Advanced Conceptual and Numerical Methods for Modeling Subsurface Processes Regarding Nuclear Waste Repository Systems

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Sandia National Laboratories

Implementation of Tunnel, Shaft, and Borehole Seal Systems

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Acknowledgements

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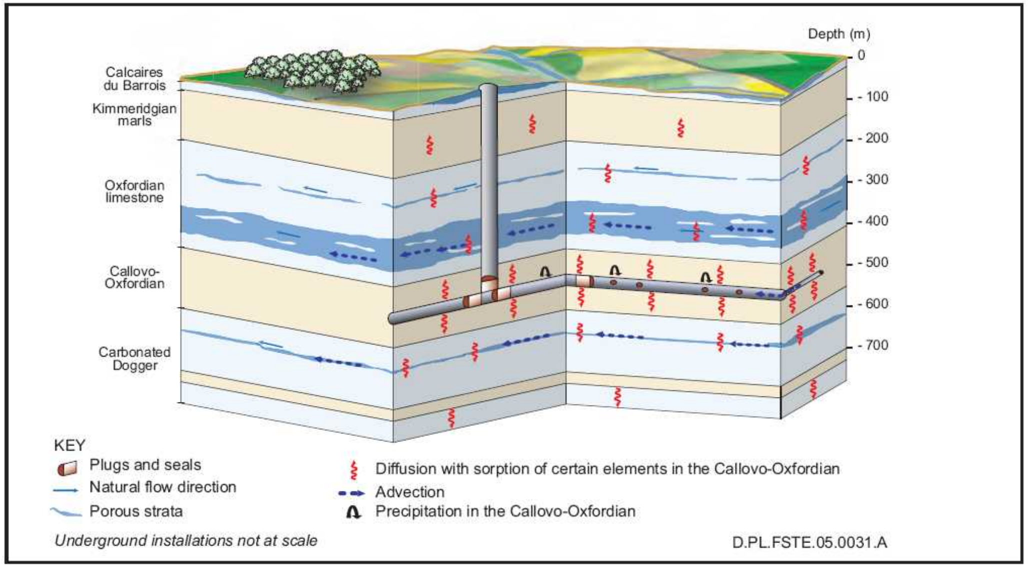
International Agencies and Investigators

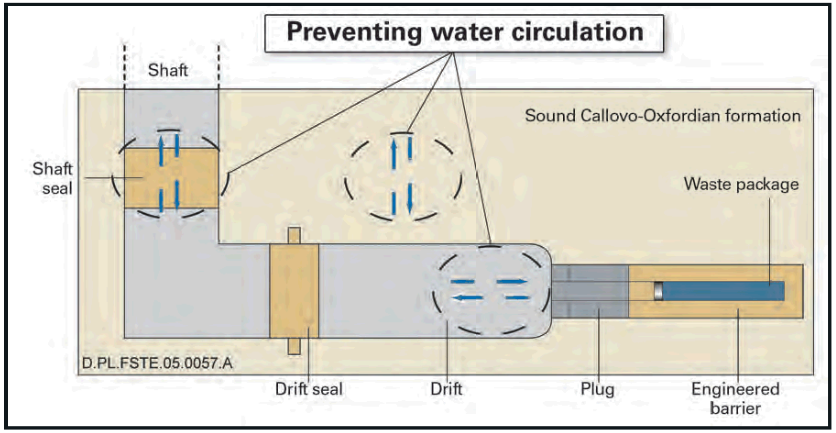
Geologic Disposal R&D - International Web Resources

- Belgium – ONDRAF/NIRAS (see also: French and Dutch language publications)
  - http://www.niras.be/engels/8.2_Pubs_eng.php
- Belgium – SCK/CEN
  - http://www.sckcen.be/en/Our-Research/Scientific-publications
  - http://publications.sckcen.be/dspace/
- Finland - Posiva
  - http://www.posiva.fi/reportsearch
- France – ANDRA
  - http://www.andra.fr/index.php?id=edition_1_5_2&recherche_thematique=all
- Germany – BfS (mostly in German)
  - http://www.bfs.de/en/endlager/publika
- Germany – BGR (many in German; higher level documents in English)
  - http://www.bgr.bund.de/cln_144/nn_335086/EN/Themen/Geotechnik/geotechnik__node__en.html?__nnn=true
- Japan – JAEA (2005 merger of JNC and JAERI)
  - http://jolissrch-inter.tokai-sc.jaea.go.jp/common/eindex.html
- Spain – ENRESA (mostly in Spanish)
  - http://www.enresa.es/publications_and_multimedia/documentation?pag=1&orden=relevancia
- Sweden – SKB
  - http://www.skb.se/Templates/Standard____17139.aspx
- Switzerland – NAGRA
  - http://www.nagra.ch/g3.cms/s_page/77900/s_name/shopengl
- USA – Department of Energy
  - http://www.ocrwm.doe.gov/Historical_Key_Documents/index.shtml
  - http://www.ocrwm.doe.gov/waste_management_background/index.shtml
- USA – Nuclear Regulatory Commission (Yucca Mountain license application and supporting references)
  - http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app/references.html

Outline - Sealing

- Seal functions and objectives
- Seal design and the repository concept of operations
- Example: Shaft seal design certified for WIPP
- WIPP shaft seal proof-of-concept testing
- Discuss seal concepts developed for international programs





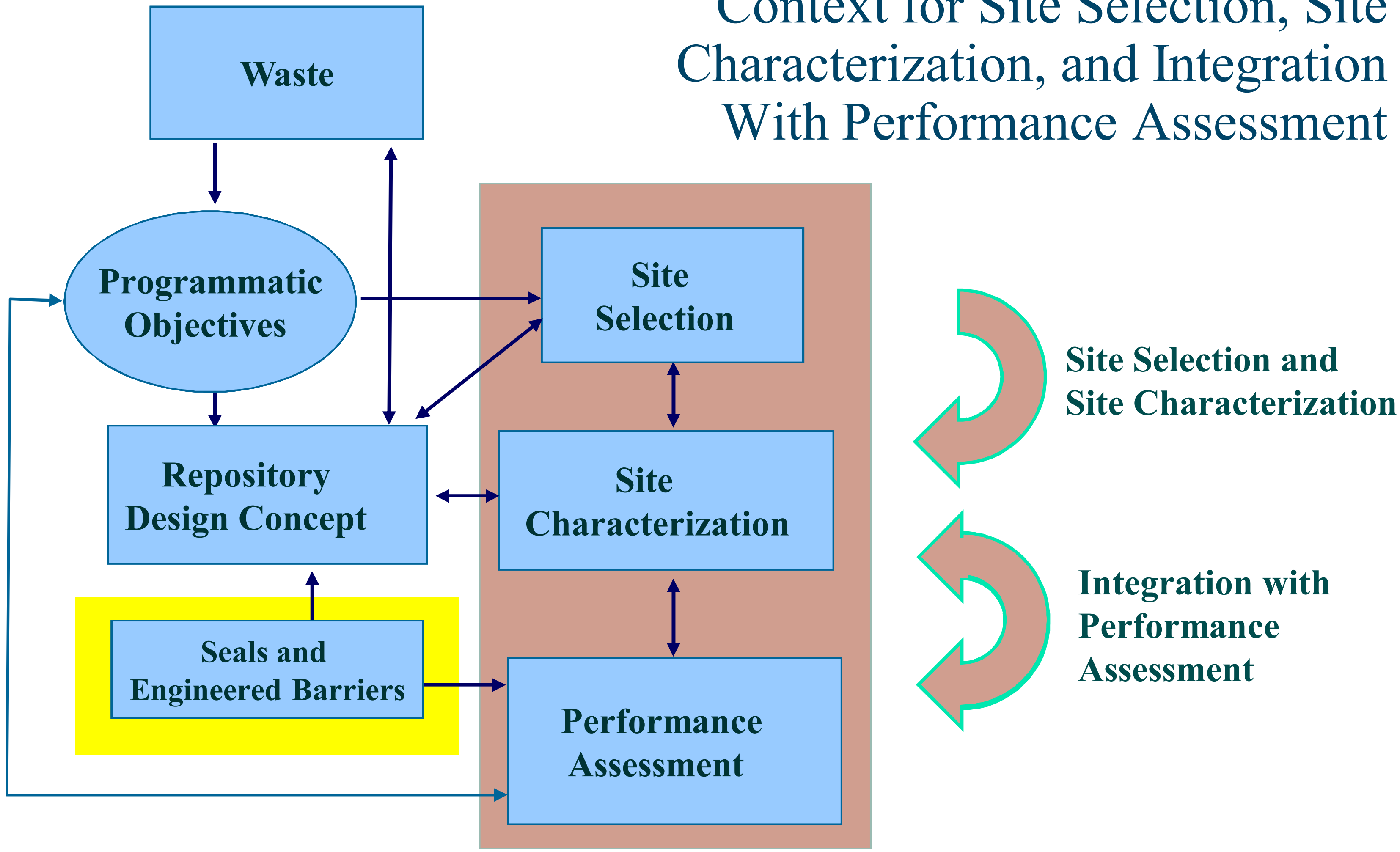
Source for figures: Andra Dossier 2005 Argile

Sealing Functions & Objectives

- **Functions:**
  - Restrict groundwater flow through the repository (maintain diffusion dominated transport)
  - Limit transport of hazardous constituents to regulatory boundaries
  - Provide structural support to system components
  - Limit subsidence and inhibit accidental or intentional entry
- **Objectives:**
  - Use materials possessing mechanical and chemical compatibility
  - Use available construction methods and materials
  - Use redundancy in design

Seal Design - Repository Concept of Operations

Context for Site Selection, Site Characterization, and Integration With Performance Assessment

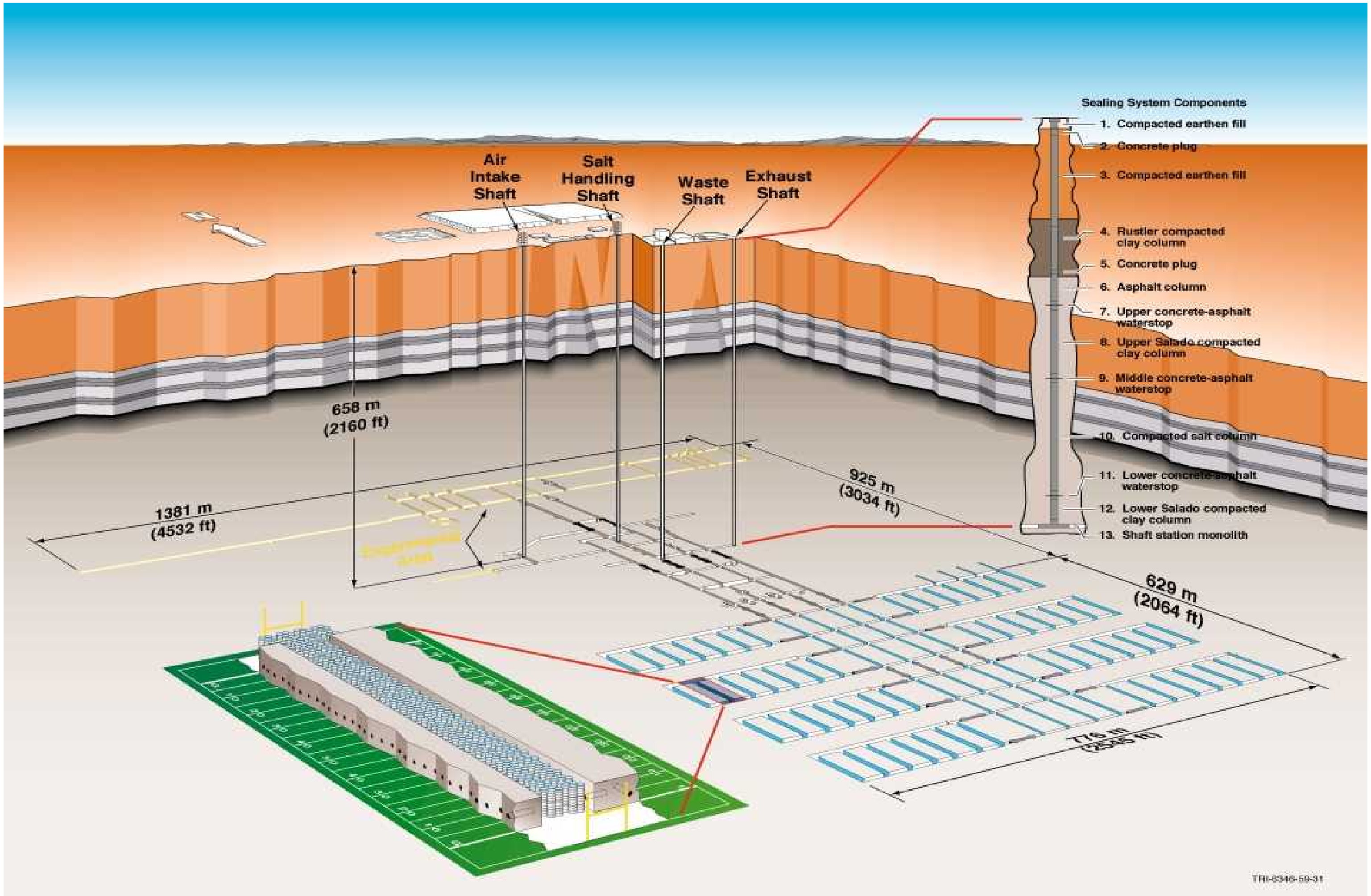


Seal Design - Repository Concept of Operations

- **A geologic repository will typically require staged, passively functioning (multiple) natural and engineered barriers**
- **Seals will support functions of the natural and engineered barriers**
  - Must be compatible with geologic and engineered materials
  - Must eliminate or control barrier bypass for the waste isolation performance period
- **Seals may be installed <u>during</u> repository operations (not only at the end)**
  - Modular repository design
  - Accommodate rock mass evolution (e.g., creep deformation)
  - Decrease risk from unplanned future events

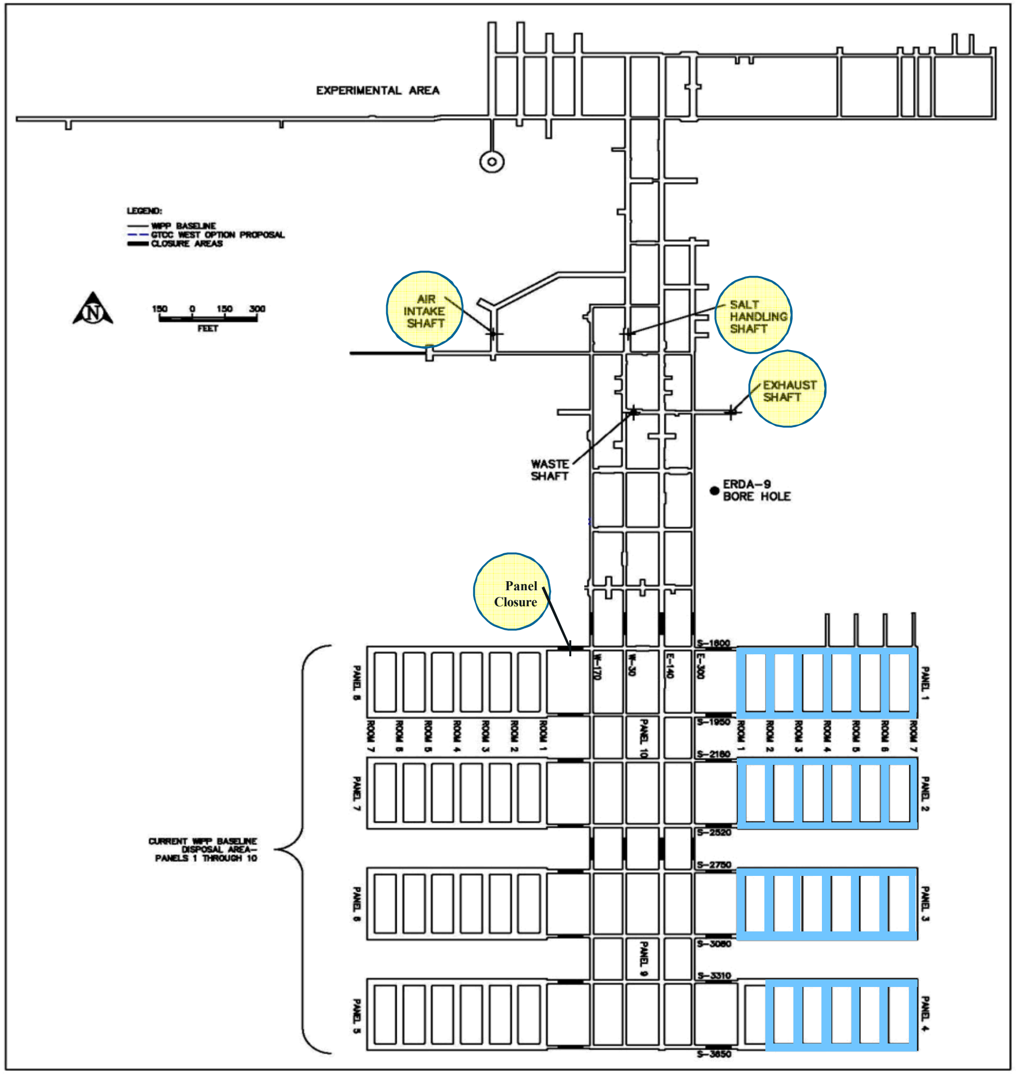
Example: WIPP Shaft Seal Design

Waste Isolation Pilot Plant Facility Layout



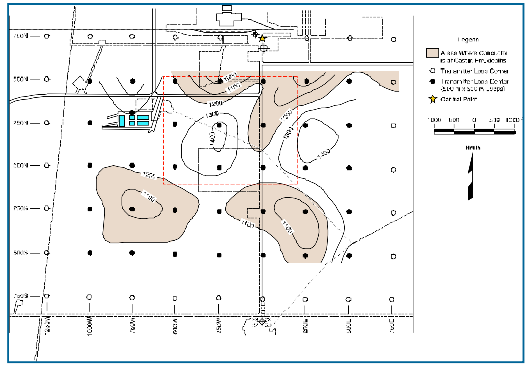
Example: Shaft Seal Design for WIPP

- **Plan View of WIPP Showing Projected Waste Storage Area**
  - Shaft Seals
  - Panel Closures
  - Backfill



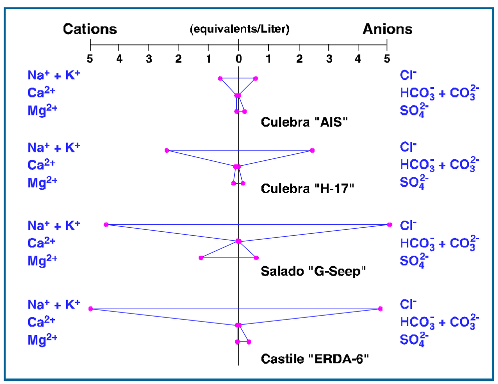
Seal Design - WIPP Site Characterization

Geologic studies



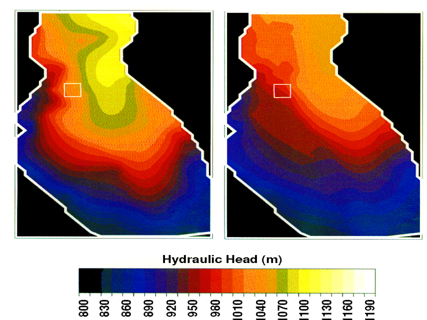
Geophysical surveys

Hydrologic testing



Geochemical sampling and analysis

Geomechanical testing



Numerical modeling

Seal Design - WIPP Geologic Studies

Geologic mapping

Surface-based geologic drilling, coring, & geophysical logging

Geologic mapping of air intake shaft

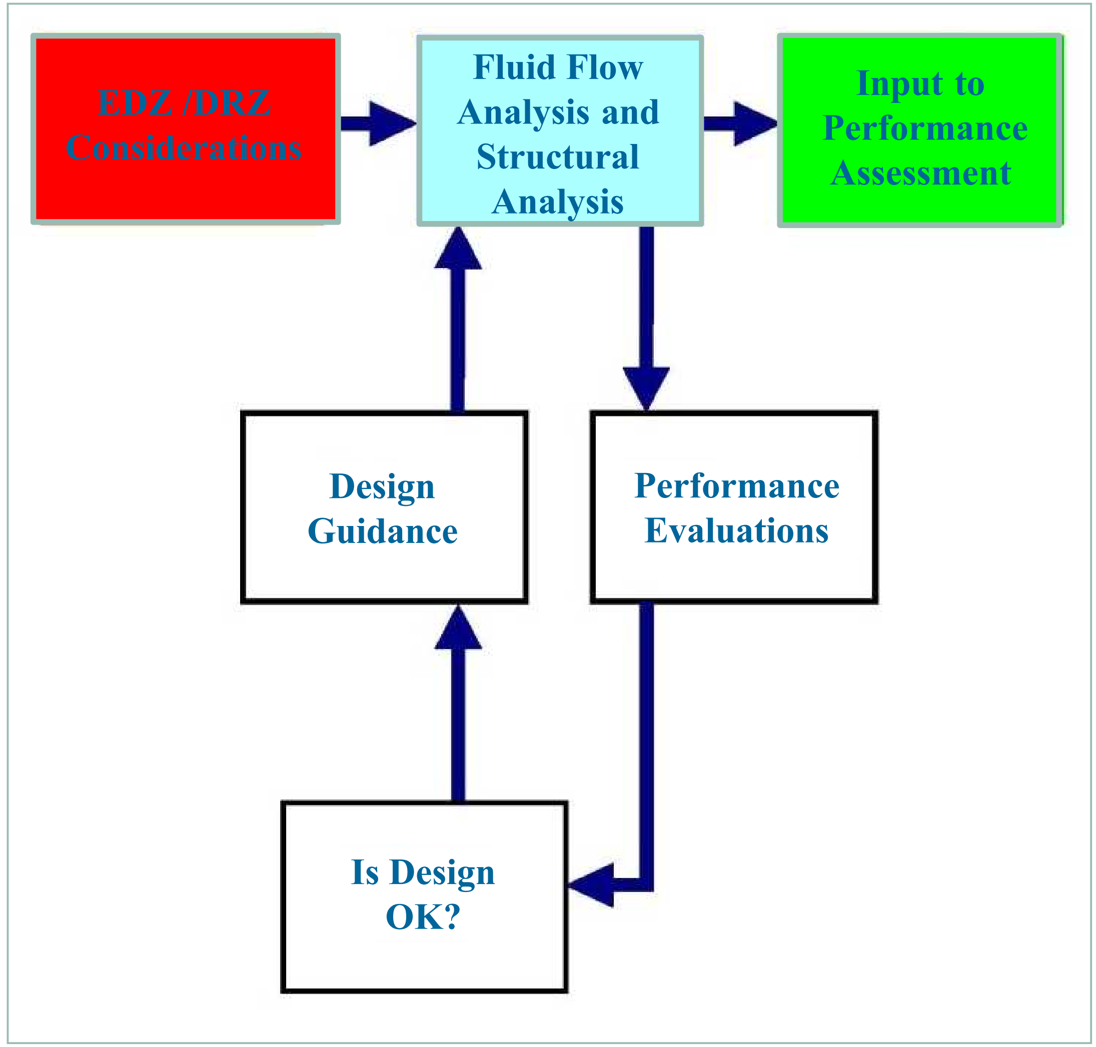
Horizontal core from air intake shaft

Seal Design - WIPP Underground Testing

- Large-scale geomechanical and hydrological testing
- Characterization of EDZ/DRZ and seal materials
- Coupled natural, excavation- induced, disposal room processes

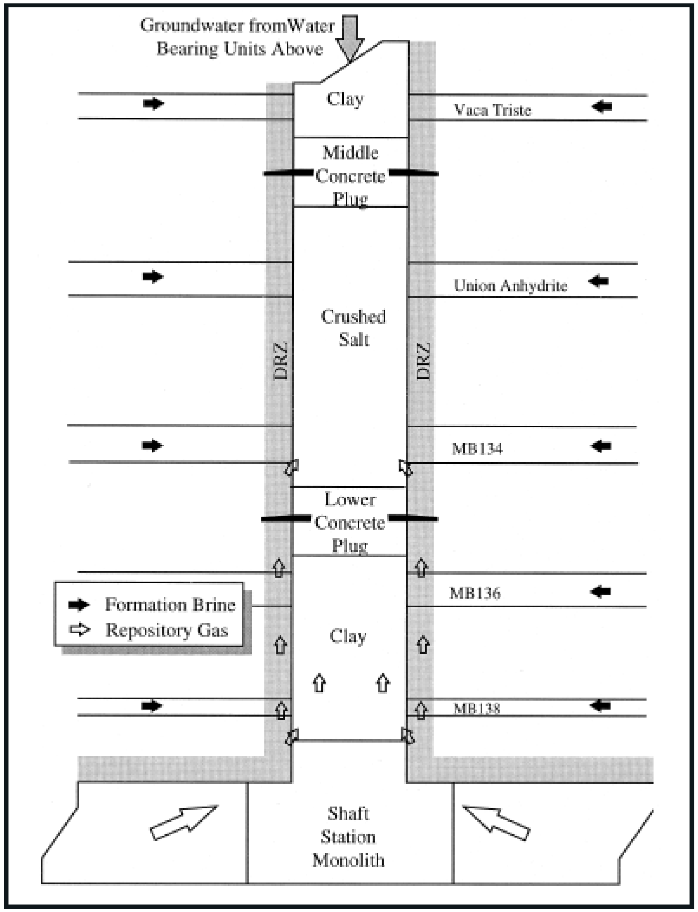
Seal Systems Analysis Process

- **Multi-year process**
- **Performance evaluations include testing**
  - Mock-up
  - Material tests
  - Construction/fabrication demonstration
  - Proof-of-concept
- **Design and testing completed prior to licensing**

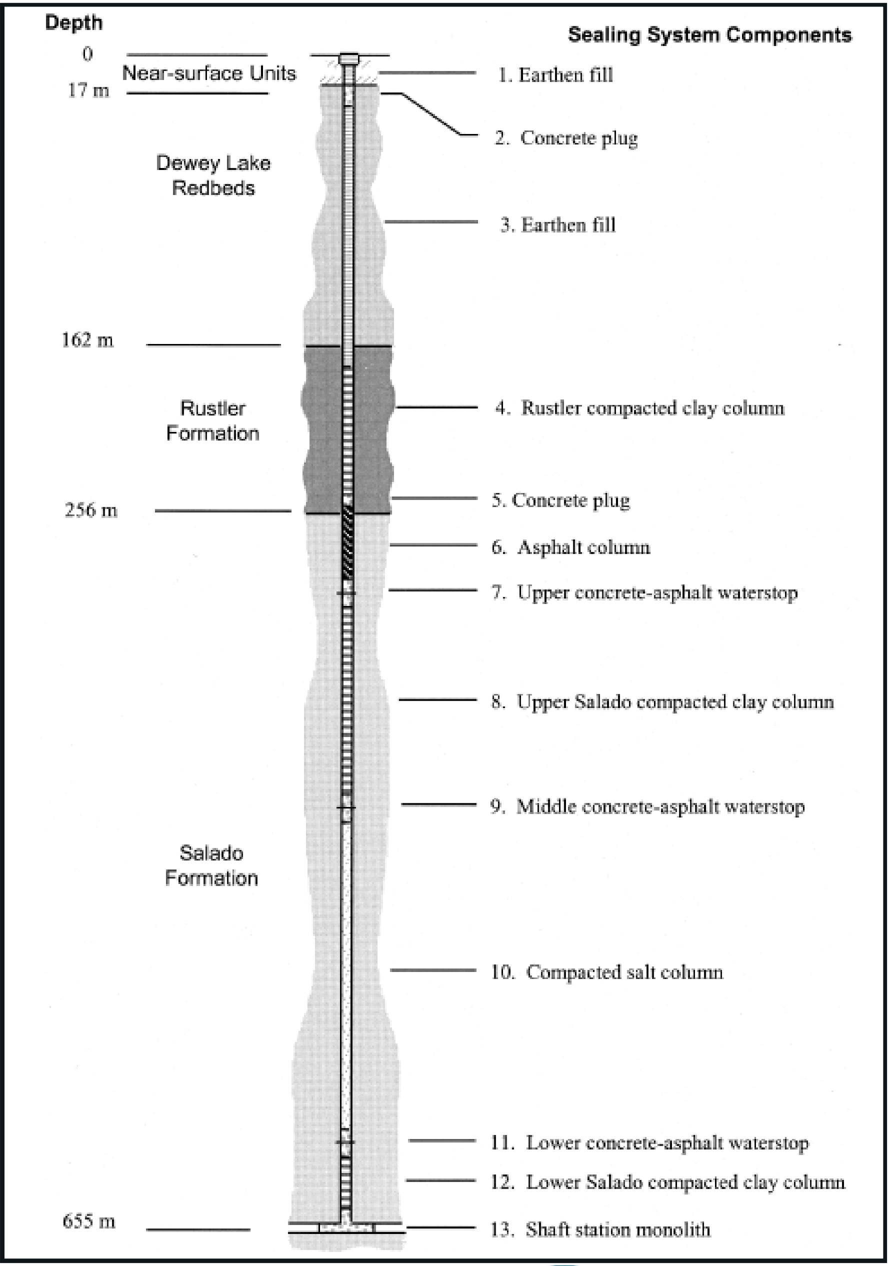


WIPP Shaft Seal Design

Physical Processes Considered:



Source: Hansen, F.D. and M.K. Knowles 2000. "Design and analysis of a shaft seal system for the Waste Isolation Pilot Plant." Reliability Engineering and System Safety. 69:87–98.



Seal Design - Material Specifications

- **Characteristics**
  - Low permeability
  - Swelling
- **Material Characteristics**
  - Compatibility
  - Longevity
- **Construction**
  - Handling
  - Method feasibility
- **Performance Requirements**
  - Source, procurement, transport, processing, properties
- **Verification**
  - Methods and criteria

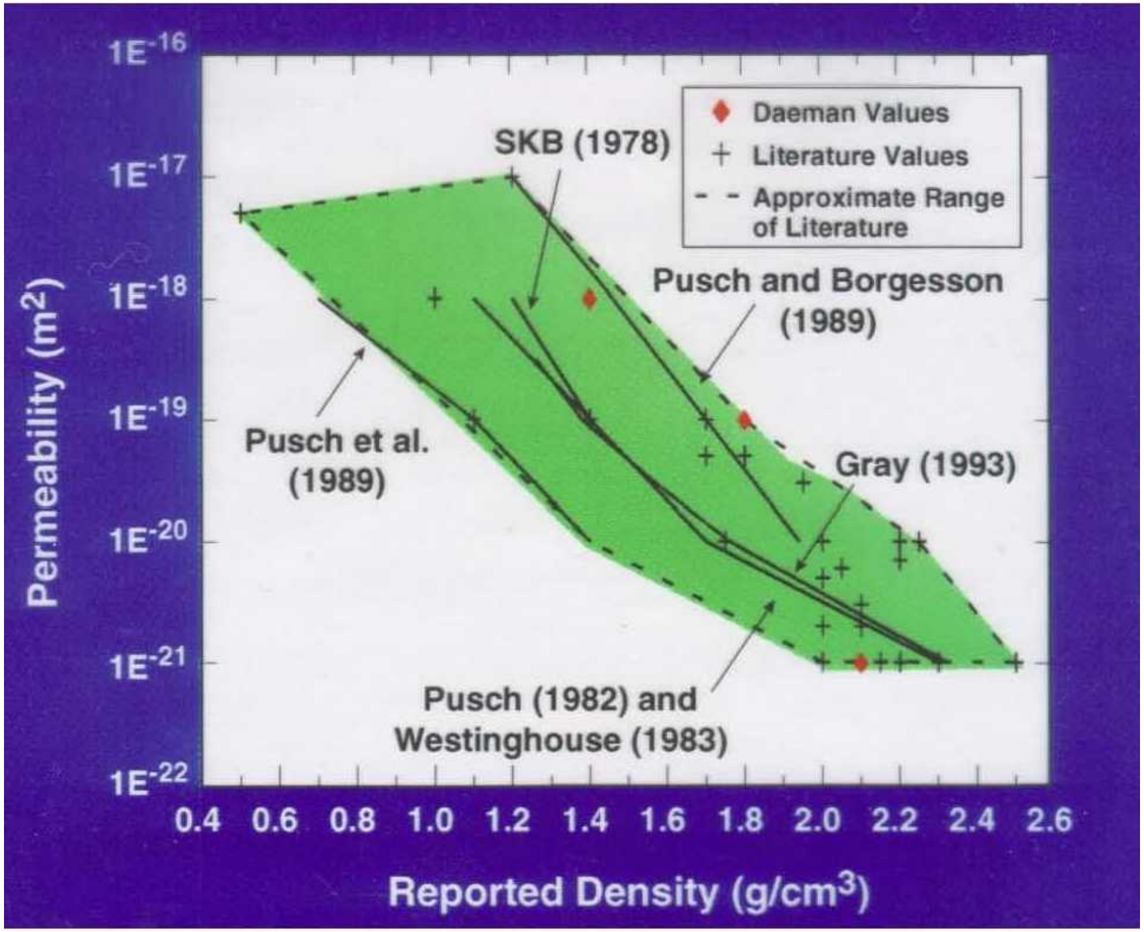
- **Functions**
  - Restrict groundwater flow
  - Limit transport of hazardous constituents
  - Provide structural support
  - Limit subsidence and inhibit entry

WIPP Shaft Seal Materials: **Concrete Mixture**

Material	lb/yd^3
Portland cement	278
Class F fly ash	207
Expansive cement	134
Fine aggregate	1292
Coarse aggregate	1592
Sodium chloride	88
Water	225

Kg/m^3 = (lb/yd^3) * (0.59) Water: Cement ratio is weight of water divided by all cementitious materials

WIPP Shaft Seal Materials: **Na-Bentonite Permeability Versus Density**



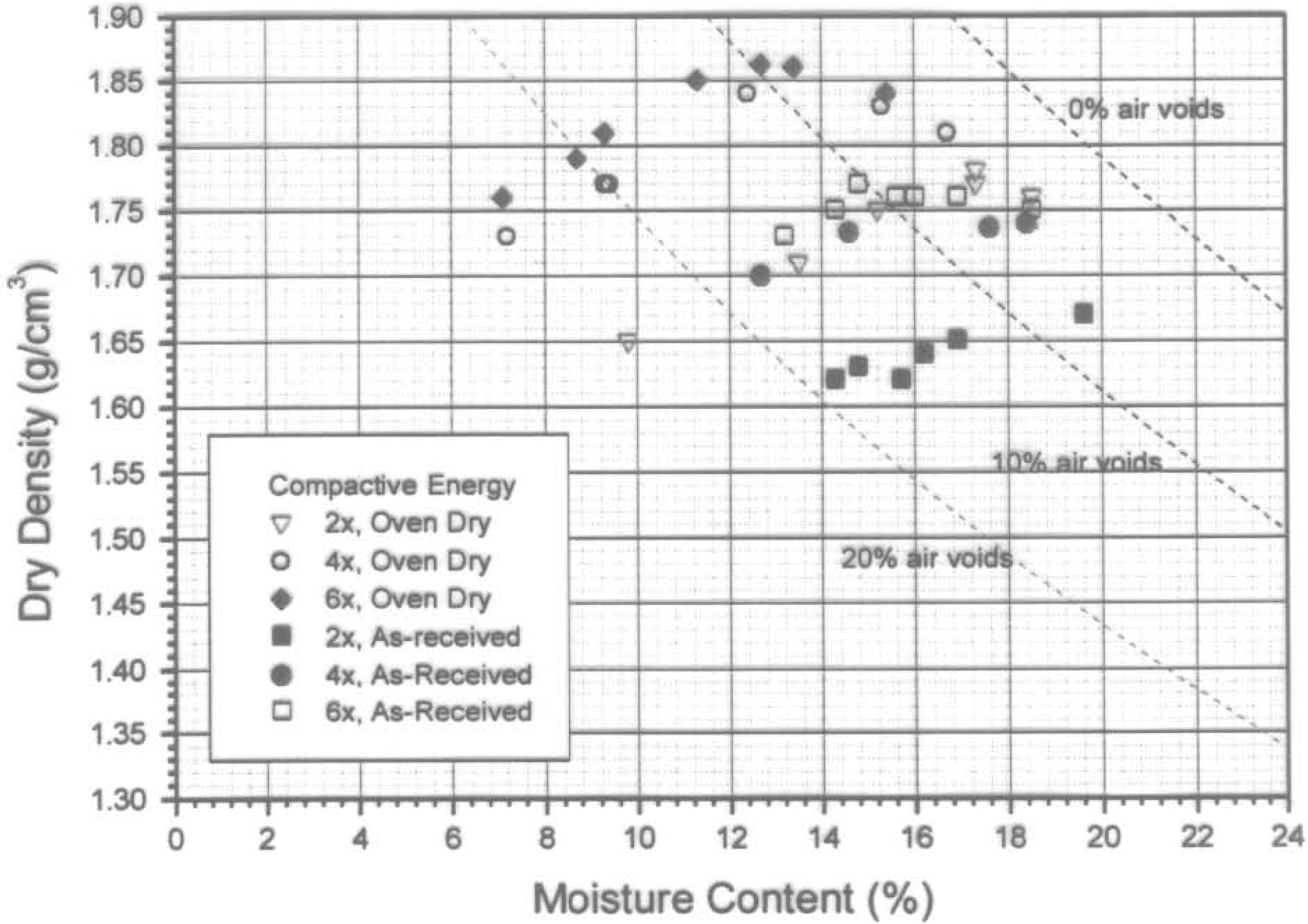
Typical Na-bentonite: MX-80 Wyoming bentonite

Studied by crystalline rock, bedded salt, and clay/shale repository programs.

Properties of interest:

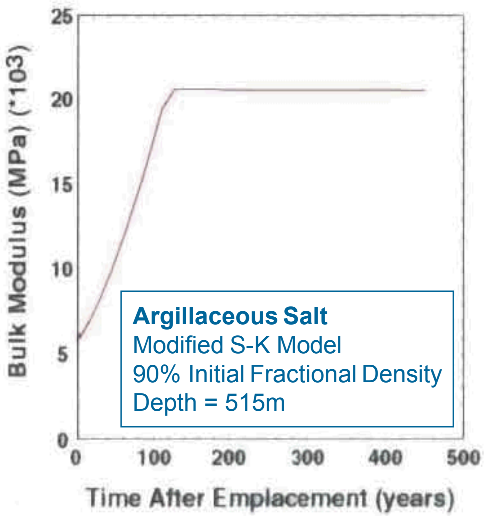
- Mineral content
- Pyrite and organic contents
- Potential water uptake
- Swelling pressure
- Cation loading
- Cation exchange capacity
- Chloride & sulfate contents
- Oxygen demand/redox potential
- pH

WIPP Shaft Seal Materials: **Bentonite Density vs. Moisture Content**

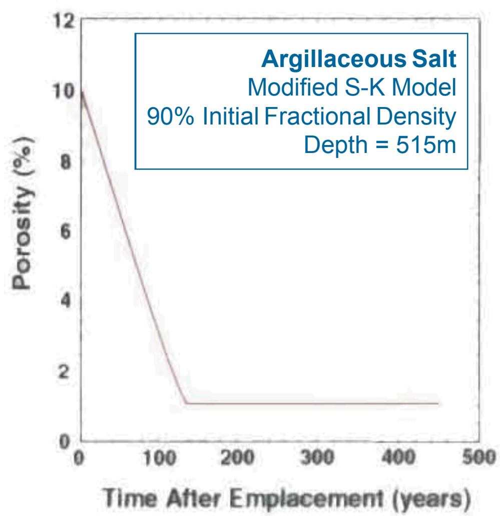


WIPP Shaft Seal Materials: **Reconsolidated Salt Properties**

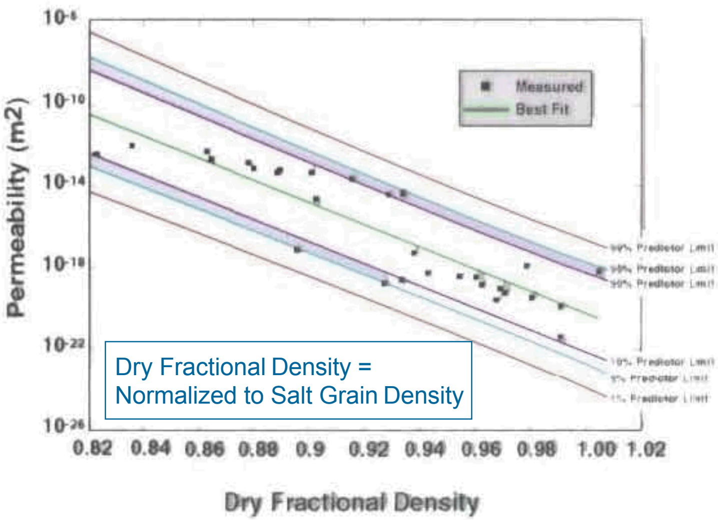
Bulk Modulus



Porosity



Permeability

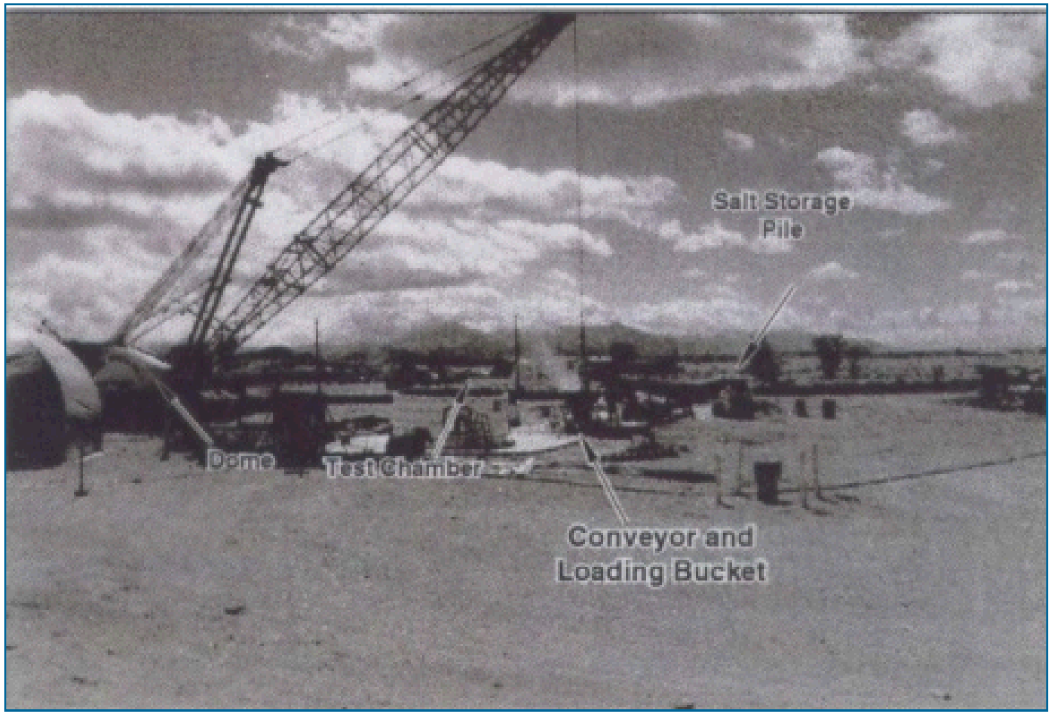


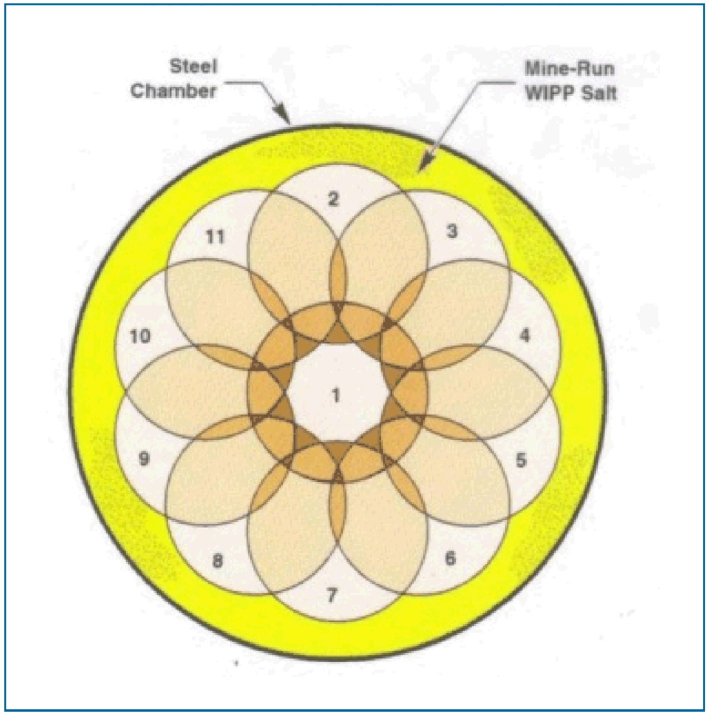
References:

Callahan, G.D., M.C. Loken, L.D. Hurtado and F.D. Hansen, 2007. *Evaluation of Constitutive Models for Crushed* Salt. SAND96-0791C, Sandia National Laboratories, Albuquerque, NM.

Sjaardema, G.D. and R.D. Krieg, 1987. *A Constitutive Model for the Consolidation of WIPP Crushed Salt and Its Use in Analyses of Backfilled Shaft and Drift Configurations*. SAND87-1977, Sandia National Laboratories, Albuquerque, NM.

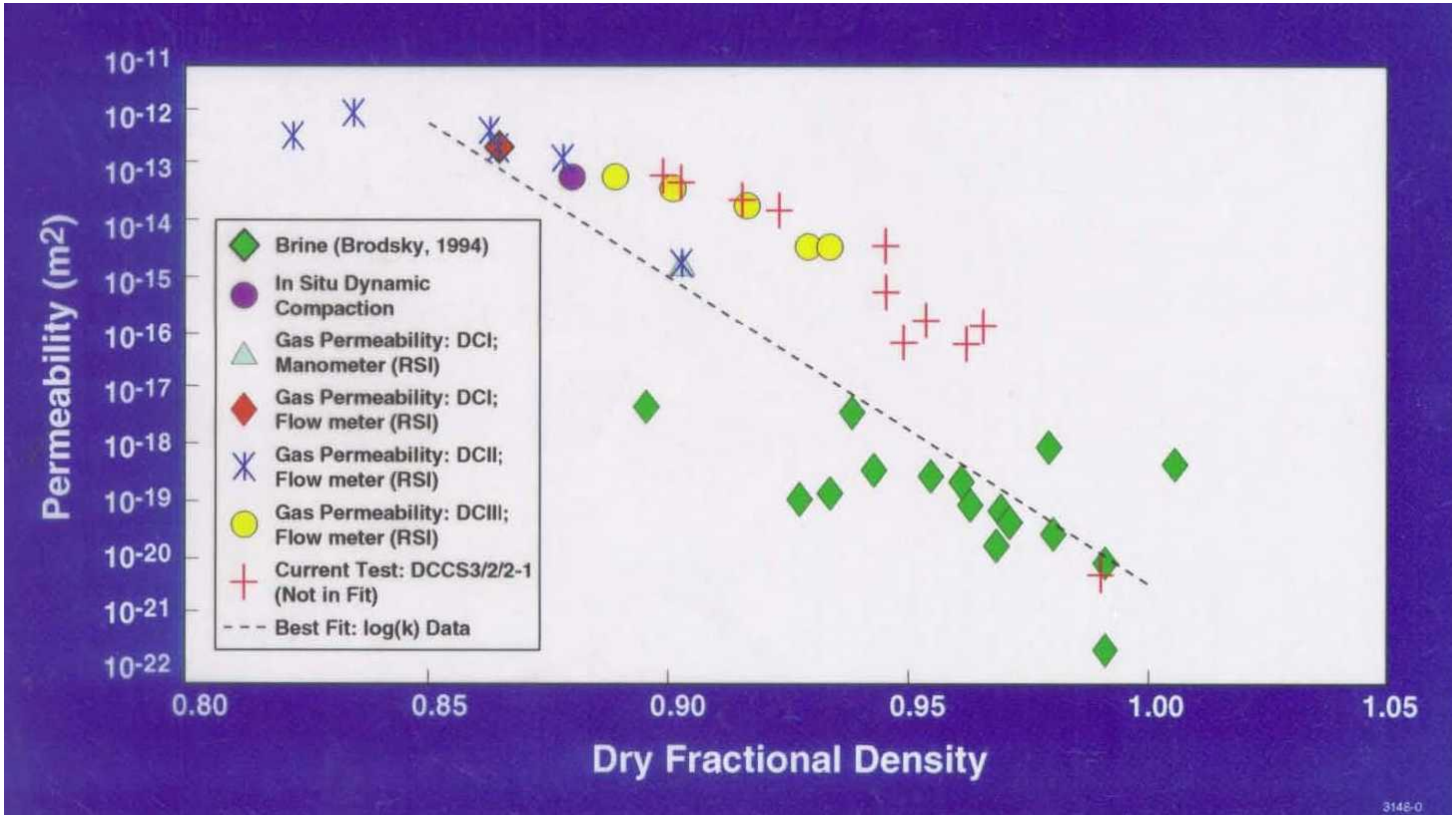
Compaction Test Area





Compaction Pattern (Shaft Face)

Permeability Versus Fractional Density for WIPP Crushed Salt

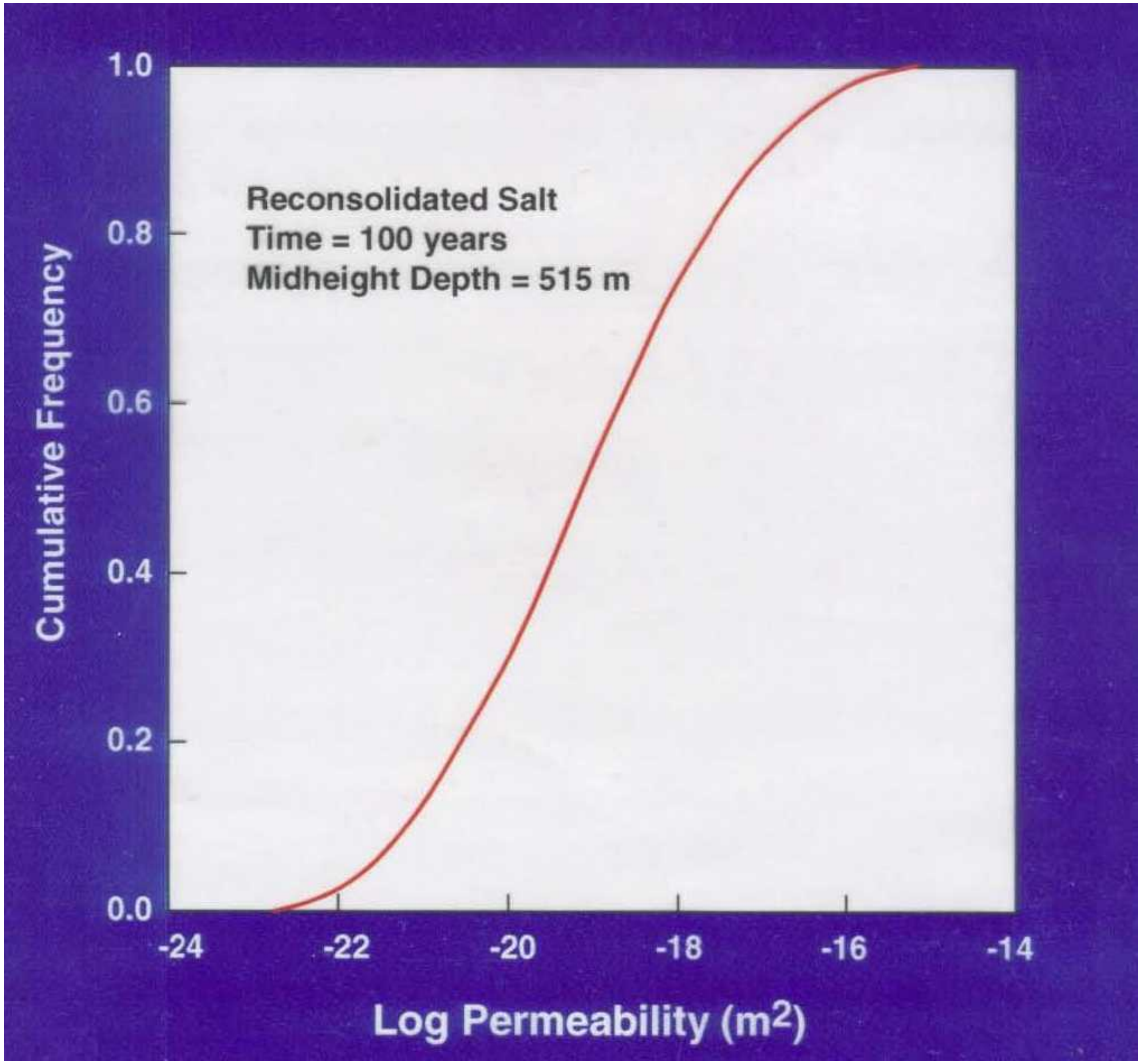


WIPP Shaft Seals: **Predicted Evolution of Compacted Crushed Salt**

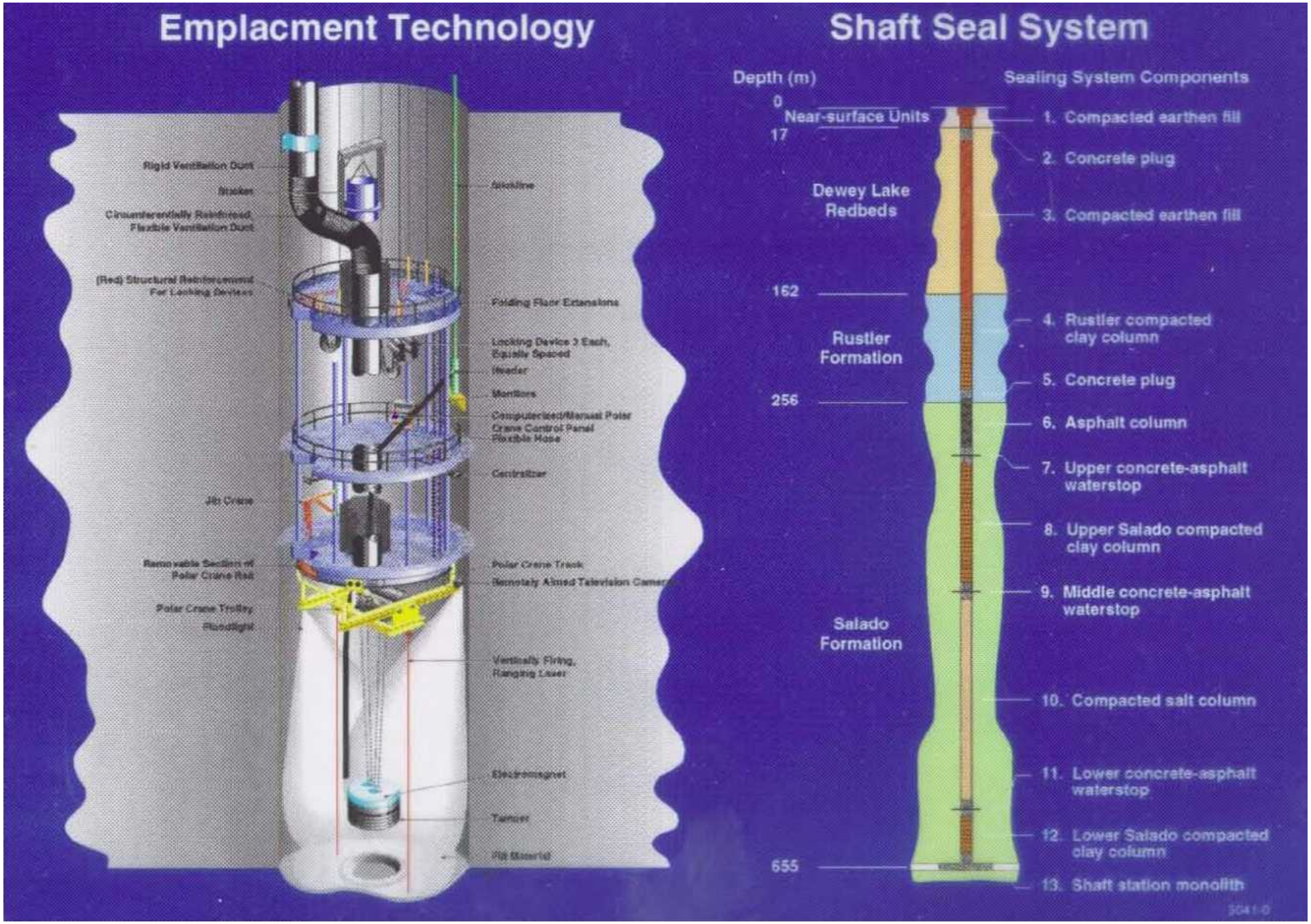
Evolution of Compacted Salt Permeability

Mid-Height of Shaft Salt Column

Prediction: Modified S-K Model



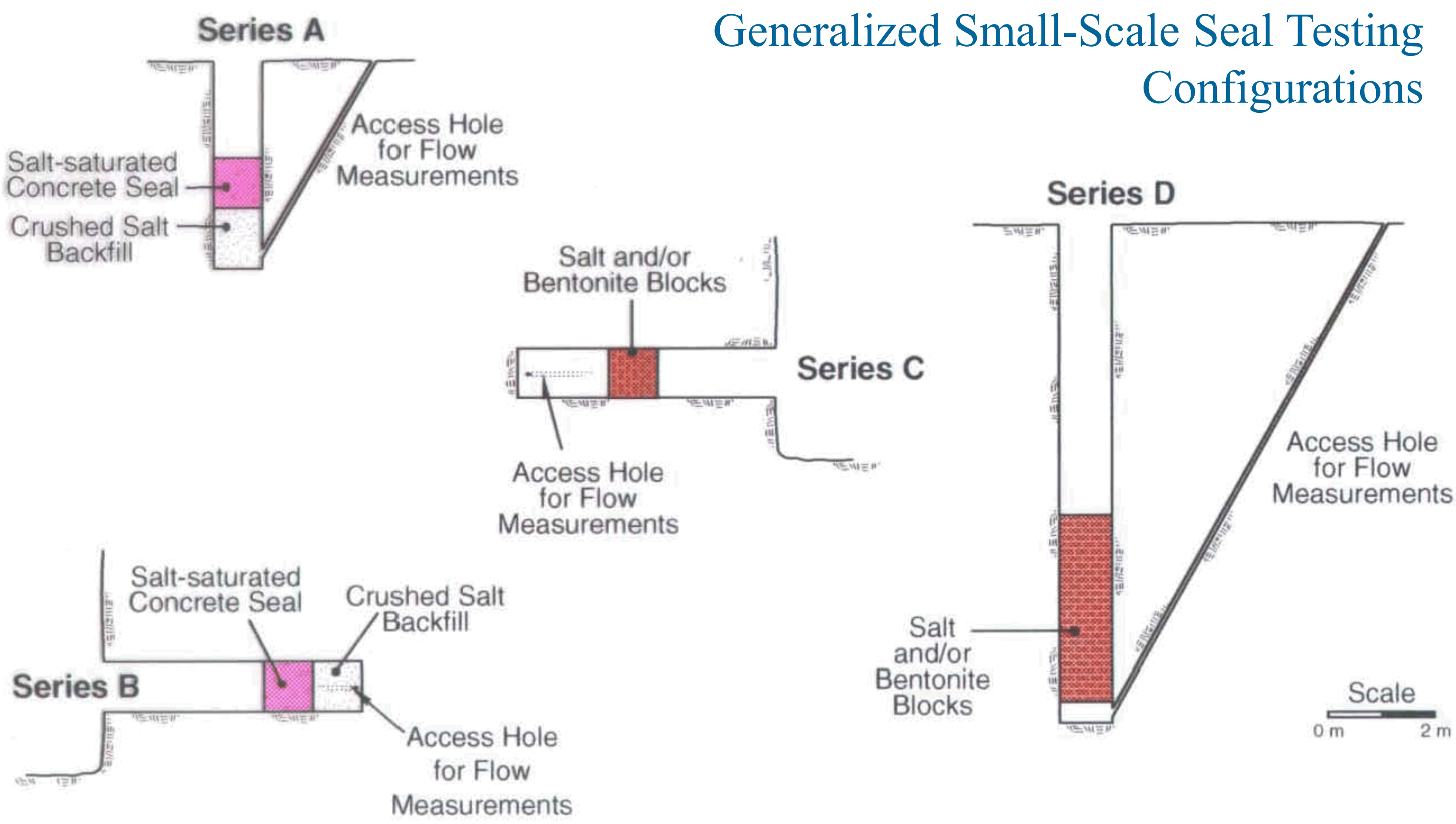
WIPP Shaft Seal and Emplacement Design



WIPP Small-Scale Seal Performance *In Situ* Testing

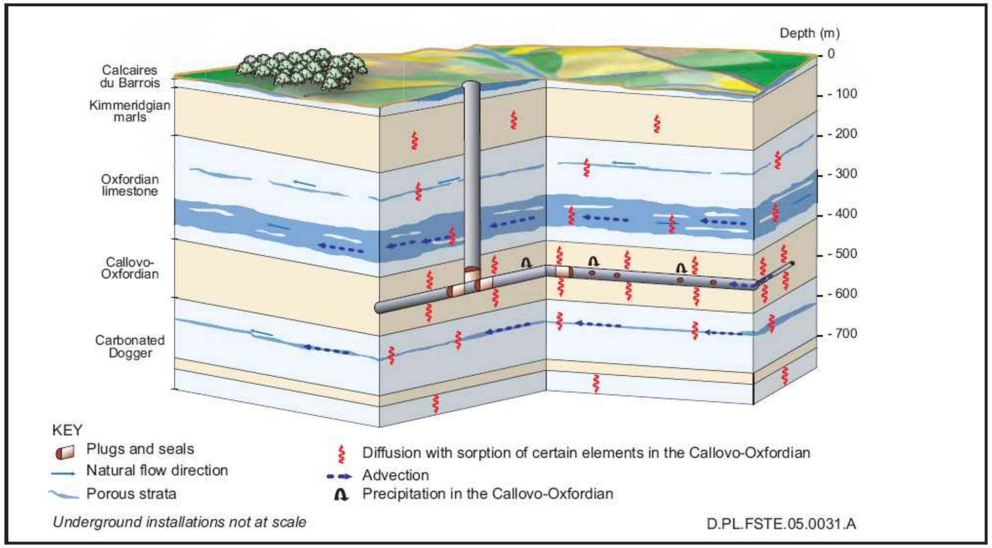
WIPP Shaft/Tunnel Seal Construction and Materials

Generalized Small-Scale Seal Testing Configurations



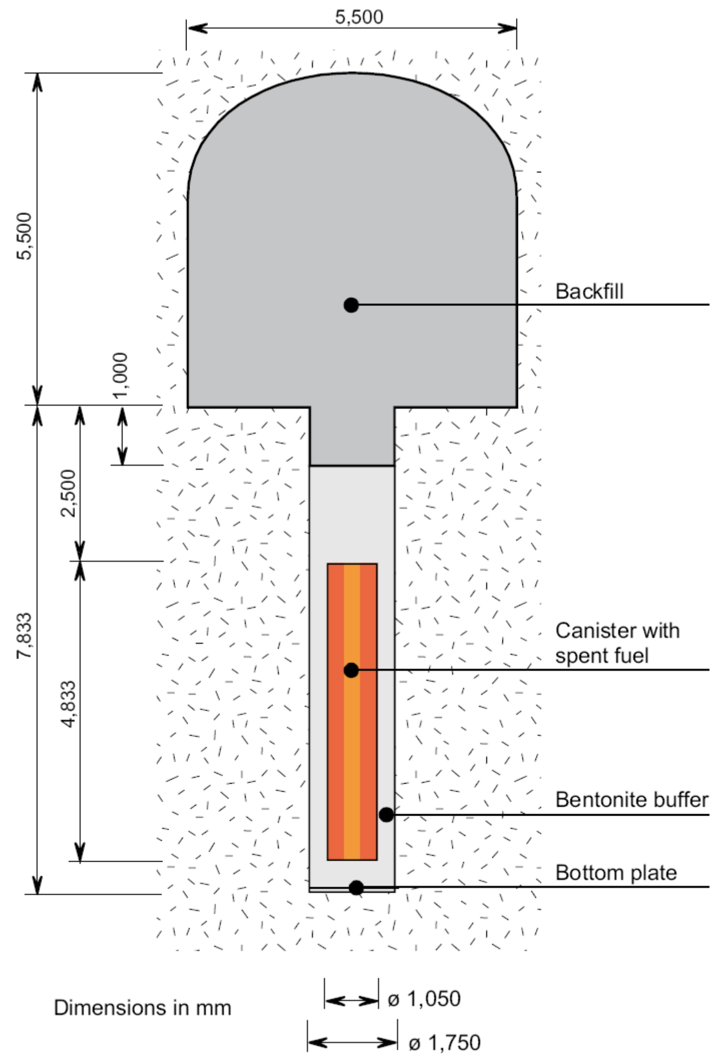
Seal Concepts for International Programs

- **Programs**
  - Sweden (SKB) Forsmark
  - France (Andra) Meuse-Haute Marne repository
- **Sealing Applications**
  - Buffer material (SKB)
  - Backfill buffer material for in-drift emplacement (NAGRA)
  - Deposition borehole seals/ plugs (Andra, SKB/Posiva)
  - Deposition tunnel backfill (SKB)
  - Deposition drift seals/plugs (SKB)
  - Repository tunnel and shaft seals (Andra, NAGRA, SKB)
  - Borehole seals (SKB)



Buffer Material Functions and Requirements - SKB

- **Functions**
  - [A] Limit advective transport (control piping)
  - Limit chemical transport (solubility, sorption)
  - Control canister corrosion environment
  - [A] Filter colloids (sat. density > 1,650 kg/m^3)
  - [A] Eliminate microbial activity ($P_{swelling}$ >2 MPa)
  - [B] Dampen rock shear
  - Resist transformation (T<100°C)
  - [A] Prevent canister sinking ($P_{swelling}$ >0.2 MPa)
  - [C] Limit pressure on canister and rock (T>-5°C)
- **Requirements**
  - Hydraulic conductivity < 10^{-12} m/s
  - [A] Saturated density > 1,950 kg/m^3
  - [B] Saturated density < 2,050 kg/m^3
  - [C] -5°C < T < 100°C in buffer



Source: SKB SR-Can 2006

Candidate Buffer Materials - SKB

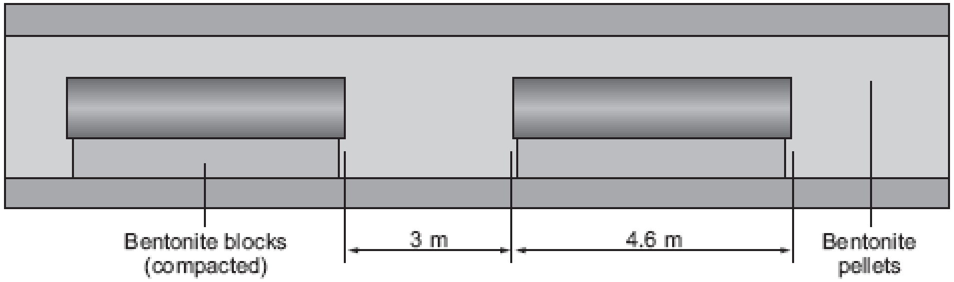
- **Composition of MX-80 (sodium) and Deponit CA-N (calcium) bentonite materials**

Component	MX-80 (wt %)	Deponit CA-N (wt %)	Uncertainty (± wt %)
Calcite + Siderite	0–1	10	1
Quartz	3	1	0.5
Cristobalite	2	1	0.5
Pyrite	0.07	0.5	0.05
Mica	4	0	1
Gypsum	0.7	1.8 (anhydrite)	0.2
Albite	3	0	1
Dolomite	0	3	1
Montmorillonite	87	81	3
Na	72%	24%	5
Ca	18%	46%	5
Mg	8%	29%	5
K	2%	2%	1
Anorthoclase	0	2	1
CEC (meq/100 g)	75	70	2
Organic carbon	0.2	0.2	–

Source: SKB SR-Can 2006

Buffer Backfill for Drift Emplacement - NAGRA

Emplacement concept (repository in crystalline or clay media)



Engineered Barrier Emplacement (EB) Project, Mont Terri URL (Opalinus Clay)

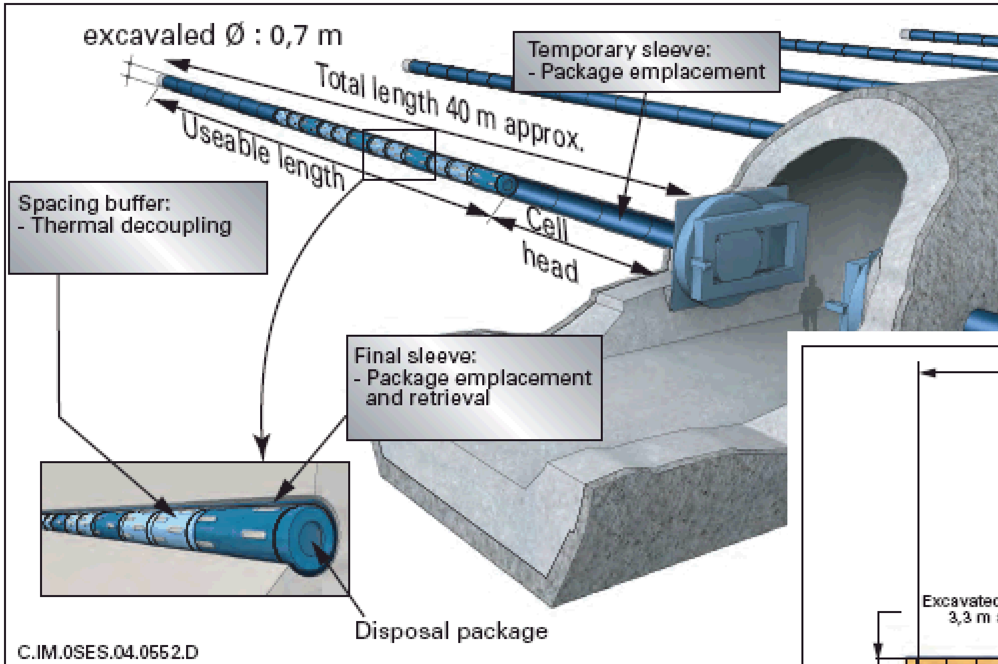
Highly compacted bentonite blocks, in-filled with bentonite pellets.

Artificial hydration, ambient temperature only.

Source: Safety Assessment Management Ltd. 2008. *The International RD&D Basis of Geological Repositories.*

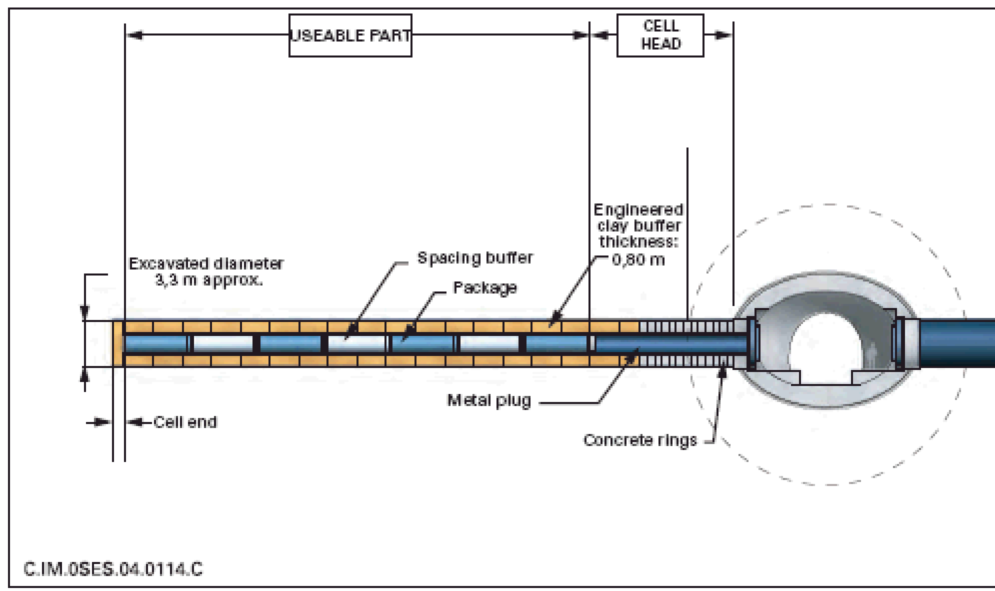
Deposition Borehole Seals/Plugs - Andra

"Dossier 2005 Argile" Concepts for Type C/CU Waste Cells - Clay Repository



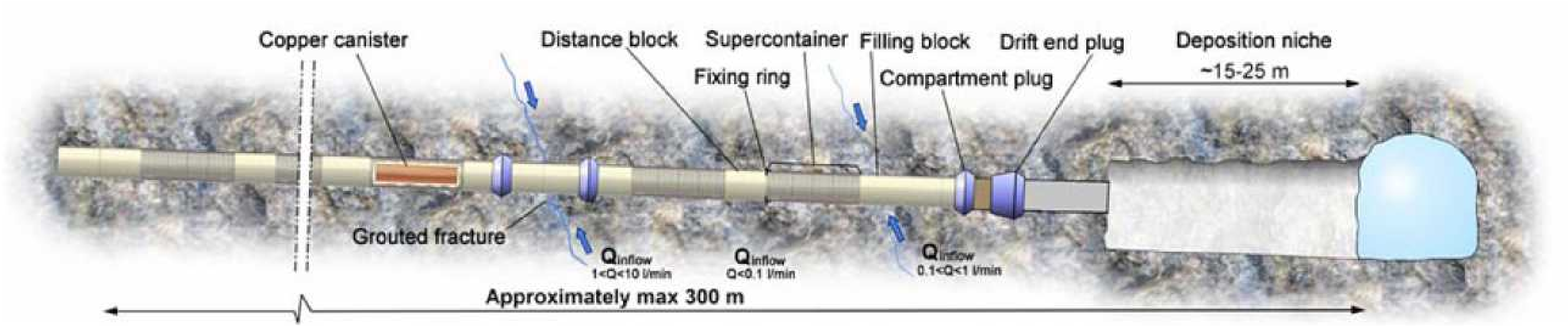
Type C - HLW disposal in ~0.7-m diameter boreholes

Type CU - Spent fuel disposal in ~3-m Ø tunnels



Source: Andra Dossier 2005 Argile

KBS-3V and -3H Deposition Borehole Seals - SKB/Posiva

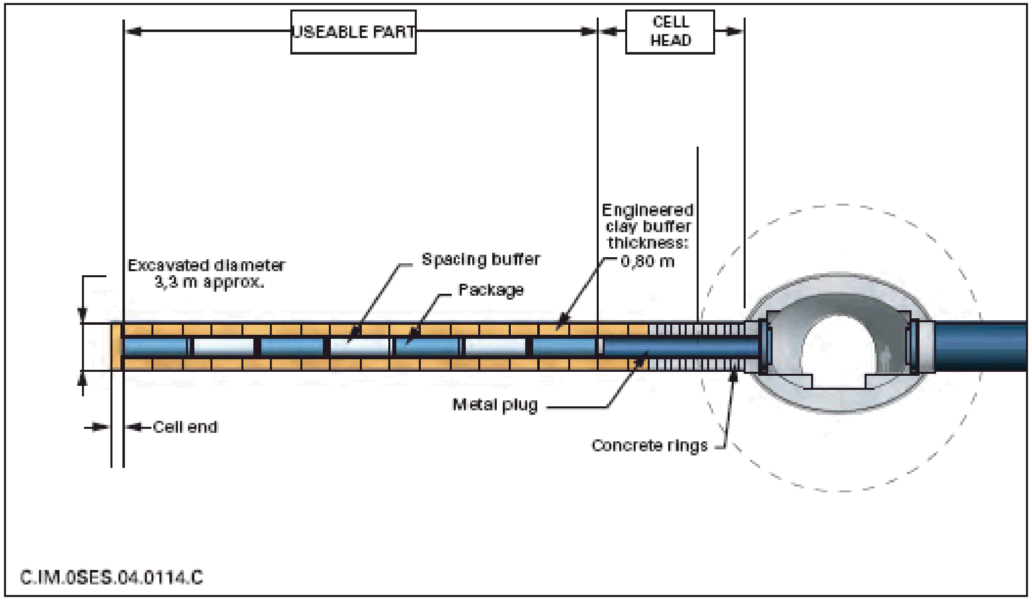


- **Control of Erosion and Piping**
  - Seals surrounding each waste package must withstand inflow of 0.1 L/min, or
  - Grouting or rock can limit inflow to 0.1 L/min, especially during initial hydration, from unsaturated to saturated conditions
  - Limit buffer loss (e.g., < 100 kg/waste package)
  - Evaluate clay/sand mixtures for resistance to erosion and piping

Source: SKB SR-Can 2006

Deposition Borehole Seal/Plug Functions and Requirements - Andra

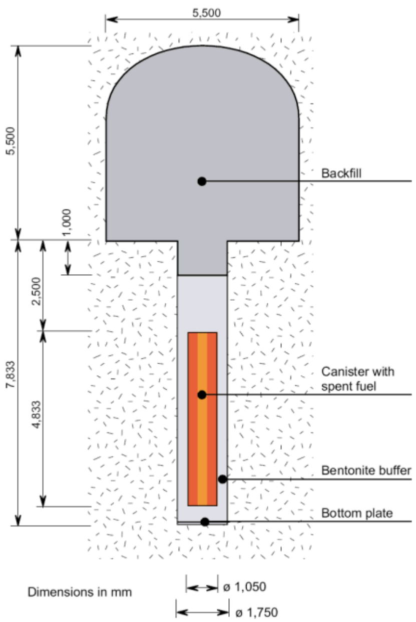
- **Functions**
  - Compacted bentonite seal isolates waste from the tunnel and its EDZ
  - Hydrated seal allows gas pressure to escape, then re-seals
  - Rigid plug stabilizes seal
    - Concrete plugs in cells containing spent fuel
    - Metal plugs in cells containing HLW glass
  - Maintain diffusion-dominated transport (Peclet Number < 1)

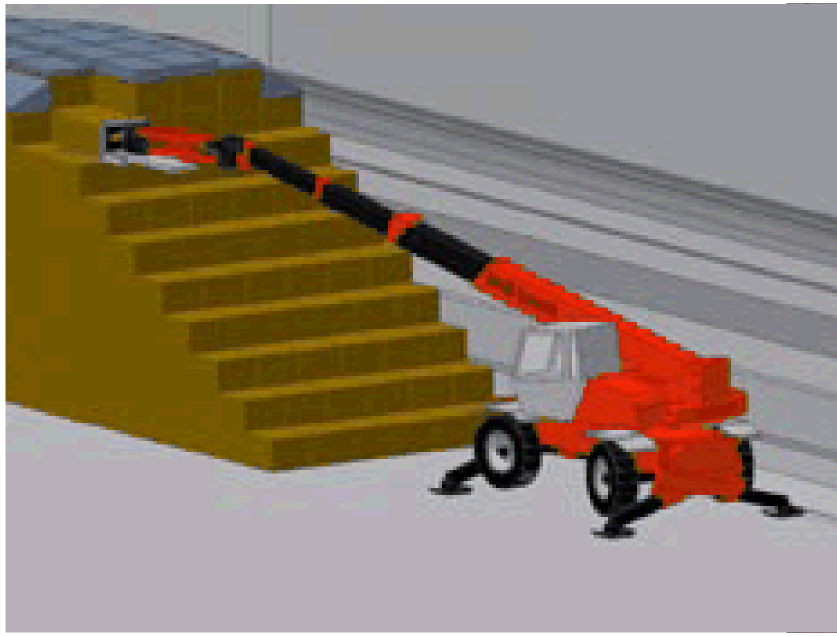


- **Requirements**
  - To be determined

Source: Andra Dossier 2005 Argile

Deposition Tunnel Backfill - SKB



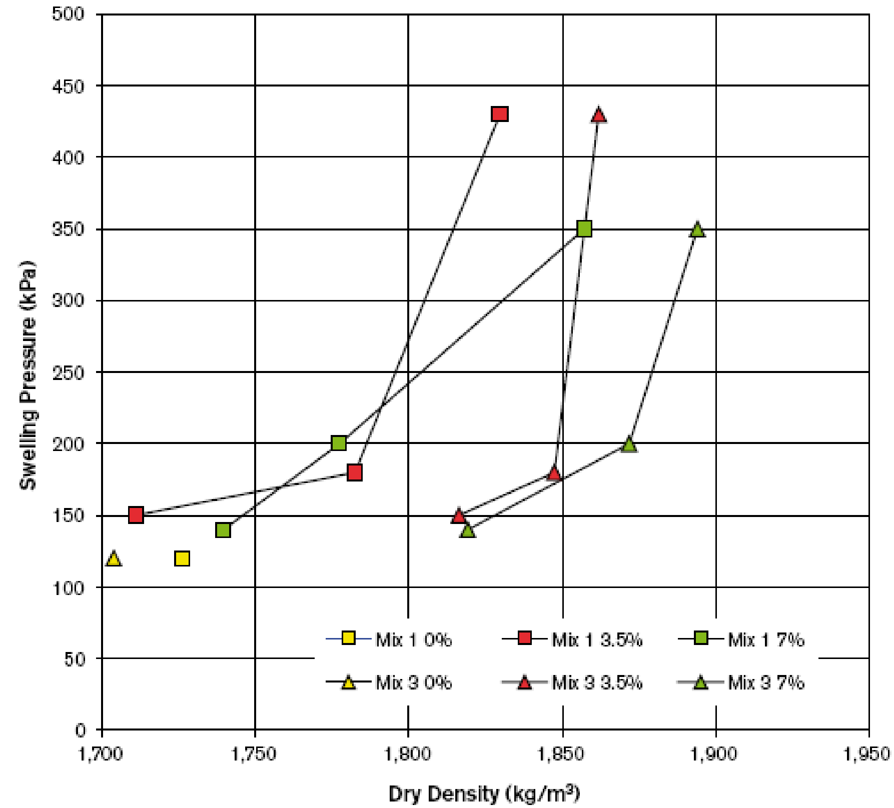


- Deposition tunnel + upper 1 m of deposition holes
- Backfill, grouted holes, and other materials (e.g., shotcrete)

Source: SKB SR-Can 2006

Deposition Tunnel Backfill - SKB

- **Backfill Requirements:**
  - Minimum swelling pressure 0.1 MPa
  - Hydraulic conductivity $<10^{-10}$ m/s
  - Swelling pressure >0.1 MPa
  - Temperature >0°C
- **Candidate Materials**
  - 30/70 bentonite/sand mix
  - Natural Friedland Clay



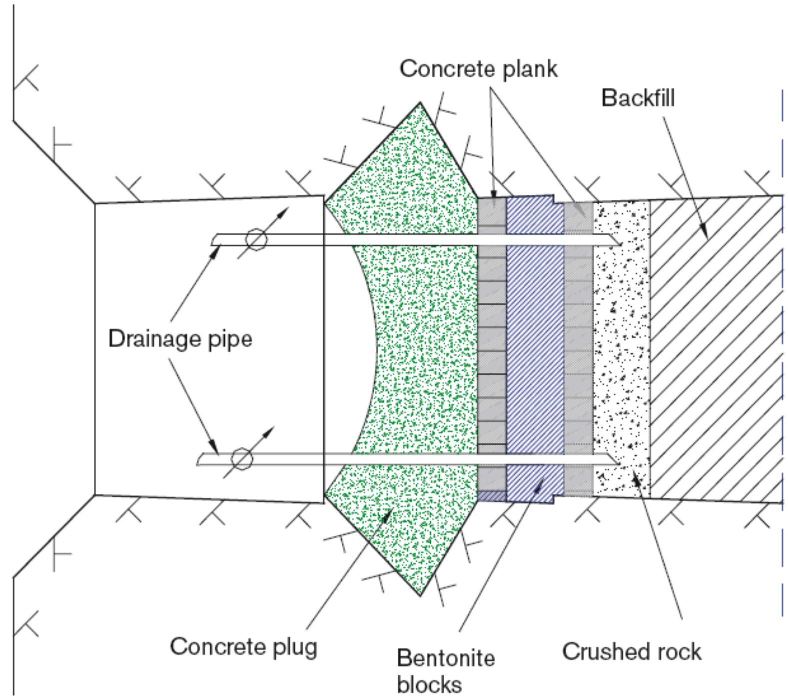
Swelling pressure of different bentonite/sand (30/70) mixtures in 3.5% and 7% NaCl

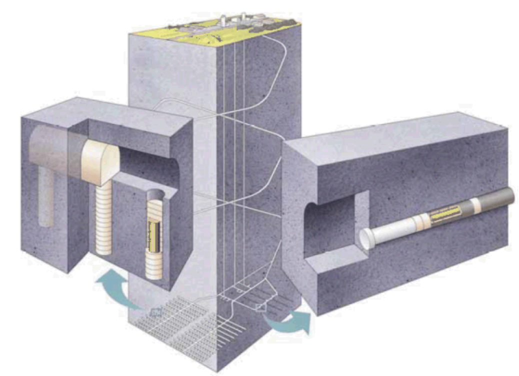
(Mix 1 is *MX-80*; Mix 3 is *Deponit CA N*, a Ca,Mg montmorillonite)

Source: SKB SR-Can 2006

Deposition Drift Seals/Plugs - SKB

- **Deposition tunnels will be sealed before backfill of the main tunnel**
- **Functions:**
  - Mechanical support for hydrostatic and swelling pressures
  - Prevent water inflow (piping)
- **Design:**
  - Low pH reinforced concrete
  - Anchored by friction or notch
  - Bentonite seal
  - Slimilar to prototypes at Aspo URL
  - No postclosure safety function

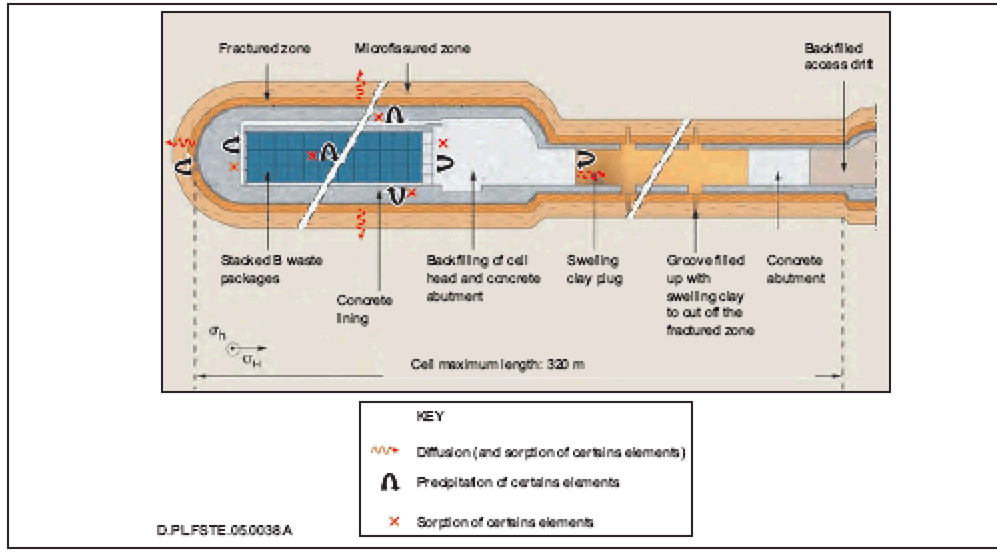




Source: SKB SR-Can 2006

Repository Tunnel, Shaft and Ramp Seals - Andra

- Drift/Tunnel Seal Design
  - Core of swelling clay
  - Core retained by concrete
  - Granular backfill
  - “Scrape” EDZ before sealing, or
  - Excavate a hydraulic keyway
  - Tens of meters long



- Shaft Seals
  - Fill the shaft base and stations with concrete
  - Emplace a swelling clay seal over a height of about 30 in the shaft
  - Backfill the shaft with argillite up to the surface
  - Emplace a plug of swelling clay (10 to 15 m) at hydrologic units where groundwater is present

> ***“Seals play an important part….but should not compromise, on their own, the overall repository safety.” (Andra Dossier 2005 Argile)***

Shaft Seal - NAGRA

- Similar to Andra concept
- Protect repository from aquifer inflow above/below host rock
- Remove rock from EDZ in seal section
- Use concrete for structural stability
- Isolate concrete from bentonite seal materials

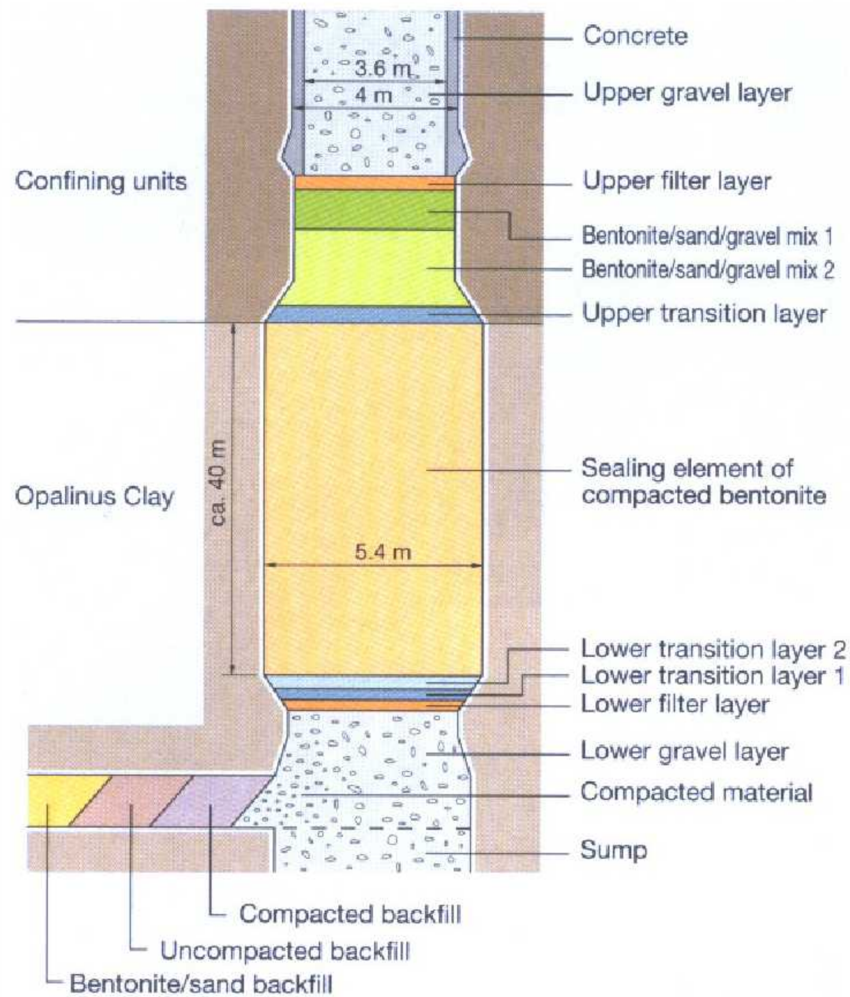
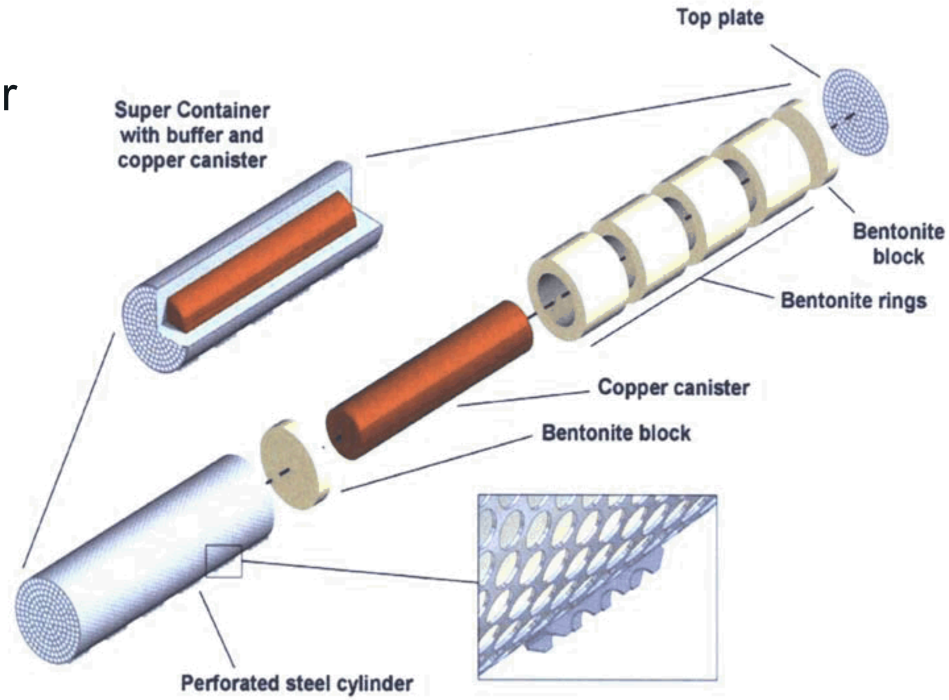


Figure source: Safety Assessment Management Ltd. 2008. *The International RD&D Basis of Geological Repositories.*

Borehole Seals - SKB

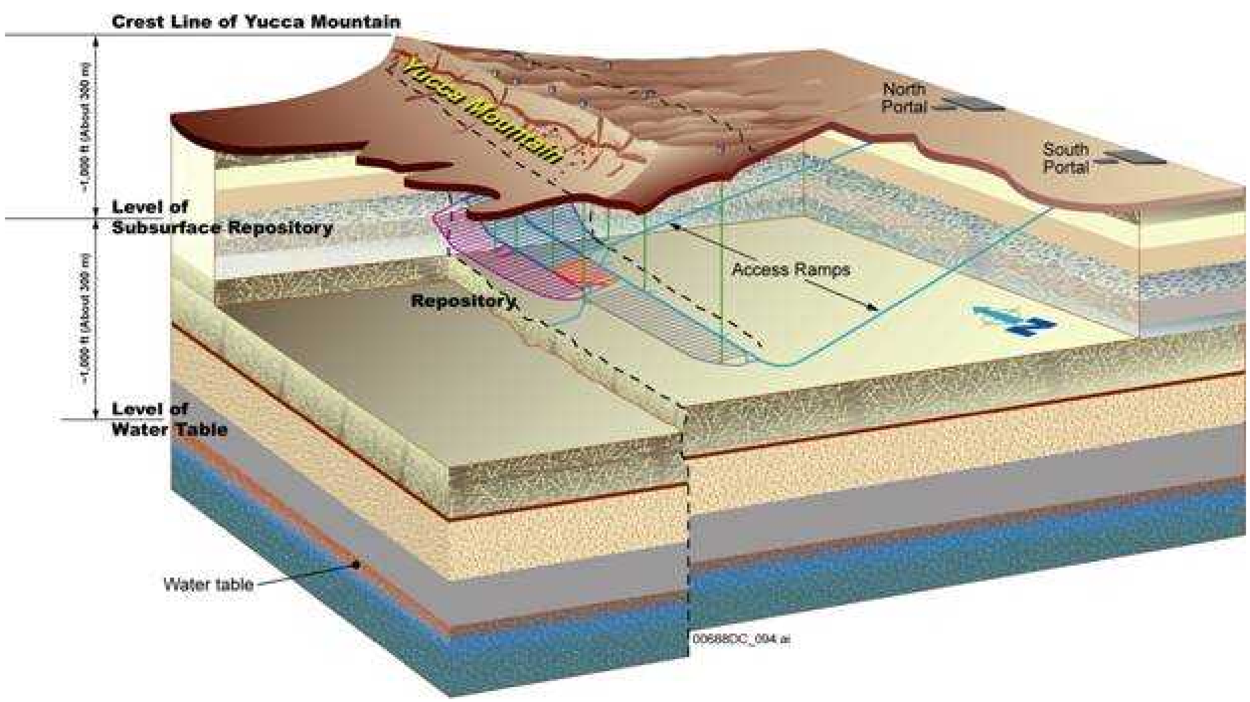
- **Functions and Objectives**
  - Prevent short-circuiting of flow of potentially contaminated groundwater from the repository
  - Less transmissive than the undisturbed, surrounding rock
  - Plug materials maintain their constitution and tightness for a long time
- **Description**
  - Surface boreholes
    - Compacted till (0–3 m)
    - Close-fitting rock cores (3–50 m)
    - Compacted till (50–60 m)
    - Bentonite pellets (60–100 m)
    - Highly compacted smectite clay contained in perforated copper tubes (below 100 m)



  - Tunnel-based boreholes
    - Filled with highly compacted smectite clay in perforated copper tubes

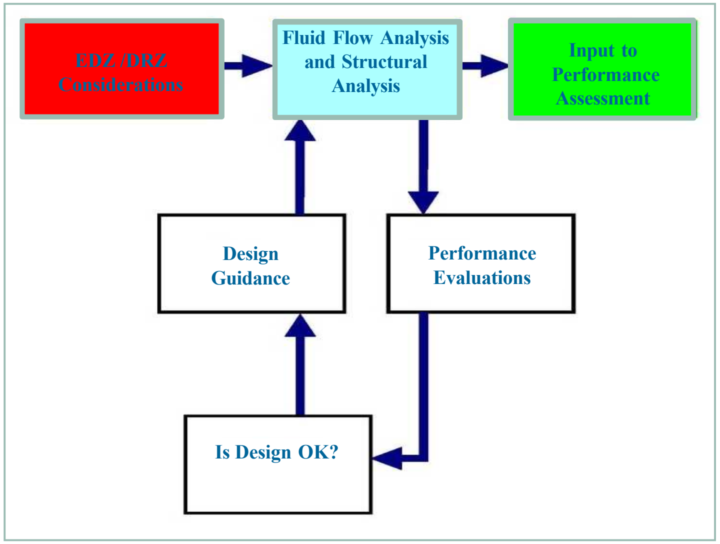
Seals for Unsaturated Host Media

- Sealing and plugs control access, not flow
- Encourage inflow to flow back into the rock without accumulating (promote free drainage)
- Shafts, drifts, ramps
  - Crushed rock
  - Surface plugs
- Boreholes
  - Crushed rock
  - "Plug and abandon"



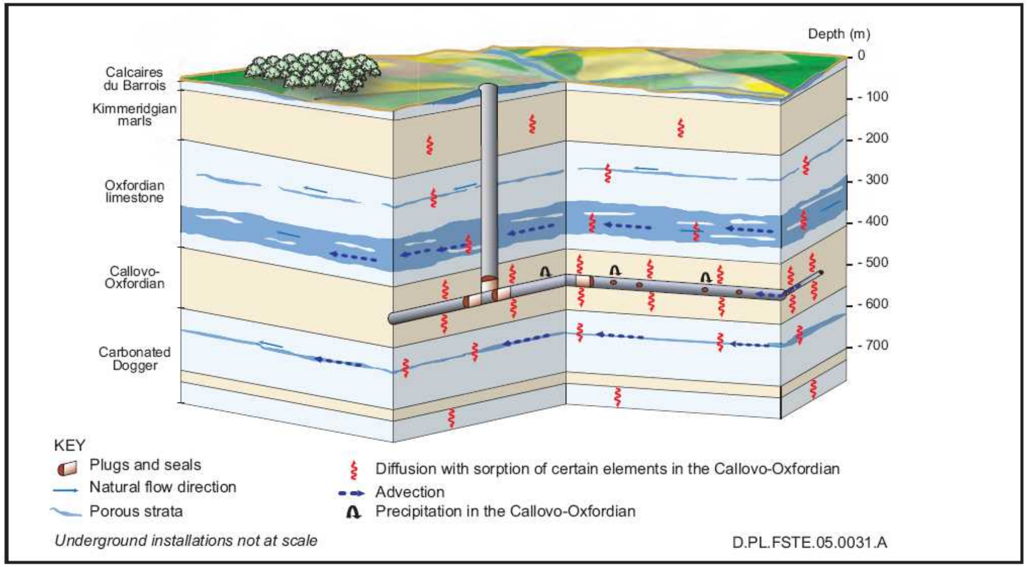
Summary

- Systems approach to seal design
- Functions
  - Restrict groundwater flow
  - Limit transport of hazardous constituents
  - Provide structural support
  - Limit subsidence and inhibit entry
- Objectives
  - Mechanical and chemical compatibility
  - Use available construction methods and materials
- Requirements
  - Determine from performance evaluations



Summary, continued

- Use of clay materials
  - Low permeability
  - Swelling (self-sealing, support pressure)
- Buffer/seal degradation mechanisms
  - Piping during initial hydration (e.g., limit inflow to 0.1 L/min per waste package; use grouting)
  - Erosion against high-permeability faults/fractures (e.g., limit to < 100 kg buffer per waste package)
  - Alternating salt-fresh water inflow
  - Over-temperature and freezing



Ideally, seals and plug functions ensure host-rock barrier integrity.

Backup Slides

Bedded Salt Attributes

- Easily mined or excavated
- High thermal conductivity (~5 W/m-K)
- Wide geographic distribution (many potential sites)
- Behaves plastically in repository applications *
- Essentially impermeable; porosity not inter-connected *
- Fractures in salt are self healing *
- Salt has existed underground for millions of years *

* Attributes of Natural Barrier

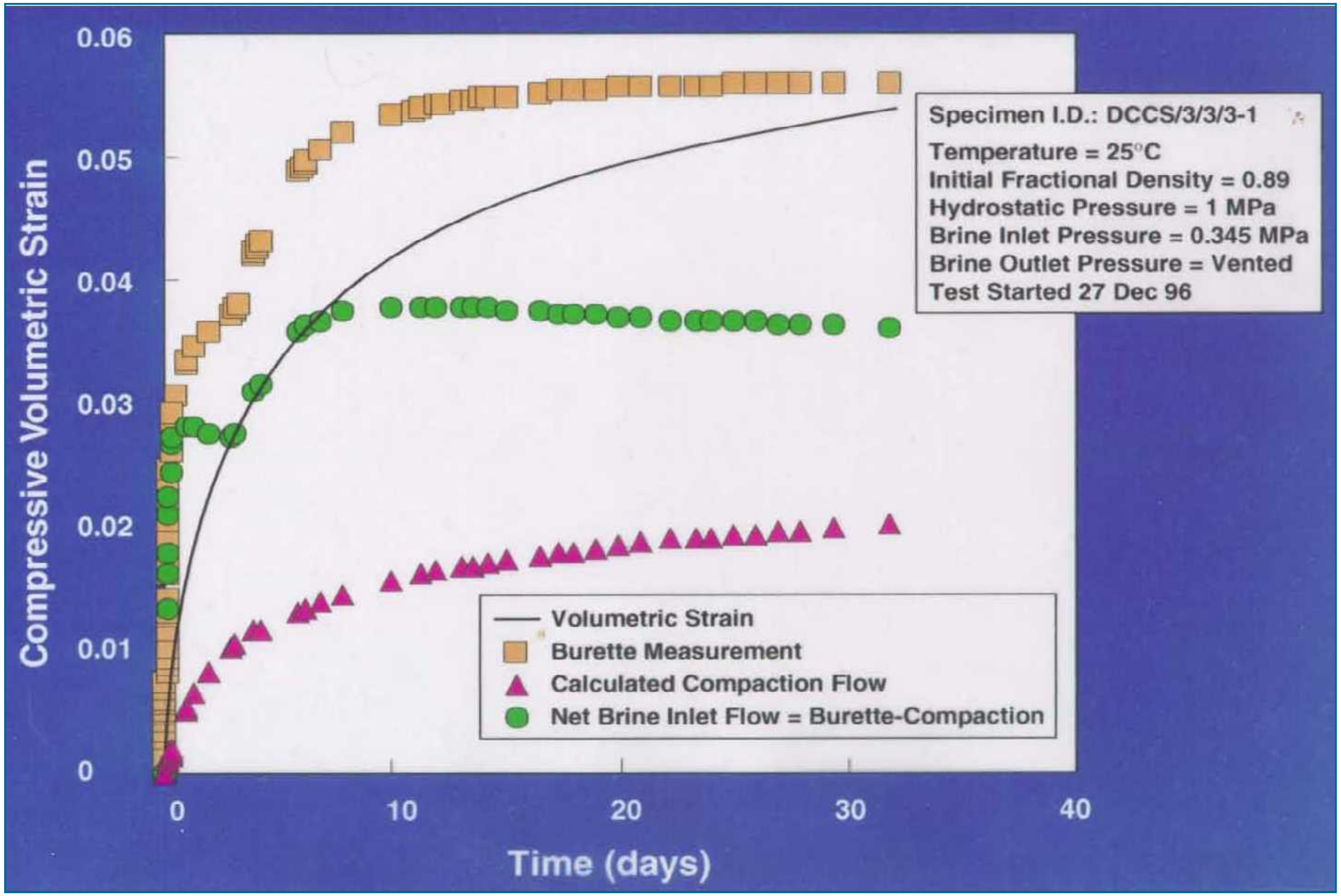
Assessing Engineered Barriers for WIPP

The U.S. Environmental Protection Agency defines barriers as

> "any material or structure that prevents or substantially delays movement of water or radionuclides toward the accessible environment"

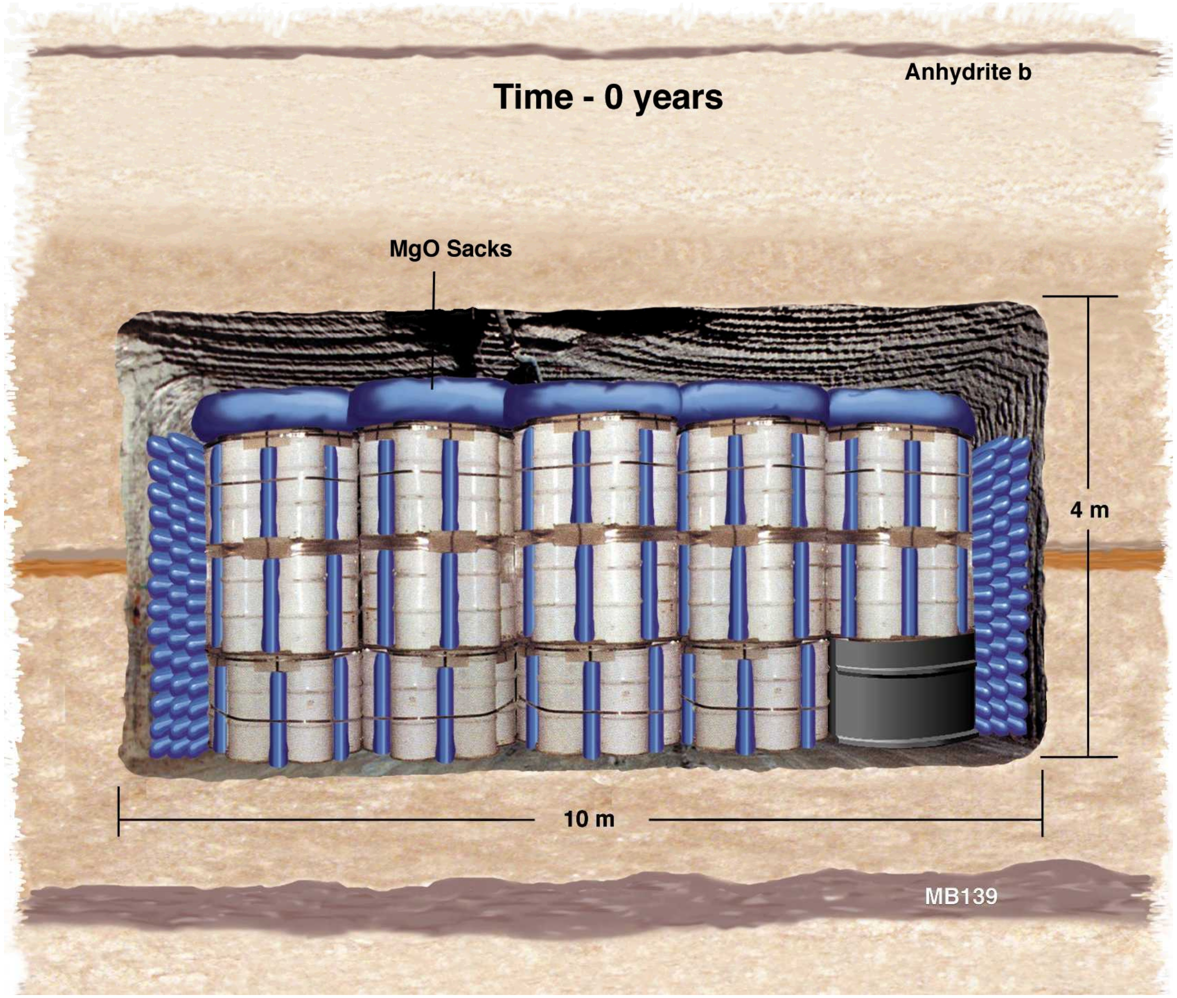
1. Geology – the Most Important Barrier
2. Shaft Sealing System
3. Panel Closure System
4. Magnesium Oxide Engineered Barrier
5. Waste Package
6. Borehole Plugs

Brine Permeability Tests on Specimen DCCS/3/3/3-1

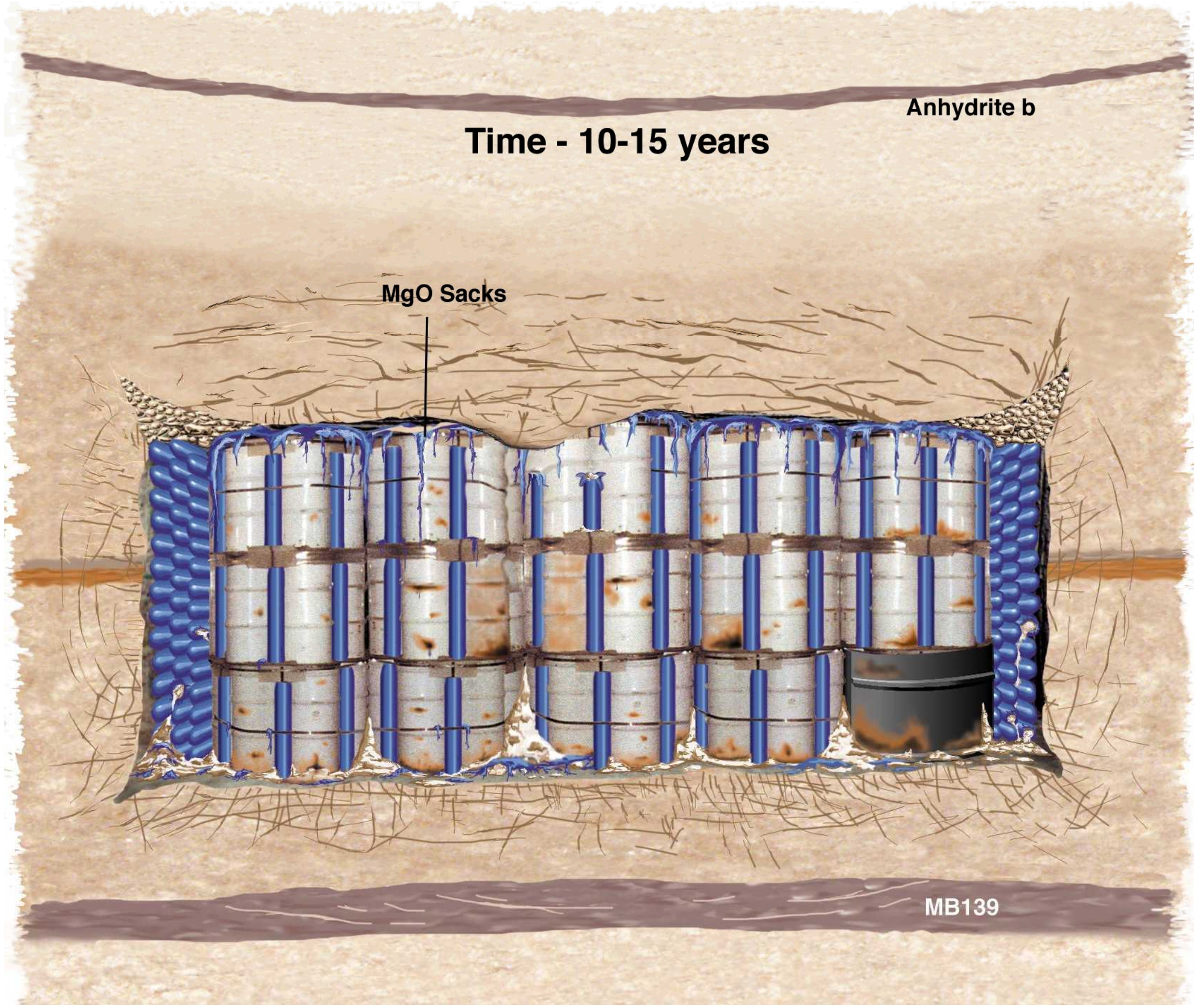


WIPP Disposal Room Evolution - Emplacement

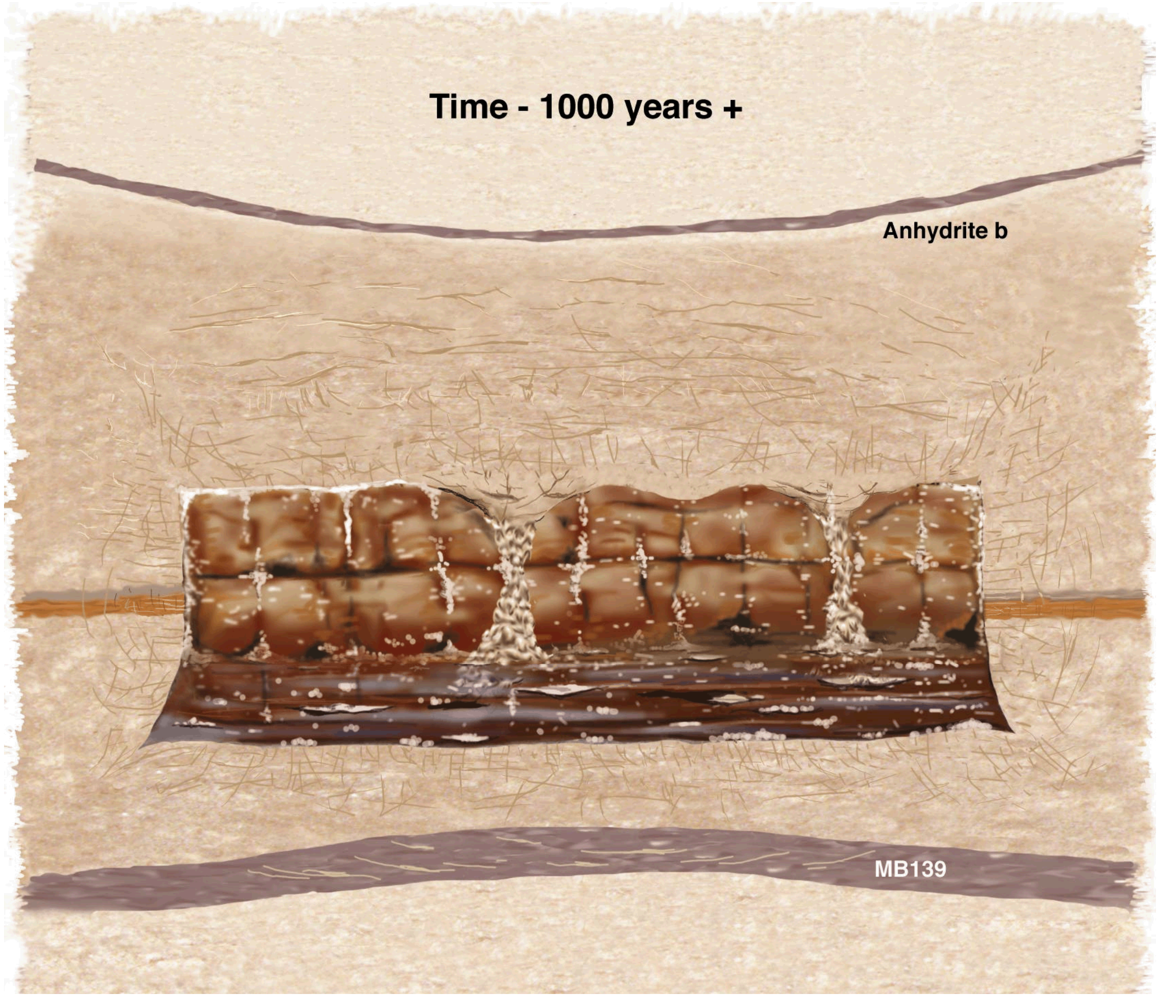
WIPP Disposal Room Evolution - Emplacement



WIPP Disposal Room Evolution - 12 Years



WIPP Disposal Room Evolution - 1,000 Years



Historical Review of WIPP Backfill

Strategic Goals*

1. Controlling radionuclide migration by scavenging specific radionuclides
2. Buffering the chemical environment to lower radionuclide solubilities, scavenge gases (notably CO_2), or minimize canister and waste corrosion
3. Providing a hydrologic barrier to divert or impede groundwater access
4. Dissipating radiogenic heat and provide radiation shielding (for defense high level waste only)
5. Providing a "sink" to chemically bind limited amounts of groundwater projected to enter the repository in certain scenarios
6. Providing these functions with regard to cost-effectiveness, operational safety, and operational simplicity

Early Testing Considered HLW

Bentonite/Salt/Sand Mixtures Were Evaluated

- Sorb radionuclides
- Withstand elevated temperature

Present Day MgO Selected to Scavenge CO_2

*Krumhansl et al., SAND 99-0404C

WIPP MgO Engineered Barrier Safety Function

- MgO will act as an engineered barrier by decreasing P_{CO2} and thereby decreasing actinide solubilities
- Control P_{CO2} and pH.
- Only engineered barrier recognized by U.S. EPA
- Lab studies show MgO will remove H_2O and CO_2.