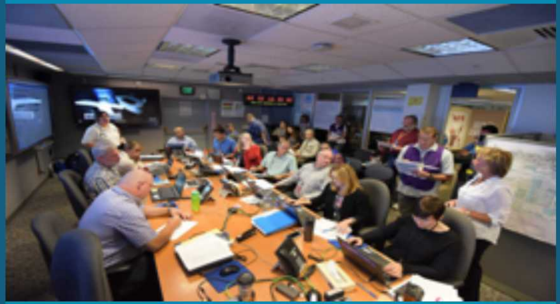
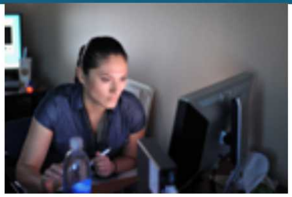
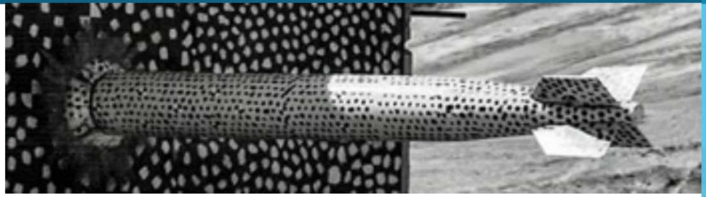
SAND2019-5255PE

L7: EBS Testing and Design







PRESENTED BY

Edward N. Matteo

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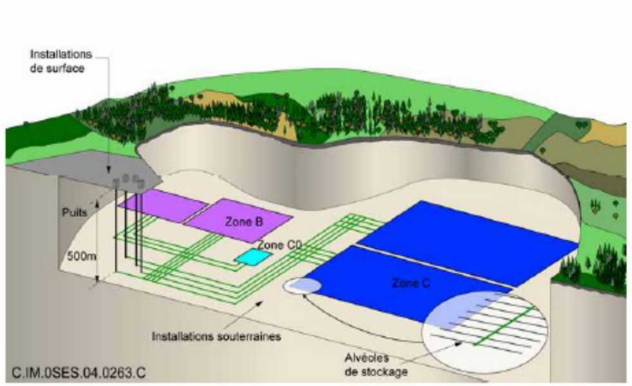
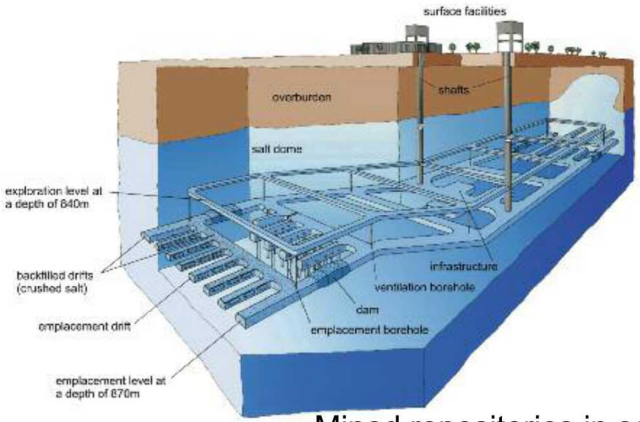
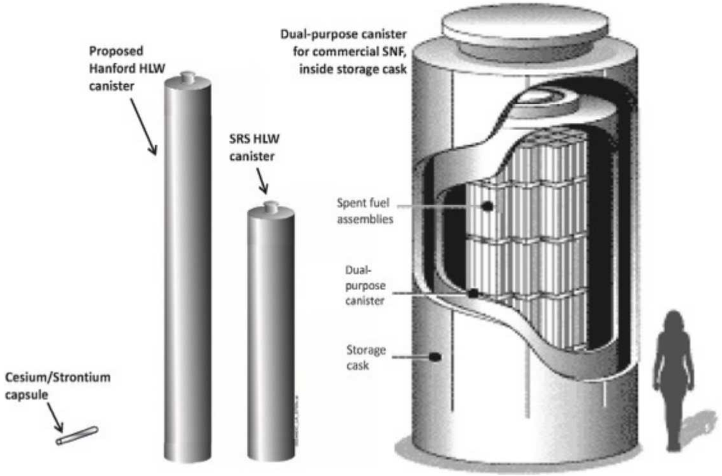
Disposal Concepts

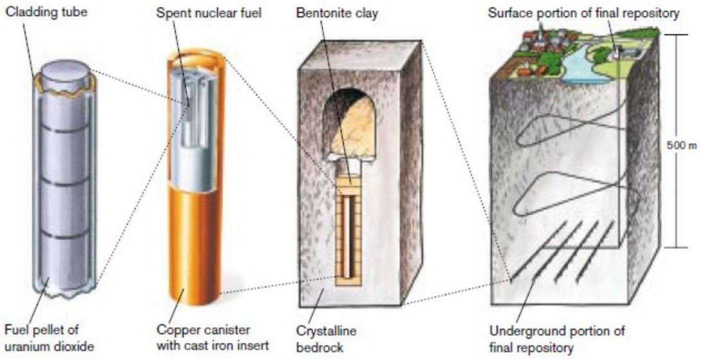


Mined repositories in clay/shale (ANDRA 2005)



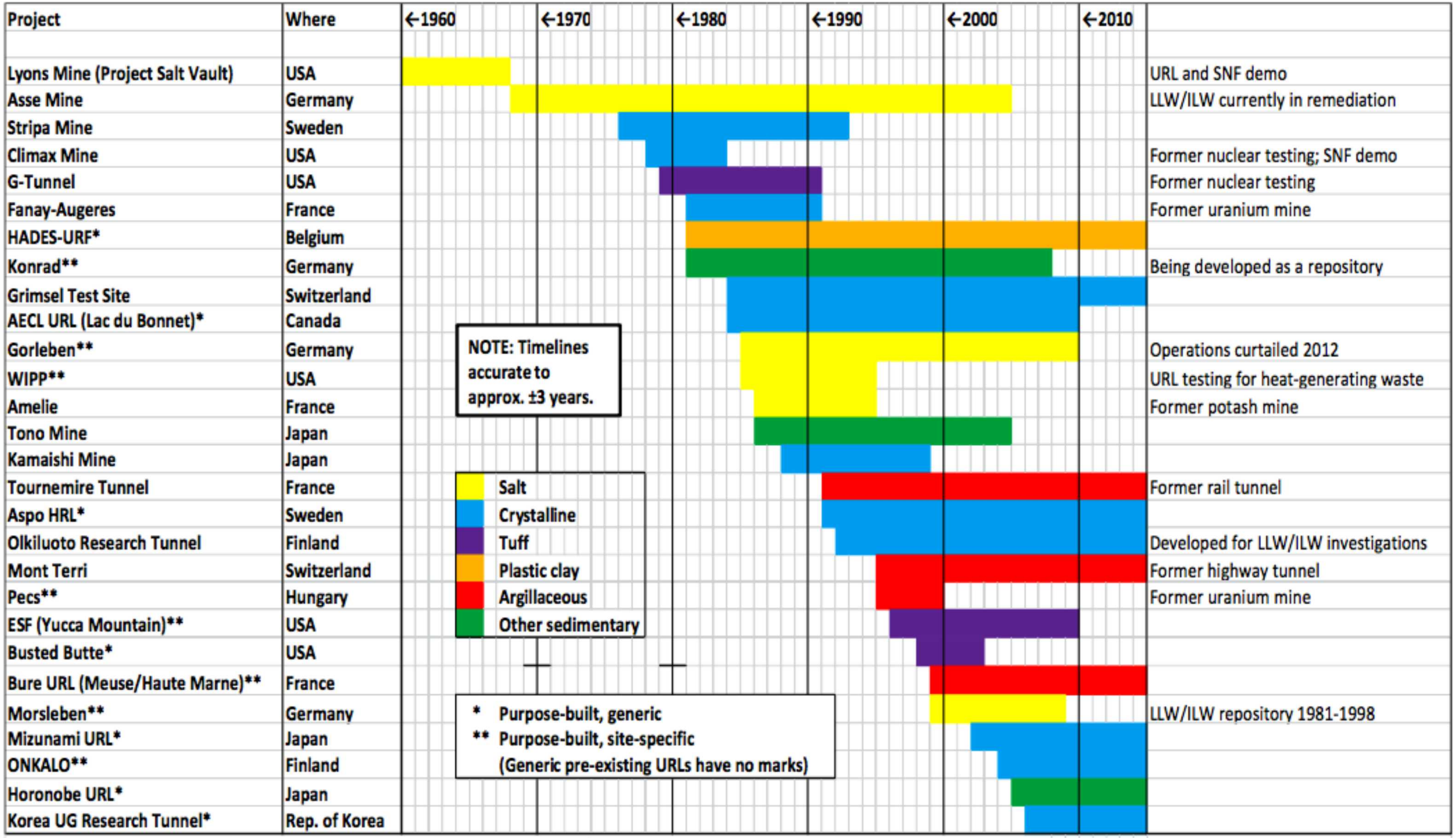
Mined repositories in salt (BMWi 2008)





Mined repositories in crystalline rock (SKB 2011)

Worldwide Rad. Waste Disposal URL Timeline



NOT SHOWN: Early U.S. URLs (Avery Island, CSM Mine, etc.) and more recent U/G investigations in the Czech Republic, Canada and elsewhere.

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Spent Fuel Test–Climax: 1978-1985 (Generic, Granite URL)

- **Test Development: $18.5M**
  - **~420 m depth, Climax granite stock, Nevada Test Site**
  - **Demonstration:**
    - Construction (surface and U/G)
    - Waste transport & handling
    - Spent fuel packaging and emplacement
    - Retrieval
  - 12 PWR assemblies, Turkey Point NPP (one per canister)
  - Lawrence Livermore National Lab (LLNL) lead
- **Total Project Cost: $34M ($90M to $130M escalated)**

Rail-mounted canister transfer and emplacement machine, main gallery (in receive position under waste handling borehole)

Patrick, W.C. 1986. *Spent Fuel Test—Climax: An Evaluation of the Technical Feasibility of Geologic Storage of Spent Nuclear Fuel in Granite (Final Report)*. Lawrence Livermore National Laboratory, Livermore, CA. UCRL-53702.

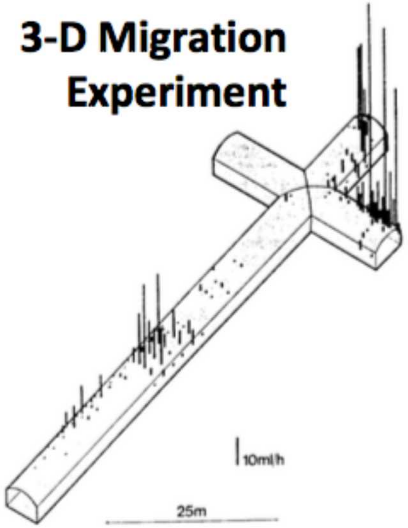
Stripa Project: 1980-1992 (Generic, Granite URL)

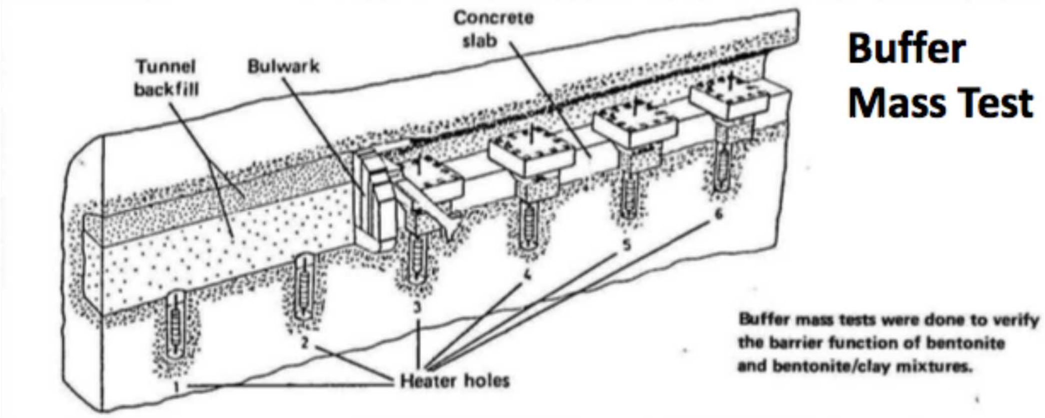
- **Swedish-American Cooperative → OECD/NEA Project**
- **Canada, Finland, Sweden, Switzerland & USA**
- **Granite depth 300 to 400 m**
- **Many experiments; 170 reports**
- **Total cost ~$33M ($60M to $80M escalated)**

Phase	Period	Budget
1	1980 - 1985	$6M
2	1983 - 1988	$9M
3	1986 - 1992	$18M

Fairhurst, C., G. Ferruccio, P. Gnirk, M. Gray and B. Stillborg 1993. *OECD/NEA International Stripa Project 1980–1992: Overview Volume I – Executive Summary*. (http://www.skb.se/Templates/Standard_17139.aspx)

3-D Migration Experiment





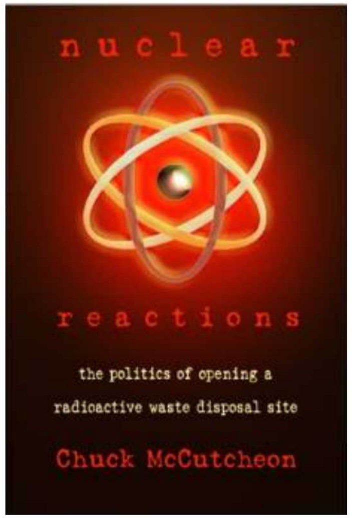
Buffer Mass Test

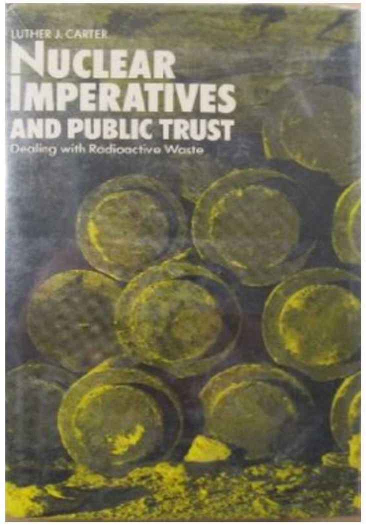
Key Reference for the History of WIPP

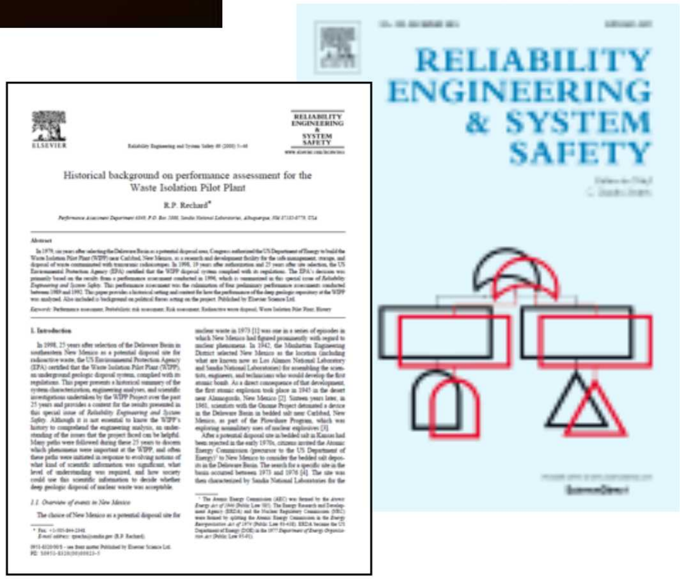
Luther Carter, 1987, *Nuclear Imperatives and Public Trust: Dealing with Radioactive Waste*, Resources for the Future, Inc. Baltimore, MD: John Hopkins University Press

Chuck McCutcheon, 2002, *Nuclear Reactions: The Politics of Opening a Radioactive Waste Disposal Site,* University of New Mexico Press.

R.P. Rechard, 2000, "Historical Background on Performance Assessment for the Waste Isolation Pilot Plant," *Reliability Engineering and System Safety* v. 69, p. 5-46 (See also other papers in this volume).







Background

1940s: Manhattan Project generates first significant volumes of spent nuclear fuel (SNF) and high-level radioactive waste (HLW)

- Waste managed on-site

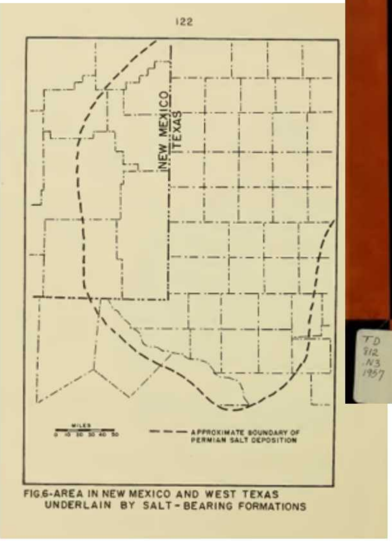
1955: National Academy of Sciences (NAS) convenes "Committee on Waste Disposal" at the request of the Atomic Energy Commission (AEC)

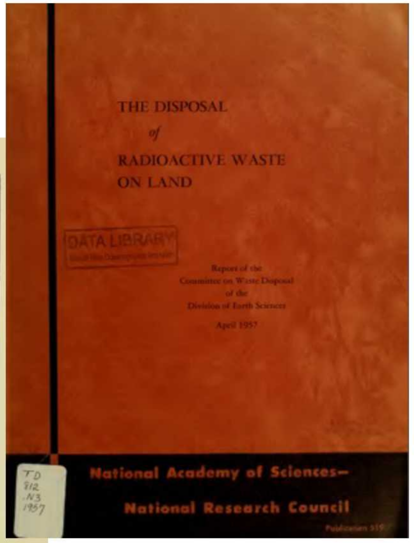
1957 NAS report *The Disposal of Radioactive Waste on Land*

- focus is on disposal of liquid HLW

"Disposal in cavities mined in salt beds and salt domes is suggested as the possibility promising the most practical immediate solution of the problem." (NAS 1957, p. 1)

"In part of the area a zone of potash salts is present which has been extensively developed near Carlsbad, New Mexico. The zone is about 250 feet thick and contains four workable beds of potash. The lowest bed is the thickest and averages about ten feet in thickness. A large area has been mined out since operations began about 25 years ago. Above the McNutt potash zone is a zone of halite about 500 feet thick, which has been named the Salado." (NAS 1957, p. 121)





- 1961: AEC conducts Project Plowshare Gnome nuclear test in bedded salt near Carlsbad, NM

Background (cont.)

1969: Fire at Rocky Flats (Colorado) weapons production facility focuses attention on transuranic waste

- Large volumes of transuranic fire waste shipped to Idaho for shallow trench disposal

1970: AEC commits to remove Rocky Flats fire waste from Idaho by 1980

1970: AEC selects salt mine at Lyons, Kansas as repository site

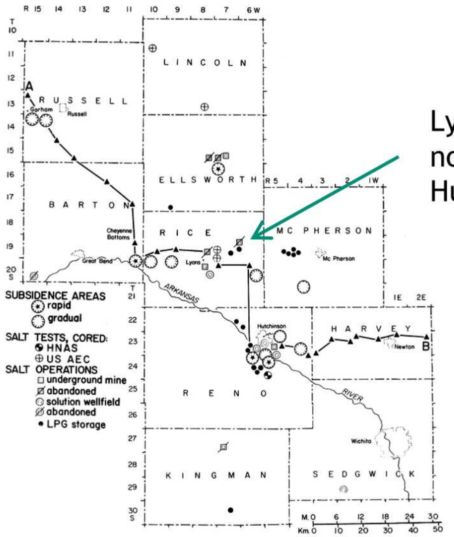
1971: AEC discovers old drill holes and solution mining at Lyons site

1971: City of Carlsbad, NM approaches NM congressional delegation seeking a repository

1972: AEC abandons Lyons site; announces plans for a "Retrievable Surface Storage Facility"

1972: City of Carlsbad meets privately with NM governor Bruce King and potash industry; governor King invites AEC to consider NM; AEC announces interest in NM salt August 14, 1972

INEEL 2003, Figure 3-8 (INEEL Photo # 69-6138)



Lyons site northwest of Hutchinson, KS

Background (cont.)

1972-1979: Political and administrative changes

- 1974: AEC splits into the Nuclear Regulatory Commission (NRC) and Energy Research and Development Agency (ERDA)
- 1977: ERDA becomes DOE
- WIPP mission shifts repeatedly regarding inclusion or exclusion of HLW
- 1979: Congress limits WIPP mission to defense TRU waste

1974: Oak Ridge National Laboratory begins field investigations in SE NM

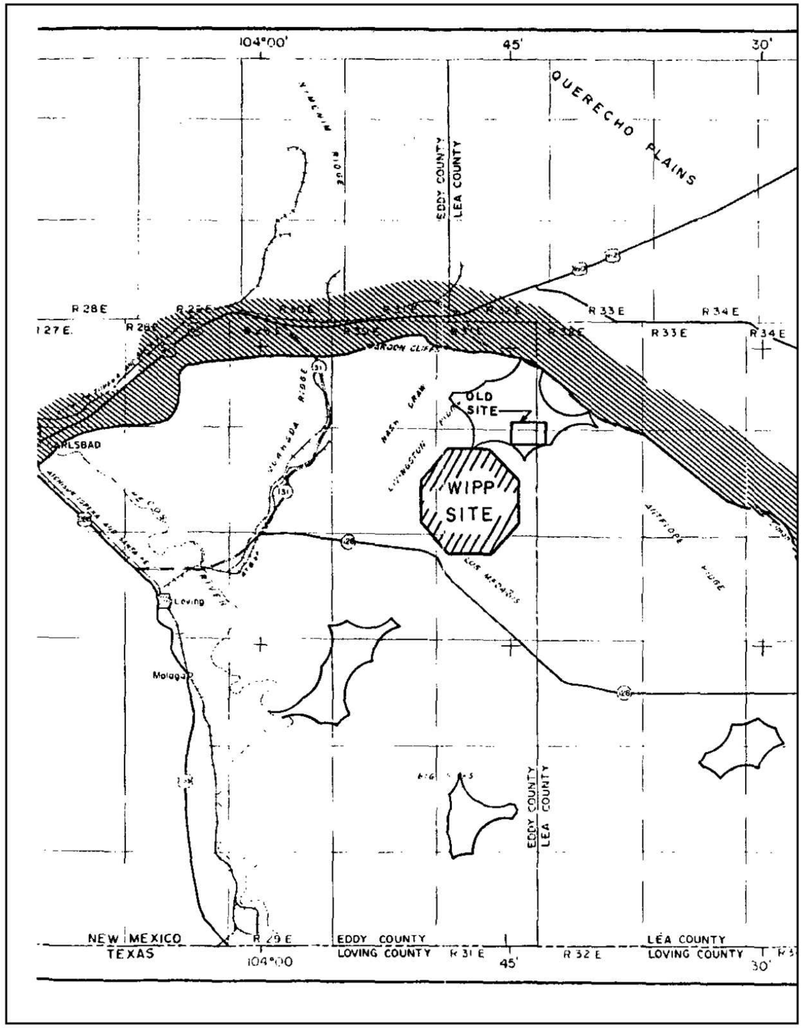
1975: Sandia National Laboratories assumes lead science role; first site identified is found unsuitable

- ERDA-6 borehole encounters steeply dipping salt beds and pressurized brine
- Proposed site is moved 11 km SW

1976: Project is named Waste Isolation Pilot Plant

- ERDA-9 borehole drilled near center of current site confirming suitable geology

1981: First shaft constructed at site, underground site characterization begins



From DOE 1996, Appendix GCR, Figure 2-3

Background (cont.)

1979-1993: Site characterization

- Geological and hydrologic investigations
- 40+ boreholes drilled from the surface

1985: Extensive testing begins in the WIPP underground

- Thermal tests investigate simulate heat generating waste
- Rock mechanics (salt creep); brine flow

1992: WIPP Land Withdrawal Act

- Transfers land ownership to the DOE
- Establishes EPA as principal regulator
- Precludes HLW and SNF from the WIPP mission

1996: DOE submits the WIPP Compliance Certification Application to the EPA

1998: EPA certifies the WIPP for disposal operations

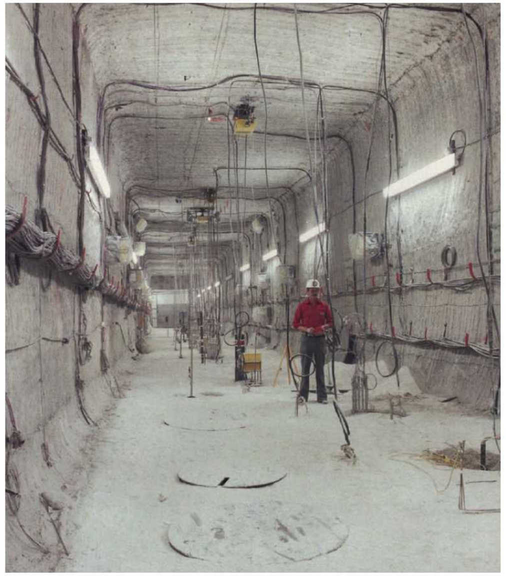
1999: First waste arrives at WIPP

- 11,894 shipments to date, all by truck http://www.wipp.energy.gov/shipments.htm

2006 and 2010: EPA recertifies WIPP

- Documentation at http://www.wipp.energy.gov/Documents_EPA.htm and http://www.epa.gov/radiation/wipp/reg.html

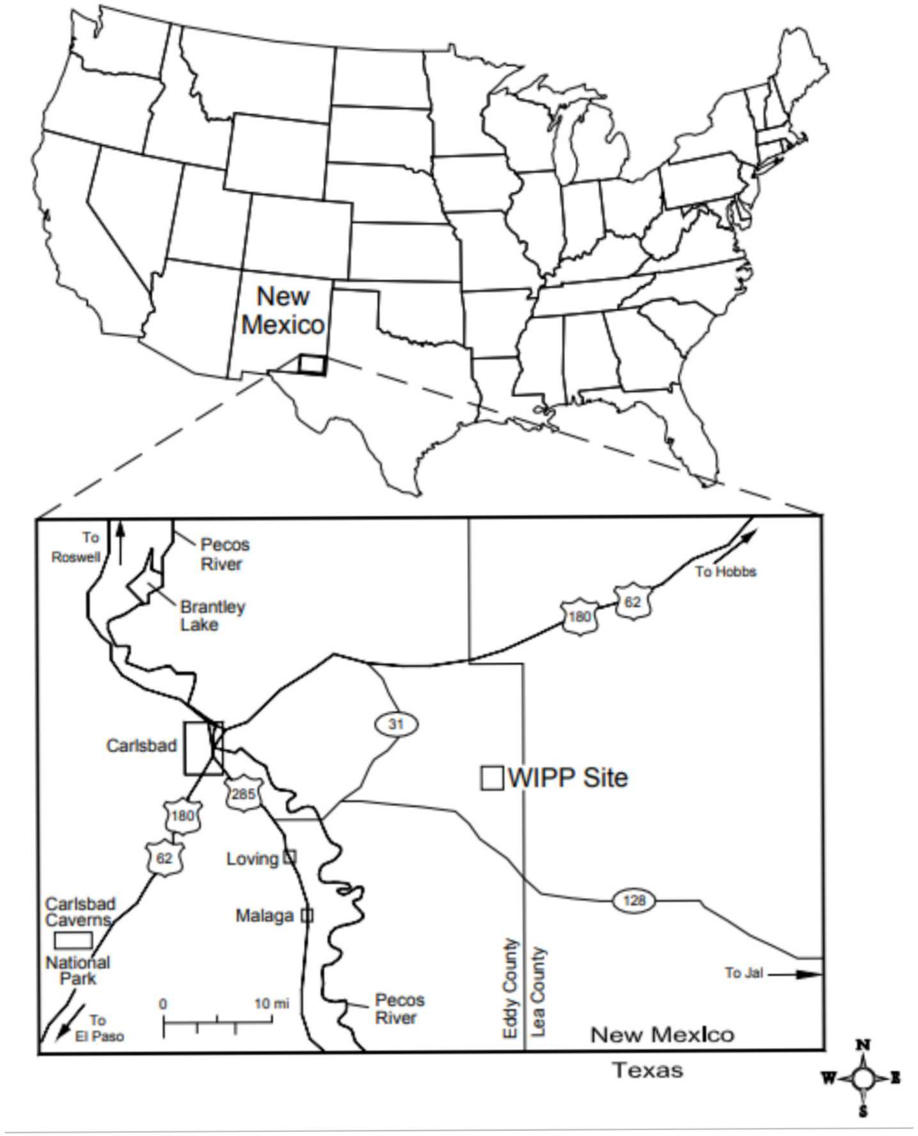
EPA action pending on 2014 Recertification Application

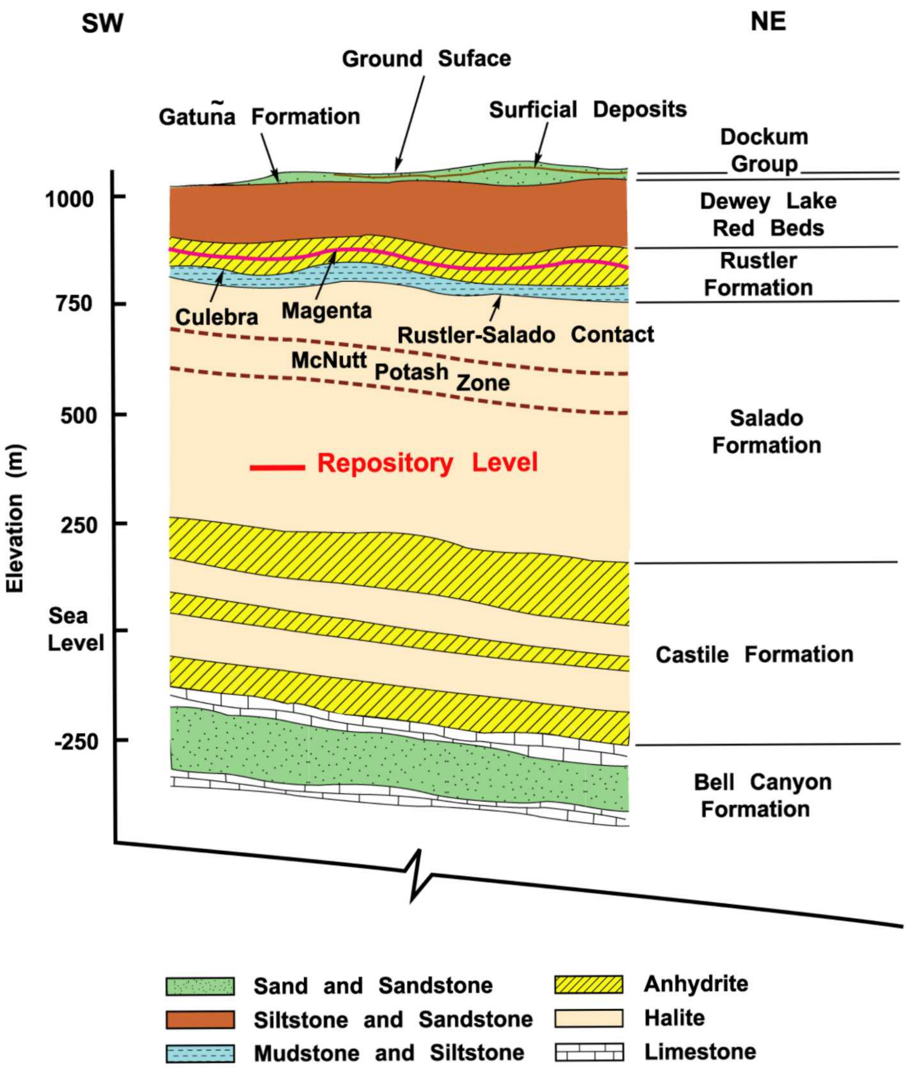


Heater Tests in WIPP Room B, 1985
from Matalucci 1987, SAND87-2382

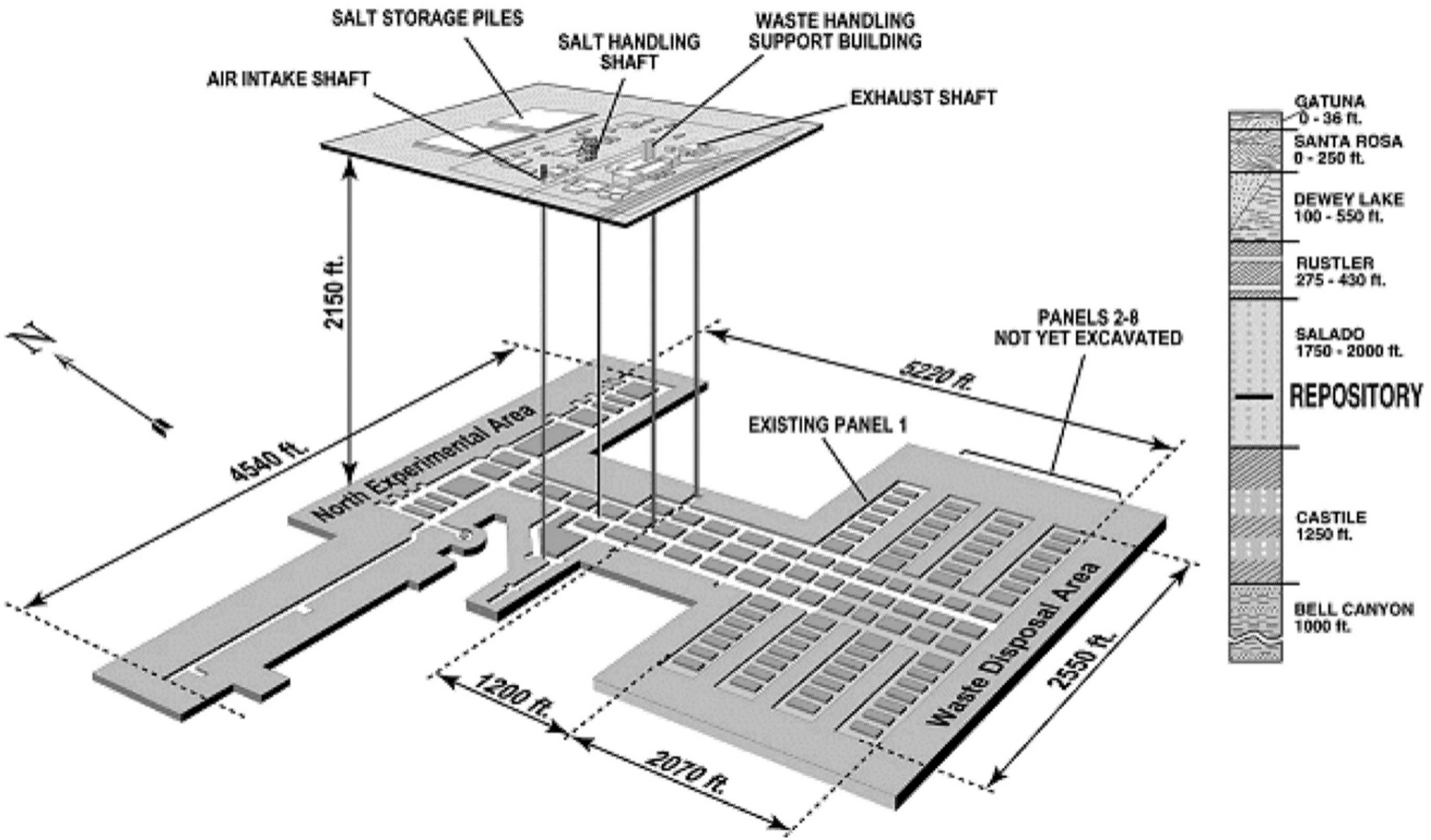
First waste arrives at WIPP March 26, 1999

Waste Isolation Pilot Plant (WIPP) Background





WIPP Facility and Stratigraphic Sequence



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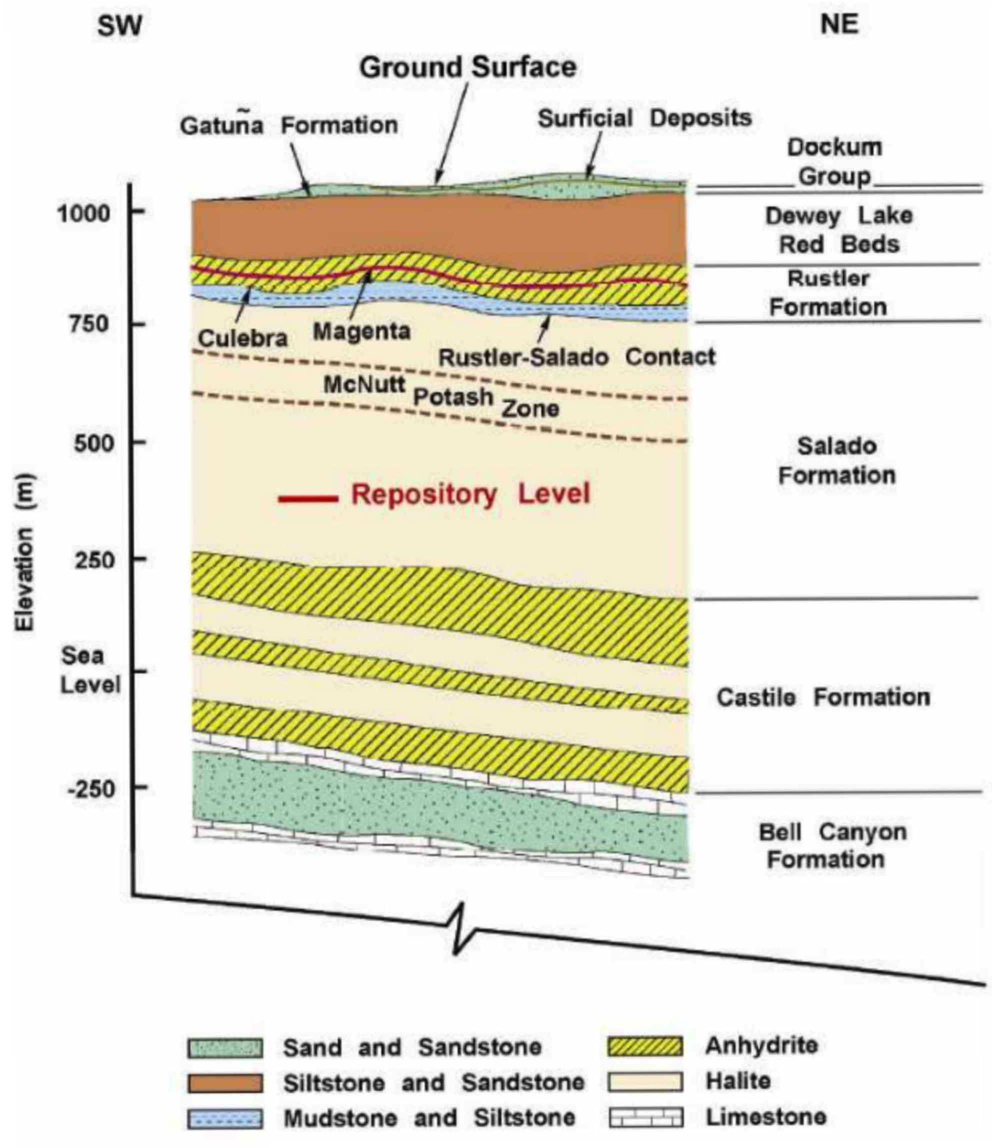
WIPP URL (Historical)

- **Operated by the U.S. DOE for R&D during 1986–1996**
- **Shafts descend ~600 m**
- **R&D conducted by Sandia and supporting researchers**
- **Construction cost ~$200M (w/out repository facilities)**
- **Total URL operating cost ~$200M** (15% of WIPP budget)
- **URL experiment cost: ~$80M (~33% of Sandia WIPP budget)**
  - **As many as 50 technical workers for 10 years**

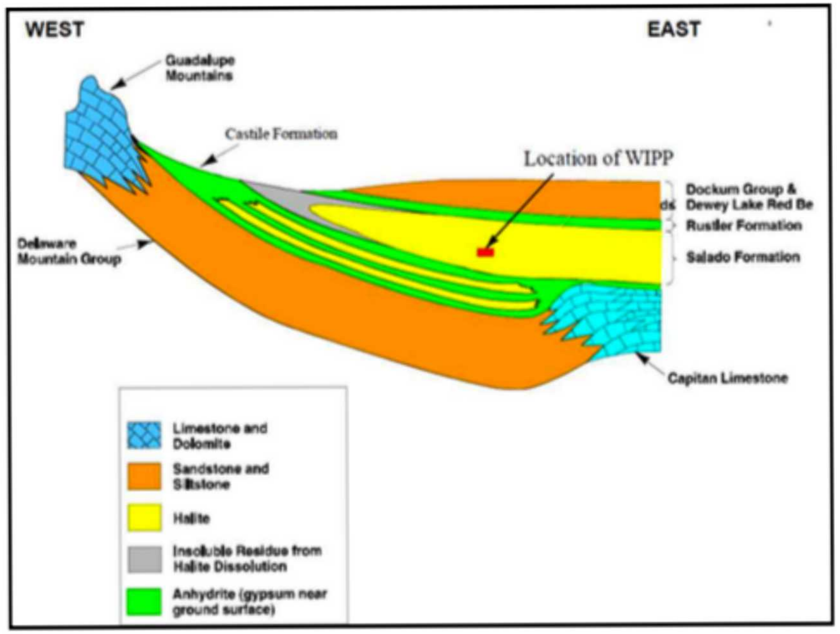
WIPP Then and Now

- ~1970 Lyons, Kansas Carey Mine Site Rejected
- 1975 – Site Selected, SNL Lead Laboratory
- 1978-1984 Testing in the Lab and Analog Field Sites
- 1981-1983 WIPP Constructed
- 1984-1986 Test Rooms Constructed
- 1985-1990 Heater Tests, Rooms A1, A2, A3 and D
- 1987 – Yucca Mountain Selected; Heated Tests Directed to Stop (TSI, WPP)
- 1987-1995 TRU Waste Studies (PSP) Continue
- 1995 – TRU Certification Application Submitted
- 1999 WIPP Waste Disposal Operation Begins

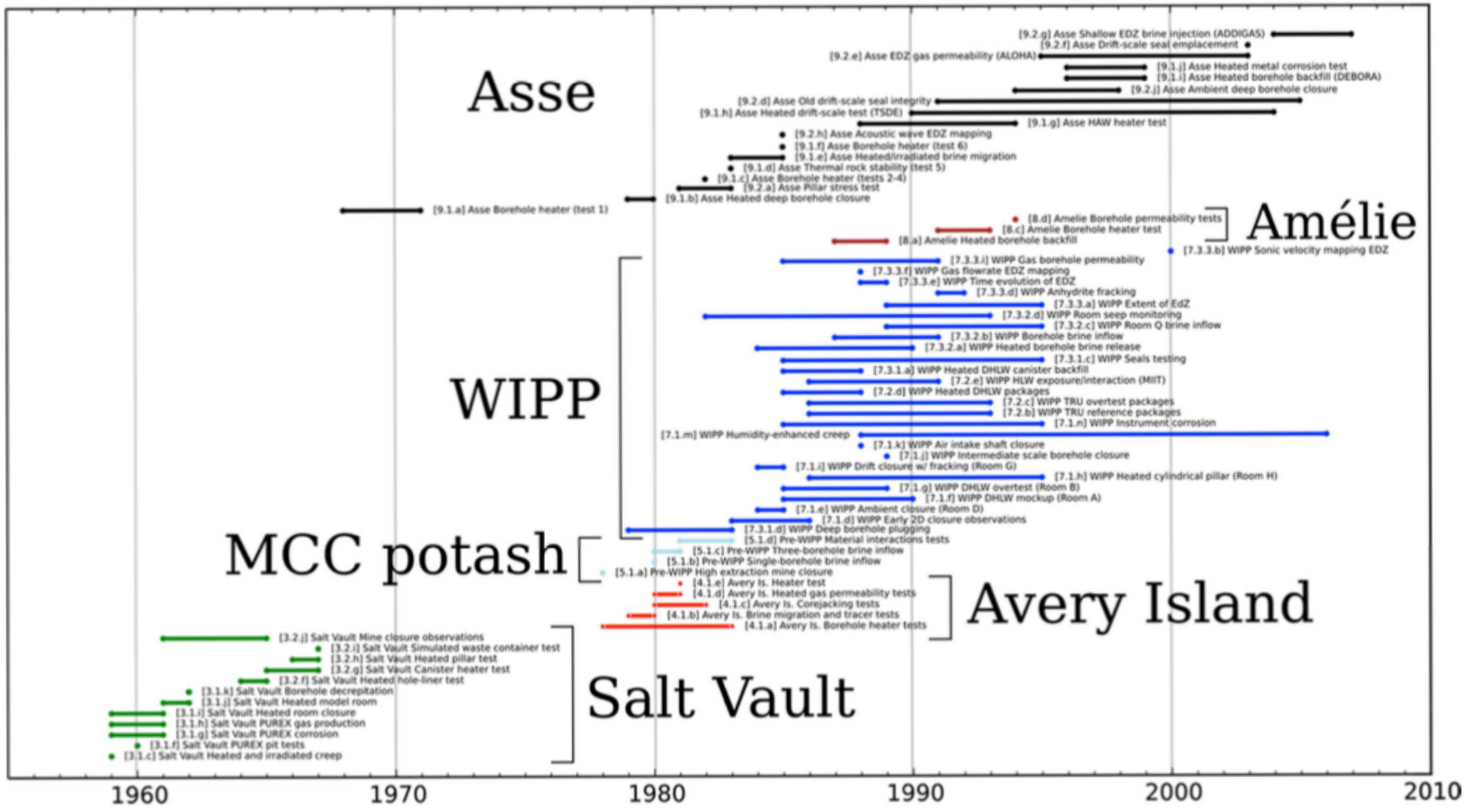
WIPP Geologic Setting



- **Permian Basin evaporite–clastic geology**
- **Dissolution feature**
- **Oil-and-gas, potash mining area**



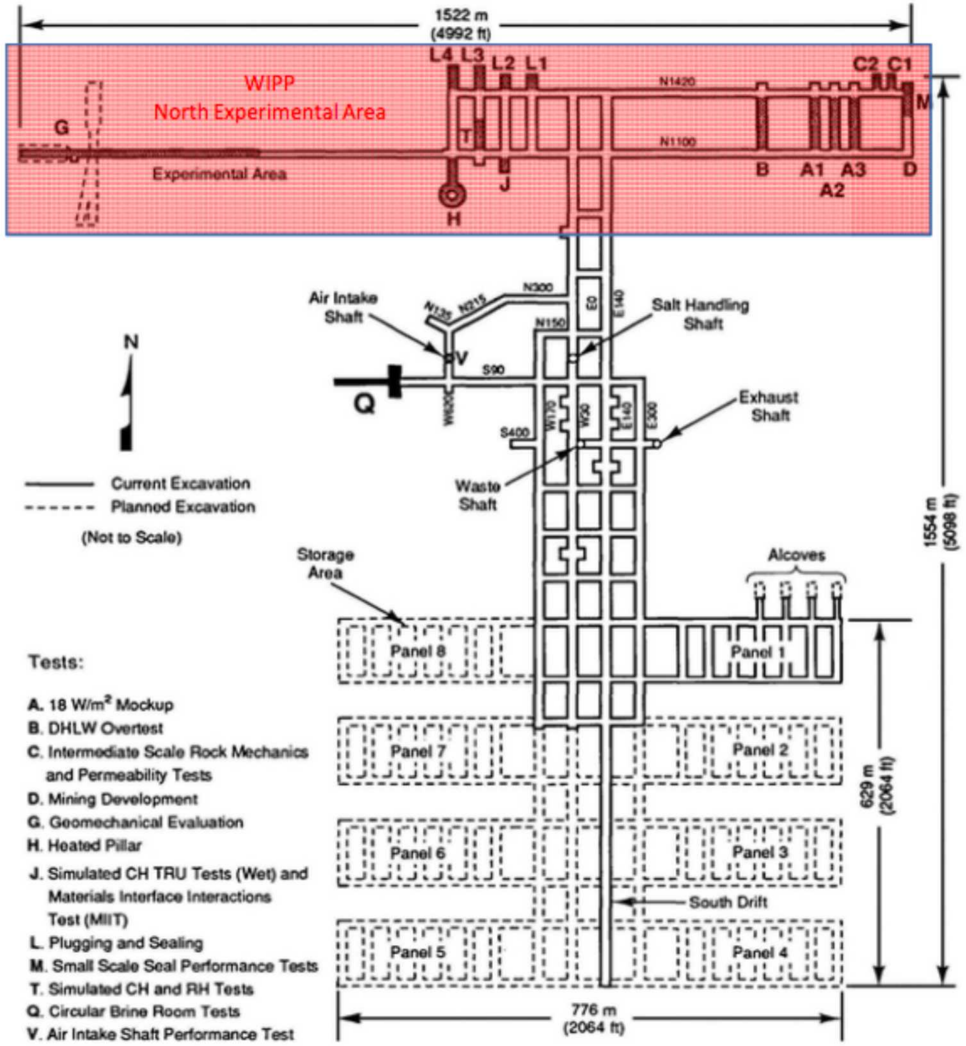
Salt URL Context (1958-2008)



Jensen et al. (1993)

WIPP URL Layout

- **3 Primary DHLW Test Programs**
  - (Designed to support repository development at the Deaf Smith site)
- **Thermal/Structural Interactions (TSI)**
  - Rooms A1-A3 (18 W/m² DHLW mockup)
  - Room B (DHLW overtest)
  - Room H (Heated axisymmetric pillar)
  - Room D (Isothermal Room B)
- **Waste Package Performance (WPP)**
  - DHLW materials tests in Rooms A1/B
    - Waste Package materials tests
    - Borehole backfill materials tests
  - Waste/package corrosion testing
    - Rooms J and T
- **Plugging and Sealing Program (PSP)**
  - Brine release in Rooms A1/B



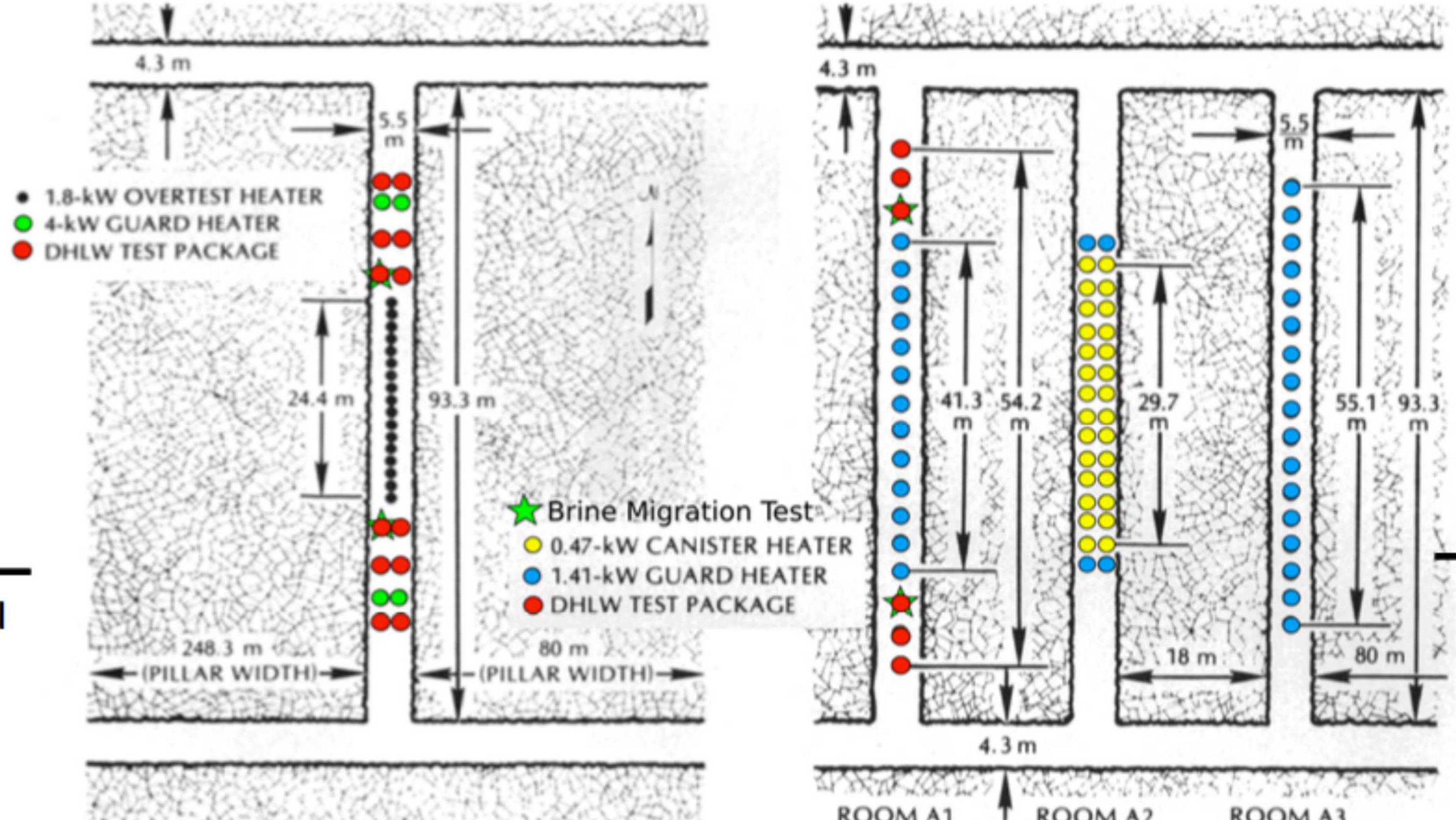
Jensen et al. (1993)

WIPP HLW Tests: Rooms A/B

- A Rooms: "design" DHLW thermal load (470 W heaters)
- Room B: "overtest" conditions (1,800 W heaters)
- 4 brine migration boreholes
- 18 Waste Package Performance tests (7 retrieved)

Room B
17 @ 1.8 kW
4 @ 4.0 kW
8 @ 1.5 kW

58.6 kW total



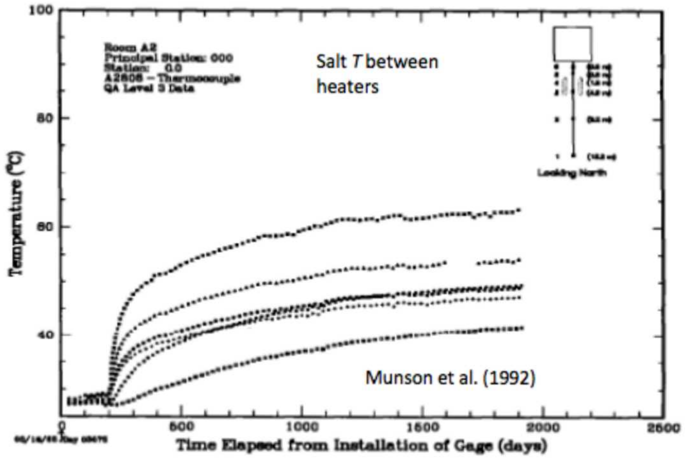
Matalucci (1987)

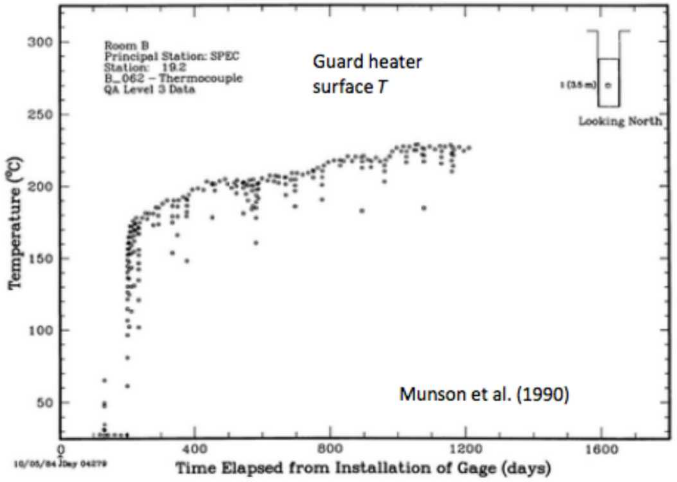
Rooms A1-A3
34 @ 0.47 kW
34 @ 1.41 kW

63.9 kW total

WIPP HLW Tests: Rooms A/B/D

- **Rooms A/B:**
  - Temperature (heat flux, heater power)
  - Differential creep
  - Oriented stress (pressure)
  - Brine inflow
  - Room closure
- **Room D:**
  - Room B geometry w/ room closure observations
- **Important Results:**
  - Roof collapse is preceded by accelerating, rapid closure
  - Ti-alloy → strength, corrosion-resistant canisters





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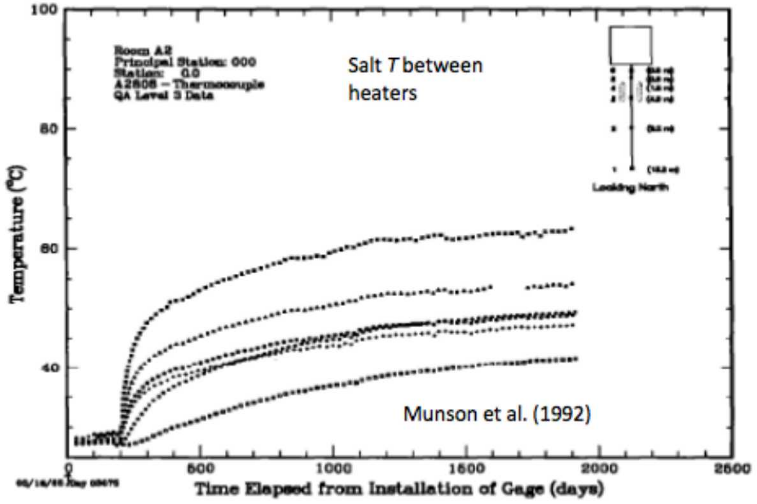
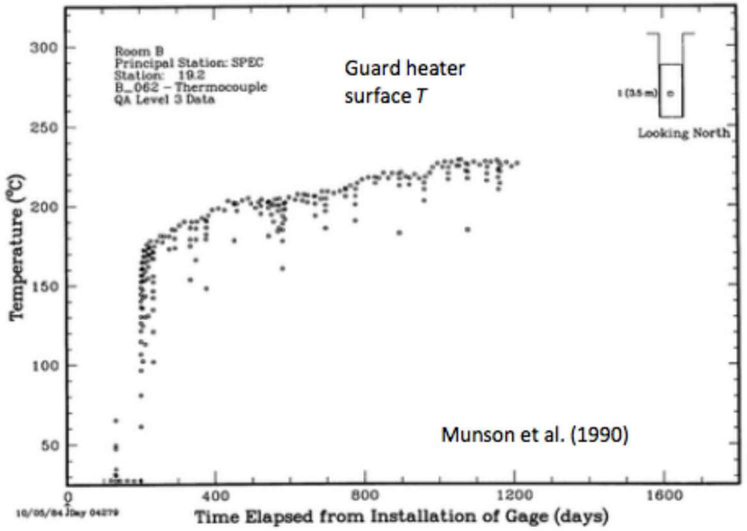




WIPP HLW: Room A2 Heater Test (1985-1990)

WIPP HLW Tests: Room B (1985-1989)

Schuhen et al. (2013)

Schuhen et al. (2013)

Typical WPP DHLW canister in Room B at installation and removal
Creep closure and salt crust deposition required overcoring to remove

WIPP: MIIT (1986-1991)

- **Materials Interface Interactions Test (MIIT) in WIPP Room J**
- **1845 "pineapple slice" waste package material samples**
  - Waste forms (glass/ceramic), canister + overpack materials, and backfills
  - Samples from: US, Belgium, Canada, France, Germany, Japan, Sweden & United Kingdom
- **In situ leaching 90°C in brine-filled boreholes**
- **Retrieved after 0.5, 1, 2 & 5 yrs**
- **Important Results :**
  - International collaboration valuable

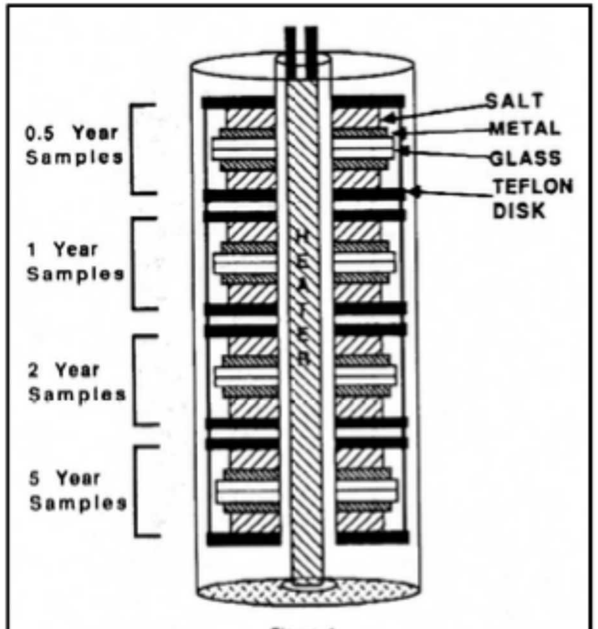


Figure 4
WIPP MIIT Sample Assembly

Discussion: WIPP URL
Test Interference/Waste Isolation Analysis

- Test interference was determined without formal analysis, using expert judgment
- Excavation is fast and cheap in salt, so URL layout is large
- Numerical models have changed in 30 years
  - 1D, 2D → 3D
  - T, H, M, TM → TH, THM
  - Single phase → Multi-phase
  - Constitutive laws
  - Meter-scale → Centimeter-scale
- ∴ Test interference is viewed differently
  - Ventilation effects
  - URL-scale hydrology and stress redistribution
- WIPP URL development cannot affect waste isolation (e.g., no flow in host rock, same # of shafts, etc.)

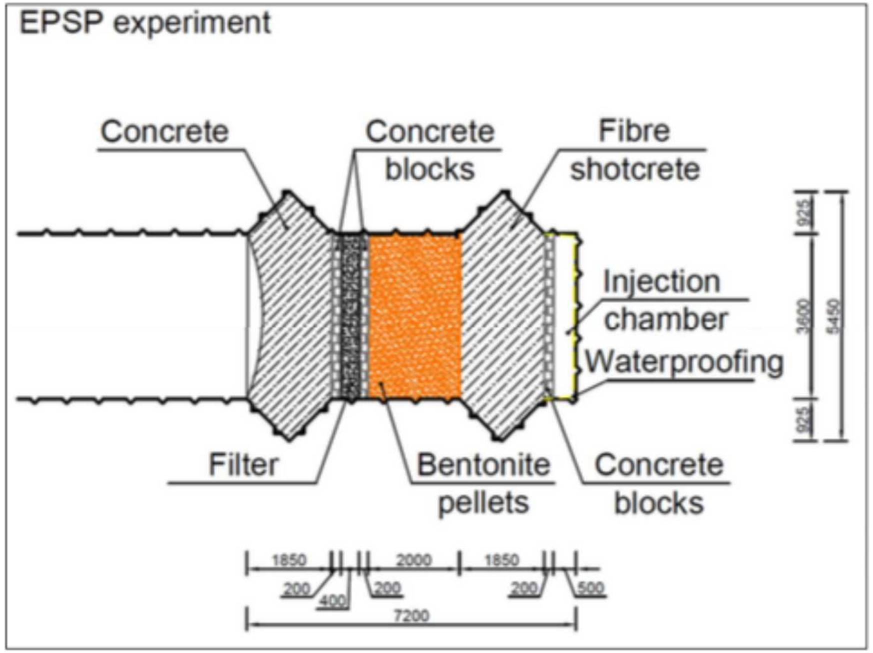
Seal functions and challenges the repository environment

The seal blocks potential preferential flow pathways, created by excavation of tunnels, shafts , and drifts

Needs account for the excavation damage zone (EDZ), e.g. design will have break-outs to seal pathways in the EDZ

Achieve both short-term an long-term isolation needs

- Cement
  - Short term hydraulic barrier, easy to emplace, setting shrinkage
- Clay long-term stability, sorption, swelling



From J. Hansen et al. 2016

From DOPAS 2016

Challenges to Seal Durability/Integrity

Thermal

- Spent fuel is generates A LOT of heat (~ kW)

Chemical durability

- Complex near field chemical environment (connate brine, evolving geochemical milieu, long timescales, subsurface heterogeneity)
- Waste form degradation, waste package corrosion, complex chemistry/geochemistry

Mechanical durability

- Convergence of excavations
- Weight of waste packages
- Discontinuous mechanical processes, e.g., roof-fall

And, oh yeah, the above can lead to … Coupled processes!!!

- Introduces a considerable amount of uncertainty

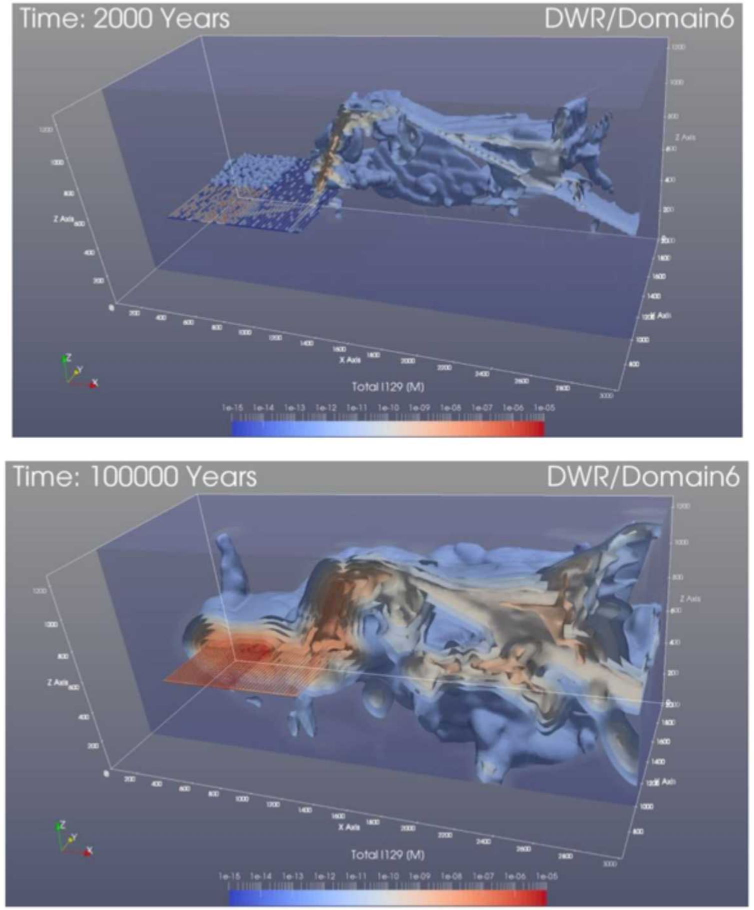
Performance Assessment (PA Models)

Performance Assessment (PA) Modeling

- Use standard reference:
  - geology
  - Repository design
- Assess long-term post-closure safety
- Thermal-hydrological-chemical processes simulated via PFLOTRAN

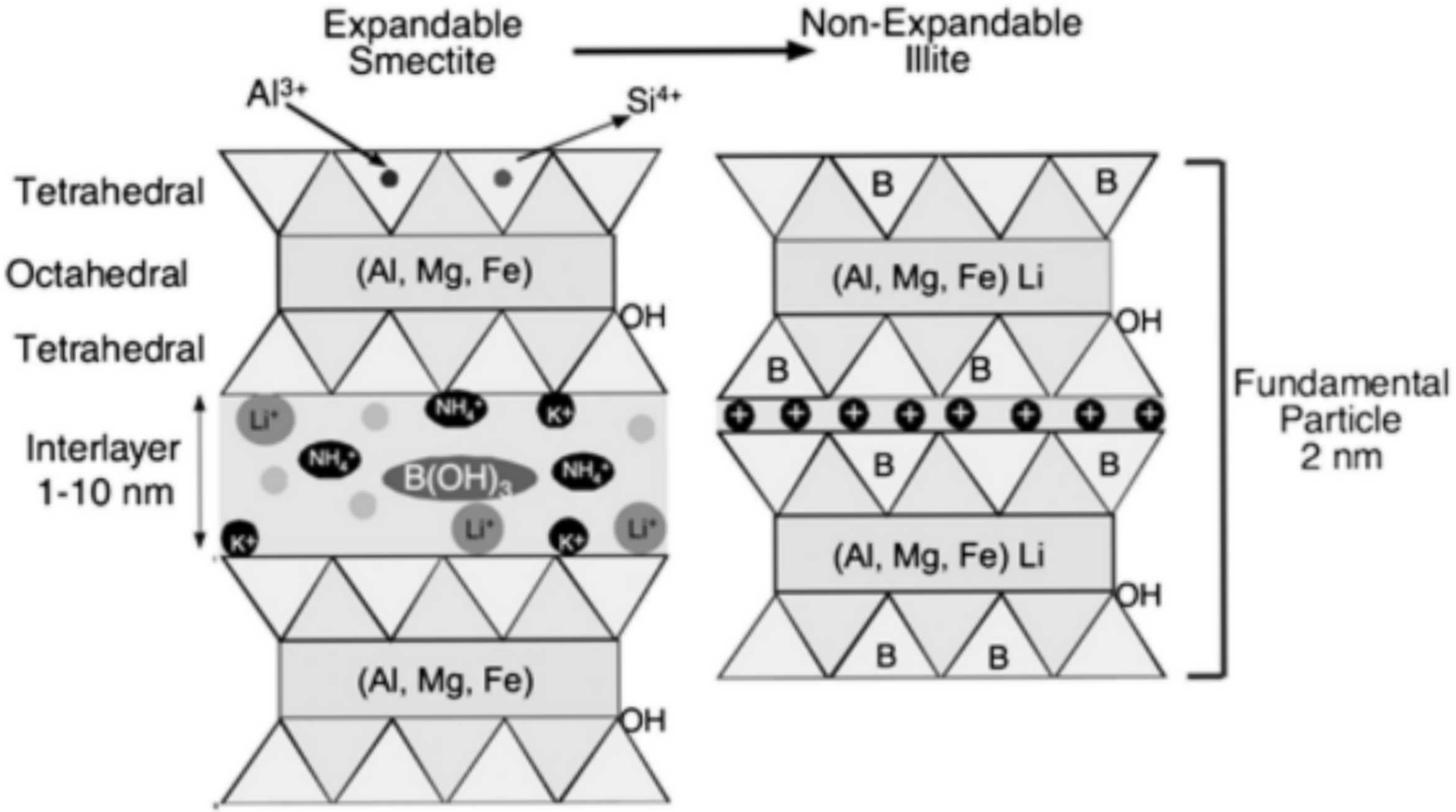
PFLOTRAN

I-129 concentrations



Sevougian et al. 2016

An example of Smectite to Illite Transition



https://www.researchgate.net/publication/301490033_Stable_isotope_constraints_on_the_origin_of_kaolin_deposits_from_Variscan_granitoids_of_Galicia_NW_Spain/figures?lo=1

Seems like a simple process, yet there are some discrepancies w.r.t. kinetics

Clay Minerals (1998) **33**, 187–196

The reactivity of bentonites: a review. An application to clay barrier stability for nuclear waste storage

A. MEUNIER, B. VELDE* AND L. GRIFFAULT†

*Hydrogéologie, Argiles, Sols, Altérations, CNRS-UMR 6532, Univ. Poitiers, 40 avenue du Recteur Pineau, 86022 Poitiers Cedex, France, *Dept. Géologie, CNRS URA 1316, Ecole Normale Supérieure, 24 rue Lhomond, 75232 Paris Cedex 05, France, and †ANDRA, DS/HG, Parc de la Croix Blanche, 1-7 rue Jean Monnet, 92298 Chatenay-Malabry Cedex, France*

(*Received 25 July 1996; revised 11 April 1997*)

ABSTRACT: The thermal stability of bentonites is of particular interest for containment barriers in nuclear waste storage facilities. The kinetics of smectite reactions have been investigated under laboratory conditions for some time. The variables of time, chemical composition and temperature have been varied in these experiments. The results of such an assessment are that there are about as many kinetic values deduced from experiments as there are experiments.

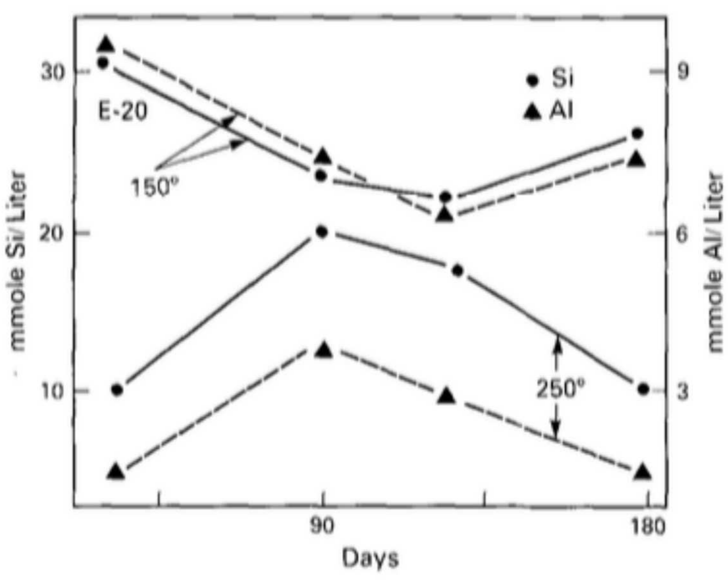
Experiments using natural bentonite to study the smectite-to-illite conversion have been interpreted as a progressive transformation of montmorillonite to illite. It is highly probable that the initial reaction product is not illite but a high-charge beidellite + saponite + quartz mineral assemblage which gives, then, beidellite-mica interstratified mixed-layer minerals. These experimental reactions are noticeably different from those of diagenesis, being closer to reactions in hydrothermal systems.

The results of such an assessment are that there are about as many kinetic values deduced from experiments as there are experiments. [!!!]

Howard and Roy, 1985

Highlights

- High T(>200 ºC) and Low T (150 ºC) mechanisms? Al re-precipiataion at High T
- Low T diffusion controlled process? Doesn't fit mechanisms
- Activation energies much lower than other studies (sol'n composition)
- Water: clay ratio
- Surface area?



Illitization after Cuadros and Linares

$$-\frac{dS}{dt} = [K^+] \cdot S_0^2 \cdot A \cdot exp\left(-\frac{E_a}{RT}\right)$$

S =1

$$-\frac{dS}{dt} = [K^+] \cdot A \cdot exp\left(-\frac{E_a}{RT}\right)$$

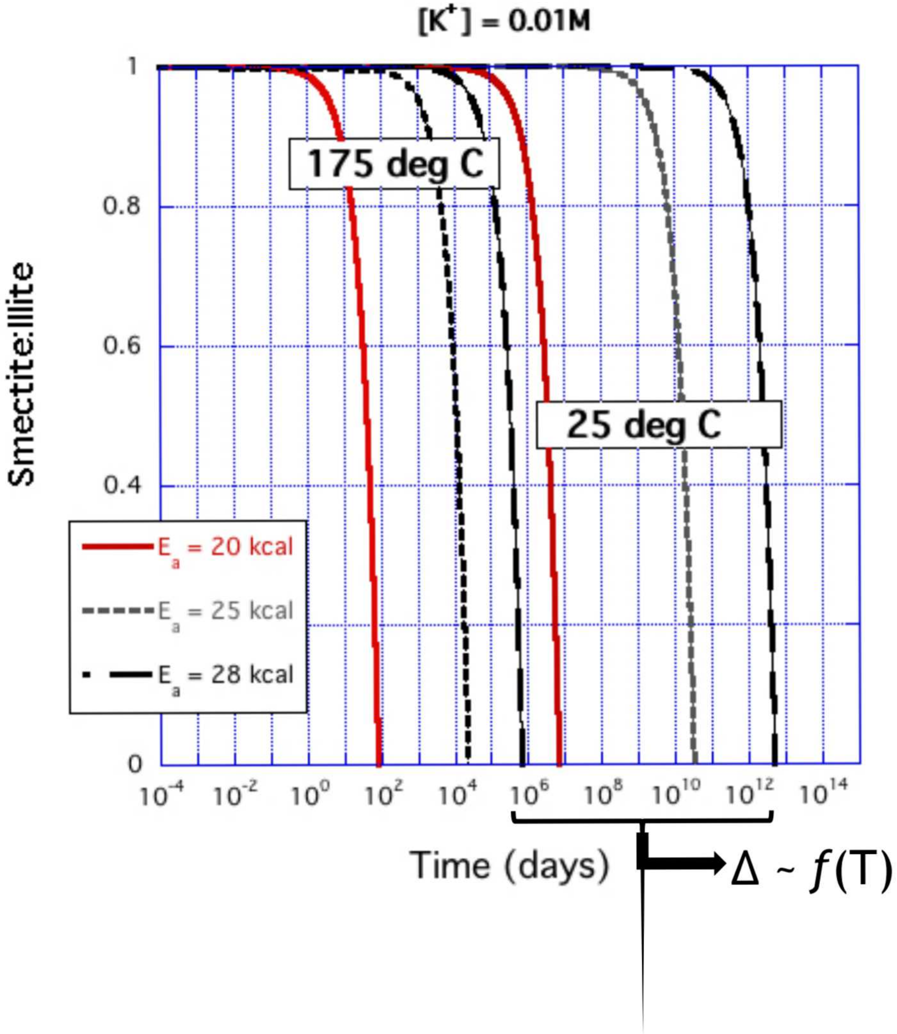
$$-\int dS = [K^+] \cdot A \int exp\left(-\frac{E_a}{RT}\right) dt$$

$$S = -[K^+] \cdot A \cdot exp\left(-\frac{E_a}{RT}\right) t + C$$

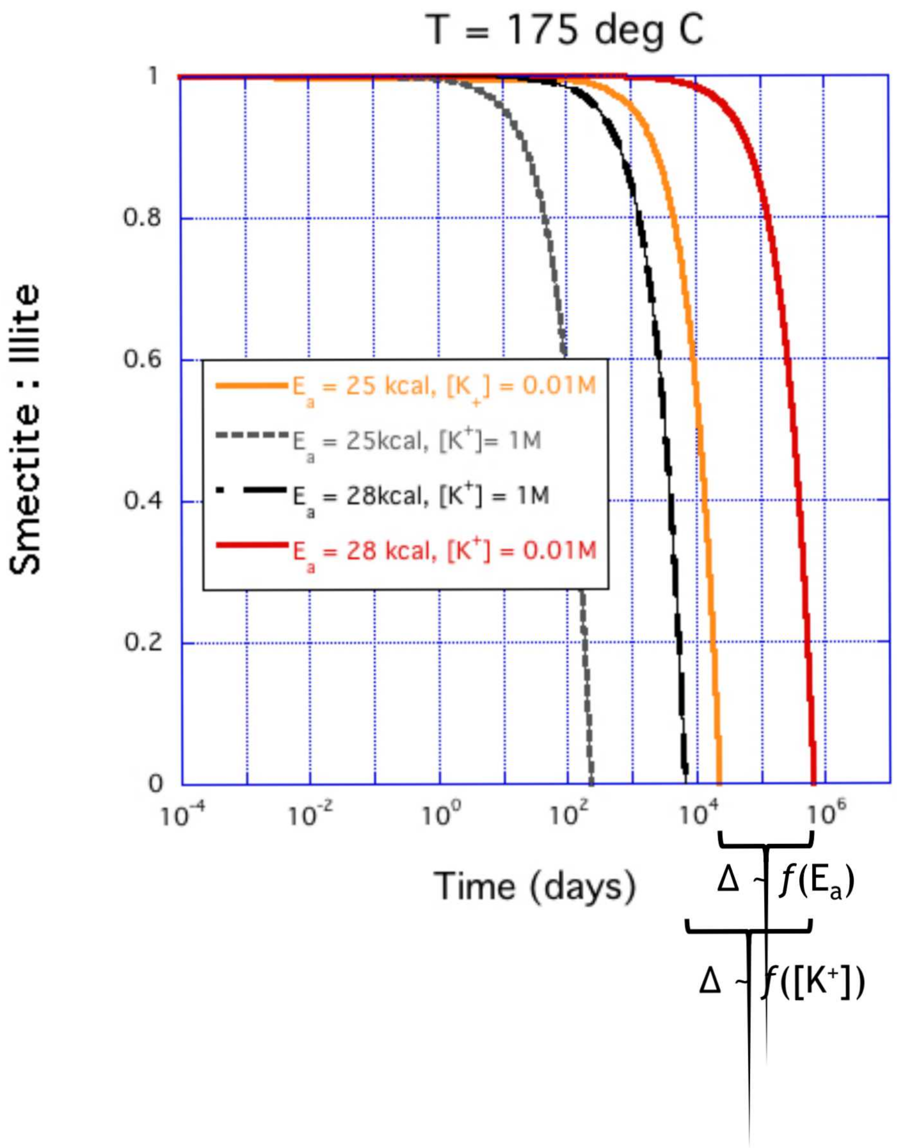
@ t=0, S=1 -> C=1

$$S = 1 - [K^+] \cdot A \cdot exp\left(-\frac{E_a}{RT}\right) t$$

Sensitivity of $[K^+]$, E_a, and T



Sensitivity of $[K^+]$, E_a, and T



Outline

Overview/ Background

- Seals for a Salt Repository
  - Salt backfill
  - Compacted salt, Clay, Asphalt
  - Salt concrete, Ultrafine grout

History of Seal Tests in the US

- WIPP Borehole Plugging Program
  - Predecessor - Salt Vault Program (early 1970's)
  - ERDA No. 10 (1977)
  - Bell Canyon Test (1979)
  - Waterways Experiment Station (WES) Grout Studies (70's and 80's)
- Small-Scale Seal Performance Tests (at WIPP)

WIPP Seal Design vs. Salt HLW Repository

Current WIPP Heater Test

  - Materials? Test design?

A Brief Timeline of Seal Testing

- 1974 - US Atomic Energy Commission (AEC) -
  - Salt Vault Borehole Plugging Test in Lyons, Kansas in 1972
  - Test led by Union Carbide, Oak Ridge, TN (ORNL)
- 1975 - AEC split into Energy Research and Development Agency (ERDA) and NRC, ERDA -> US DOE in 1977
- 1977 - ERDA No. 10 Test
  - Test led by SNL
- 1978 - Office of Nuclear Waste Isolation (ONWI) assumes lead of Borehole Sealing (and DHLW in Salt site)
- 1979 - Bell Canyon Test
- 1980's - Underground testing at WIPP of seal elements and various materials

ERDA No. 10 - Cement Plugs

Plugs were set Oct. 1977

Plug 1 (deepest in Bell Canyon Fm.) cored 48 hours after it was emplaced

Plug 1, 2, 3 included a fine granulated salt to make a salt water mixture

Plug 4 (in the surface casing) was mixed in fresh water to prevent casing corrosion

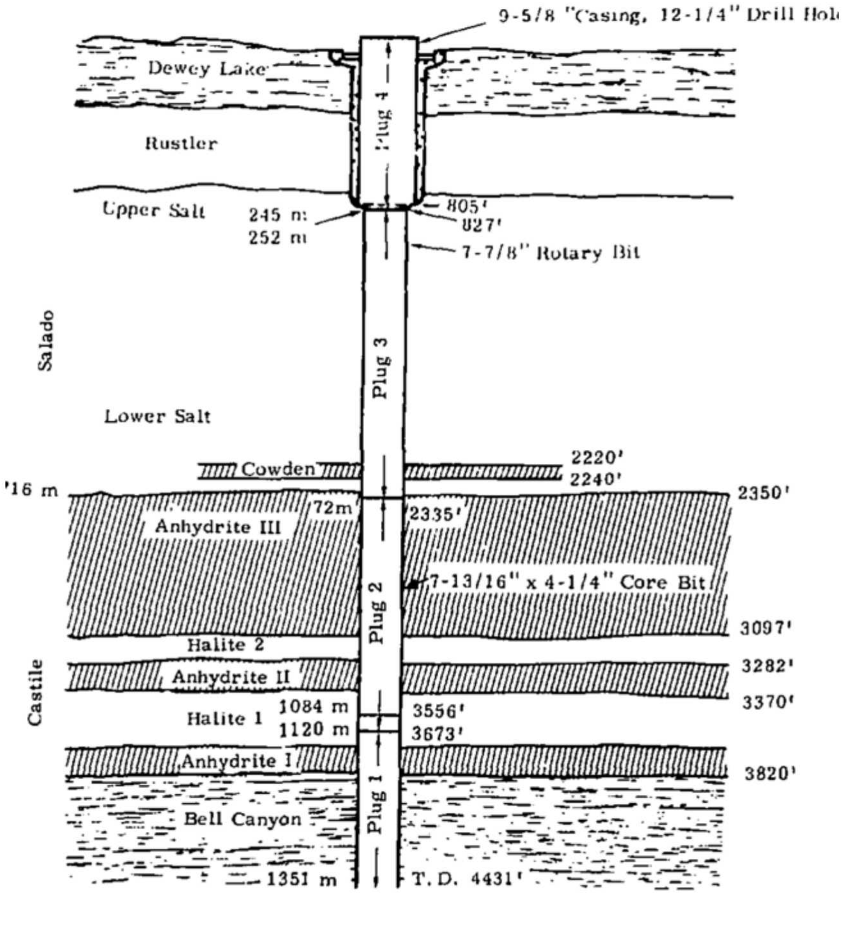


Figure 1. ERDA No. 10 Drill Hole

Gulick
1979

ERDA No. 10 - Grout and Analysis

Test Procedures

- Field sample core from Plug 1 (deepest)
- Test cores (poured at surface)

Grout Formulations

Sample Analysis was limited

- Time series mineralogy and strength on surface cores

ERDA-10 Conclusions

- Was the purpose to demonstrate that a borehole into the Bell Canyon Formation could be plugged?

ERDA-10 Grout Mixture Data*

	Units	Plug 1** 30% Salt	Plugs 2, 3** 36% Salt	Plug 4** Fresh Water
Cement, Class C(SR)	lb/ft^3	42.90	39.58	54.83
Fly ash	lb/ft^3	14.47	13.35	18.50
Salt gel (Attapulgite)	lb/ft^3	1.15	1.06	--
Bentonite gel	lb/ft^3	--	--	1.47
Salt, D44	lb/ft^3	10.77	14.15	--
Silica sand, D30	lb/ft^3	3.26	3.01	--
Dispersant, D45	lb/ft^3	0.06	0.05	0.29
Dispersant, D65	lb/ft^3	--	--	--
Calcium chloride (S1)	lb/ft^3	1.15	1.06	--
Water	lb/ft^3	36.6	39.3	36.0
Density	lb/ft^3	108.5	107.0	112.2
Density	lb/gal	14.5	14.3	15.0
Yield	ft^3/sack	1.5	1.7	1.2
Water content	gal/sack	6.6	7.8	5.2
Water/cement ratio		0.85	0.99	0.66
Water/cement and fly ash ratio		0.64	0.74	0.49
Thickening time	hr:min	4:35	7:45	5:05
Unconfined compressive strength				
24 hr	psi	712	420	1210
48 hr		1543	1032	1522
72 hr		1888	1275	2080

* This was Table 1 in Reference 6.
** Plug 1 cured at 128° F, 2445 psi; Plugs 2, 3 cured at 125° F, 2112 psi; Plug 4 cured at 80° F, 445 psi.

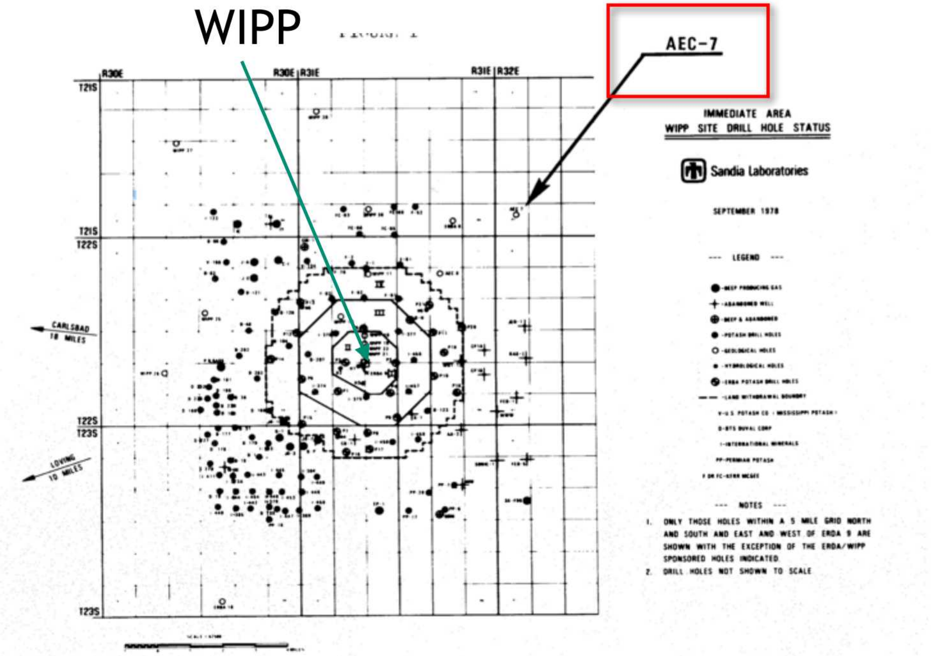
From Buck and Mather 1982

Bell Canyon Test (BCT) -1979

AEC-7 borehole, originally an exploratory borehole drilled by ORNL in 1974

Reconditioned by DOE in 1977 to evaluate the performance (permeability and durability) of state-of-the-art borehole seal technology

5 miles northeast of WIPP site



Scale bar ~ 4 miles

Christensen 1979

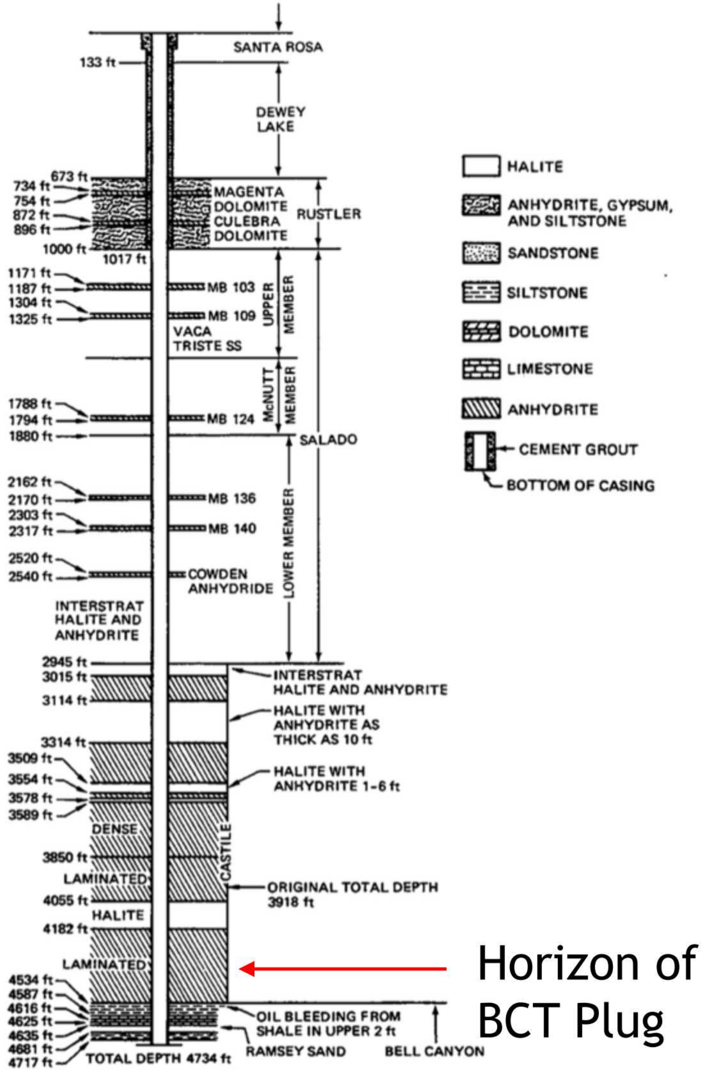
Bell Canyon Test - Plugs

Plug 217 from a potash mine

- High w/c =0.7
- Cement : formation perm
  - 5-50 mD (10^{-6} m^2)
- Deemed inconclusive since details of formulations were unknown

BCT Plug

- 2 m in length
- 20 cm diameter borehole
- 12.4 MPa pressure differential
- Emplaced in the Castile anhydrite



Christensen 1981

Bell Canyon Test - Grout

Prior to emplacement Waterways Experimental Station (WES) grouting studies narrowed to two candidate grouts:

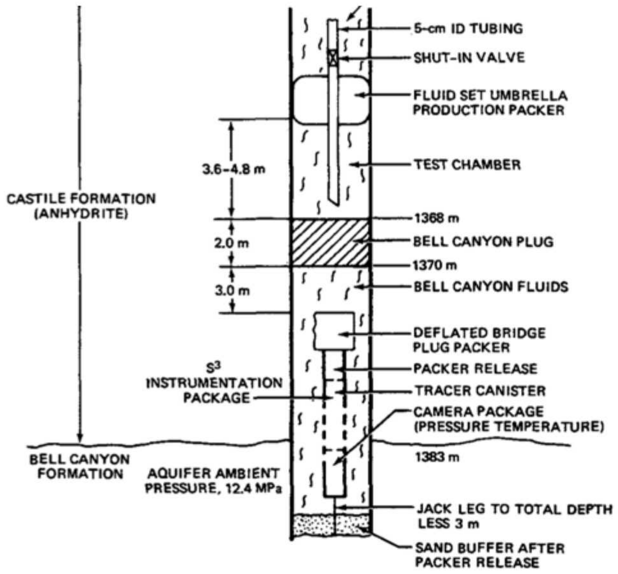
- 6% salt (BCT-1F)
- Freshwater (BCT-1FF)

On the basis of lab tests for permeability and bond strength push-out tests, BCT-1FF, the freshwater grout was chosen for emplacement

Measured 50 uD downhole in the BCT.

	BCT-1F	BCT-1FF
Ingredients, wt.%		
Class H cement	50.1	52.2
Expansive additive*	6.7	7.0
Fly ash	16.9	17.6
Salt (NaCl)	6.5	
Dispersant*	0.2	0.2
Defoamer*	0.02	0.02
Water	19.5	23.0
Properties		
Water-to-cement ratio	0.26:1.0	0.30:1.0
Fluid density, g/cm^3	2.04	1.98

**Proprietary additives of the supplier (Dowell).*



Christensen 1981

Bell Canyon Test - Highlights

It is notable that the salt water grout showed poor bonding to anhydrite in lab tests. The freshwater samples did not, and thus were chosen for the BCT.

Demonstration of:

- pressurized cementitious seal that exhibited an expected low permeability
- execution produced a plug seal that bonded well with the host and cement that was set and cured properly.

	BCT-1F	BCT-1FF
Ingredients, wt.%		
Class H cement	50.1	52.2
Expansive additive*	6.7	7.0
Fly ash	16.9	17.6
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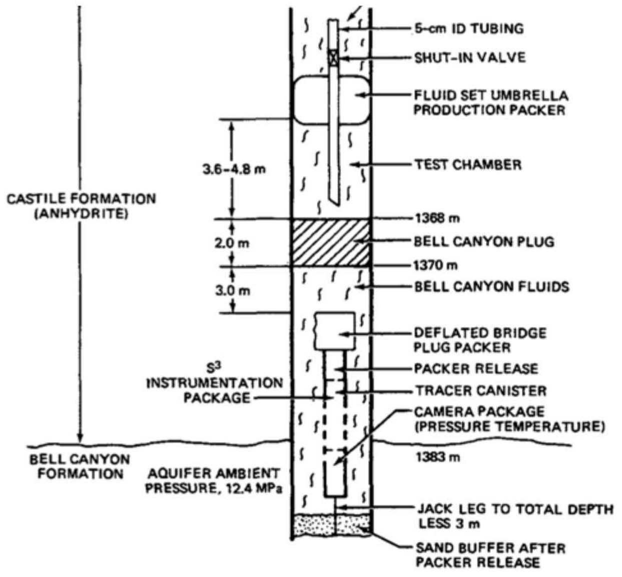


Christensen 1981

Small-Scale Seal Performance Tests (SSSPT)

WIPP Experimental Area - Rooms L, M

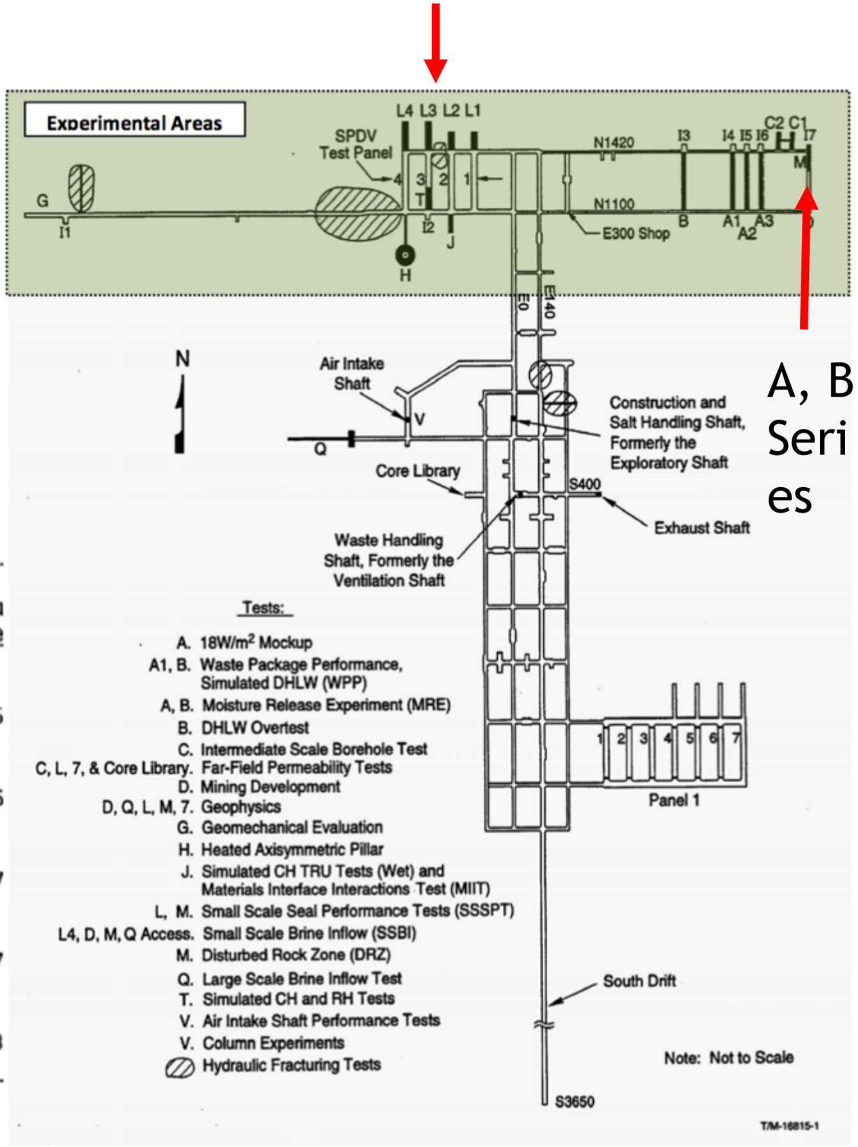
Vertical and horizontal boreholes

Expansive Salt Concrete (ESC), Salt blocks, salt/bentonite blocks and backfill, ultrafine grout (F series)

Test Series Schedule

Test Series	Seal Material	Direction	Schedu Emplace
A	Salt-based concrete	Vertical	7/85
B	Salt-based concrete	Horizontal	2/86
C	Salt and bentonite block and mortar	Horizontal	3/87
D	Salt and bentonite backfill	Vertical	9/87
E	Salt-based concrete	Vertical (thru Marker Bed 139)	3/88

From Stormont 1987



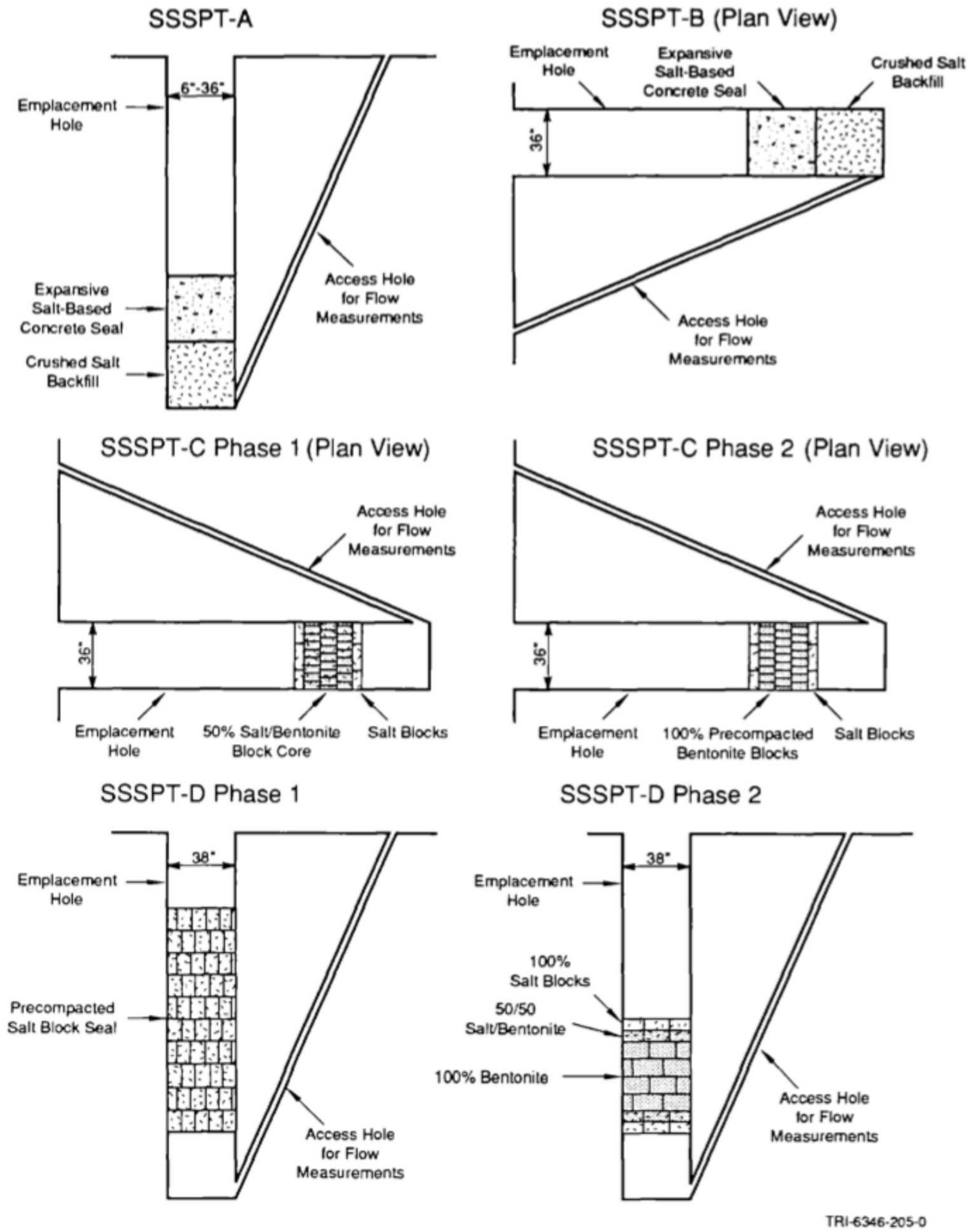
A, B Series

SSSPT Configurations

TABLE 1. TEST SERIES CURRENTLY PLANNED FOR SSSPT

Test Series	Seal Material	Seal Emplacement Orientation	Emplacement Date	Measurements*
A	Salt-Based Concrete	Vertical	7/85	Seal Pressure; Displacement and Temperature; Gas and Brine Flow
B	Salt-Based Concrete	Horizontal	2/86	Seal Pressure; Gas and Brine Flow
C Phase 1	Salt and 50/50% Salt/Bentonite Block	Horizontal	9/86	Seal Pressure; Brine Flow
C Phase 2	Bentonite Block	Horizontal	12/90	Seal Pressure; Brine flow
D Phase 1	Salt Block	Vertical	1/88	Seal Pressure; Hole Closure; Floor Heave; Gas Flow
D Phase 2	Bentonite Block (short-term)	Vertical	9/89	Seal Pressure; Brine Flow

* Note: Instruments include strain gages, stress meters, thermocouples, pressure cells, borehole displacement gages, Multiple Point Borehole Extensometers (MPBX), and the Four Packer Fracture Flow Tool (FPFFT) for fluid flow measurements.



From Finley et al. 1992

SSSPT Highlights, 1/2

- SSSPT Tests provide confidence to Performance Asessment in the form of *in situ* data on permeability and mechanical performance

Table III. Summary of SSSPT Seal System Permeabilities

Test Fluid	Concrete Permeability (m^2)	Concrete Permeability (m^2)	50%/50% Salt/bentonite Permeability (m^2)	100% Bentonite Permeability (m^2)
Test Period	**(1985-1987)**	**(1993-1995)**	**(1986-1990)**	**(1988-1995)**
Gas	$10^{-17} - 10^{-20}$	$10^{-19} - 10^{-23}$	–	see Figure 3
Brine	$\sim 10^{-19}$	$10^{-19} - 10^{-22}$	$\sim 10^{-16}$	$\sim 10^{-19}$

From Knowles and Howard 1995

SSSPT Highlights, 2/2

Expansive Salt Concrete Seals

- Exhibited sub-microdarcy permeability for both gas and brine (9 seals tested)
- Flow path decreased within a year of emplacement (tracer test)
- Emplaced using commercial equipment
- AND optimized for key operational attributes including:
  - slump, limited bleed, segregation, limited air entrainment, self-leveling behavior, and workability
- BUT…, in the late 80's the expansive agent became commercially unavailable (enter Salado Mass Concrete)

Lessons learned with respect to cement formulations (from Wakeley 1987)

- Simpler is better … for prediction, batching, sourcing, etc.
- Working time is a critical property
- By the 1987, it became evident that **concrete** (not grout) would play a central role at WIPP as components in the sealing system for bulkheads and drift, panel, and shaft seals - as opposed to the primary seal
  - Lifetime requirements on the order of 100 years instead of 10,000 years

Salado Mass Concrete

Incorporates the lessons from WES Grout Studies

Dry batched at the surface, mixed underground

As with previous grout/concrete studies, lab and field tests worked iteratively to meet targets for material properties

Table 3-1. SMC-3 and SMC-5 Mixture Proportions

Material	SSD Batch Quantities, lb/yd^3*	
	SMC-3	SMC-5
Cement, API Class H	278	221
Class F Fly Ash	207	247
Chem Comp III	134	112
Fine Aggregate	1255 to 1292**	1283
Coarse Aggregate	1579 to 1615**	1645
Salt	88	86
Water	216 to 260 ***	226 to 295***

* kg/m^3 = (lb/yd^3) × (0.59)

** Quantities may change with aggregate density or grading; see ACI, 1991.

*** Changes with w/c

From Wakeley, Harrington, and Hansen 1995

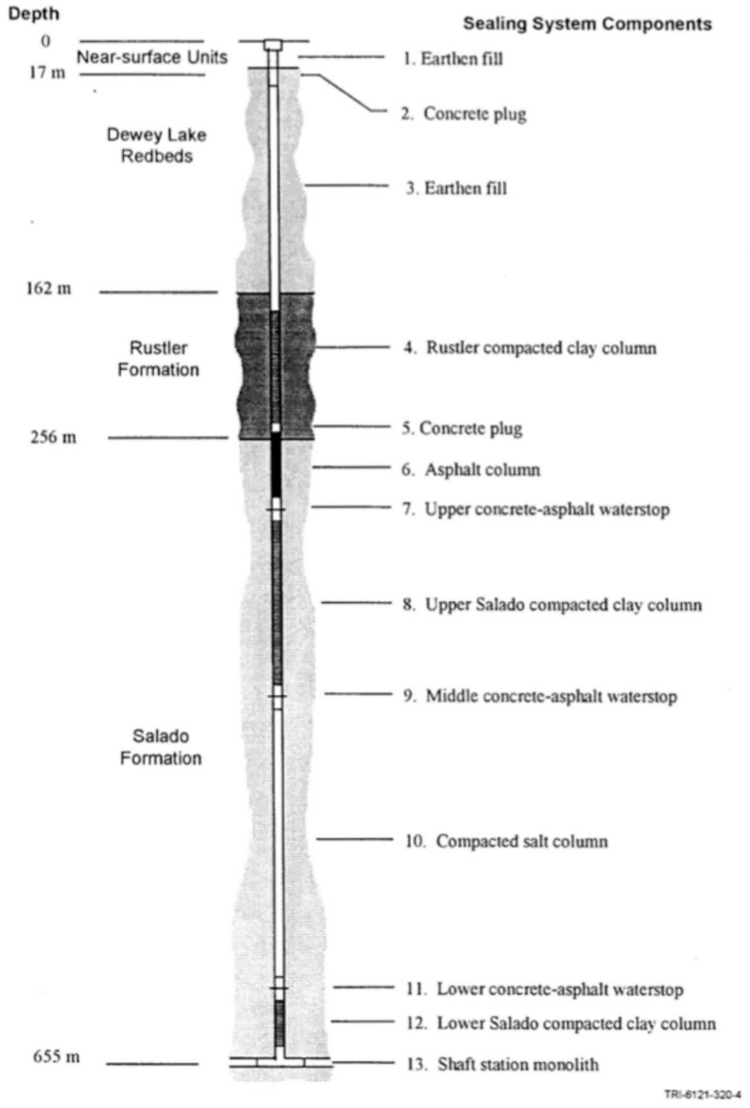
Design Bases, 1/2

Seal performance standards (WIPP)

- Concrete/grouts:
  - Have been proven/tested in the WIPP underground
  - Provide design redundancy as one element in a suite of seal materials in the overall seal design (**salt**, clay, asphalt)

WIPP vs. DHLW

- Increased radiologic source term
- Thermal effects - cracking of seal materials
- Chemical evolution in shaft and drift seals
  - Low pH cement?



FROM HANSEN AND KNOWLES 1999

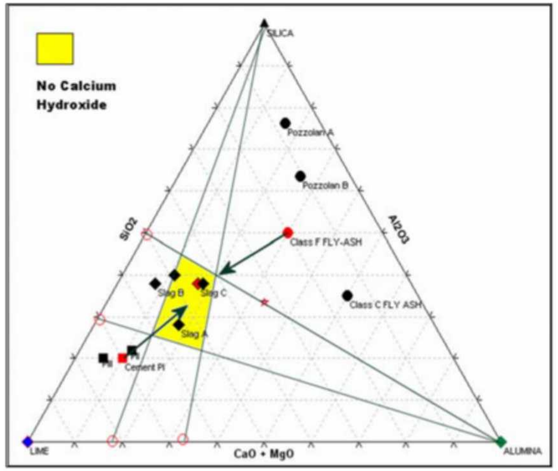
Design Bases, 2/2

Why low pH cement?

- Concern that $Ca(OH)_2$ dissolution increases RN solubility and mobility
- Dehydration of cement introduces water into the repository
- Superplasticizers -> increased colloid mobility
- Organics -> microbial growth

Low pH cement

- Pore solution pH ~ 10
- Low $Ca(OH)_2$ content
- Fly ash, silica fume, basalt furnace slag increase available silica -> more CSH, less $Ca(OH)_2$
- Denser, less permeable paste



Dole et al. 2004

Cementitious Seals Test 1/2

Key issues for Cementitious Seal Performance Evaluation

- Autogenous shrinkage of seal (during setting)
  - Gap formation at cement/salt interface
  - Crack formation in cement plug
- Heat output of mass concretes
  - Crack formation in cement plug
- Material selection (i.e., Sorel cement, salt concrete, low pH?)
- Effects of salt host closure on the seal

Why do a field-scale test of seals in bedded salt

- Most recent field tests have been in domal salt (saltcrete, Sorel)
- Bedded salt tests at WIPP - Small Scale Seal Performance Tests Series A, B, C
  - Used a very specific formulation of "Expansive Salt Concrete"
  - Key ingredients are unavailable and potential difficult to reproduce

Cementitious Seals Test 2/2

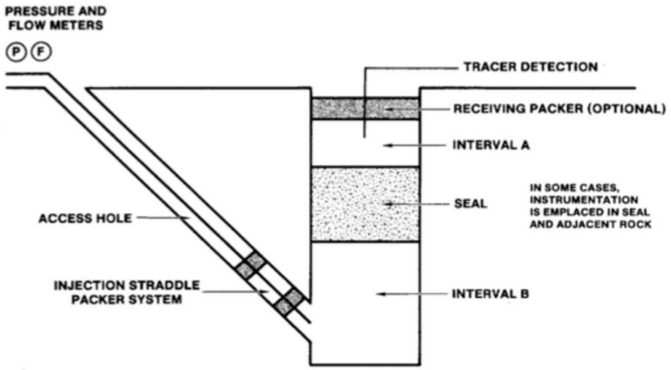
Relevant Tests in Domal Salt

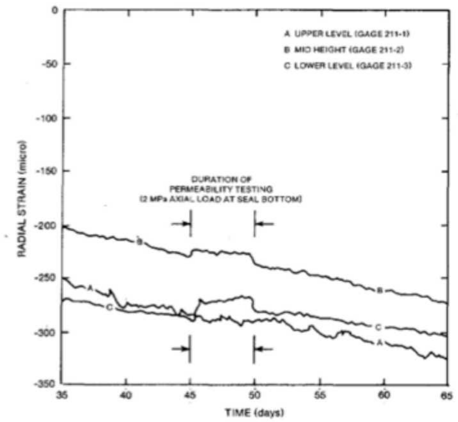
- Lab-scale Tests for DOPAS (Czaikowski et al. 2016)
- ERAM Test Seal - salt concrete
- Asse tests - Sorel cement and salt concrete

From Czaikowski et al. 2016

Create a seal test at WIPP with the concept of a potential HLW Salt Repository in mind (with relevance to some generic, bedded salt site)

- Measure borehole closure and permeability of the seal





From Stormont 1987

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