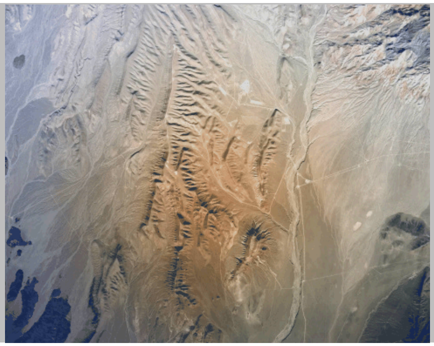
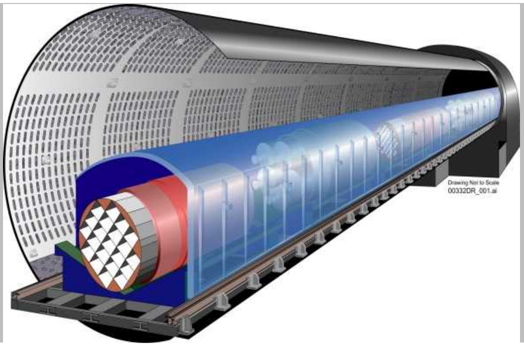
SAND2014-20055PE

Exceptional service in the national interest

Sandia National Laboratories





A3 & A4: URLs in the U.S.: Planning, Design, Construction and Operation

Ernest Hardin
December, 2014

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

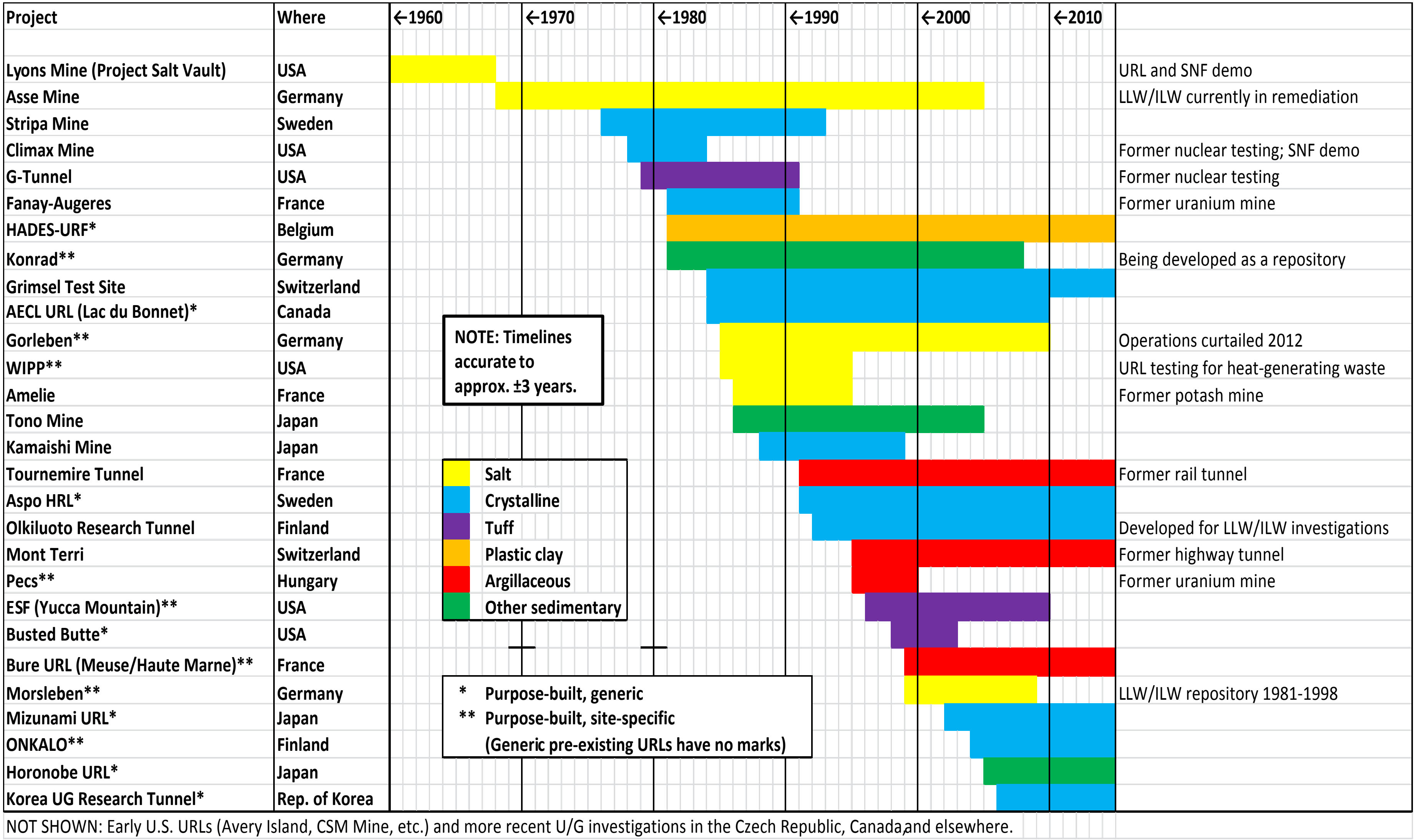
Acknowledgements

Based on input and previous presentations developed by Dave Kessel, Kris Kuhlman, Rick Beauheim, Leif Eriksson, Al Stevens, Bill Boyle, Mark Peters, and many others.

Outline

- **Introduction to URLs in the U.S.**
  - Waste Isolation Pilot Project (WIPP)
  - Yucca Mountain Exploratory Studies Facility (ESF)
- **URL planning, design, construction and operation**
  - Siting, design, construction and testing (WIPP URL and YM ESF)
  - Test interference and waste isolation analyses (Yucca Mountain examples)
  - Lessons learned

Worldwide Rad. Waste Disposal URL Timeline



Project	Where	
Lyons Mine (Project Salt Vault)	USA	URL and SNF demo
Asse Mine	Germany	LLW/ILW currently in remediation
Stripa Mine	Sweden	
Climax Mine	USA	Former nuclear testing; SNF demo
G-Tunnel	USA	Former nuclear testing
Fanay-Augeres	France	Former uranium mine
HADES-URF*	Belgium	
Konrad**	Germany	Being developed as a repository
Grimsel Test Site	Switzerland	
AECL URL (Lac du Bonnet)*	Canada	
Gorleben**	Germany	Operations curtailed 2012
WIPP**	USA	URL testing for heat-generating waste
Amelie	France	Former potash mine
Tono Mine	Japan	
Kamaishi Mine	Japan	
Tournemire Tunnel	France	Former rail tunnel
Aspo HRL*	Sweden	
Olkiluoto Research Tunnel	Finland	Developed for LLW/ILW investigations
Mont Terri	Switzerland	Former highway tunnel
Pecs**	Hungary	Former uranium mine
ESF (Yucca Mountain)**	USA	
Busted Butte*	USA	
Bure URL (Meuse/Haute Marne)**	France	
Morsleben**	Germany	LLW/ILW repository 1981-1998
Mizunami URL*	Japan	
ONKALO**	Finland	
Horonobe URL*	Japan	
Korea UG Research Tunnel*	Rep. of Korea	

NOTE: Timelines accurate to approx. ±3 years.

🟨 Salt
🟦 Crystalline
🟪 Tuff
🟧 Plastic clay
🟥 Argillaceous
🟩 Other sedimentary

* Purpose-built, generic
** Purpose-built, site-specific
(Generic pre-existing URLs have no marks)

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

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.

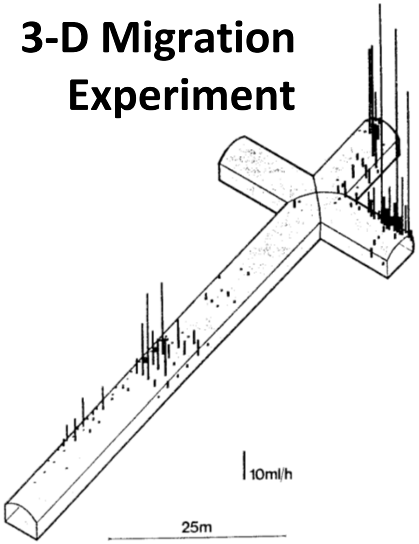
Stripa Project: 1980-1992 (Generic, Granite URL)

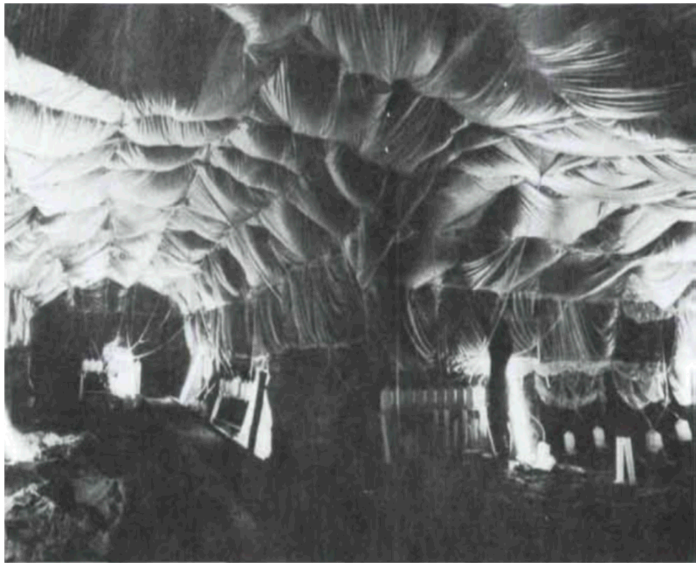
- **Swedish-American Cooperative → OECD/NEA Project**
- **Canada, Finland, Sweden, Switzerland & USA**
- **Granite depth 300 to 400 m**
- **Many experiments; 170 reports**
- **Total cost ~$33M ($60M to $80M escalated)**

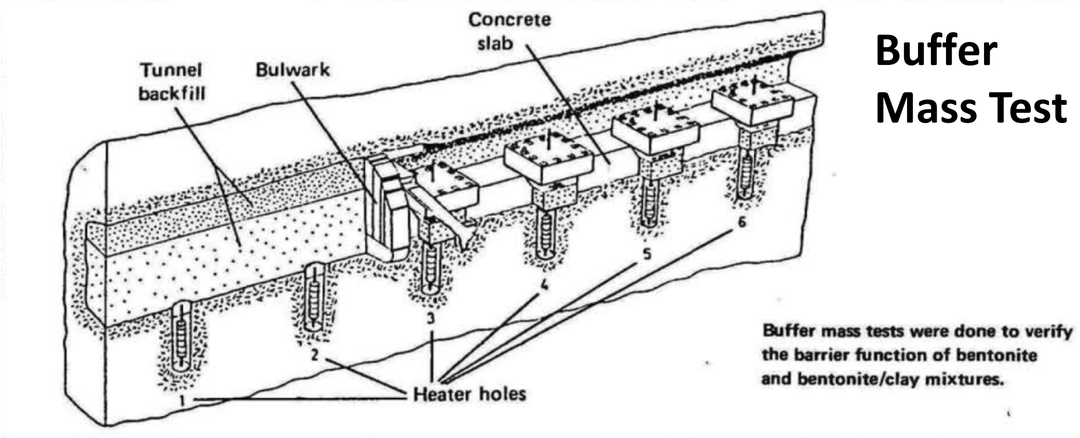
Phase	Period	Budget
1	1980 - 1985	$6M
2	1983 - 1988	$9M
3	1986 - 1992	$18M

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 tests were done to verify the barrier function of bentonite and bentonite/clay mixtures.

Buffer Mass Test

Introduction to URLs in the U.S.

Waste Isolation Pilot Plant URL (1981-1995)

Introduction and Timeline

Geology

Experiments

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

1978-1984
Testing in the
Lab and Analog
Field Sites

1985-1990
Heater Tests,
Rooms A1, A2,
A3 and D

1995 – TRU
Certification
Application
Submitted

1975 – Site
Selected,
SNL Lead
Laboratory

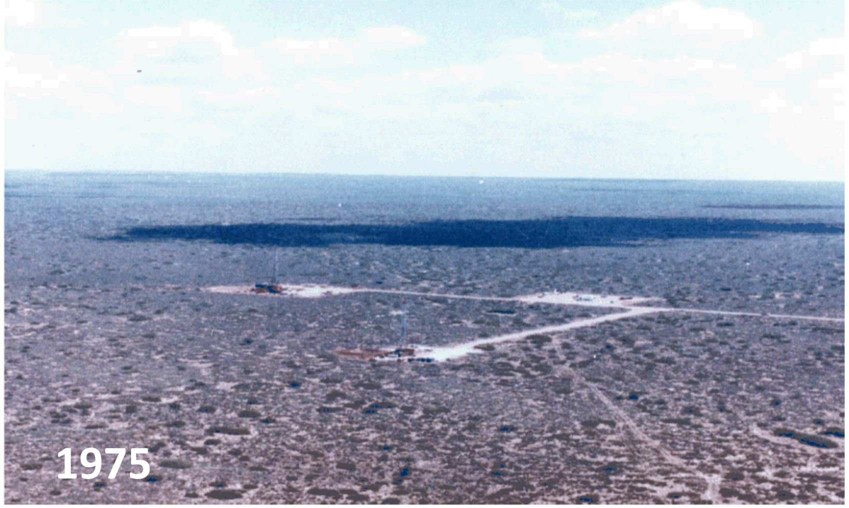
1981-1983
WIPP
Constructed

1984-1986
Test Rooms
Constructed

1987-1995
TRU Waste Studies
(PSP) Continue

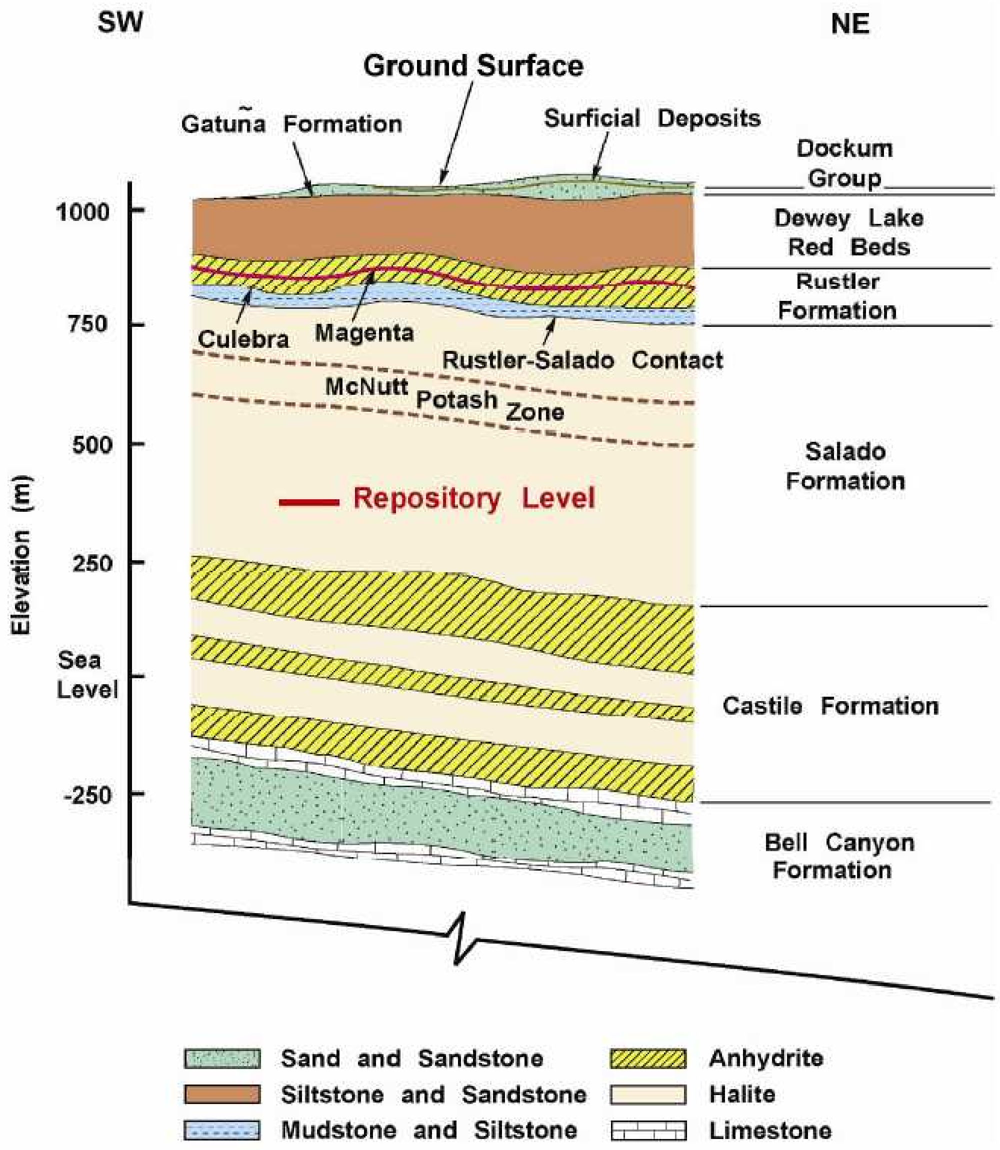
1999
WIPP Waste
Disposal Operation
Begins

1987 – Yucca Mountain Selected;
Heated Tests Directed to Stop (TSI, WPP)

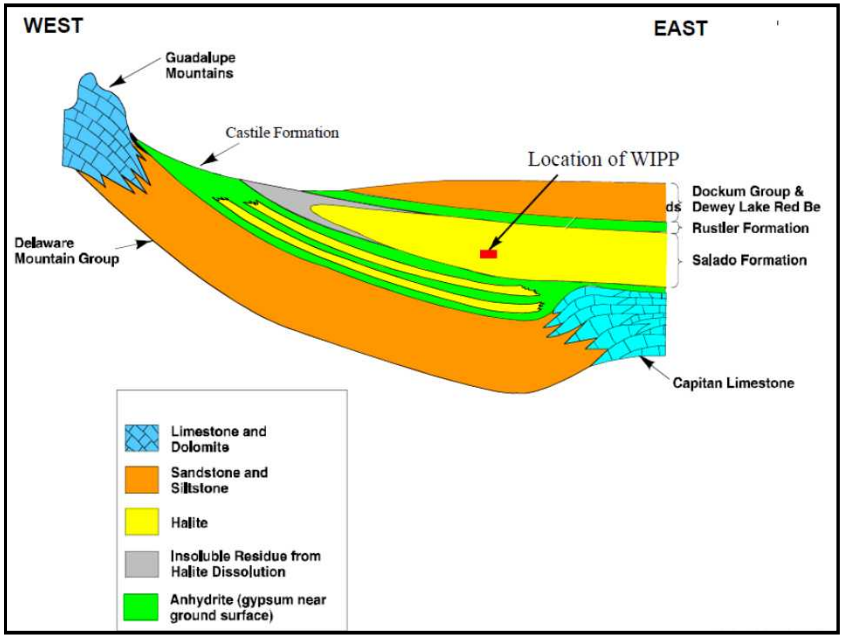

1975


1995

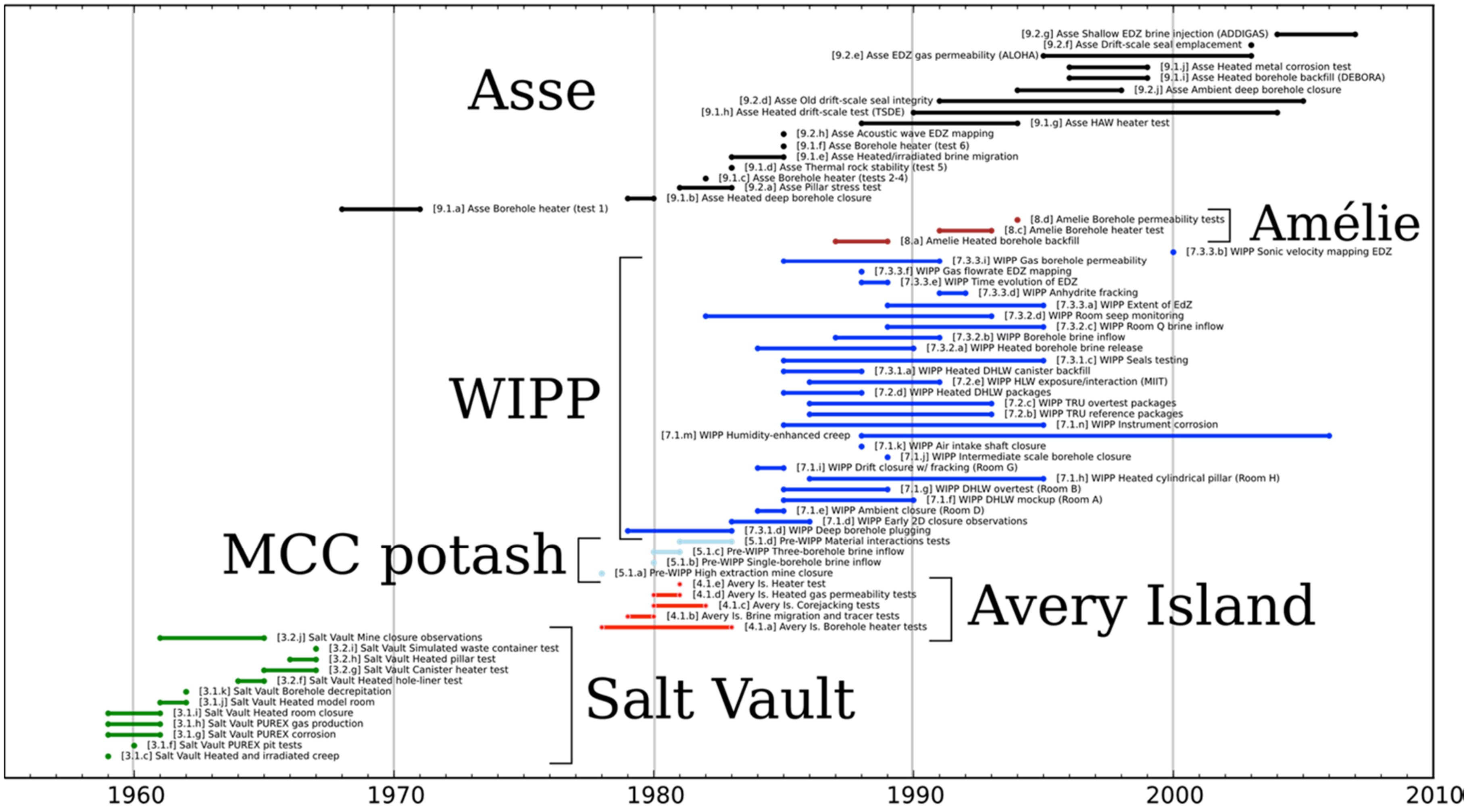
WIPP Geologic Setting



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



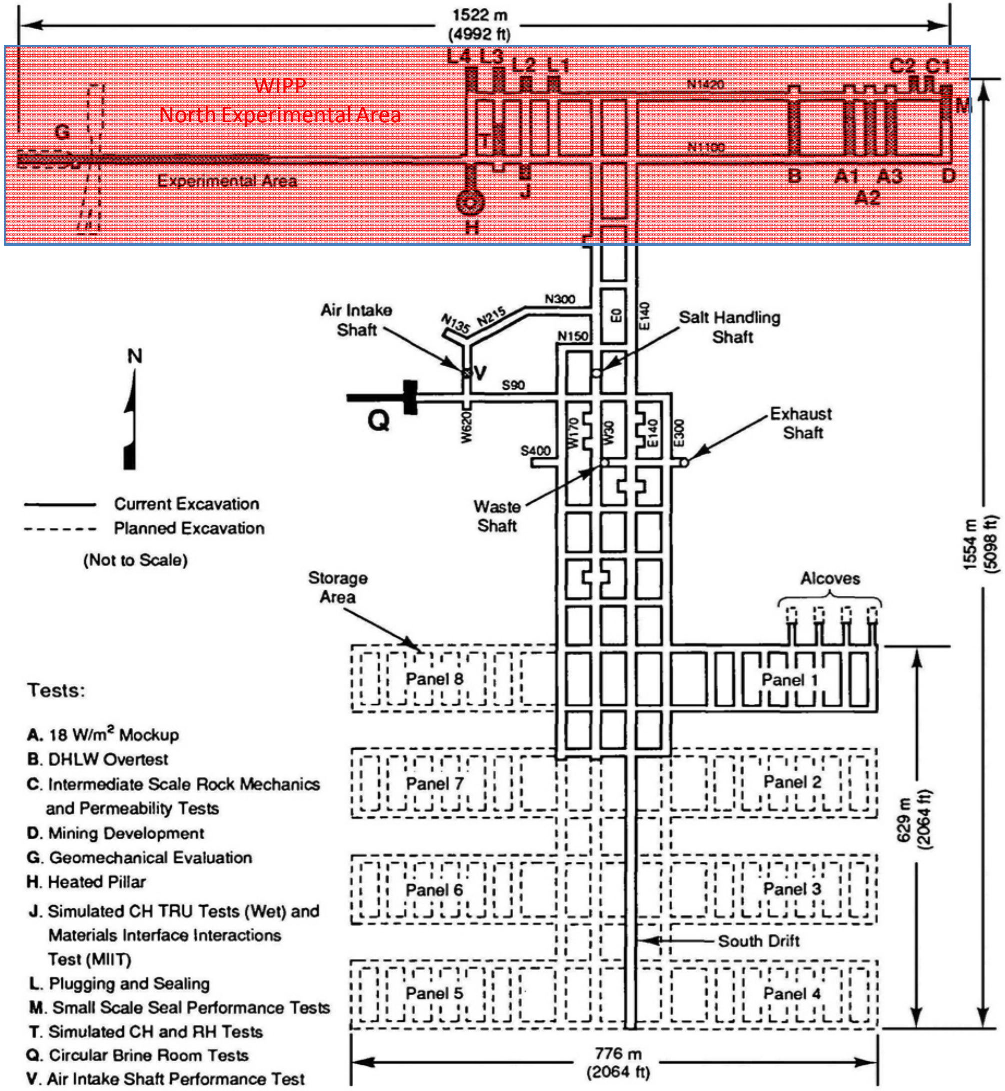
Salt URL Context (1958-2008)



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/m^2 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



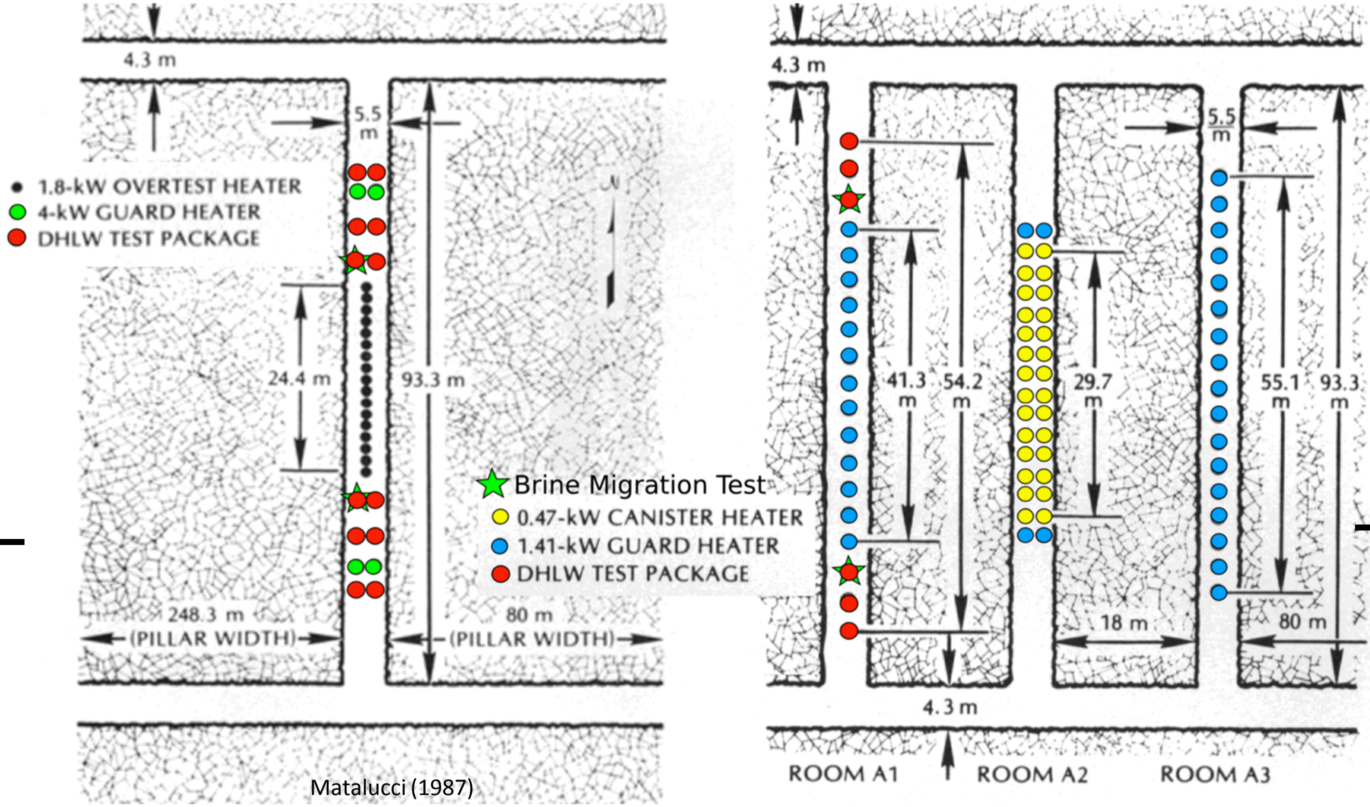
Jensen et al. (1993)

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



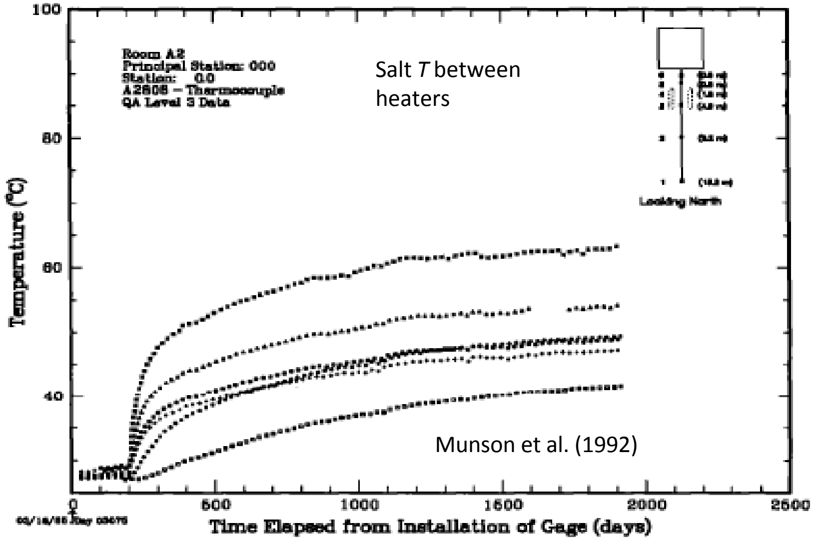
Matalucci (1987)

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

63.9 kW total

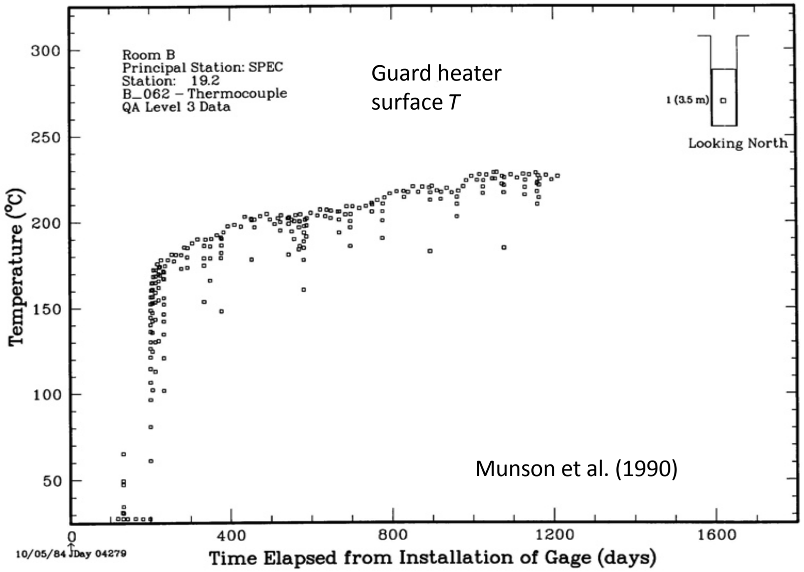
WIPP HLW Tests: Rooms A/B/D

- **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



Salt *T* between heaters

Munson et al. (1992)



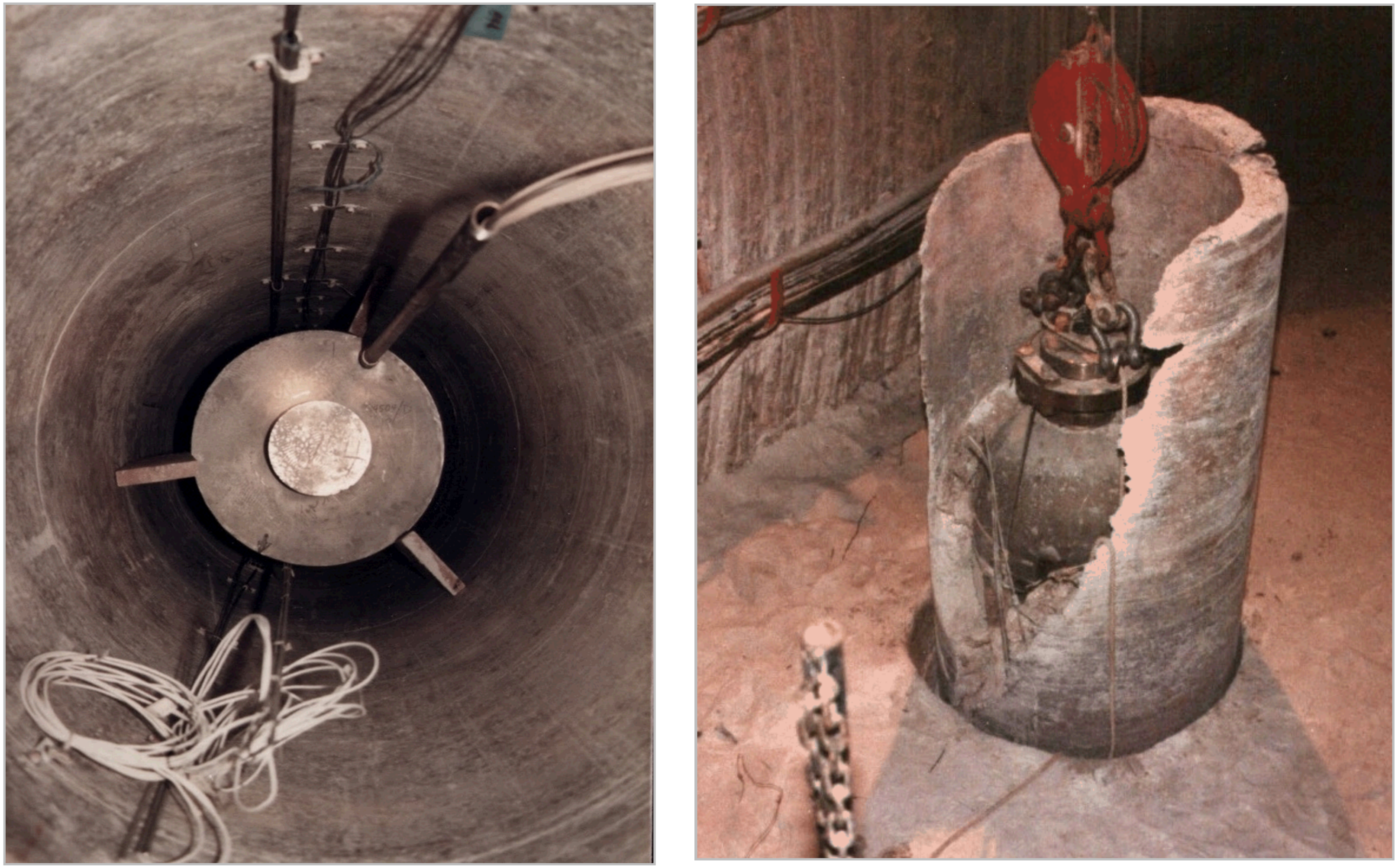
Guard heater surface *T*

Munson et al. (1990)

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

atalucci (1987)

WIPP HLW Tests: Room B (1985-1989)



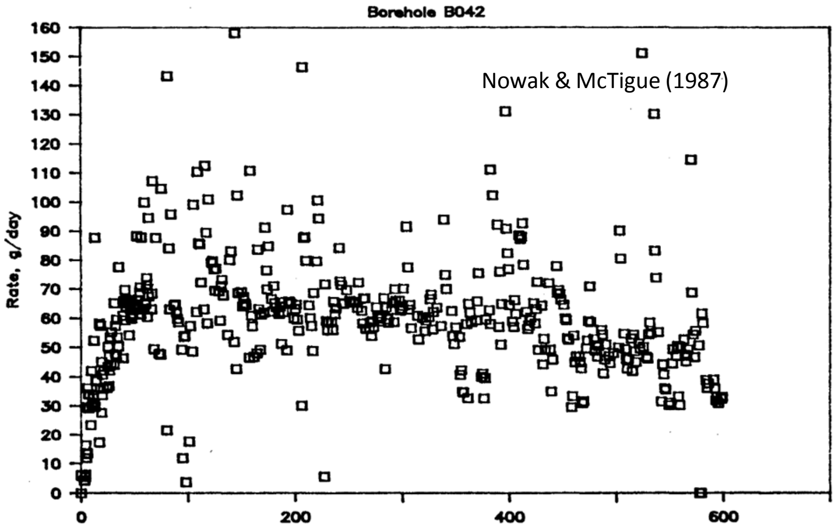
Schuhen et al. (2013)

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 HLW: A1/B Brine Release

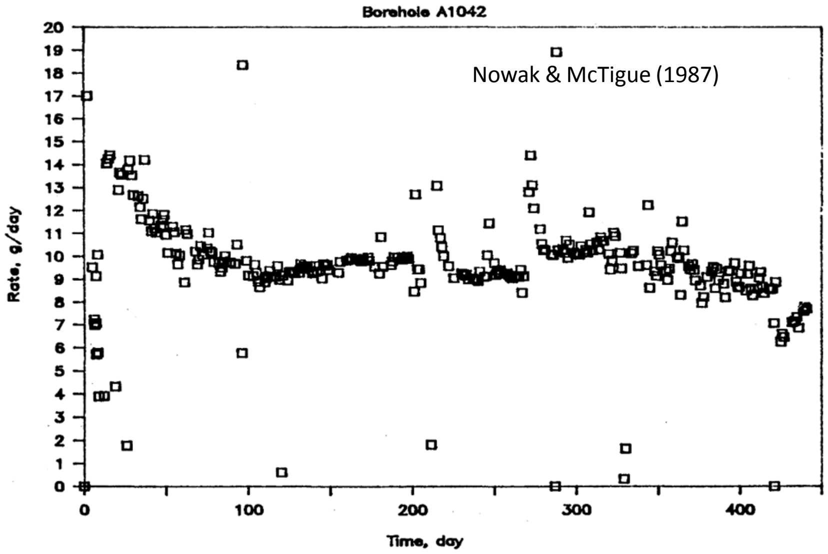
- **Brine Release:**
  - Brine collected and measured before and during heating.
  - Room B produced ~8× more brine at ~3× higher dT/dr
  - Significant brine inflow at clay seam
- **Important Results:**
  - Vapor transport of brine in intact salt is insignificant
  - Observed brine inflow is consistent with salt rind observed
  - Thermo-poro-elastic model



Nowak & McTigue (1987)

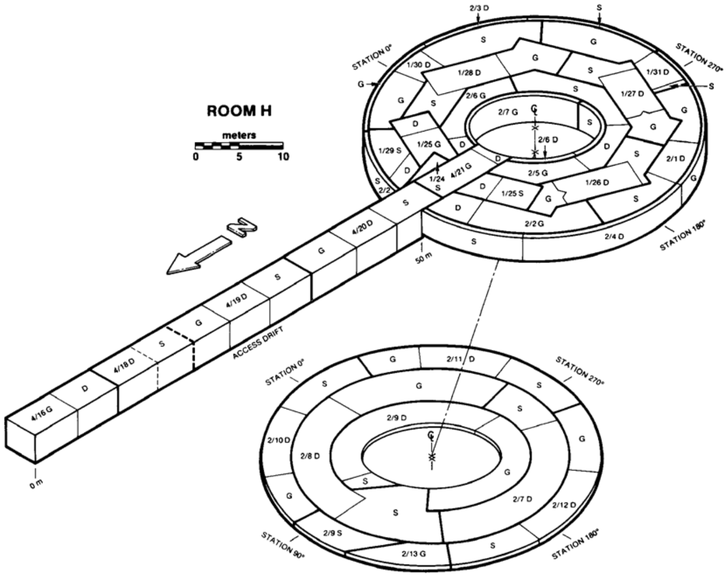
↑Room B: 130° C, 35 L brine/borehole

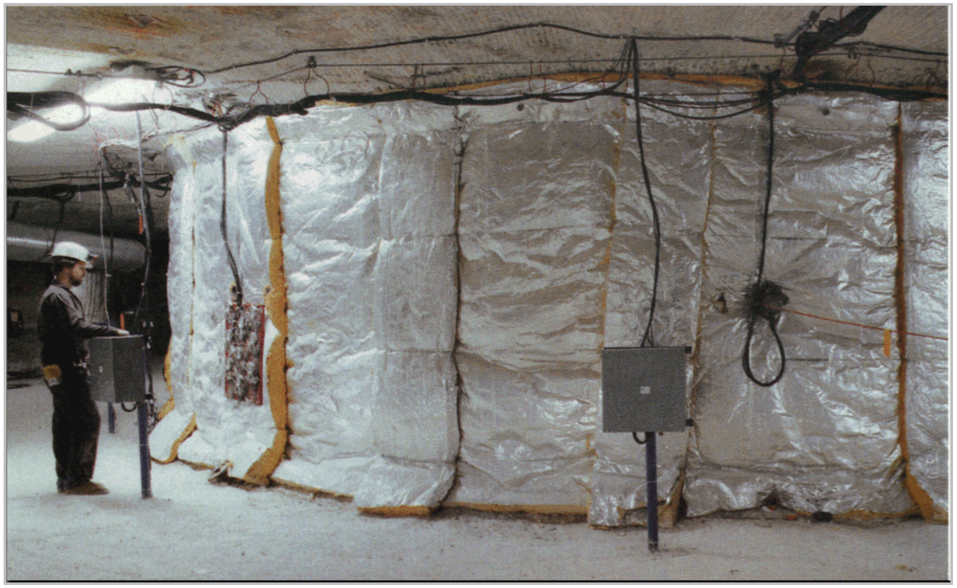
↓Room A1: 50° C, 4.5 L brine/borehole

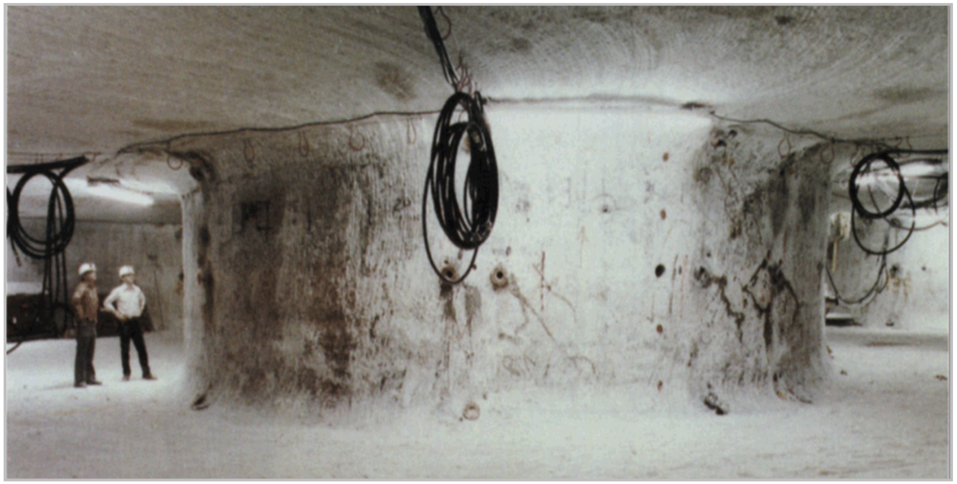


Nowak & McTigue (1987)

WIPP: Room H Heated Circular Pillar (1986-1995)







- **Axisymmetric room heated 9 years**
- **Radial cracking**
- **Important Results:**
  - Successful field experiments are difficult

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

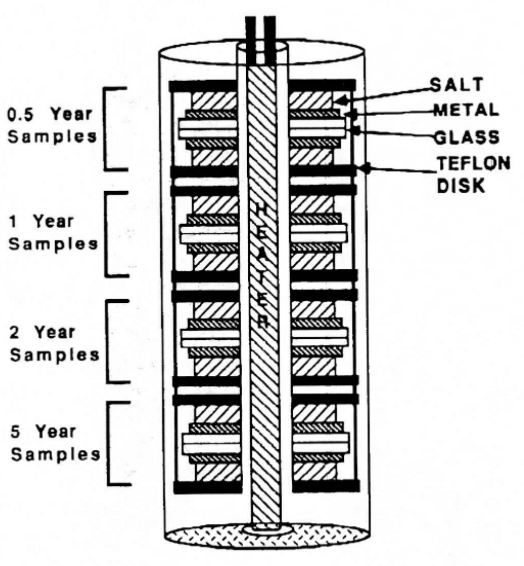
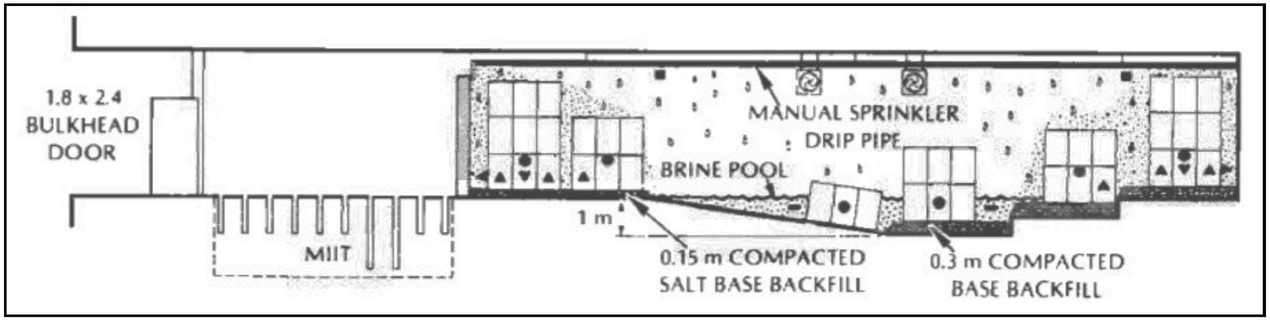


Figure 4

WIPP MIIT Sample Assembly

WIPP: TRU Overtest (1986-1990)

- **Overtest of WIPP-like conditions**
  - Brine pool, 40°C, high humidity, radionuclide tracers, crushed salt
- **Investigated**
  - Drum corrosion
  - Backfill reconsolidation
  - Radionuclide migration
- **Learned:**
  - Canister corrosion is significant in brine



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.)**

Introduction to URLs in the U.S.

Yucca Mountain Exploratory Studies Facility (1981-1995)

Introduction and Timeline

Geology

ESF Alternatives Design Study

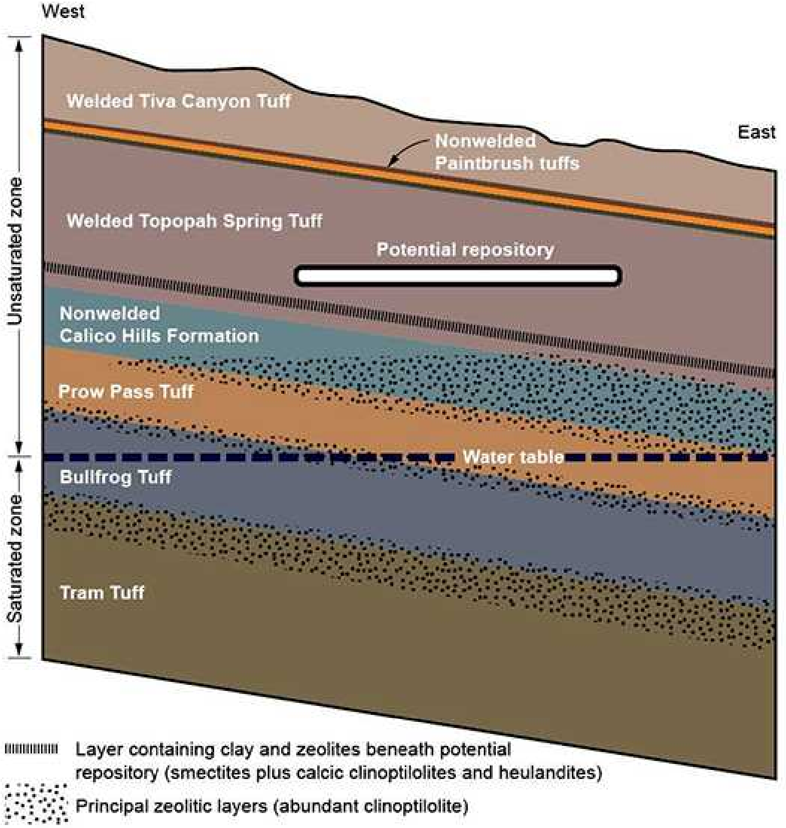
ESF Construction

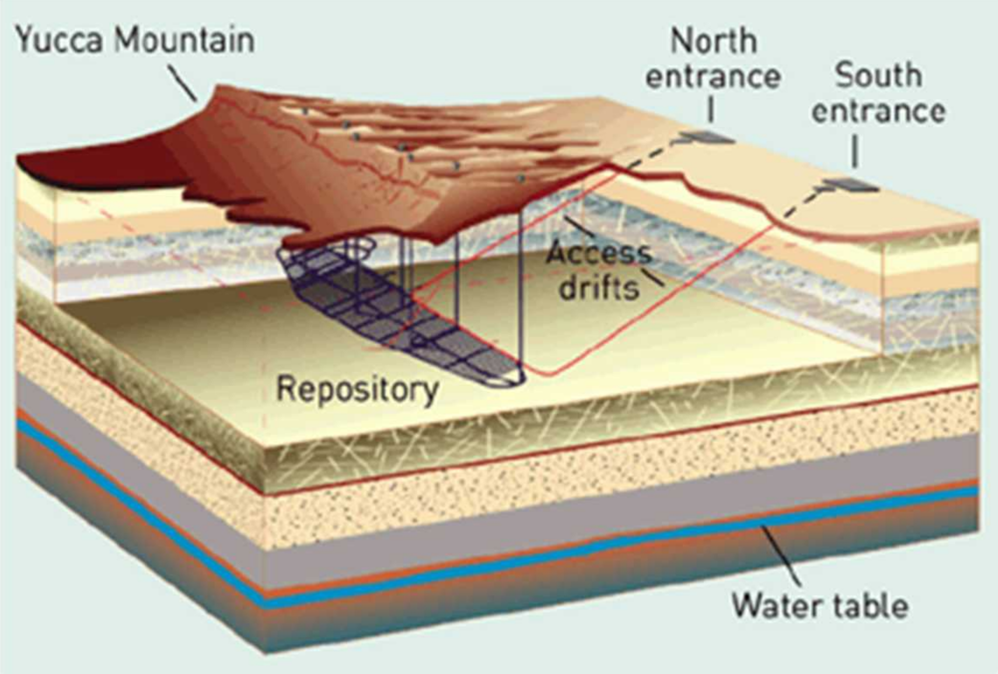
ESF Underground Experiments

Test Interference and Waste Isolation Impact Analysis

Yucca Mountain, Nevada USA

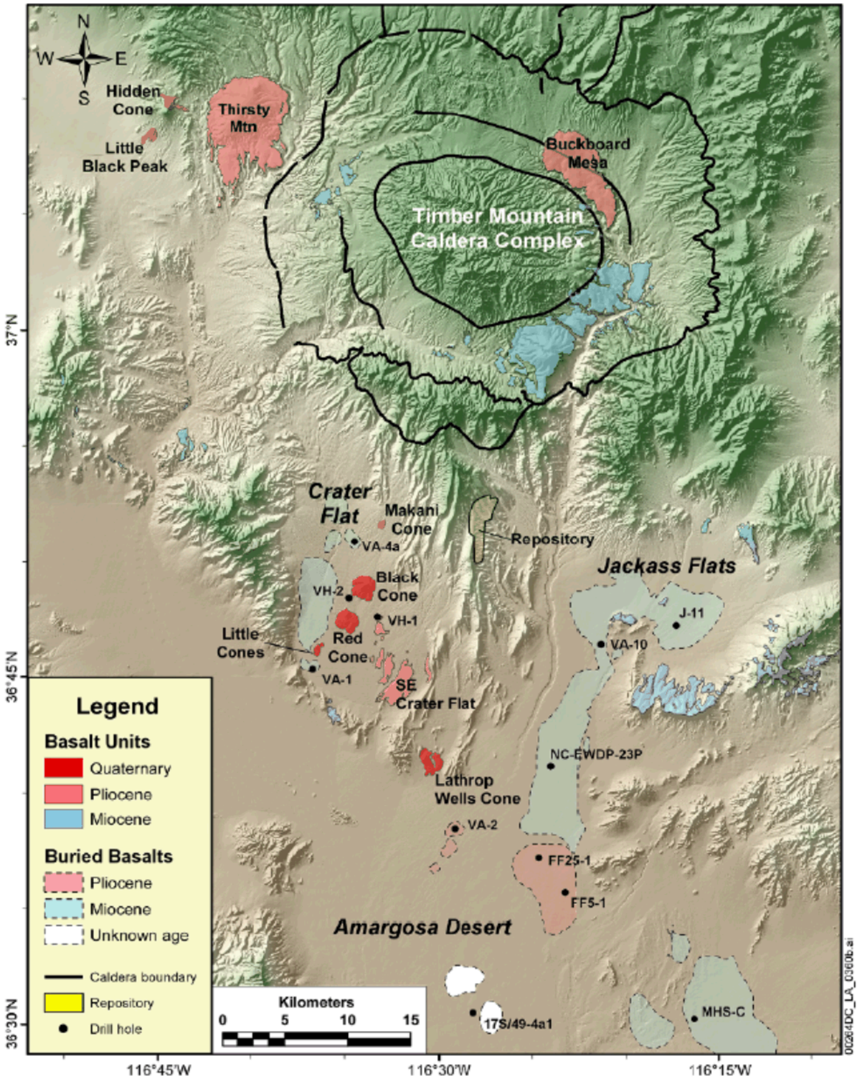
- Sparsely populated, arid desert, closed basin
- Water table 300–600 m below surface
- Miocene caldera tuffs
- Recent seismic, volcanic activity
- Future climate cooler wetter (Milankovich)





Yucca Mountain – Regional Geologic Setting

Great Basin and Basin and Range Province



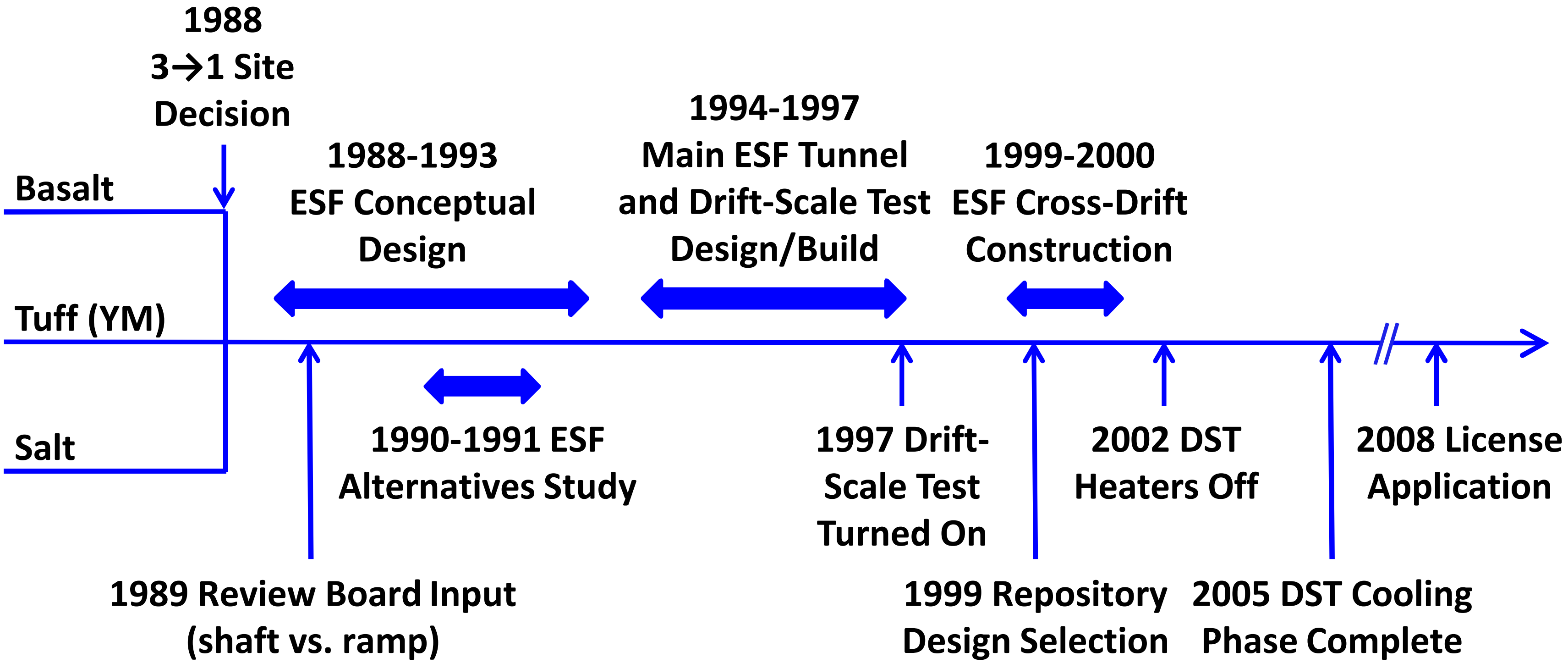
Yucca Mountain Exploratory Studies Facility (ESF)

YM ESF Test	Total Cost	Cost Basis
Single Heater Test (2 yr)	$6M	Construction, Drilling: $1M Procurement, Design, Install, Baseline: $3M Annual Operation: $1M
Drift Scale Test (8 yr)	$59M	Construction, Drilling: $8M Procurement, Design, Install, Baseline: $11M Annual Operation: $5M
Other Tests	~$60M	Roughly equivalent to heated tests
Testing Support (1996–2007)	$50M	Annual Test Operations Support: ~$5M
ESF Construction & Operation	$240M	Surface and U/G Construction: ~$120M Annual Operation: ~$10M

Drift Scale Test (9 simulated packages; ~200 kW)

Aerial view of ESF surface facilities; north and south portals

Yucca Mountain ESF Timeline (1988–2008)



Basalt

Tuff (YM)

Salt

1988
3→1 Site
Decision

1988-1993
ESF Conceptual
Design

1994-1997
Main ESF Tunnel
and Drift-Scale Test
Design/Build

1999-2000
ESF Cross-Drift
Construction

1990-1991 ESF
Alternatives Study

1997 Drift-
Scale Test
Turned On

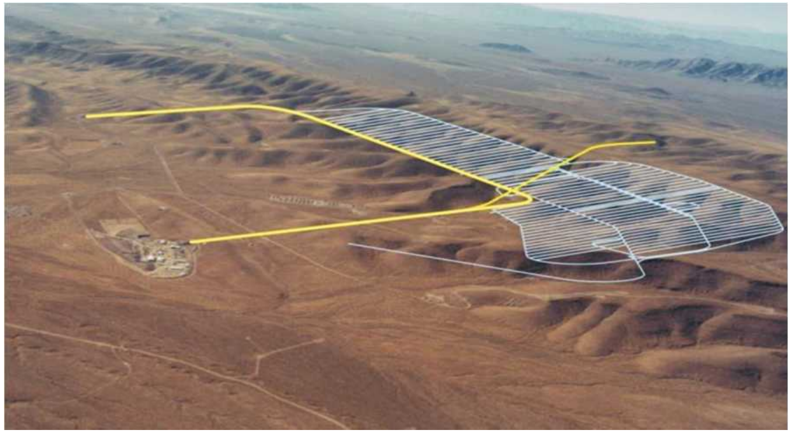
2002 DST
Heaters Off

2008 License
Application

1989 Review Board Input
(shaft vs. ramp)

1999 Repository
Design Selection

2005 DST Cooling
Phase Complete



Introduction to URLs in the U.S.

Yucca Mountain Exploratory Studies Facility (1981-1995)

Introduction and Timeline

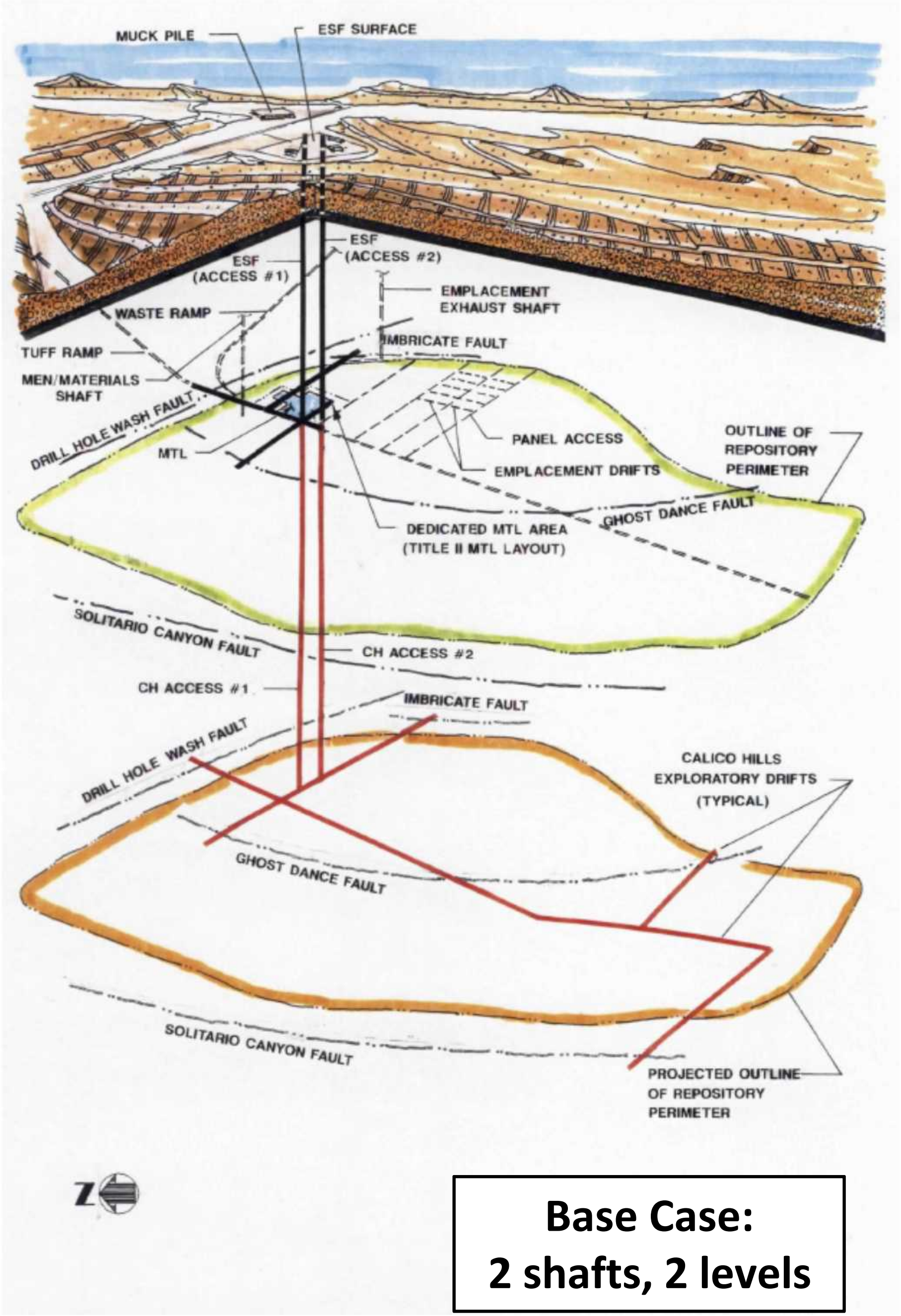
Geology

ESF Alternatives Design Study

ESF Construction

ESF Underground Experiments

Test Interference and Waste Isolation Impact Analysis

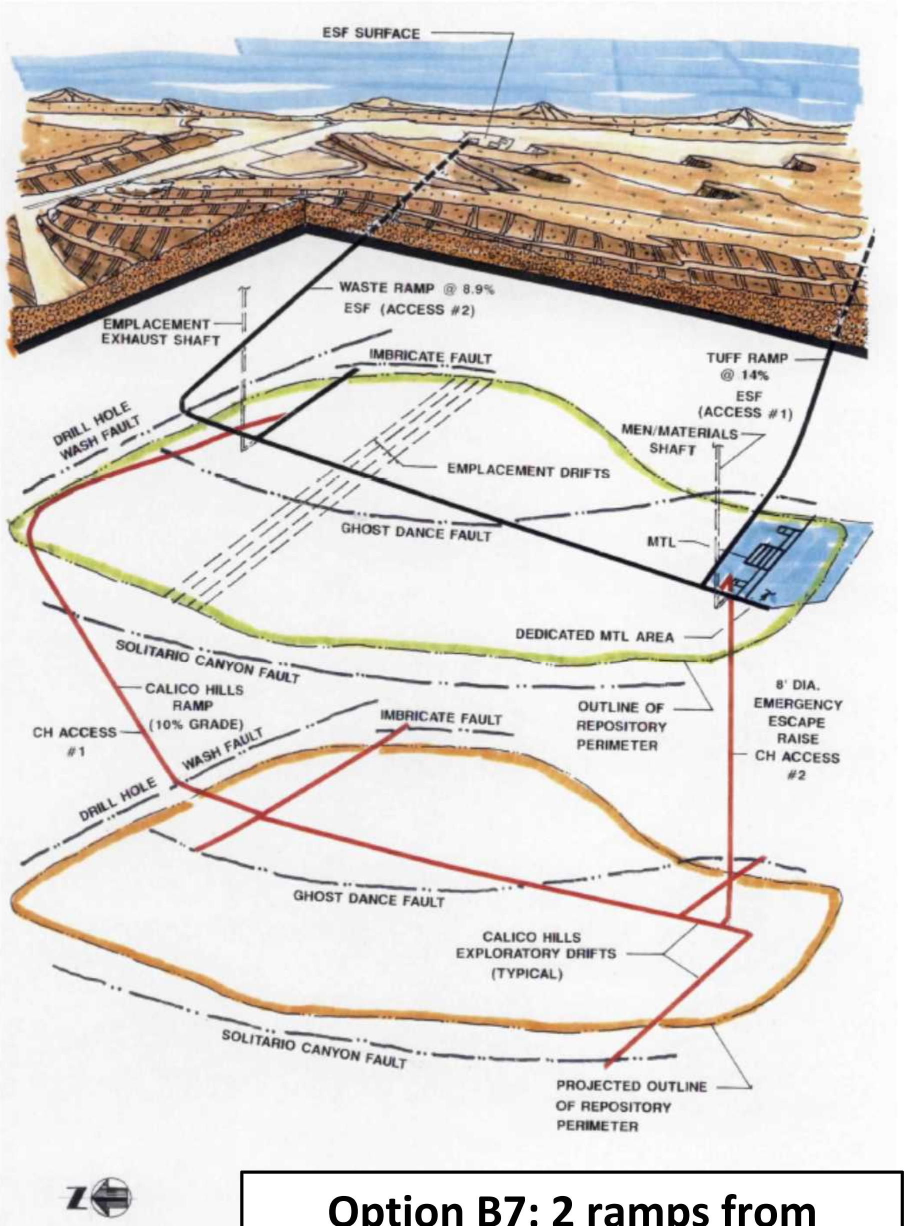


Base Case:
2 shafts, 2 levels

ESF Design Alternatives Study (1990)

- 17 Basic Options
  - Shaft vs. ramp access from surface
  - Drill & blast or raise bore, vs. TBM or roadheader
  - Accesses north, south or both
  - Testing areas north, south or both
- × 2 Variations = 34 Alternatives
  - Access the lower (CHn) level by shafts or ramps, or boreholes only
- Base Case (#1): 2 shafts
- Shaft access to CHn (as needed)

ESF Design Alternatives Study (1990)



Option B7: 2 ramps from surface, 2 levels

- Option B7 (#13 closest to final ESF design)
- 2 Ramps from Surface
- Additional Ramp and Raise Bore Access to CHn Level (as needed)
- Refinements:
  - Testing area later moved to mid-block
  - Ramp grades reduced to ≤ 2.5%
  - Main test area increased to limit interference (> 3×10^5 m^2)

ESF Alternatives Study: Regulatory Objectives

- Conduct site characterization in a manner that limits adverse effects, limits number of boreholes and shafts, and coordinates with repository design.
- Support comparative evaluations of major repository design features.
- Limit test-test and construction-test interference.
- Limits impacts from construction method (e.g., rock damage, water, etc.)
- Ensure adequate characterization to evaluate repository siting.

ESF Design Alternatives Study Methodology

- **Methodology:**
  - Explicit consideration of URL impact on repository design
  - Use formal decision logic (multiattribute utility analysis, MUA)
  - High-level objectives:
    - Maximize programmatic viability
    - Maximize value (e.g., relevance, timeliness) of characterization testing
    - Maximize compliance with regulations
    - Minimize negative impacts on repository design
- **Inputs:**
  - Documented information:
    - Sketches and data sheets
    - Constructability and operability assessments
    - Cost and schedule assessments
    - Repository radionuclide release analysis
  - Expert judgement panels
    - Separate ratings witih respect to URL and repository objectives

Reference: Merkhofer, et al. 1991. *Exploratory Studies Facility Alternatives Study Final Report*. SAND91-0025, Sandia National Laboratories.

ESF Alternatives Study Methodology: Decision Tree

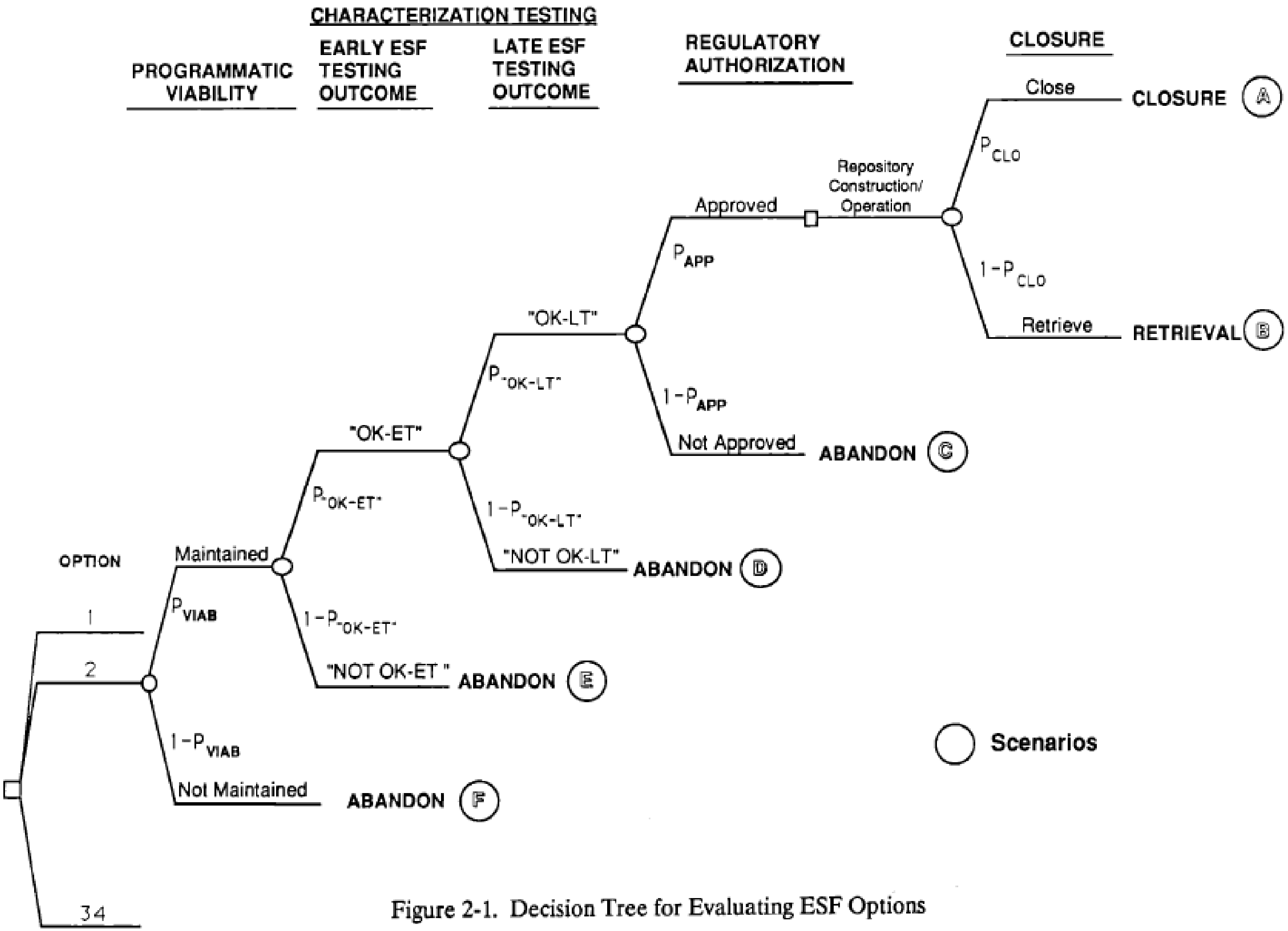
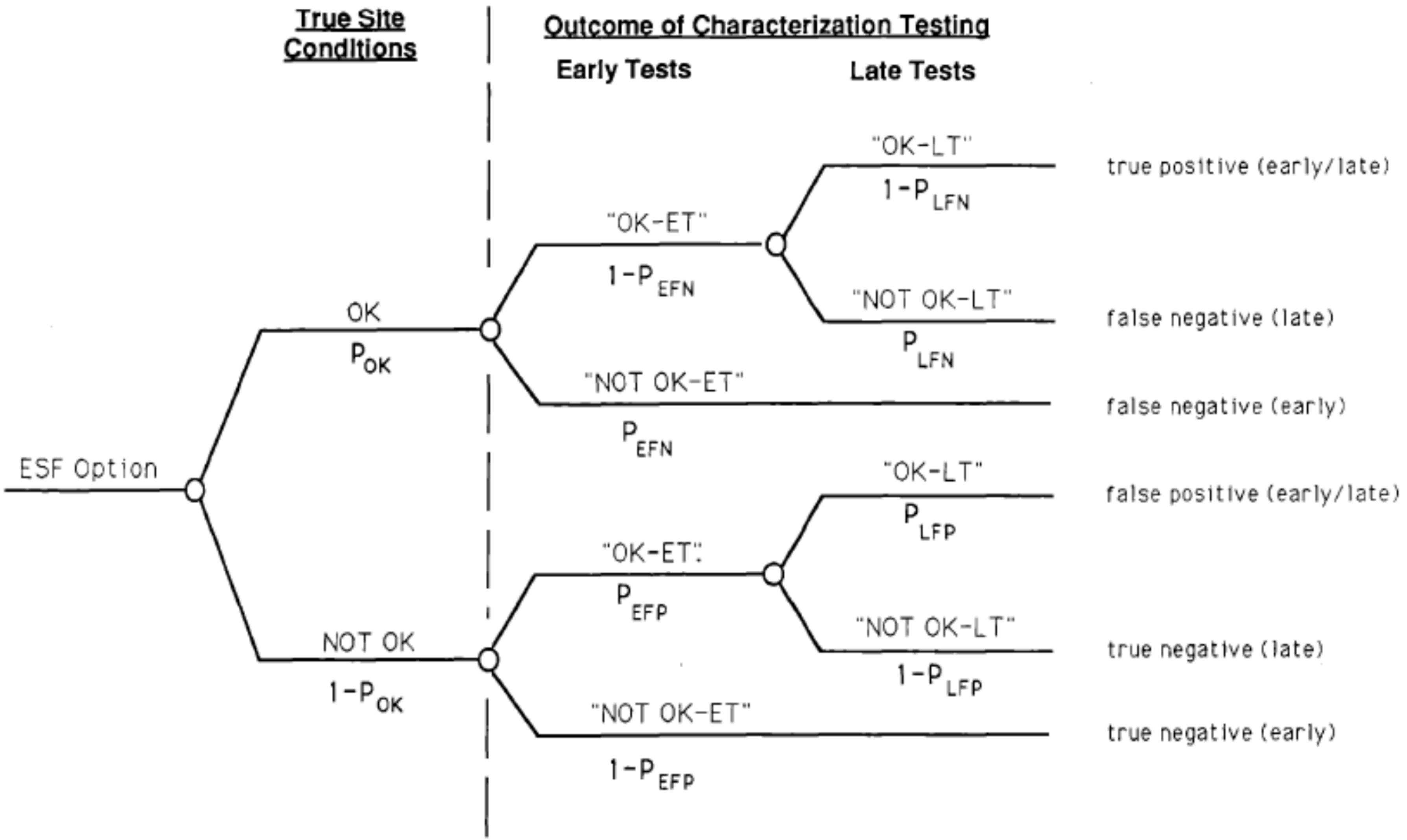


Figure 2-1. Decision Tree for Evaluating ESF Options

ESF Alternatives Study: Characterization Testing Tree



ESF Alternatives Study Results Table

Closest to final design →

Conceptual Design involves adjust-ments to optimize design

Note: criteria are non-discriminating for the top ~10 options

Rank Order	ESF Option	Net Benefit ($B)	Probabilities						RN Release	
			Scenario A (Closed Repository)	Program-matic Viability	Testing Results		Regula-tory Approval	Reposi-tory Closure	Aqueous	Aqueous +C-14
					OK (early)	OK (early + late)				
1	30	24.3	.60	.89	.85	.91	.87	.999	6E-7	.017
2	23	23.3	.58	.87	.83	.89	.90	.998	6E-7	.017
3	24	23.0	.57	.90	.82	.89	.86	.997	8E-7	.020
4	13	22.9	55	.81	.85	.91	.89	.999	6E-7	.017
5	6	22.5	.54	.78	.83	.90	.93	.999	6E-7	.017
6	7	22.3	.54	.79	.82	.90	.92	.998	8E-7	.020
7	2	21.1	.51	.73	.83	.91	.93	.998	7E-7	.019
8	19	20.4	.51	.77	.83	.89	.90	.997	7E-7	.019
9	4	20.0	.49	.74	.83	.92	.87	.999	2E-6	.019
10	25	19.9	.50	.84	.83	.90	.80	.997	2E-6	.020
11	21	19.6	.49	.77	.84	.90	.84	.998	2E-6	.019
12	28	19.2	.48	.79	.83	.90	.82	.997	8E-7	.020
13	22	17.8	.45	.77	.84	.90	.78	.997	8E-7	.017
14	29	16.9	.43	.73	.84	.90	.79	.997	8E-7	.017
15	32	16.8	.42	.62	.80	.90	.94	.998	3E-7	.017
16	20	16.6	.41	.67	.83	.89	.83	.997	6E-7	.020
17	27	16.3	.42	.83	.79	.89	.73	.996	9E-7	.020
18	8	16.0	.40	.64	.83	.90	.85	.998	9E-7	.020
19	31	15.9	.41	.70	.84	.90	.77	.997	2E-6	.017
20	15	15.5	.38	.54	.83	.90	.95	.999	3E-7	.017
21	33	15.4	.39	.59	.83	.90	.88	.998	2E-7	.017
22	5	14.7	.37	.58	.84	.90	.85	.999	8E-7	.017
23	12	14.0	.35	.58	.84	.90	.81	.998	8E-7	.017
24	3	13.9	.35	.52	.83	.90	.89	.998	6E-7	.020
25	16	13.8	.35	.53	.81	.89	.90	.999	2E-7	.017
26	11	13.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.997	8E-7	.020
27	1	12.3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.995	1E-6	.020
28	14	11.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.998	2E-6	.017
29	10	11.3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.996	9E-7	.020
30	17	11.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.997	2E-6	.020
31	18	11.0	.29	.52	.82	.88	.77	.995	1E-6	.020
32	34	9.8	.26	.53	.83	.89	.69	.995	2E-6	.020
33	26	7.7	.22	.55	.74	.83	.66	.991	5E-6	.023
34	9	6.3	.19	.45	.74	.84	.67	.991	5E-6	.023

Introduction to URLs in the U.S.

Yucca Mountain Exploratory Studies Facility (1981-1995)

Introduction and Timeline

Geology

ESF Alternatives Design Study

ESF Construction

ESF Underground Experiments

Test Interference and Waste Isolation Impact Analysis

Yucca Mountain Main Pad, High-Wall and Starter Tunnel

Yucca Mountain Main Starter Tunnel

Yucca Mountain Main Tunnel TBM

Manufacturer: CTS, Length: 140 m, Weight: 654 MT, Diameter: 7.62 m, Max. Advance Rate: 5.3 m/hr, Power: 12 electric motors (2.9 MW)

ESF Construction – Roadheader
(Niches and Alcoves from TBM tunnel)

Yucca Mountain Main Tunnel

TBM Operation, Geologic Mapping

Yucca Mountain Main Tunnel

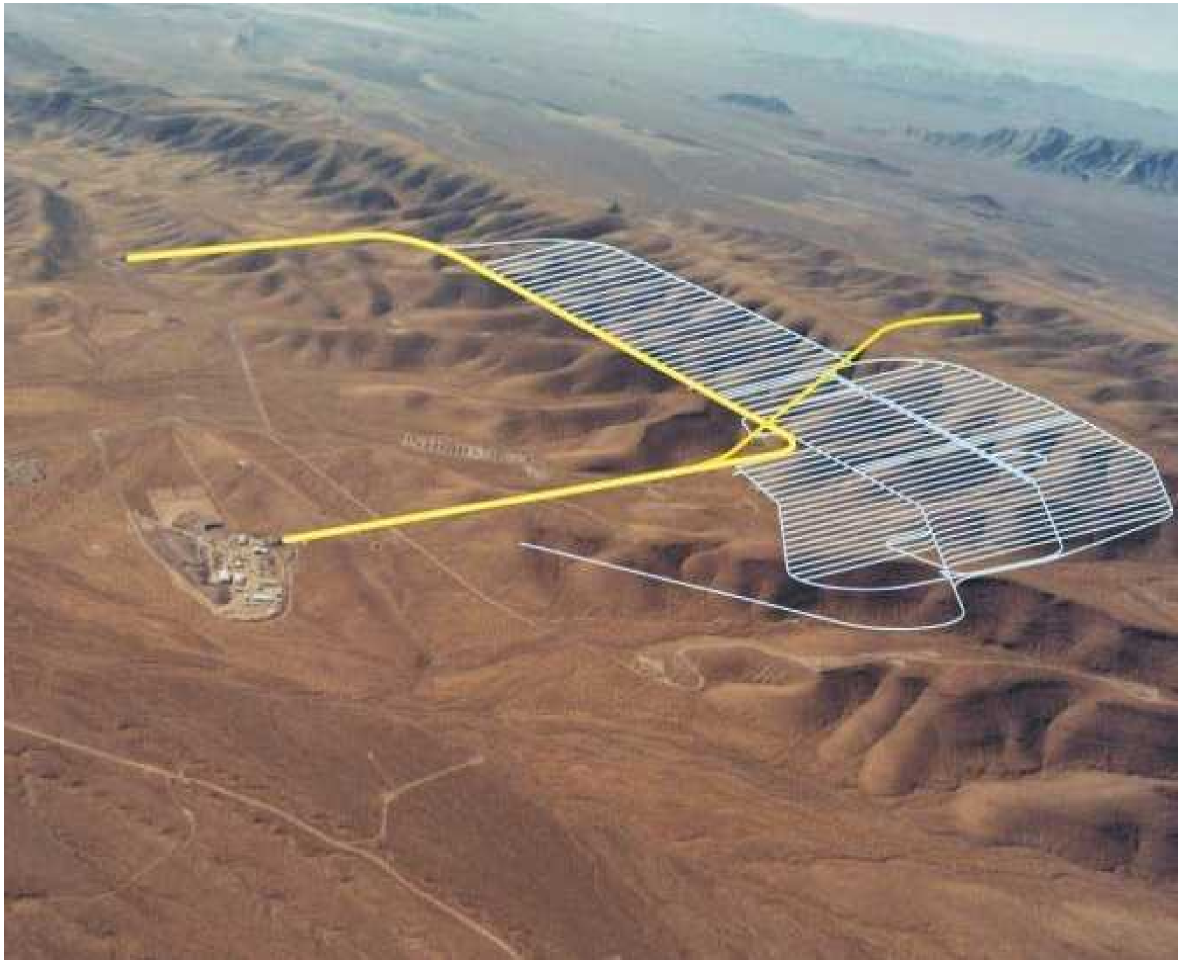
Diameter 7.62 m, Max. Grade: 2.5%, Length: 7 km

Yucca Mountain Main Tunnel

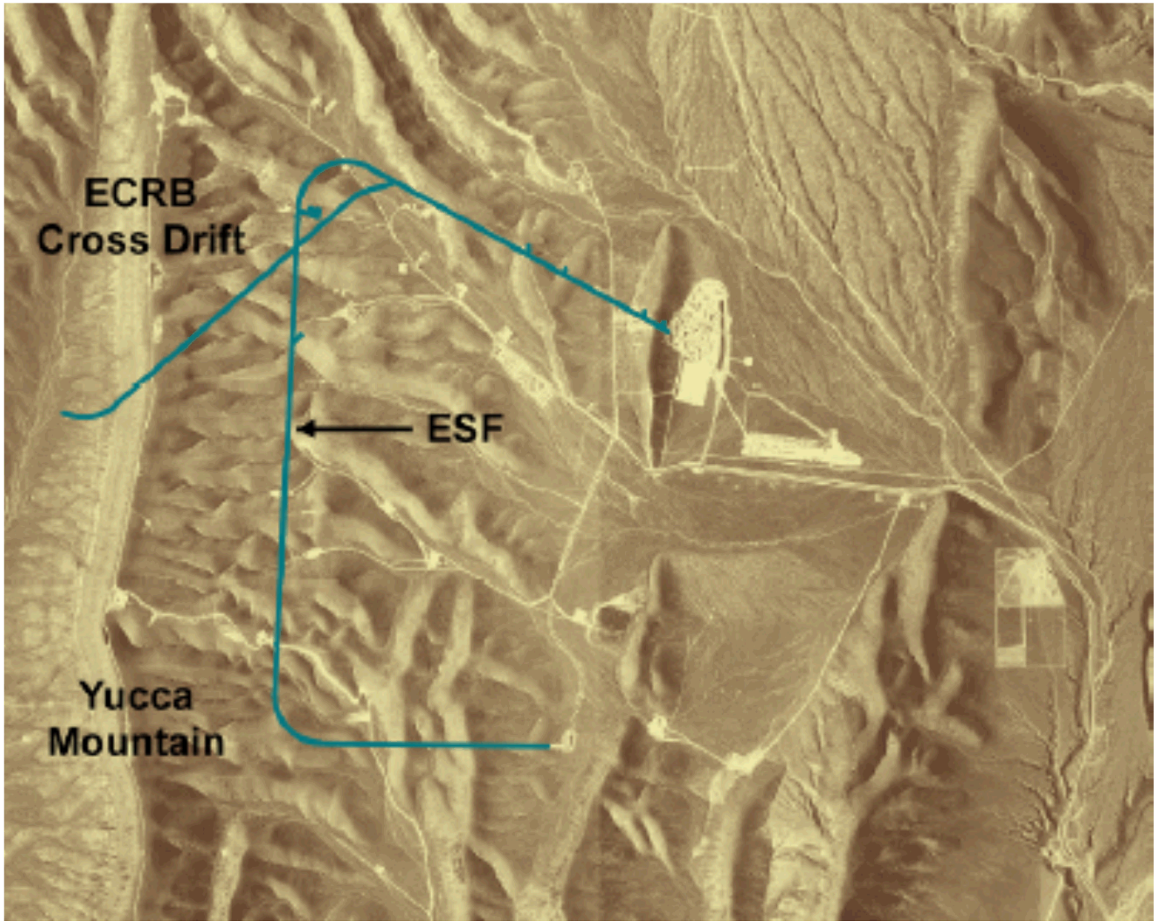
Breakthrough at South Portal

Yucca Mountain ESF Design Considerations

- Purpose built, site-specific URL
- Main tunnels to be part of repository →
  - Regulatory reviews
  - Quality assurance
  - Administrative controls (e.g., materials and water use tracking)



Yucca Mountain ESF – Exploratory TBM Tunnels



- **Enhanced Characterization of the Repository Block (ECRB) TBM tunnel**
- **Crosses over and above into the Lower Lithophysal unit of the Topopah Spring Tuff**
- **Repository host rock**
  - Mostly Lower Lithophysal
  - Also parts of Upper and Middle Non-Lithophysal units

Introduction to URLs in the U.S.

Yucca Mountain Exploratory Studies Facility (1981-1995)

Introduction and Timeline

Geology

ESF Alternatives Design Study

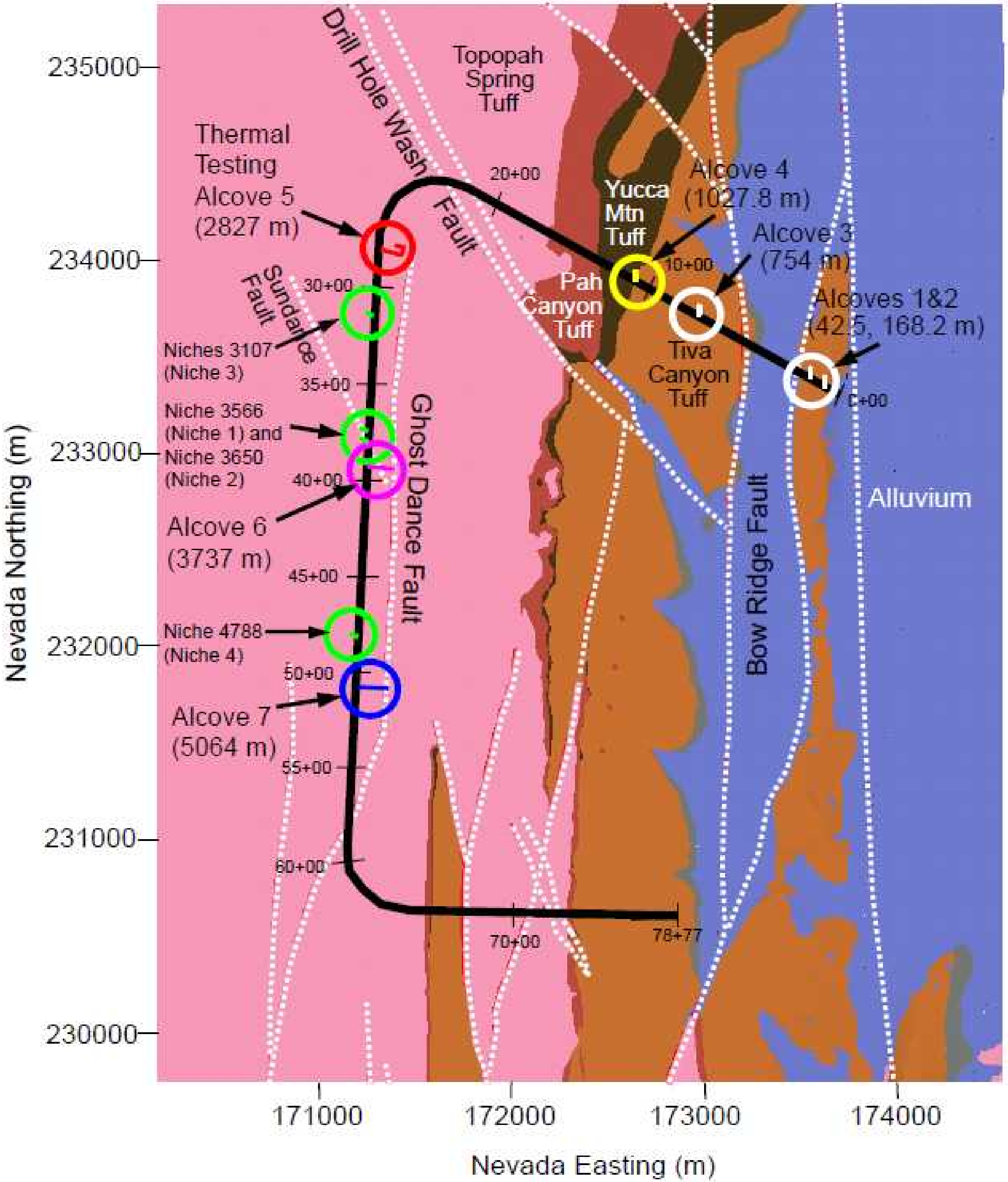
ESF Construction

ESF Underground Experiments

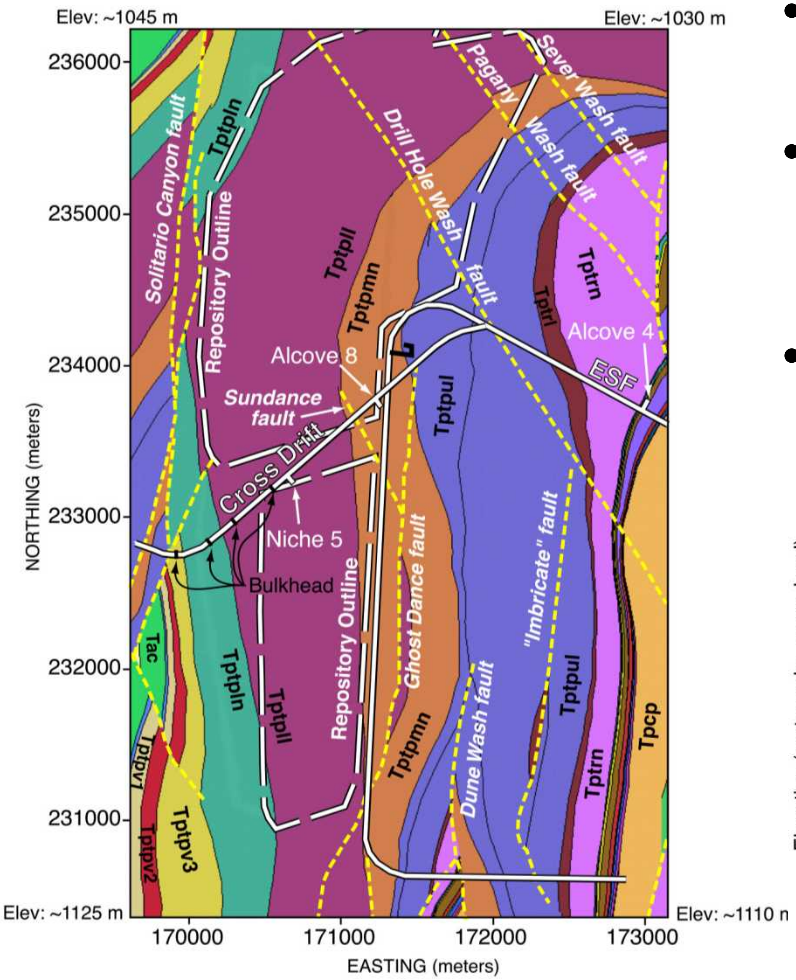
Test Interference and Waste Isolation Impact Analysis

ESF Underground Testing Locations - Excavations

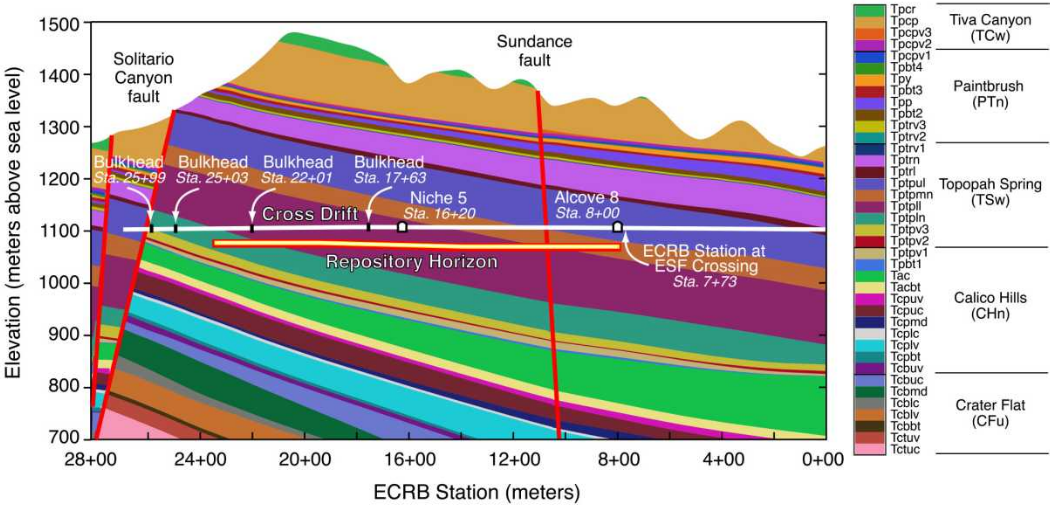
- Access host rock subunits and faults
- Curtains or light bulkheads used to isolate alcoves and niches from ventilation



Host Rock Stratigraphy and ECRB Cross-Drift



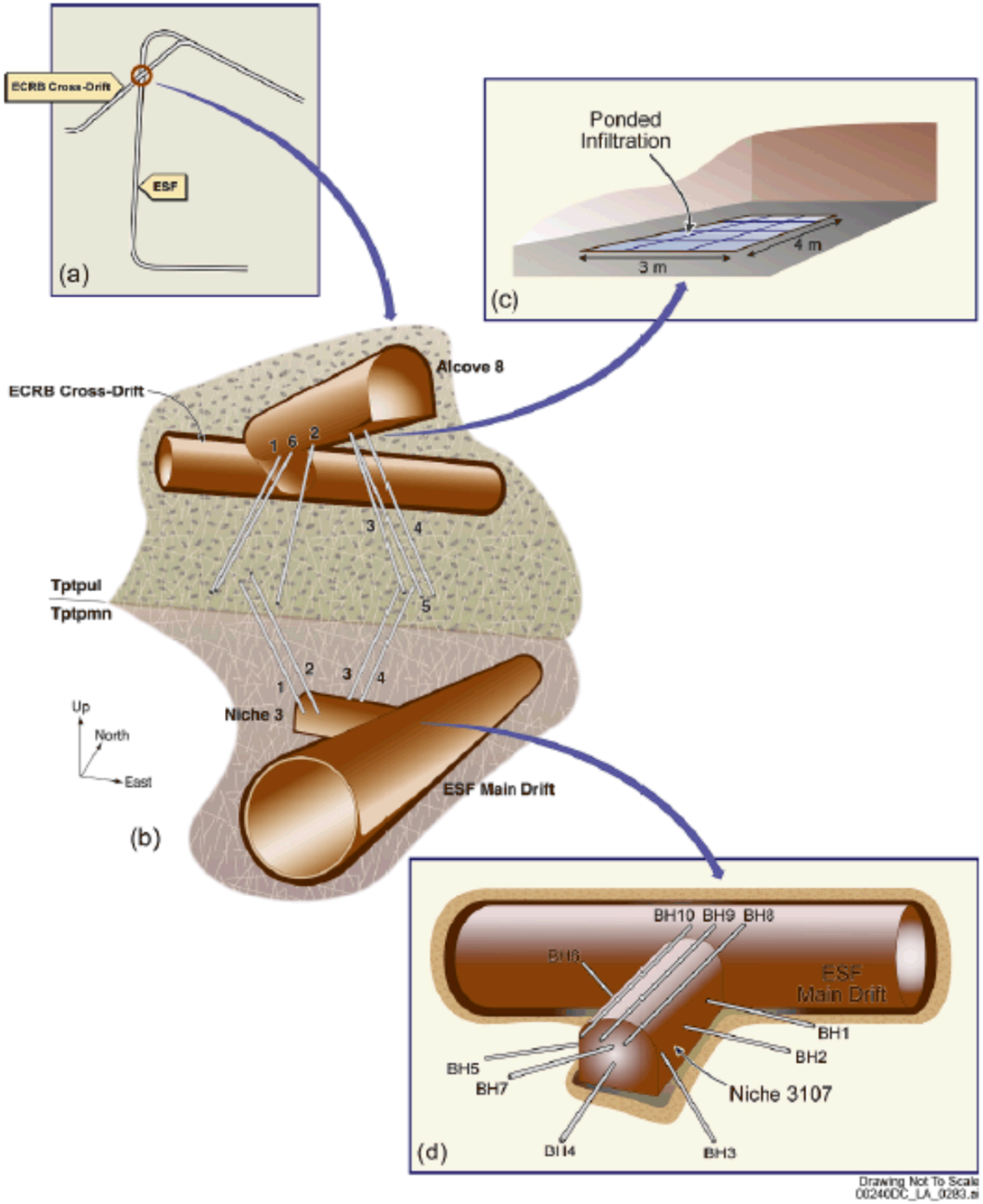
- **Enhanced Characterization of the Repository Block (ECRB)**
- **Target: Lower Lithophysal tuff unit (ESF Main Drift mostly in Middle Non-Lithophysal tuff unit)**
- **Lithophysal tuff favored for excavation/construction**



Summary of ESF Experiments

- Geologic mapping and sampling
- Hydrologic measurements, monitoring, core testing, flow testing, tracer transport testing
- Geochemical sampling
- Geophysical ground motion and strain monitoring
- Geomechanical monitoring, borehole measurements, jacking tests, mine-by
- Thermal tests: Single-Heater Test (SHT) and Drift-Scale Test (DST; thermal, hydrologic, mechanical, geophysical and geochemical measurements)
- **Examples: SHT, DST and Alcove 8/Niche 3 transport test**

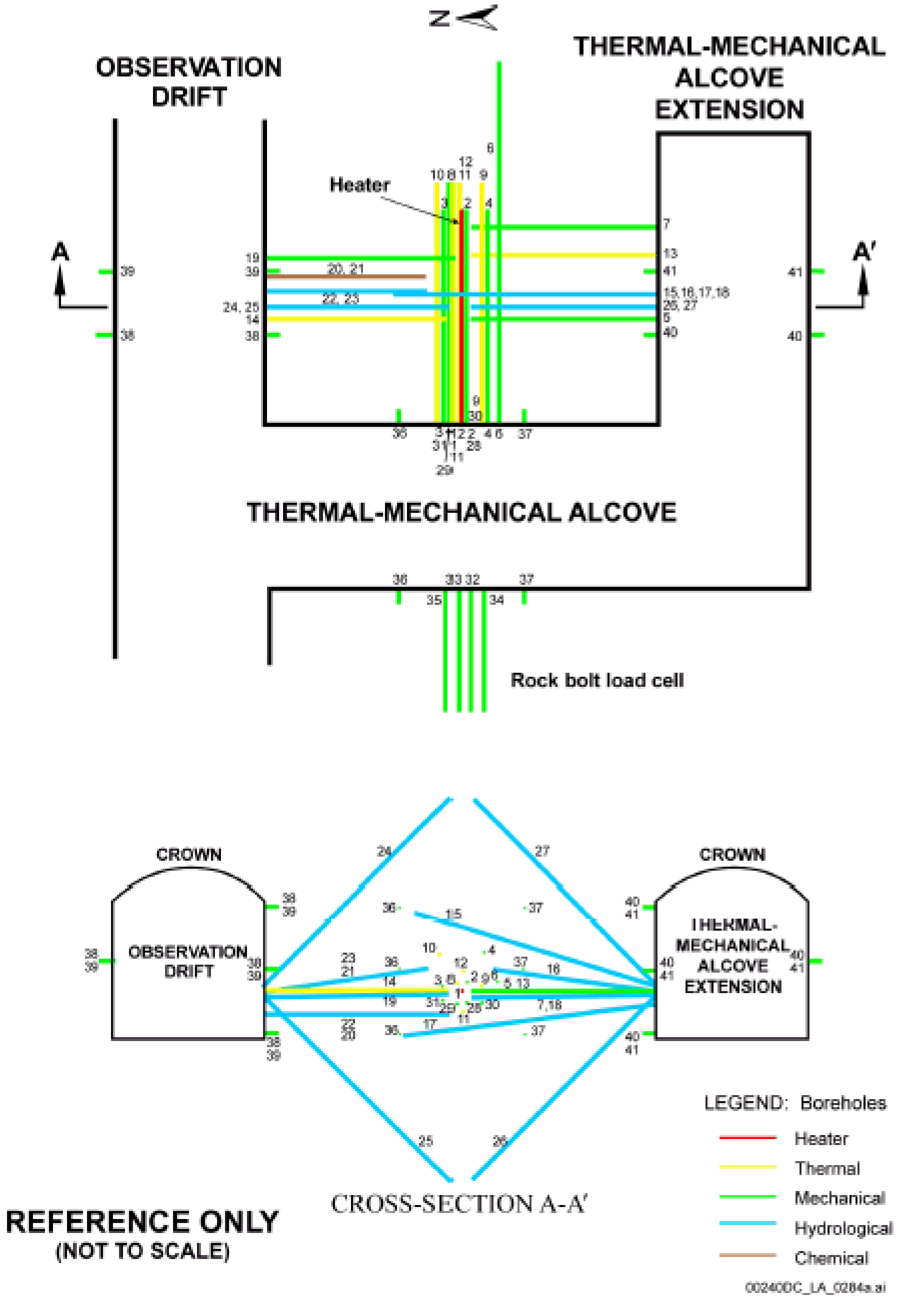
Example: Alcove 8/Niche 3 Test



- Hydrology tracer test in pillar where ECRB drift crosses over ESF Main Drift
- Ponded infiltration in Alcove 8 above
- Borehole sampling from Niche 3 below
- Tracers: various soluble hydro-fluoro-carbon compounds

Single-Heater Test

- First thermal test
- Excavated pillar
- Borehole heaters
- 2-year duration
- Measurements: thermal mechanical, hydrologic, chemical
  - Thermocouples, etc.
  - Borehole extensometers
  - Strain gauges
  - Pressure/flow testing
  - Water sampling
  - Electrical resistance tomography



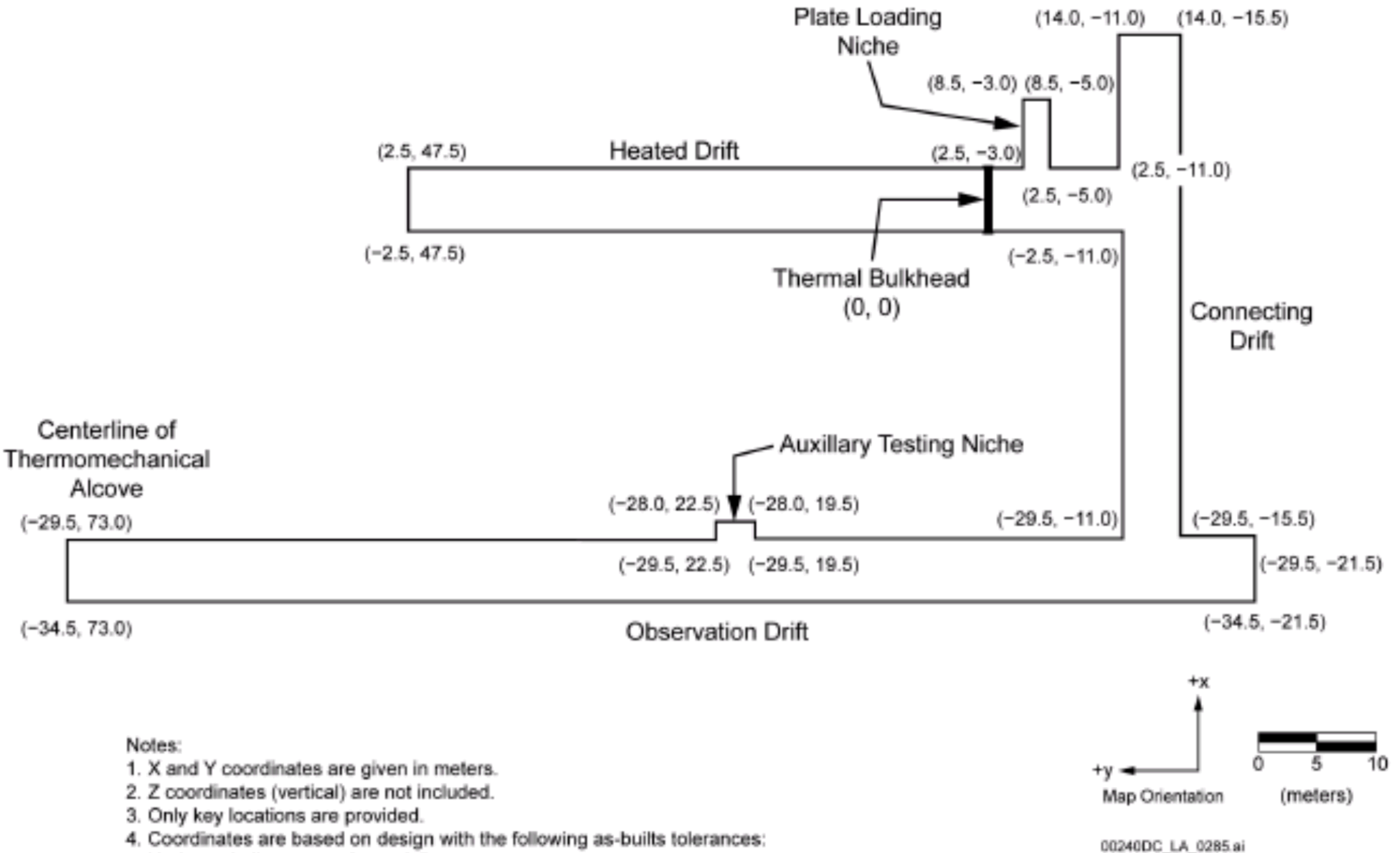
Single-Heater Test

← SHT pillar excavation (Alpine roadheader)

↙ Borehole packer string installation

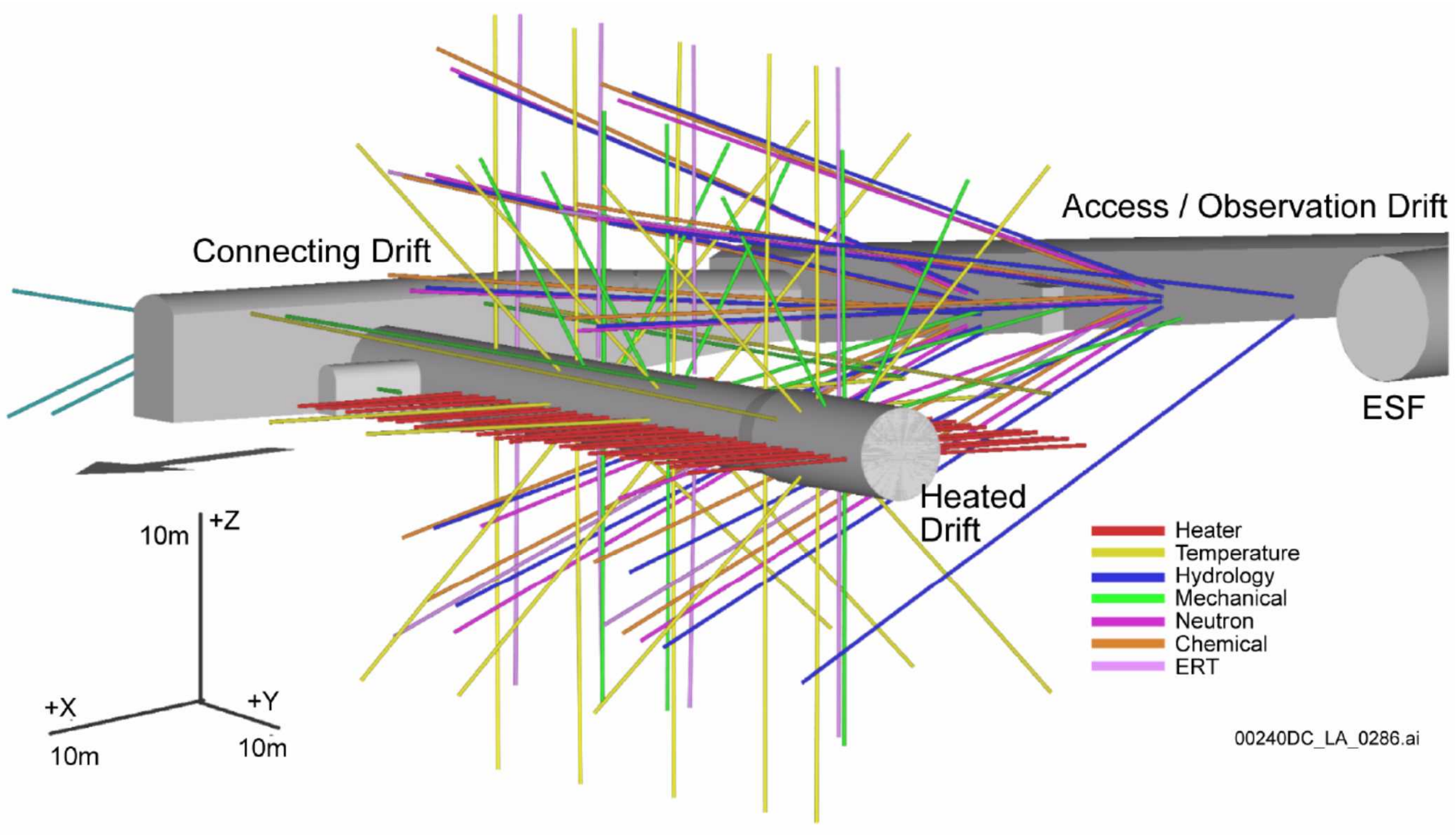
↓ After instrumentation and insulation, heaters energized

Drift-Scale Test Layout



Notes:
1. X and Y coordinates are given in meters.
2. Z coordinates (vertical) are not included.
3. Only key locations are provided.
4. Coordinates are based on design with the following as-builts tolerances:
   Horizontal alignment = 0 to + 0.5m
   All other = −0 to + 0.3m

Drift-Scale Test Borehole Array



Drift-Scale Test Construction

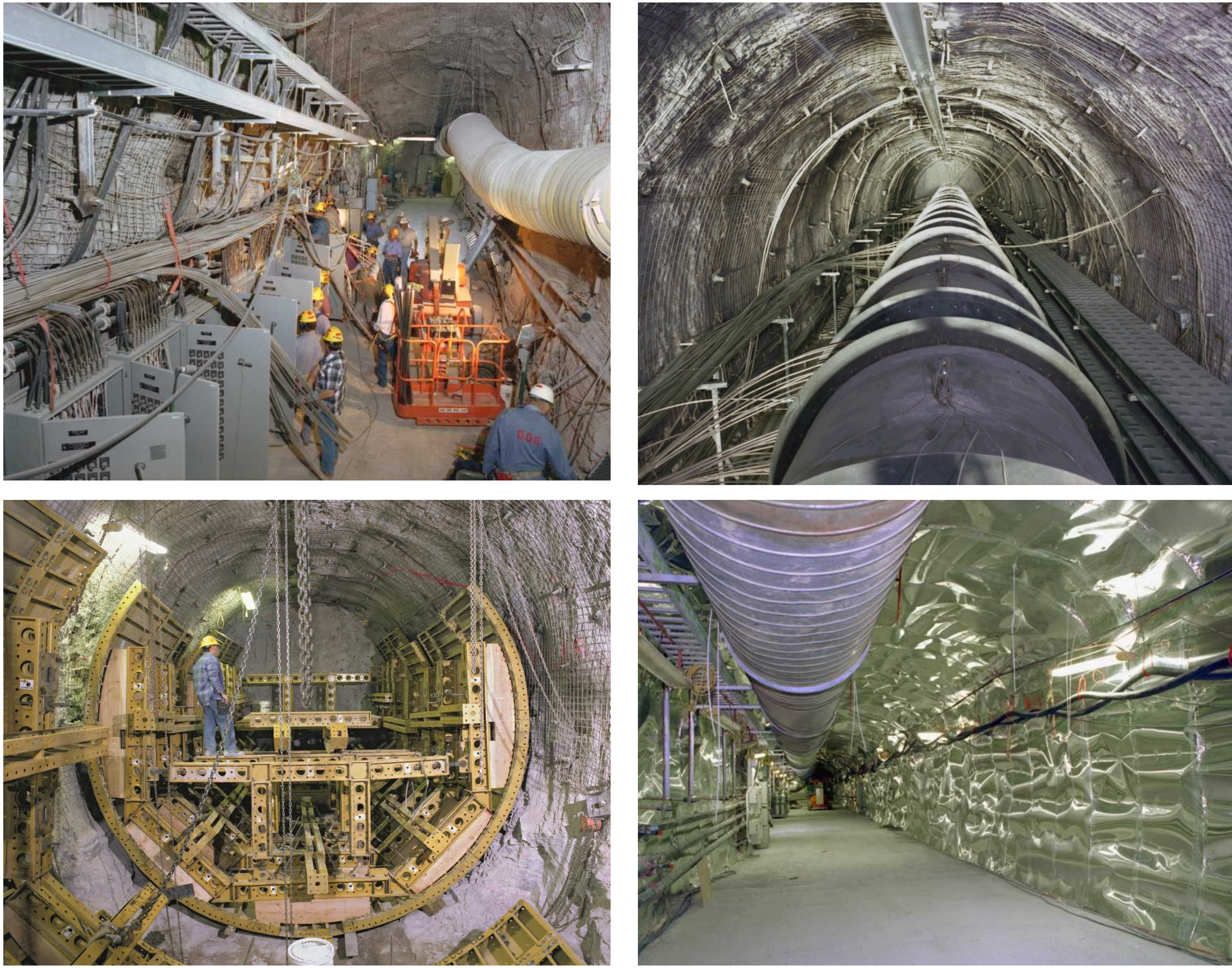
Clockwise from upper left:

Connecting Drift (electrical cabling for >200 kW heater power)

Heated Drift (mockup waste packages, view through window while heating in progress)

Connecting Drift with thermal insulation

Installation of cast-in-place concrete liner in back third of Heated Drift



Introduction to URLs in the U.S.

Yucca Mountain Exploratory Studies Facility (1981-1995)

Introduction and Timeline

Geology

ESF Alternatives Design Study

ESF Construction

ESF Underground Experiments

Test Interference and Waste Isolation Impact Analysis

Yucca Mtn. Impact/Interference Analysis Format

- **Description of Activities**
- **Coordination with Design**
- **Affected Q-List Items**
- **Expected Conditions (geoscientific features, characteristics, etc.)**
- **Analyzed Impact on Testing**
  - Site, facilities, existing/planned boreholes and excavations
  - Tracers, fluids and materials
  - Methods and operations
- **Analyzed Impact on Waste Isolation Characteristics**
  - Hydrology, geochemistry, thermal/mechanical
- **Assumptions and Controls (e.g., water use, materials, excavation method)**

Examples: Limited use of organic and cementitious materials, and metals; spill management; selection of drilling fluids, etc.

Yucca Mountain Impact/Interference Analysis Products

ESF Construction Begins →

- **ESF Subsurface Construction/Operation (1994)**
  - Supported ESF Final Design and Construction Readiness Review
- **ESF Surface Construction/Operation (1996)**
  - Prepared when the scope of ESF <u>surface construction</u> was fully realized.

ESF Main Tunnel Complete →

- **ESF Subsurface Testing (1997)**
  - Test-test interference and waste isolation impacts

Drift-Scale Test Begins →

- **YM Surface-Based Testing (1997)**
  - Companion to ESF testing analysis

ECRB Cross-Drift Begins →

- **ESF ECRB Cross-Drift TBM Starter Tunnel Construction (1997)**
  - Addressed unique aspects of drill-and-blast excavation and use of concrete

Design-Build Strategy + Evolving Performance Assessment (managed by system engineering organization)

Yucca Mountain Impact/Interference Controls

- **Tracers, Fluids & Materials database**
  - Geographic information system (GIS) spatial database
  - Localized uses of water, both surface and underground
  - Final total usage report (2008)
- **Disallowed certain salt- and organic-based compounds**
- **Reliance on separation of activities (test-test, test-construction, test-operations)**
- **Most controls related to waste isolation (not test interference)**
- **Few instances of changes to maintenance, operations or test plans**
- **Diesel exhaust and cementitious materials remain as technical challenges**

YM ESF Planning, Design, Construction & Operation
Lessons Learned

Planning and Construction

- Avoid tendency to over-plan
- Allow ample time (>10 years) for characterization
- Design lifetime of URL facilities should be > 10 years
- Remove construction equipment when done (e.g., TBM)
- Agile design and analysis processes allow adaptive changes in layout and testing (e.g., ^{36}Cl sampling, South Ramp seepage, etc.)

YM ESF Planning, Design, Construction & Operation
Lessons Learned, continued

Testing

- **Ventilation dryout effect and dust will be present**
- **Use “separate effects” or bench-scale tests to design full-scale *in situ* tests**
- **Rock mass stress redistribution processes are 3D and evolve**
- **Emphasize pre-test simulation for large-scale *in situ* tests (especially involving flow or thermally driven coupled processes)**
- **Mine-water tracers are difficult to control at constant concentration (e.g., LiBr at constant 20 mg/L)**
- **Thermal breakdown of halogenated rubber compounds (Neoprene+H_2O→HCl; Viton+H_2O→HF)**

YM ESF Planning, Design, Construction & Operation

Lessons Learned, continued

Testing, continued

- Structural materials (steel, galvanizing Zn, plating Cr, etc.) will corrode and affect mine waters
- Long-term testing programs are difficult to finish (orderly completion)
- Independent expert panel review is needed for test planning, progress review, and interpretation

YM ESF Planning, Design, Construction & Operation
Lessons Learned

Test Impact/Interference

- Large testing area layout minimizes thermal/mechanical interference
- Use chemical/isotopic tracers
- Plan categories of materials where possible rather than specific compounds
- Find appropriate scope for impact/interference regulation
- Worker health and safety is always first priority