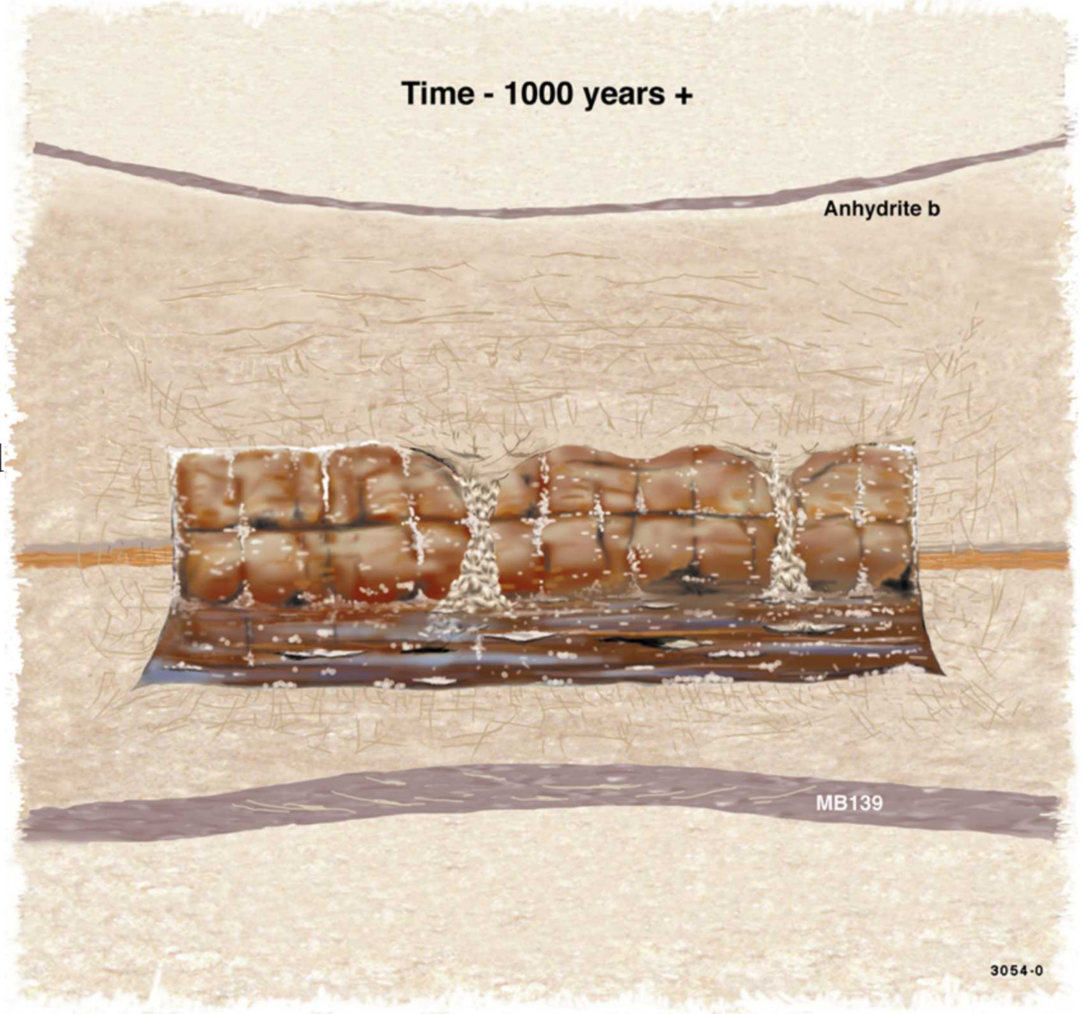
Processes
- Salt creep
- Floor heave
- Roof fall
- Collapse of salt into waste
- Disturbed-rock-zone dewatering
- Drum crushing
- Porosity, permeability reduction
- Breaching of MgO sacks
- Minor corrosion
- Degradation of organic waste



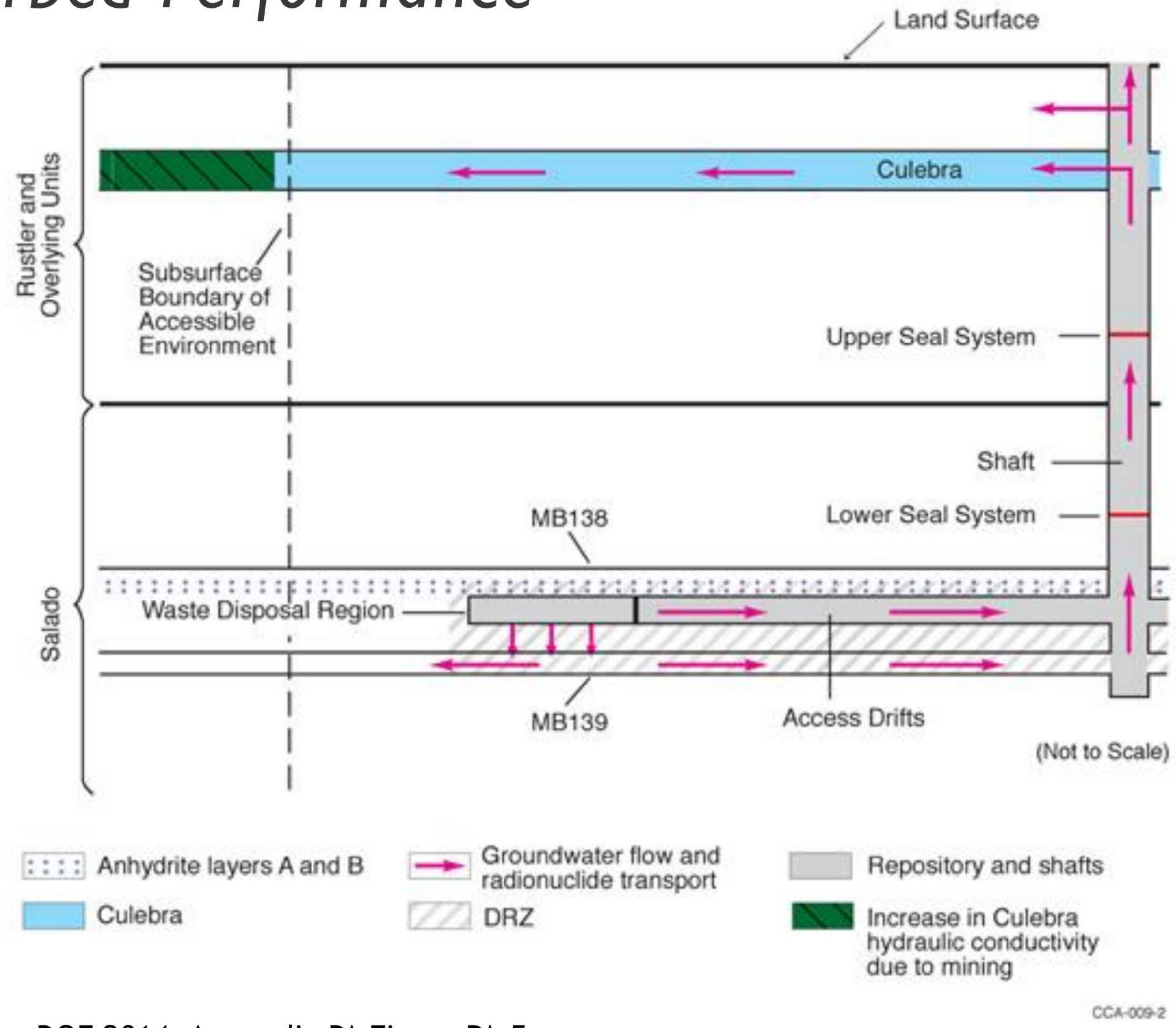
# Conceptual Model for Long-term Performance: Final State?

***Salt Creep Encapsulates Waste***

- Processes
  - Salt creep
  - Consolidation and healing of fractures
  - Porosity, permeability reduction
  - Extensive corrosion of drums and degradation of waste
- Processes of gas generation, brine inflow, and salt creep are highly coupled
- Uncertainty remains about final extent of consolidation and brine saturation



# Scenarios for WIPP Performance Assessment:
## *Undisturbed Performance*

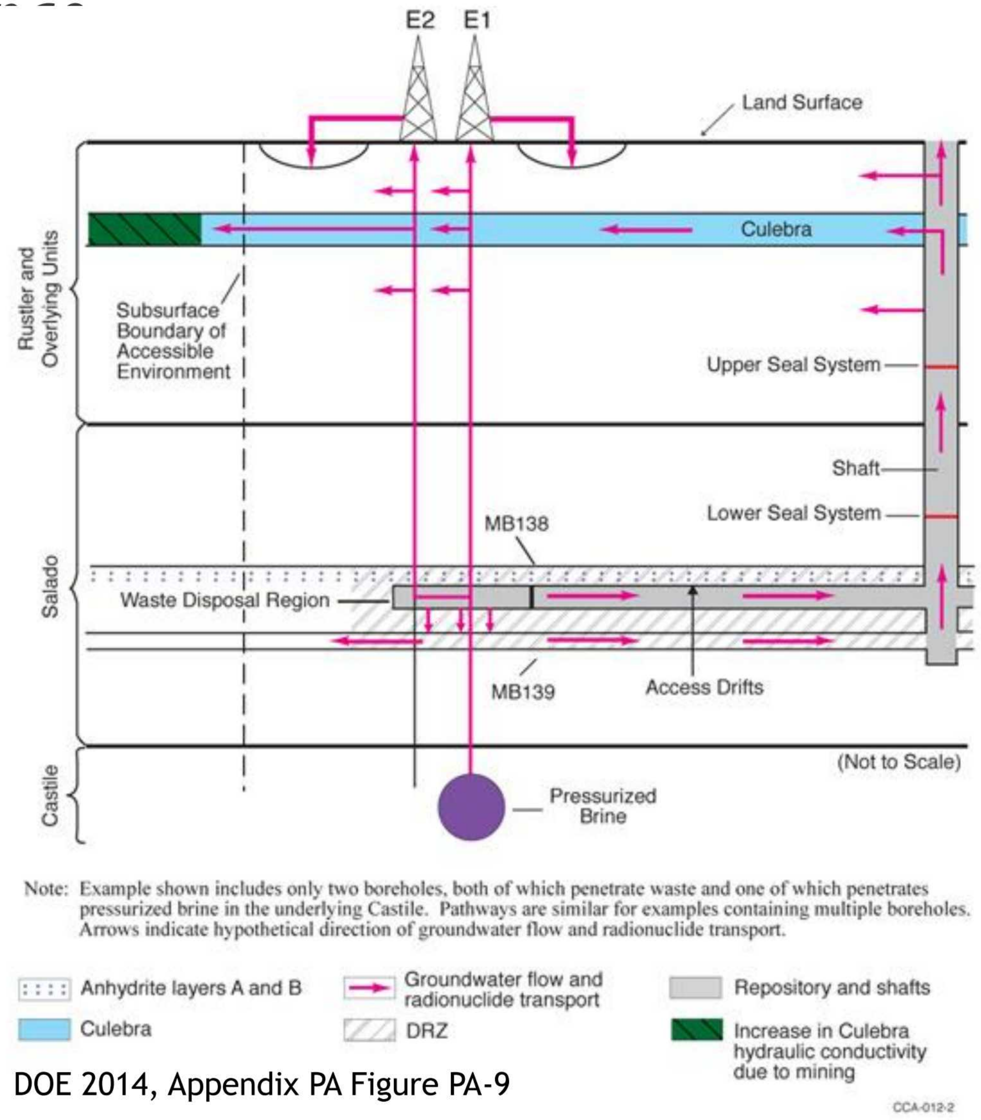



DOE 2014, Appendix PA Figure PA-5

# Scenarios for WIPP Performance Assessment:
## *Disturbed Per*

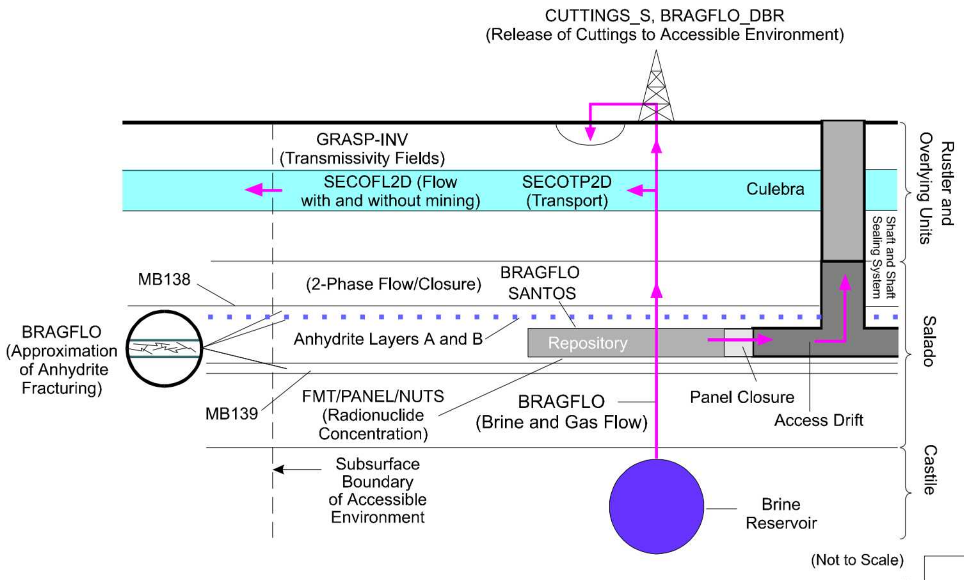
This example shows two intrusion boreholes into the same disposal panel.

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



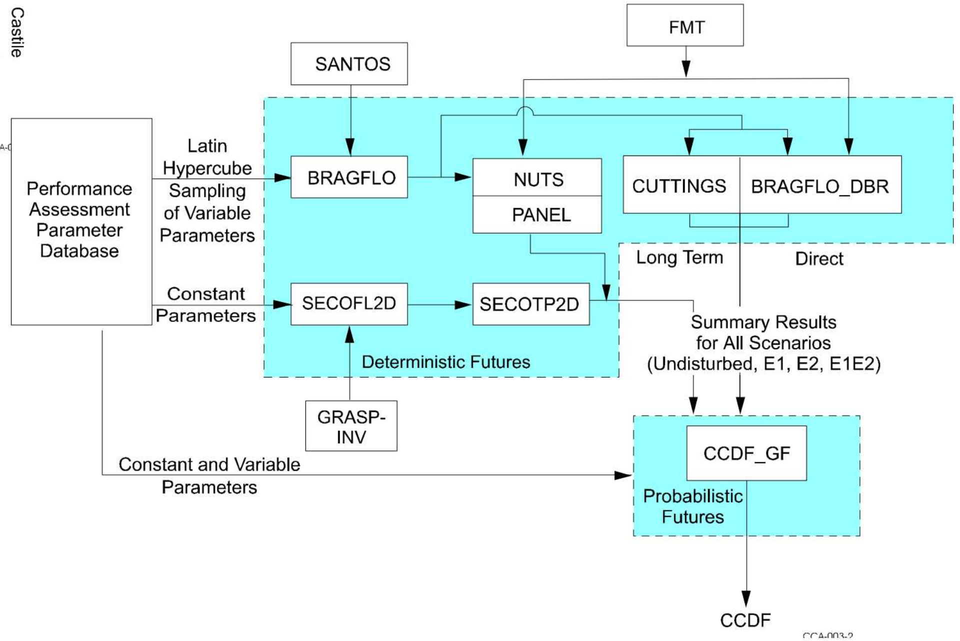

DOE 2014, Appendix PA Figure PA-9

# 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

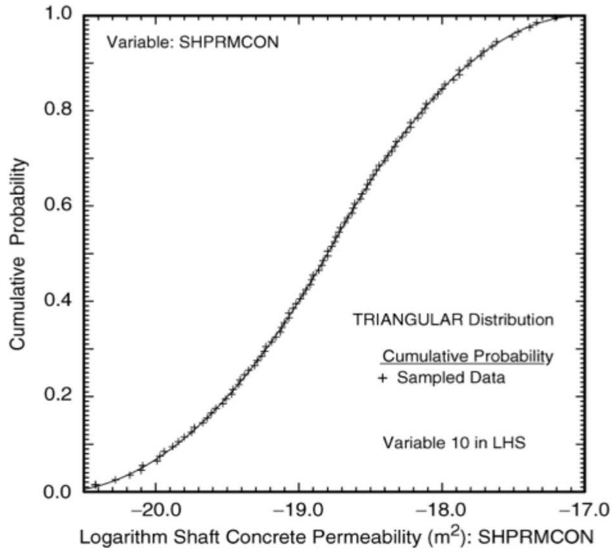
- Each simulation requires a different set of input values

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

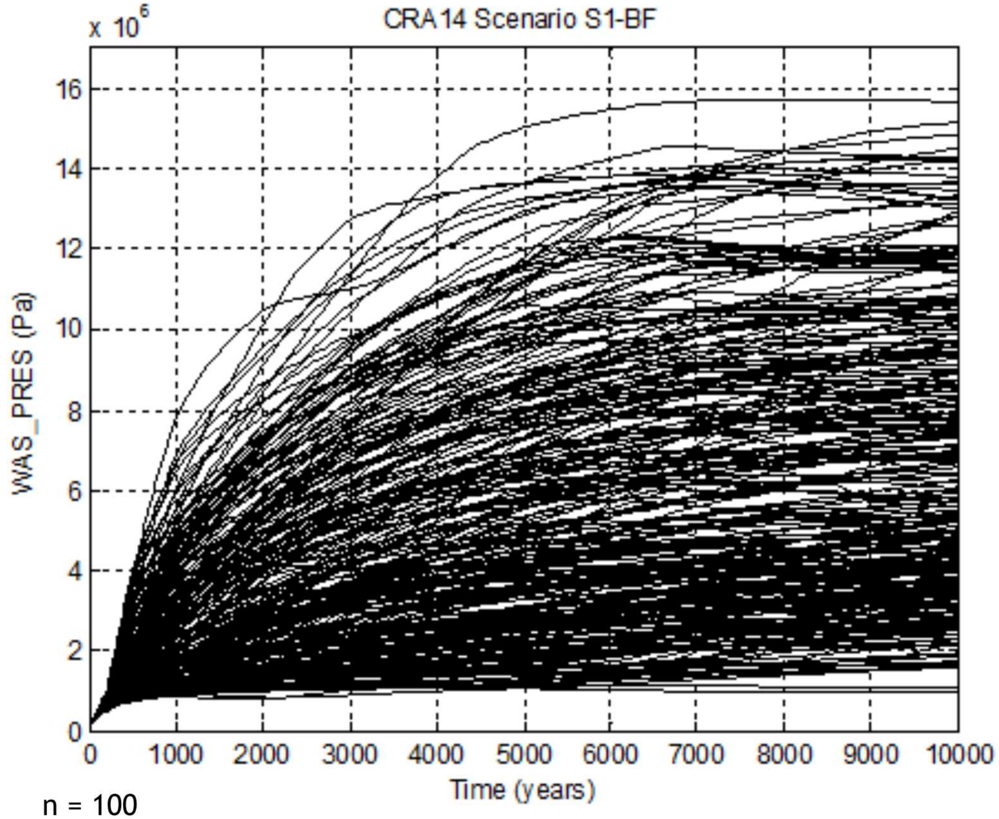
Uncertainty in system performance is given by the distribution of results from the individual simulations




*Example Cumulative Distribution Function, showing 100 sampled values*

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

10,000-year Undisturbed Performance




n = 100

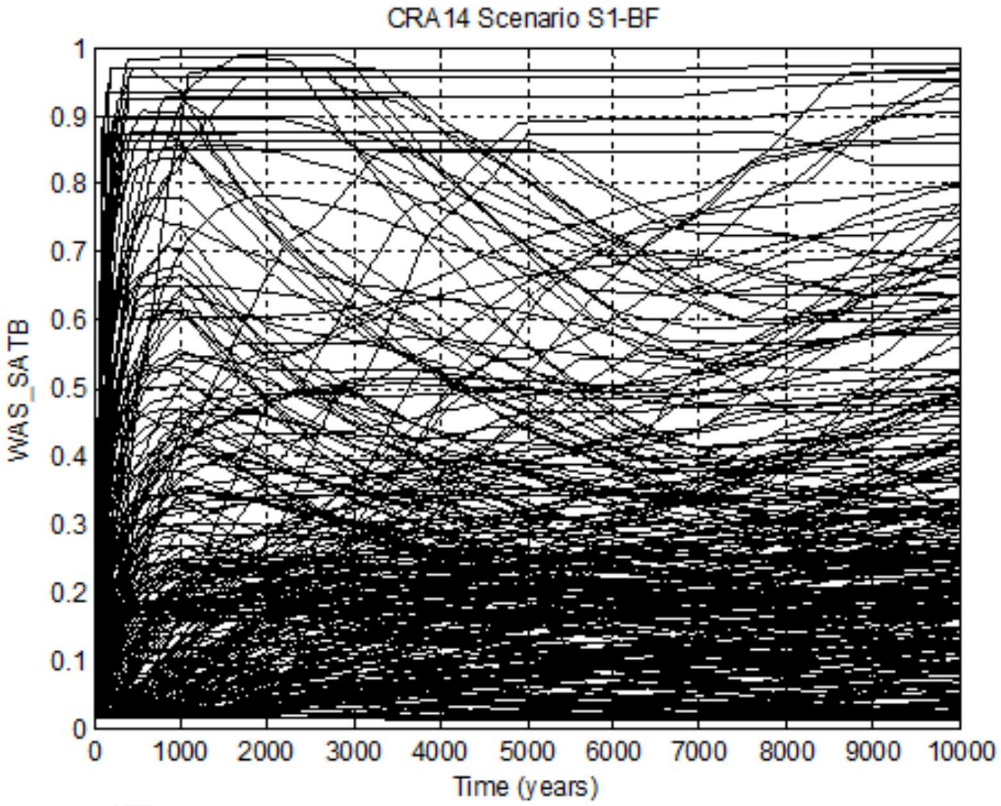
DOE 2014, Appendix PA, Figure PA-35

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 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

# Summary of Long-term WIPP Performance

Geologic barriers provide long-term isolation

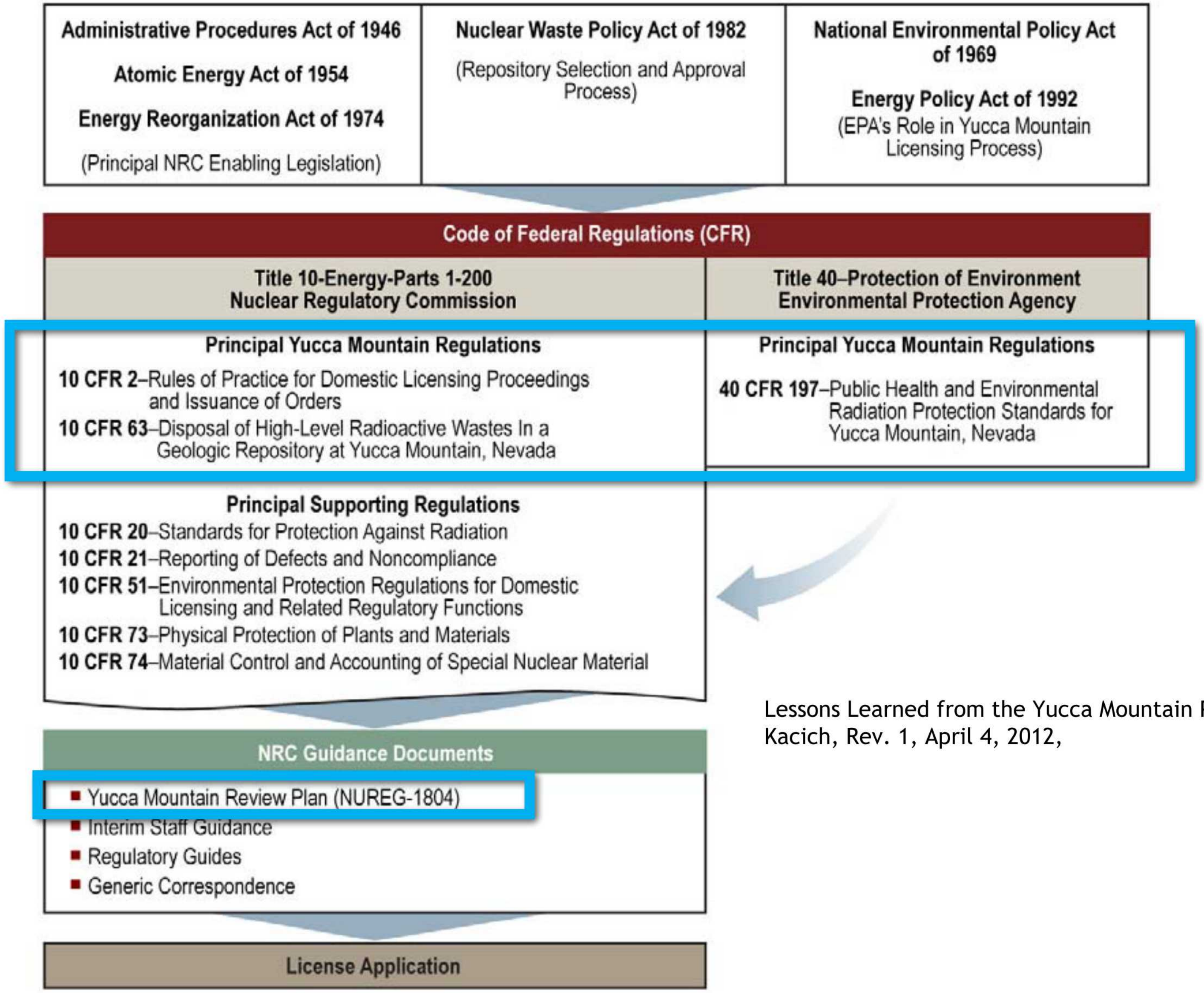
- Dry climate
- Very low permeability of salt
- No naturally-occurring disruptive events are sufficiently likely to impact 10,000-year performance

No radionuclide releases to accessible environment during 10,000-year performance period without human intrusion

Hypothetical borehole intrusions as a result of future oil and gas exploration are evaluated as part of the long-term performance assessment

- Estimated releases due to multiple human intrusions are well below regulatory limits

# Regulatory Framework for Yucca Mountain




Lessons Learned from the Yucca Mountain Project, Richard M. Kacich, Rev. 1, April 4, 2012,

# 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

# Waste for Yucca Mountain

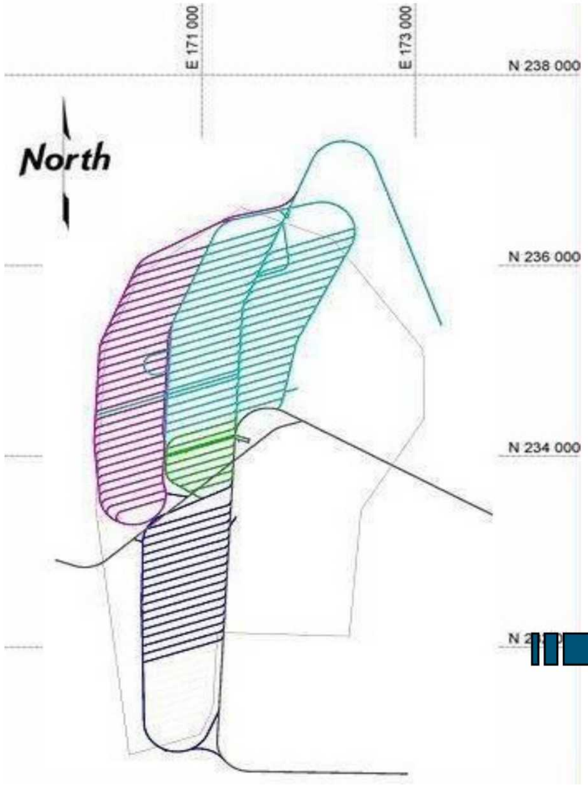
**Commercial Spent Nuclear Fuel:**
**63,000 MTHM (~7500 waste packages)**

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


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

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

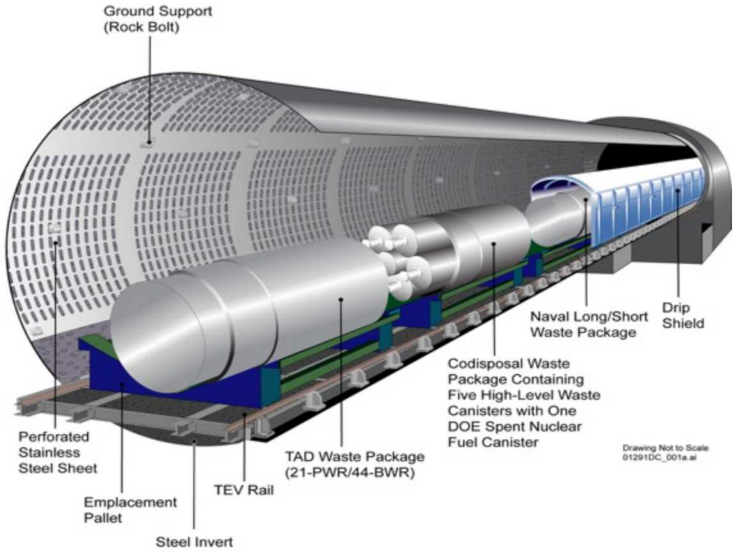
# Yucca Mountain Subsurface Design



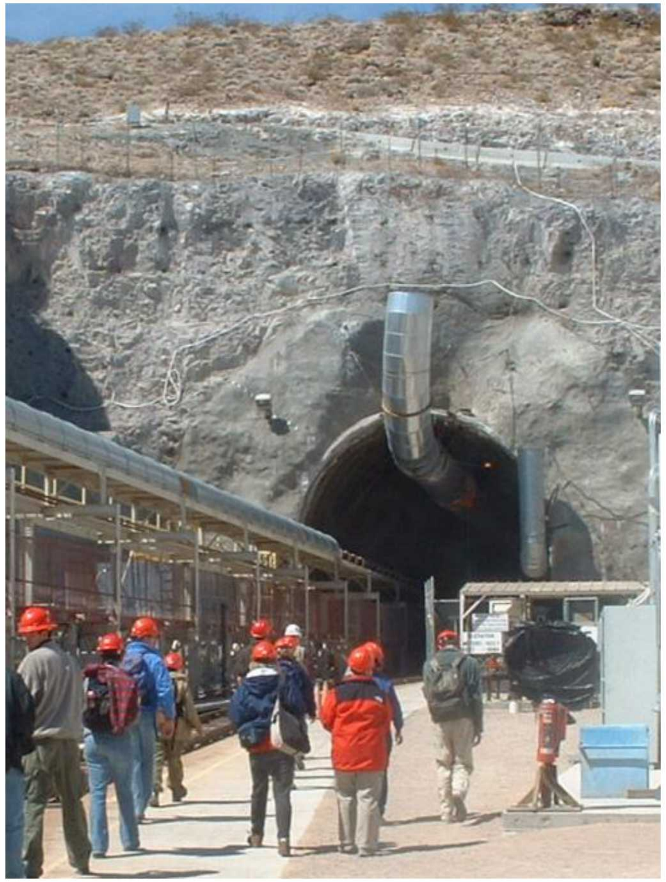

**Emplacement drifts**
- 5.5 m diameter
- approx. 100 drifts, 600-800 m long

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

**Drip shields**
- free-standing 1.5 cm Ti shell

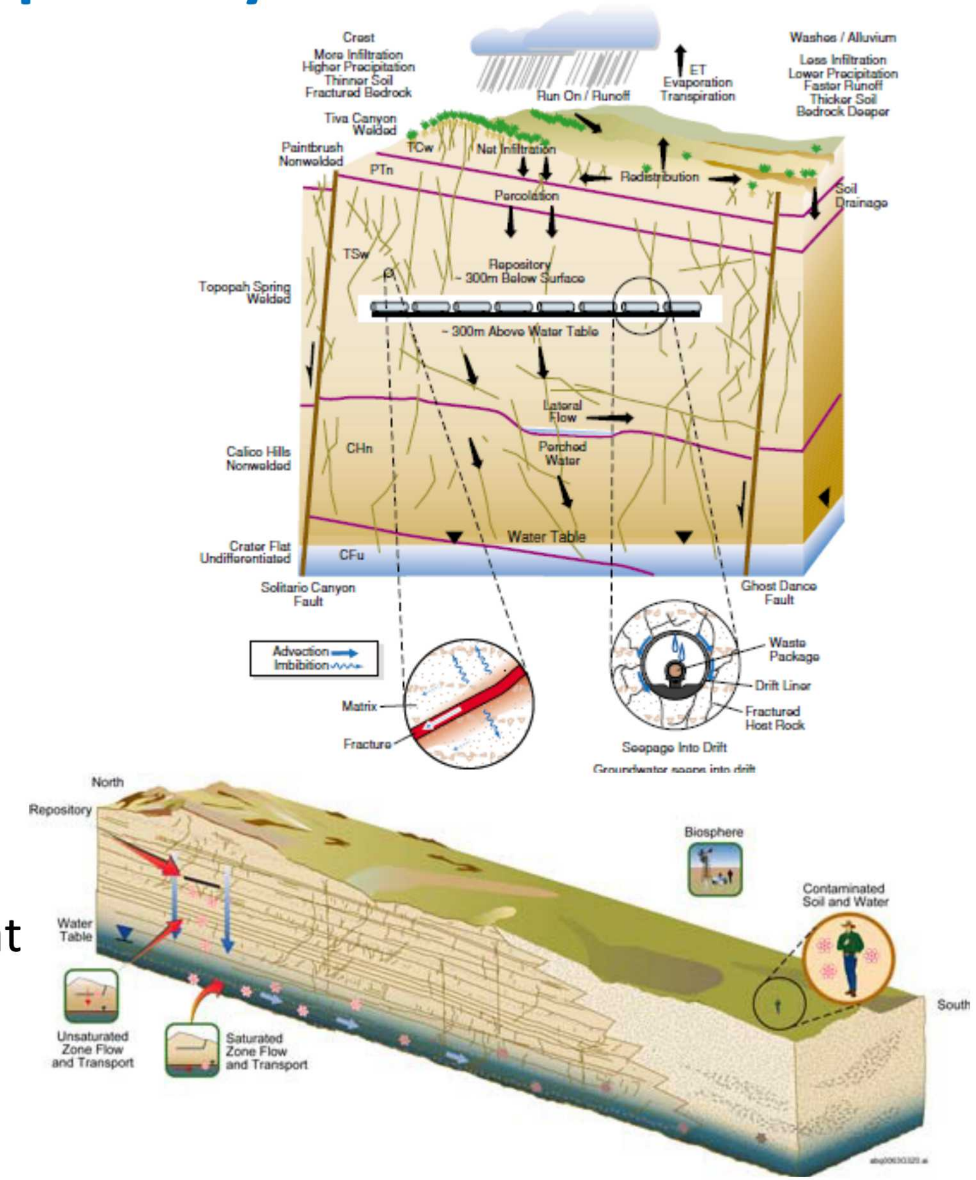


# Yucca Mountain Exploratory Studies Facility

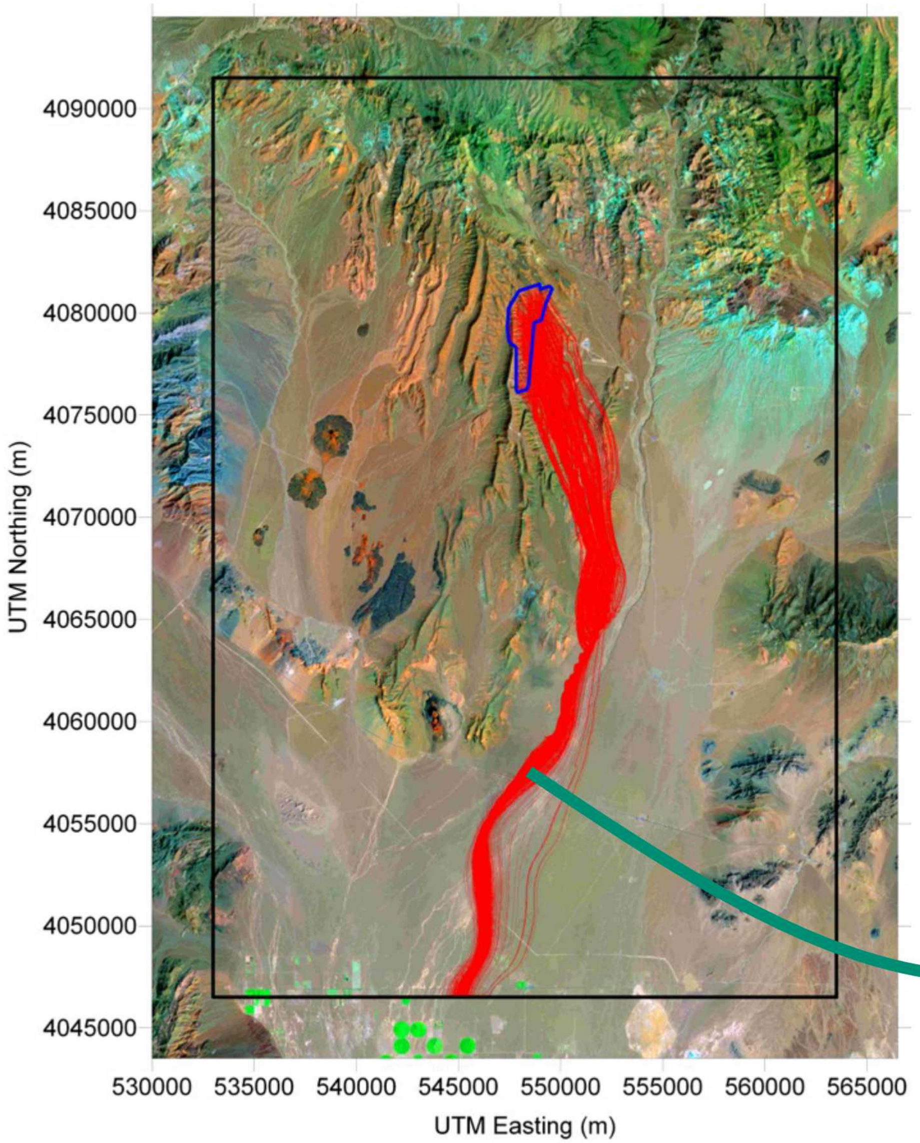


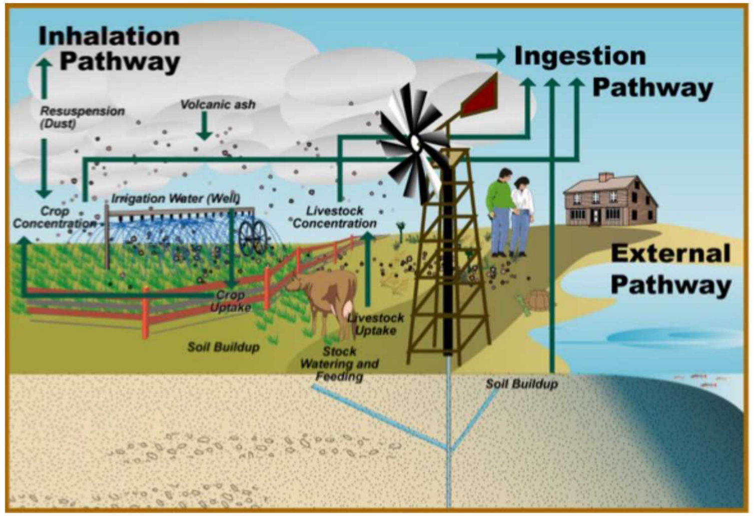
# Long-term Performance of the Proposed Yucca Mountain Repository

- Water provides the primary release mechanism
  - Precipitation infiltrates and percolates downward through the unsaturated zone
  - Corrosion processes degrade engineered barriers, including the waste form
  - Radionuclides are mobilized by seepage water and percolate downward to the water table
  - Lateral transport in the saturated zone leads to biosphere exposure at springs or withdrawal wells



# Estimating Dose to Hypothetical Future Humans




*Modeled groundwater flow paths and hypothetical exposure pathways*

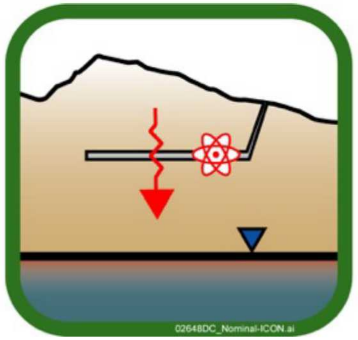
# Four scenario classes divided into seven modeling cases

## Nominal Scenario Class

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

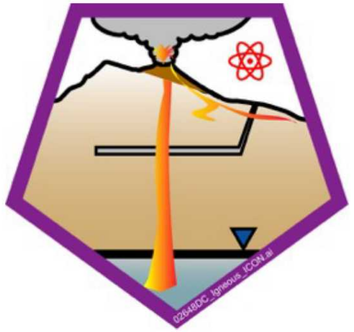
## Early Failure Scenario Class

- Waste Package Modeling Case
- Drip Shield Modeling Case




## Igneous Scenario Class

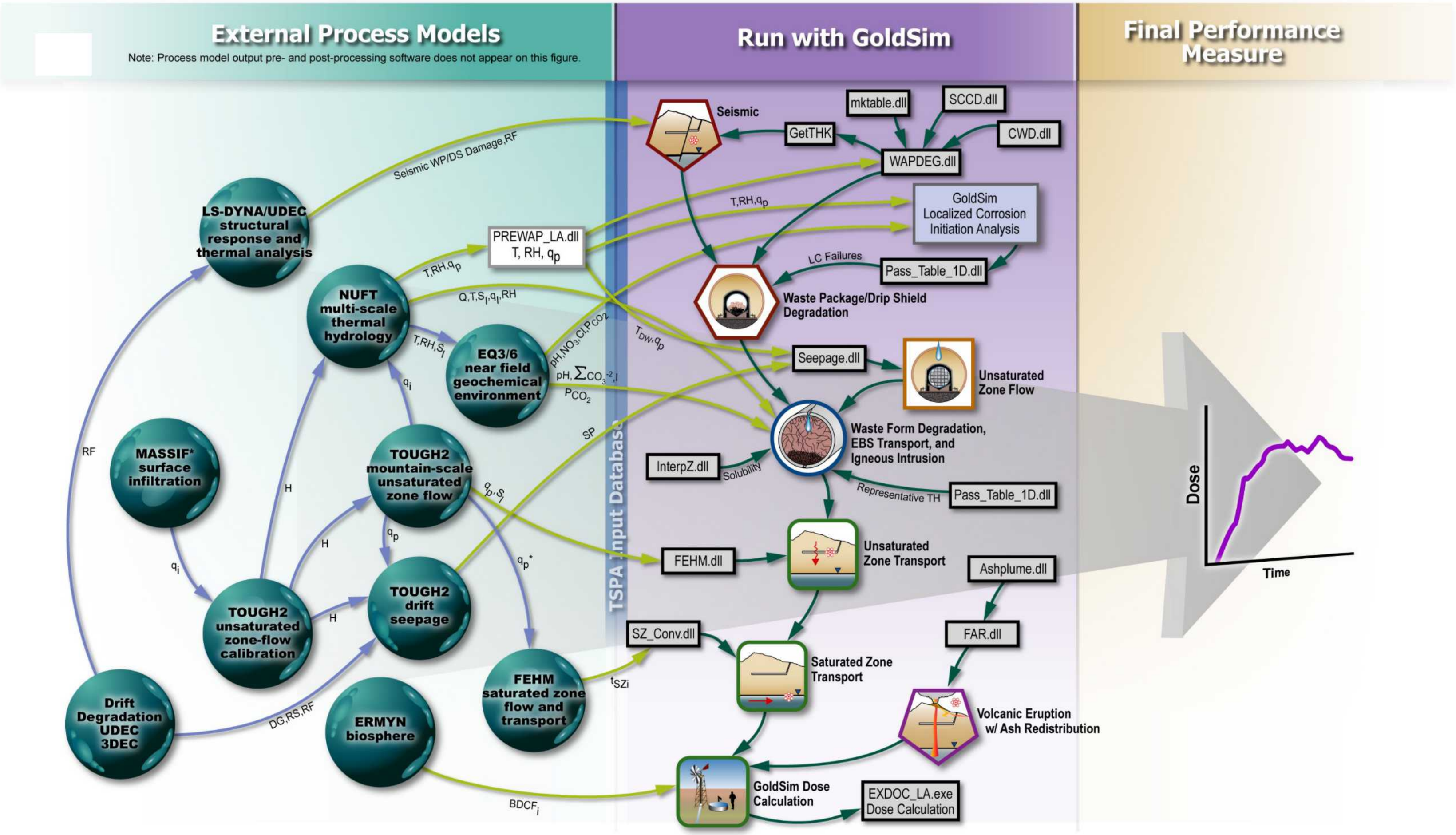
- Intrusion Modeling Case
- Eruption Modeling Case



## Seismic Scenario Class

- Ground Motion Modeling Case
- Fault Displacement Modeling Case

# Yucca Mountain Total System Performance Assessment




**Output Parameters**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $f_S$ | Fraction of WPs with Seeps | $q_p$ | Percolation Flux | $q_i$ | Infiltration Flux | H | Hydrologic Properties |
| EBS | Engineered Barrier System | $NO_3$ | Nitrate Concentration | DG | Drift Geometry | SP | Seepage Parameters |
| $Q_S$ | Seep Flow Rate | T | Temperature | Cl | Chloride Concentration | RS | Rock Strength |
| Q | Evaporation Rate | RH | Relative Humidity | I | Ionic Strength | RF | Rockfall Size and Number |
| pH | pH | $S_l$ | Liquid Saturation | $t_{SZi}$ | Saturated Zone Transport Time | | |
| $\Sigma CO_3^{-2}$ | Carbonate Concentration | $X_a$ | Air Mass Fraction | $BDCF_i$ | Biosphere Dose Conversion Factor | | |
| $P_{CO_2}$ | Partial Pressure of $CO_2$ | $q_l$ | Liquid Flux | $q_g$ | Gas Flux | | |

*Note: $q_p$ derived from INFIL model

**Legend**

- Response Surface between Process Models
- Response Surface from Process Model to GoldSim
- Connection in GoldSim
- Preprocessor
- TSPA Model DLL

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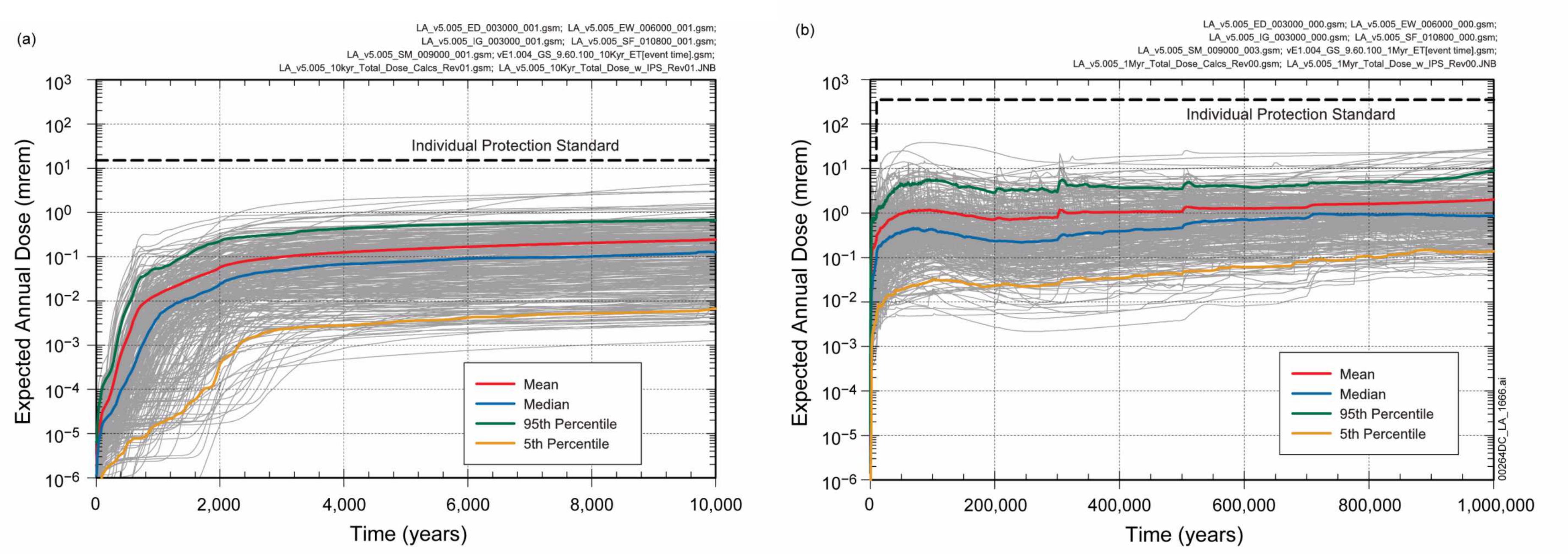
# Long-Term Performance of Yucca Mountain




**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)**

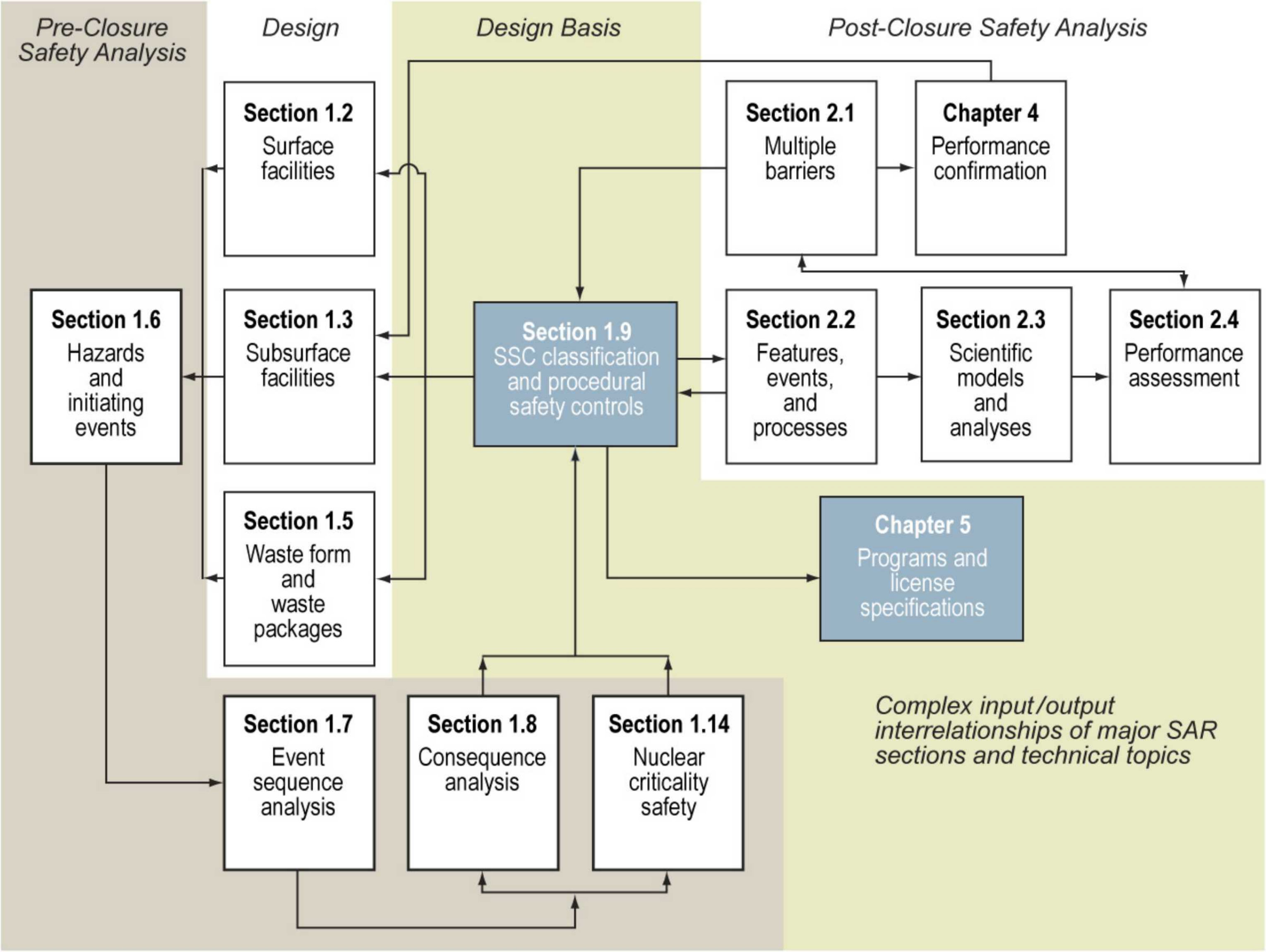
**TSPA-LA estimated 10,000 yr maximum mean annual dose: 0.0024 mSv (0.24 mrem)**

## 1,000,000 years

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

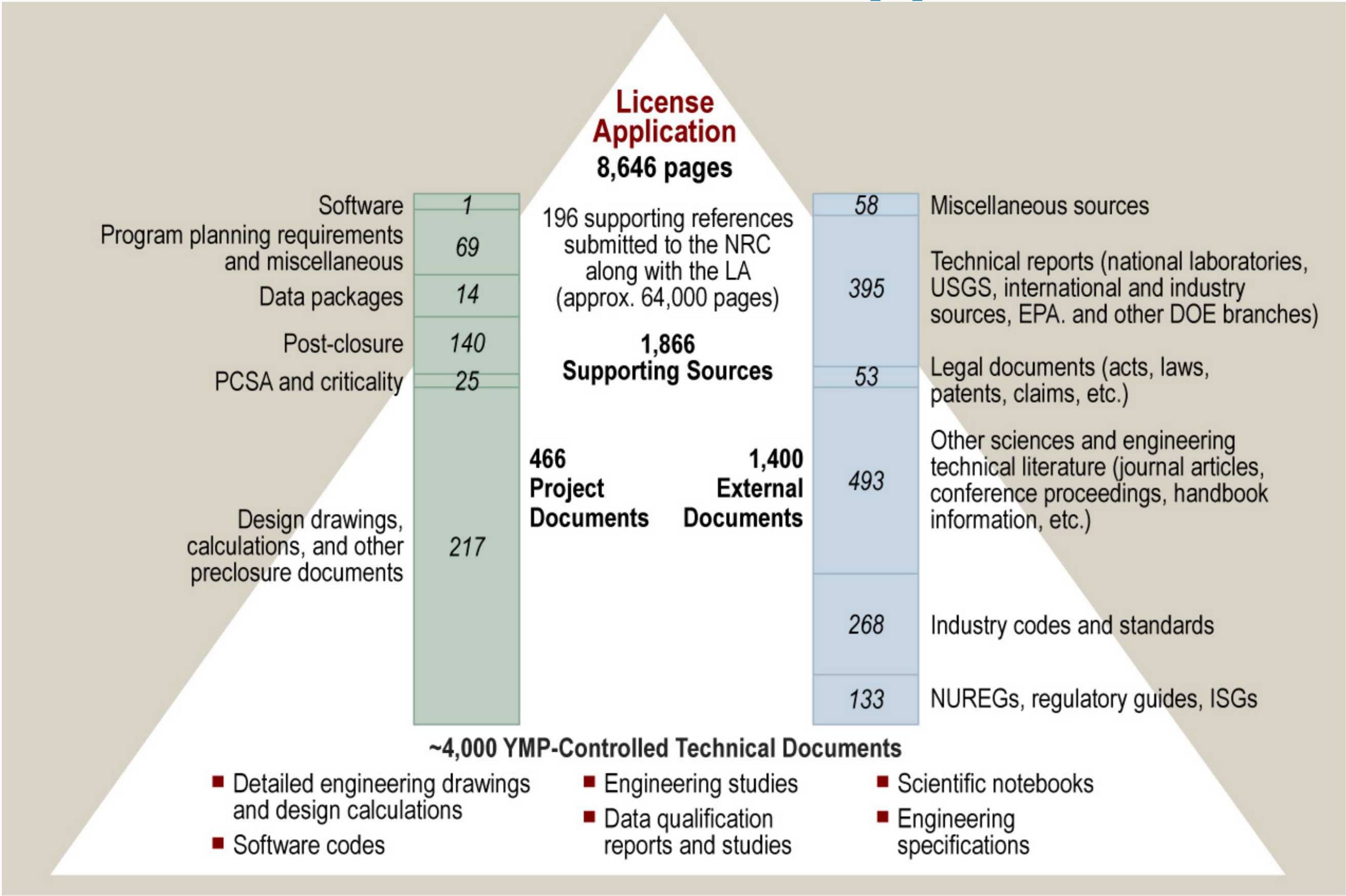
**TSPA-LA estimated 1,000,000- yr maximum mean annual dose: 0.02 mSv (2.0 mrem)**

# Safety Analysis Report




Lessons Learned from the Yucca Mountain Project, Richard M. Kacich, Rev. 1, April 4, 2012,

# Yucca Mountain License Application



# Yucca Mountain Knowledge Preservation

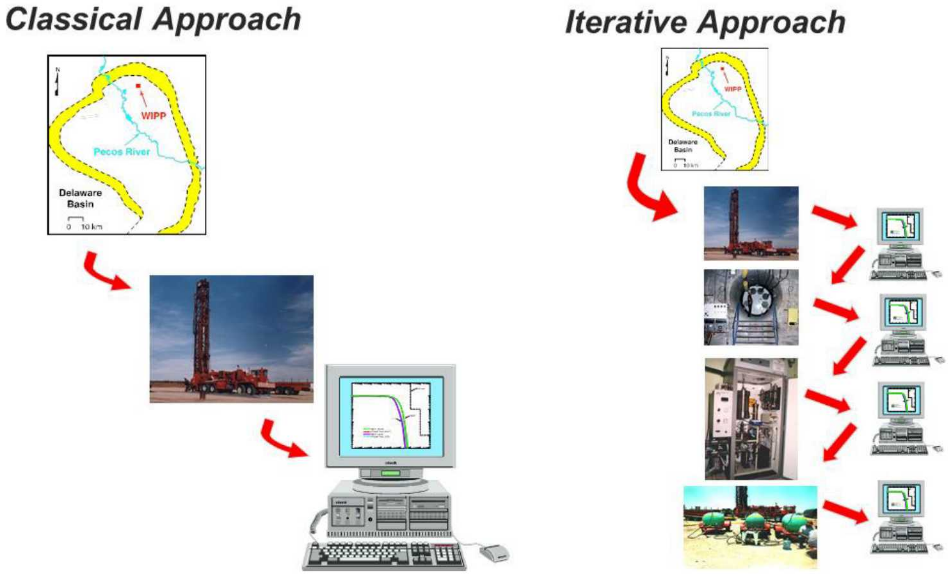
- **Current Status**
  - Licensing Proceeding is not concluded… future uncertain
  - SNL, DOE, and NRC preserved scientific, technical and procedural information from the project
- **Knowledge from Yucca Mountain Project is preserved** in the following systems:
  - USNRC ADAMS (Agency Document and Management System) Collection
  - USNRC ASLAB LSN (Licensing Support Network) Collection
  - USDOE Legacy Management Collection
  - Yucca Mountain Project Lead Laboratory Archive (SNL)
  - Other Proceeding Participant Collections (e.g., State of Nevada)

# Yucca Mountain Knowledge Preservation

- DOE's Legacy Management office has most comprehensive YMP collection
  - More than 62 million records, including:
    - over 3.6 million project documents in the LSN collection:
    - other artifacts (computer programs, etc.) related to research conducted in USDOE's Waste Management program over 30 years
- USNRC 'Licensing Support Network' (LSN)
  - Electronic system, established by the NRC and operated by the NRC's Atomic Safety and Licensing Board (ASLAB) to provide internet access to documents that may be used as evidence in the licensing proceedings
    - 3.6 million documents at the time of the license submittal
    - Public access to the LSN was terminated in August, 2011
    - USNRC committed to transfer this document collection to a publicly accessible library FY15

# Key Lesson Learned

***The Yucca Mountain Project could have been more efficient if the project had adopted a total integrated systems approach to performing the necessary science and engineering***




**Early in the Yucca Mountain program performance assessment methodology and models were developed in parallel with site-characterization activities rather than integral with them**

**During the latter stage of the Yucca Mountain program probabilistic performance assessment methodology and models were used to identify and prioritize site characterization activities**

**Repository programs should use probabilistic performance assessments throughout the life of a program to help set priorities among site-characterization activities.**

**Management attention, funding, and manpower resources should be allocated to those variables and processes identified by performance assessment to be important to reducing uncertainty and demonstrating compliance**

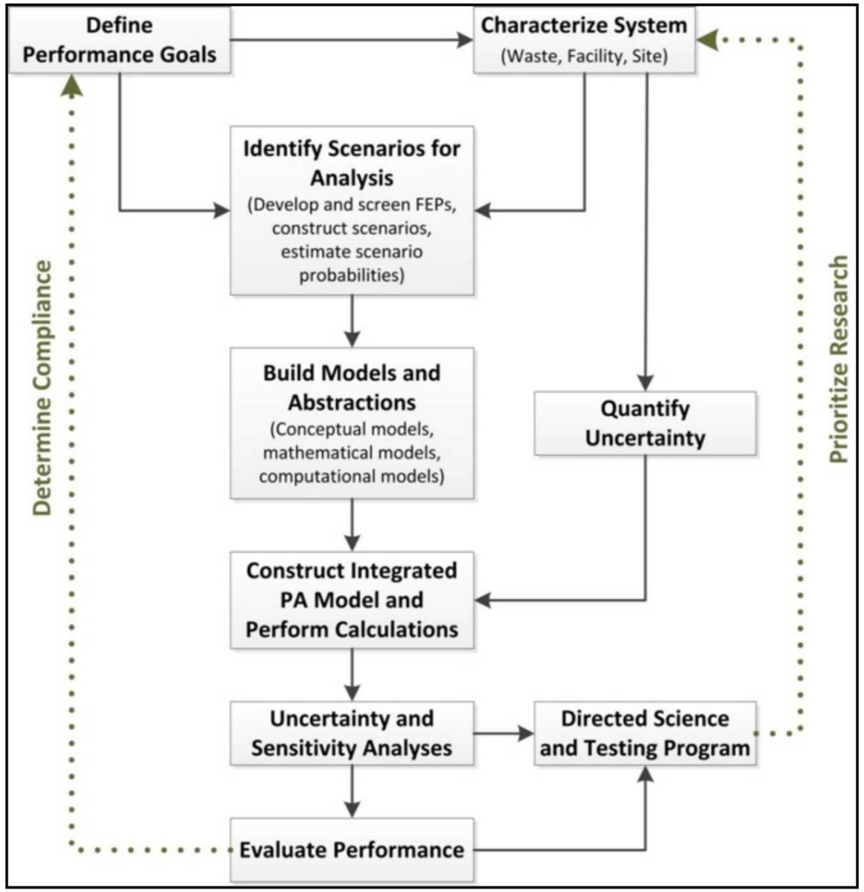
# Site Characterization

## Primary challenges of early site characterization

- Making decisions about where to focus and how to prioritize multiple site characterization activities

- Making decisions about what data and models will ultimately be required to assess the performance of the total repository system

- Making decisions about how much information is enough



# Site Characterization: Key Point

- Recognize *Compliance* rather than *Science* is the primary purpose of characterization
    - Focus program on uncertainties that matter
    - Document decisions and rationale

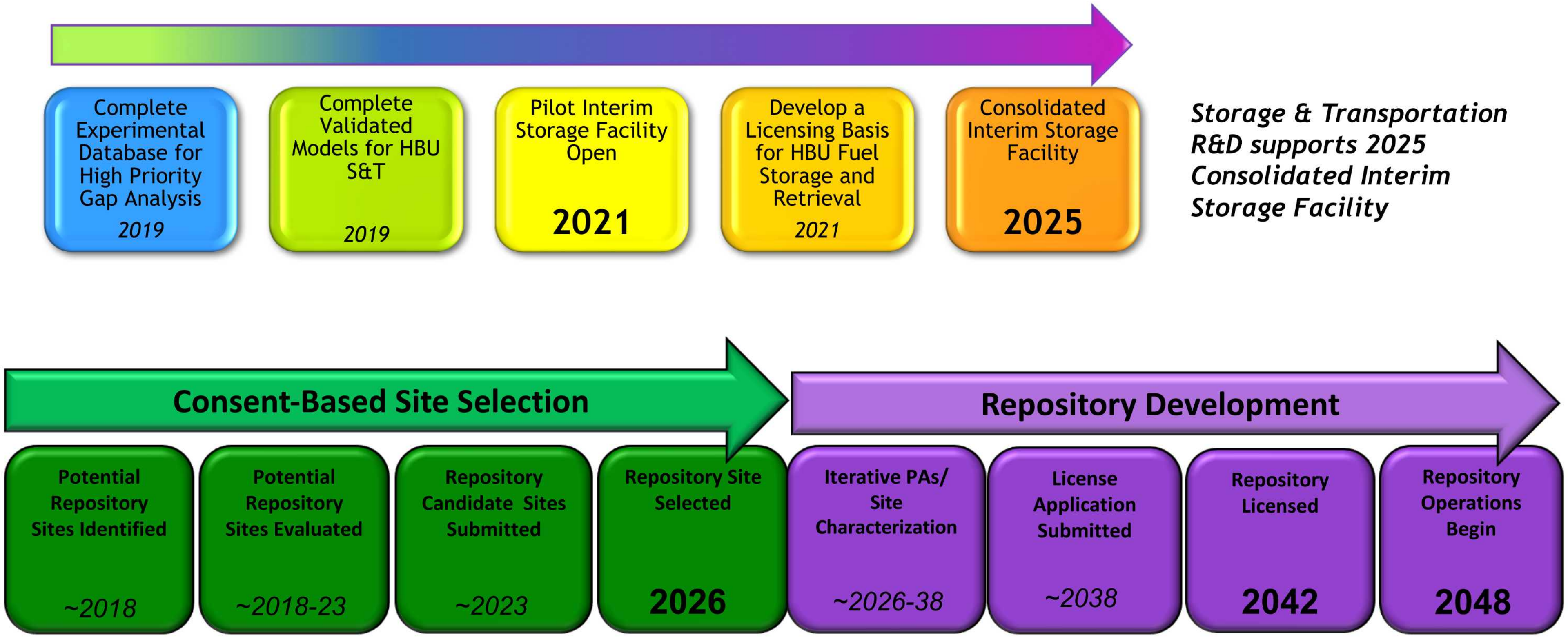
# Site Characterization and Performance Assessment

- Site characterization should be cautious about focusing attention on assumed dominant processes or pathways before performance assessment modeling is performed
- Caution should also be exercised when interpreting early performance assessments as they are only as good as the data and models that support them
- Perform experiments and develop detailed models to understand processes are essential for demonstrating adequacy of performance assessment models
- For experimental guidance, performance assessment should use reasonable estimates of parameter and conceptual uncertainty and not conservative assumptions that may bias results towards preconceived ideas
- Neither site characterization nor performance assessment should completely dominate iterative interactions

# Interactions Between Site Characterization, Repository Design, and PA Staff

- Site characterization, repository design, and performance assessment groups have important contributions to make to understanding uncertainty
- Formalized integration between site characterization, repository design, and performance assessment groups can be facilitated through workshops on major system components
- Integration can be enhanced by encouraging collaboration between individual staff members from site characterization, repository design, and performance assessment groups
- Mutual technical review of project documentation by site characterization, repository design, and performance assessment groups contributes to information exchange and consistency

# R&D Mission to Support Current US DOE Waste Management Strategy




***Storage & Transportation R&D supports 2025 Consolidated Interim Storage Facility***

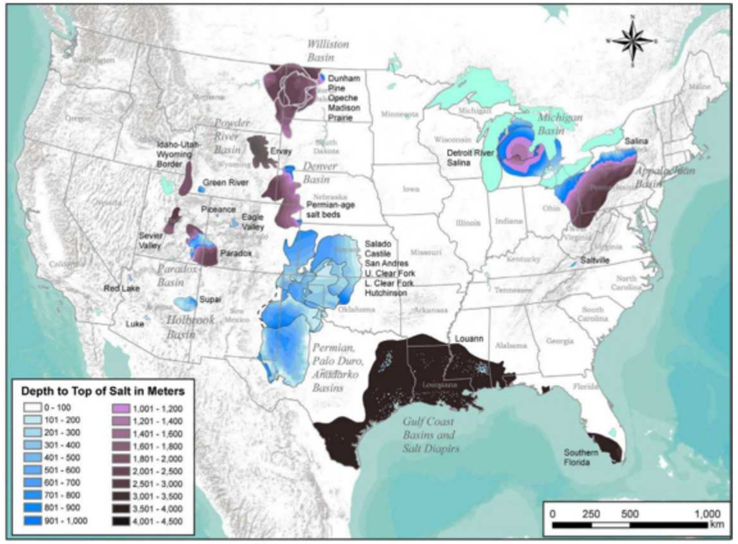
Approximate target dates (in *italics*) needed to meet milestones (in bold) set out in the 2013 DOE *Strategy*

***Disposal R&D supports 2026 Repository Site Selection and 2042 Repository Licensing***

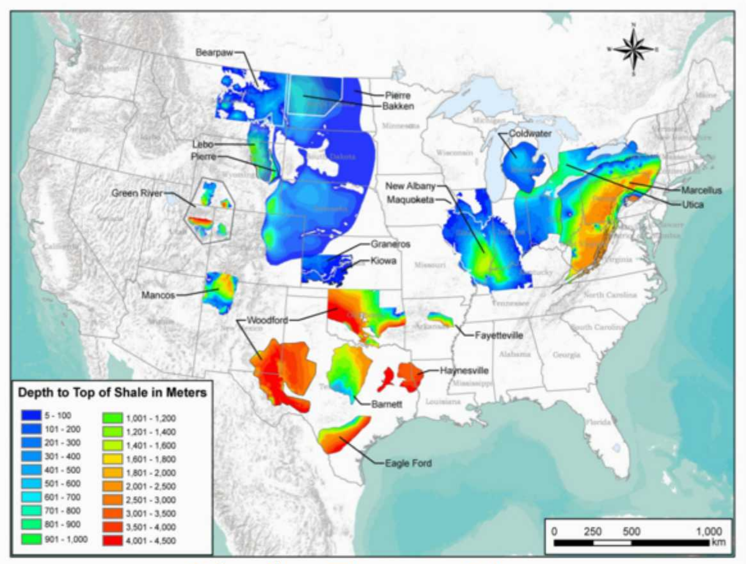
# Generic Disposal R&D

- The Nuclear Waste Policy Act precludes site-specific repository investigations at locations other than Yucca Mountain
- All disposal research must be generic
- What can generic R&D accomplish?
  - Provide technical basis supporting multiple viable US disposal options available when national policy is ready
  - Identify and research the generic uncertainty sources that can challenge disposal concept viability
  - Increase confidence in robustness of generic disposal concepts to reduce the impact of site-specific complexity
  - Develop tools in science and engineering to address other goals

# Alternative Host Rock Formations

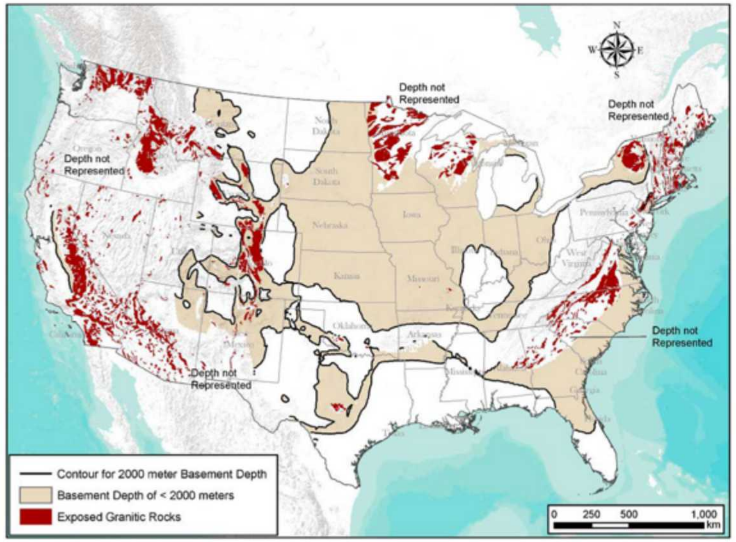



Salt Formations



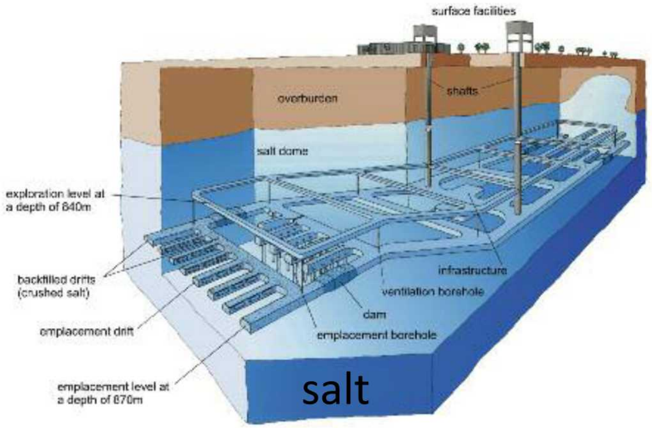

Shale Formations

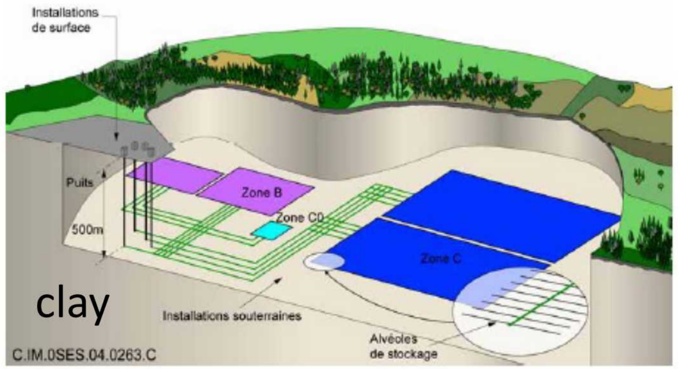
Crystalline Formations

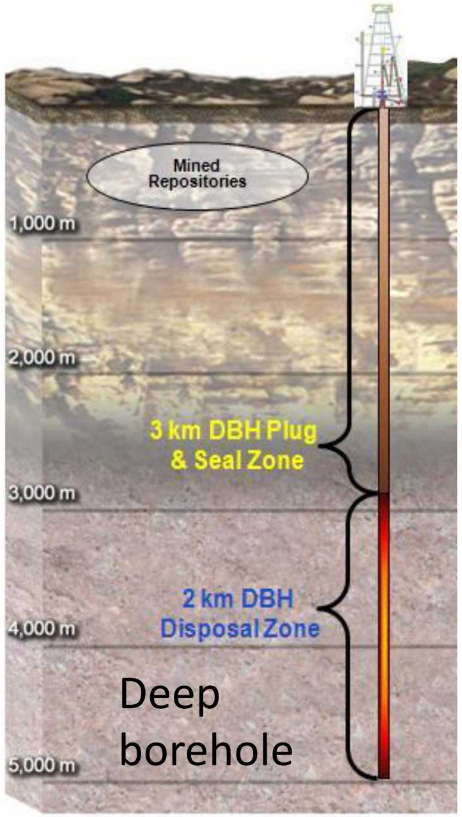


# U.S. Disposal R&D Focuses on Four Options

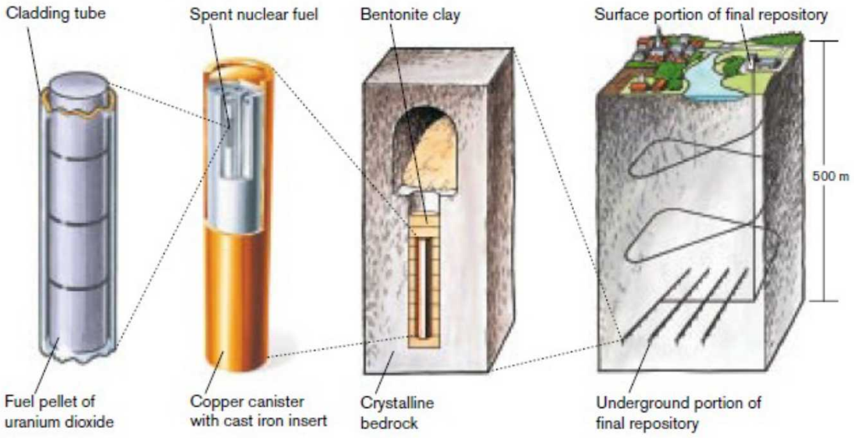
- Three mined repository options (granitic rocks, clay/shale, and salt)
- One geologic disposal alternative: deep boreholes in crystalline rocks




granite



# Overview and Status of International Collaboration

- Promising international opportunities for "active" collaboration were identified, evaluated, and selected
- DOE has joined formal collaborative R&D agreements with multinational collaborative initiatives as well has bilateral agreements with selected international programs in Europe and Asia
- Several UFD funded collaborative R&D projects have been initiated within these R&D agreements

## Multinational Initiatives

- Mont Terri Project
  - *Participate in experiments at Mont Terri clay URL in Switzerland*
- DECOVALEX Project
  - *Participate in model comparison initiative for several URL related tasks in different host rocks*
- Colloid Formation and Migration Project
  - *Participate in colloid research at Grimsel granite URL in Switzerland*
- SKB Task Forces
  - *Participate in crystalline rock research centered around Äspö HRL in Sweden*
- FEBEX DP
  - *Participate in FEBEX dismantling project, which will analyze bentonite-rock behavior after 17 years of heating*

## Bilateral Agreements

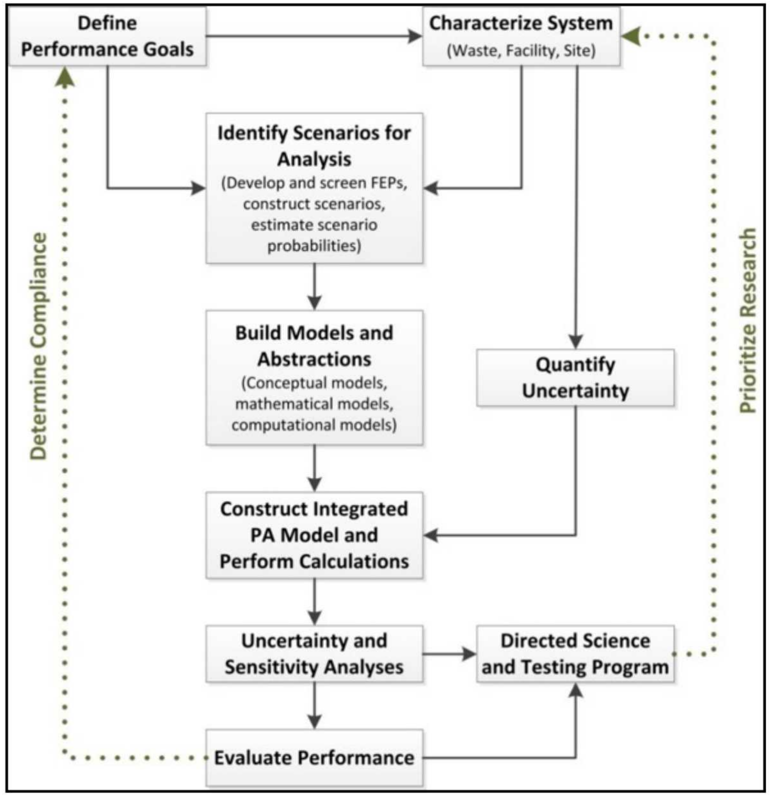
- KAERI Underground Research Tunnel (KURT)
  - *Participate in collaborative US/ROK experiments in crystalline rock*
- US-German benchmarking study for salt
  - *Participate in model comparison for TM behavior of domal and bedded salt*
- Other
  - *Other opportunities may be pursued, as bilateral agreements exist with France, Japan, Belgium, etc.*

*Also NEA Salt Club, Clay Club, Thermochemical Database Project*

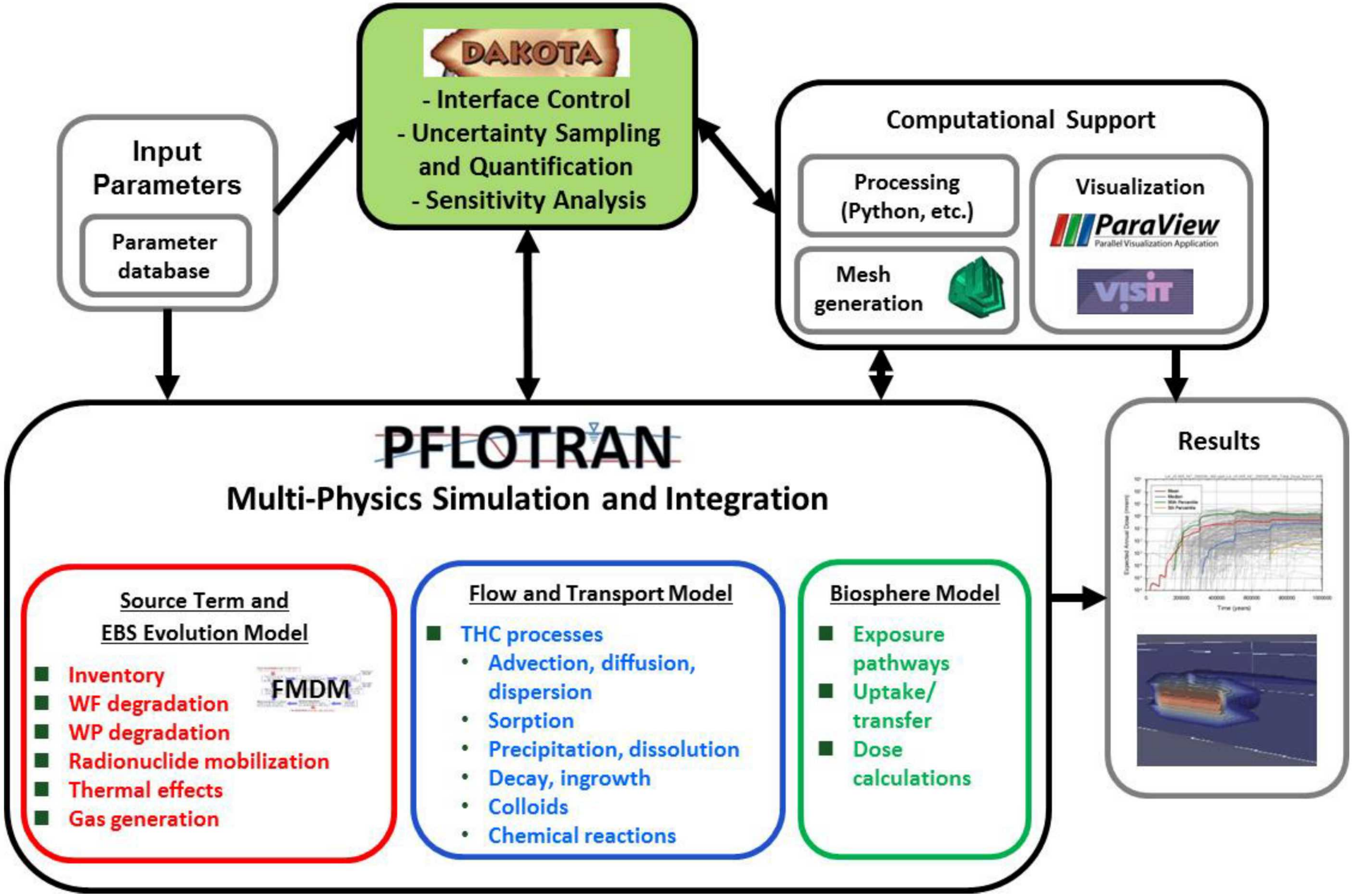
# PA Model/Code Development Philosophy

- **Objective: More accurate solution to the coupled continuum field equations (mass, momentum, energy) over a large heterogeneous domain, including**
  - **Quantification and propagation of uncertainties, both aleatory and epistemic**
  - **Direct representation in PA model of significant coupled multi-physics processes in three dimensions (3-D)**
  - **Realistic spatial resolution of features and processes**
    - *Explicit representation of all waste packages*
- **Key points:**
  - **Less reliance on assumptions, simplifications, and process abstractions**
  - **Adopt a numerical solution and code architecture that can evolve throughout the repository lifecycle (decades!) and is able from the outset to use the most advanced hardware and numerical solvers available**


*Fig. 1: J.C. Helton et al. / Reliability Engineering and System Safety 122 (2014) 267–271.

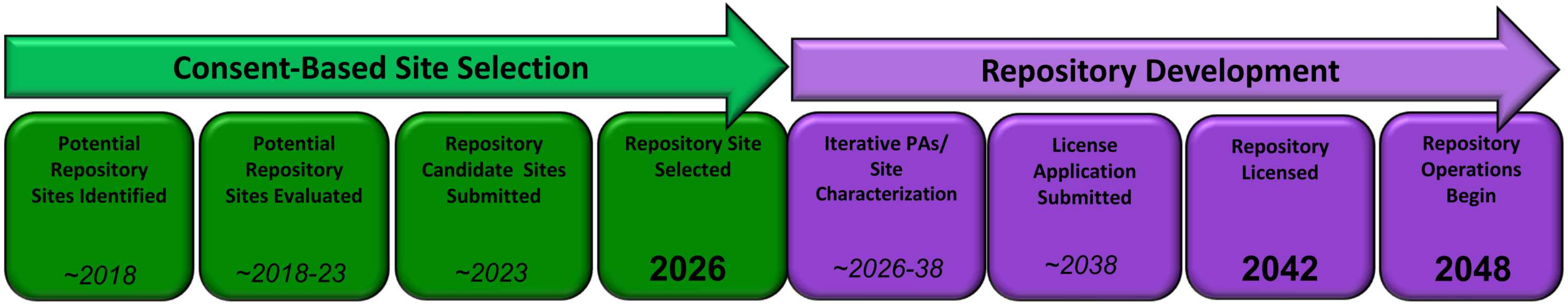


# Enhanced PA Computational Model Architecture



# Goals/Uses of the Enhanced PA Capability

- **Goals:**
  - Enhance confidence and transparency in disposal system safety case
  - Enable better decisions (technical, political, fiscal)
- **Uses:**
  - Evaluate potential disposal concepts and sites in various host rock media
  - Help prioritize **Site Characterization** and RD&D activities (initially *generic*; later *site-specific*)
  - Support safety case development during all phases of lifecycle




Approximate target dates (in *italics*) needed to meet milestones (in bold) set out in the 2013 DOE *Strategy*

***Disposal R&D supports 2026 Repository Site Selection and 2042 Repository Licensing***

# Conclusions

Siting, site characterization, and licensing can take decades

Repository programs should use probabilistic performance assessments throughout the life of a program to help set priorities among site-characterization and design activities

Performance assessment, Site Characterization, and Design groups should be organized to facilitate integration and iterative development of the Safety Case and License Application

Performance assessment, Site Characterization, and Design groups should be involved in identifying and characterizing uncertainties

Maintaining and managing project knowledge are important

An effective Quality Assurance Program should emphasize best scientific practices

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