UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201-3367

Winter 2003 Board Meeting
January 28, 2003

Crowne Plaza Hotel
4255 South Paradise Road
Las Vegas, NV 89109
Tel: (702) 369-4400
Fax: (702) 369-3770

8:00 a.m. **Call to order and Introductory Statements**
Michael Corradini, Chairman,
Nuclear Waste Technical Review Board (NWTRB)

8:20 a.m. **Overview of Programmatic Developments**
Margaret Chu, Director
Office of Civilian Radioactive Waste Management (OCRWM)
Department of Energy (DOE)

8:40 a.m. *Questions, discussion*

8:50 a.m. **Operating the Waste Management System (waste acceptance, packaging, transportation, repackaging, emplacement)**
Jeff Williams, OCRWM

9:10 a.m. *Questions, discussion*

9:20 a.m. **Yucca Mountain Project Status**
W. John Arthur III, Deputy Director for Repository Development
Office of Repository Development (ORD), OCRWM

9:40 a.m. *Questions, discussion*

9:50 a.m. **BREAK**

10:05 a.m. **Science and Engineering Update**
Mark Peters
Bechtel SAIC Company, LLC/Los Alamos National Laboratory (BSC/LANL)

11:15 a.m. *Questions, discussion*

11:45 a.m. **Public Comments**

Telephone: 703-235-4473 Fax: 703-235-4495

12:00 noon **LUNCH**

1:10 p.m. **Session Introduction**
David Duquette, NWTRB

1:15 p.m. **Nevada-Sponsored Corrosion Studies**
Roger Staehle, Consultant to State of Nevada
Don Shettel, Geosciences Management Inst., Inc.

1:55 p.m. *Questions, discussion*

2:15 p.m. **Materials Testing Update**
Joe Farmer, BSC/Lawrence Livermore National Laboratory

2:45 p.m. *Questions, discussion*

3:00 p.m. **Waste Package Manufacturing and Closure Welds**
Jack Cloud, BSC

3:15 p.m. *Questions, discussion*

3:25 p.m. **BREAK**

3:40 p.m. **Influence of Paleosols on Fluid Flow and Solute Transport**
Graham Fogg, University of California, Davis

4:15 p.m. *Questions, discussion*

4:30 p.m. **Planned Barrier Capability Analyses**
Peter Swift, BSC/Sandia National Laboratories

5:00 p.m. *Questions, discussion*

5:15 p.m. **Public Comments**

5:30 p.m. **Adjourn**

U.S. Department of Energy
Office of Civilian Radioactive Waste Management

Operating the Waste Management System

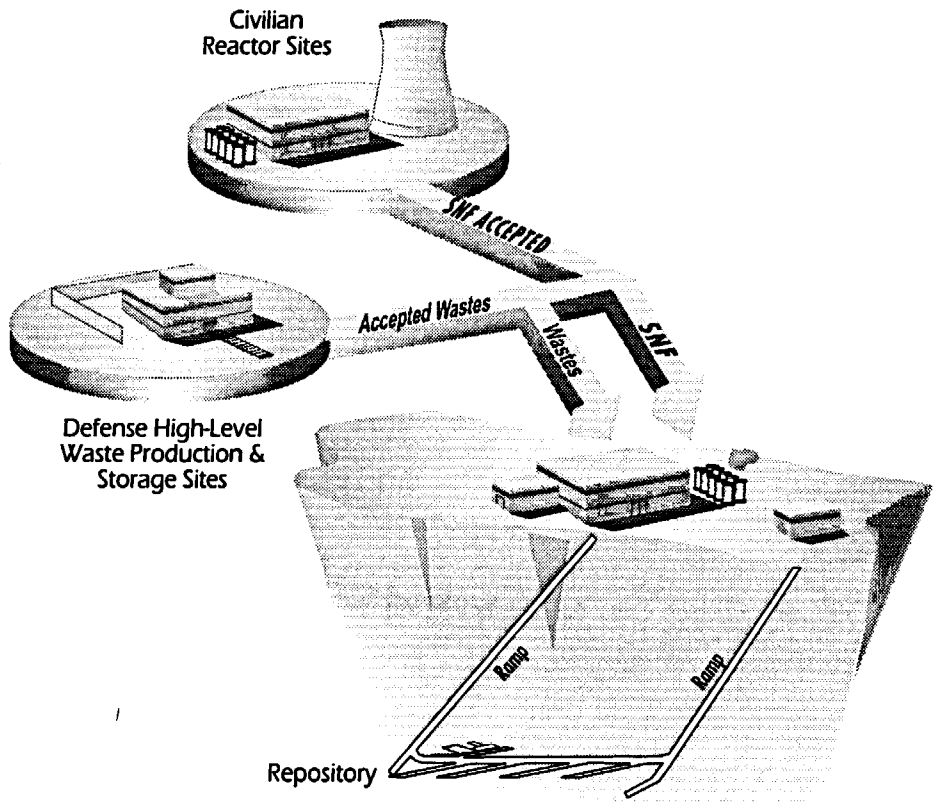
Presented to:
Nuclear Waste Technical Review Board

Presented by:
Jeff Williams
Acting Director, Office of National Transportation
U.S. Department of Energy

January 28, 2003
Las Vegas, Nevada

System Architecture

- Underground repository
- Surface facilities
- Nevada transportation mode
- National transportation mode
- Receipt, storage, and emplacement rates and quantities
- Operating mode
- Waste types and quantities



SNF = Spent Nuclear Fuel
HLW = High-Level Waste

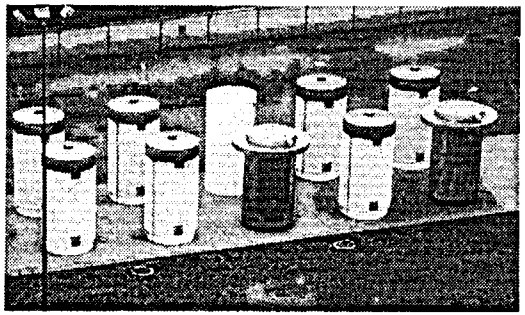
U.S. Commercial SNF in 2010

- **72 commercial reactor sites with SNF onsite**
  - 104 operating reactors
  - 14 shutdown reactors
- **≈ 64,000 MTU - Projected inventory of CSNF**
- **≈ 2,000 MTU/year - Projected generation rate**
- **≈ 53,000 MTU are projected to be in pool storage**
- **≈ 11,000 MTU are projected to be in dry storage**
- **44 at-reactor CSNF dry storage facilities in 29 states**

Dry Storage Technology

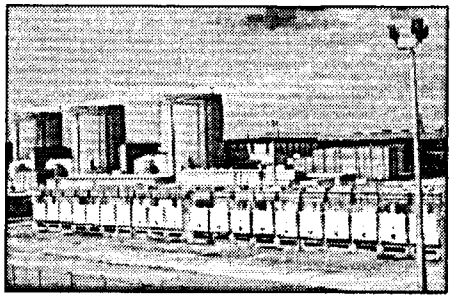
First Use — 1986 — 1990* (SP) — 2000 (DP) — 2000

Single-Purpose Casks: Casks certified for storing uncanistered SNF at Purchaser sites.



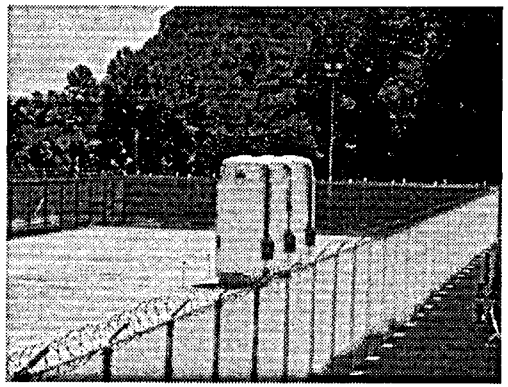
Canister-based Storage Systems:

Single-Purpose - Canisters certified for only for storing SNF at Purchaser sites



Dual-Purpose - Canisters (DPC) certified for storing SNF at Purchaser sites and are also licensed for transportation.

Transportable Storage Casks: Dual-Purpose casks certified for storing uncanistered SNF at Purchaser sites and are also licensed for transportation.



*earlier loading of canisters in 1986 at Robinson for demonstration purposes

Waste Acceptance - CRWMS Target Receipt Rates

Year	Commercial SNF Target Receipt Rate
2010	400
2011	600
2012	1,200
2013	2,000
2014	3,000

The rates in this schedule are targets only and do not create any binding legal obligation on the Department of Energy

Waste Acceptance - Standard Contract Provisions

- **Allocation Methodology**
  - **Allocations earned by purchasers based on "Oldest Fuel First" (OFF) Principle**
  - **DOE Issues Annual Capacity Report (ACR) and Acceptance Priority Ranking (APR)**
  - **SNF earning allocation is not necessarily the SNF to be delivered**

Waste Acceptance - Standard Contract Provisions

- Acceptance Criteria
  - All of Purchasers' SNF (regardless of type and condition) is acceptable
  - Purchasers classify SNF as "standard", "non-standard", or "failed"
  - DOE's obligation extends to "other than standard" SNF, but delivery may be subject to delayed acceptance
  - Multi-element canisters not covered by contract

Waste Acceptance - Standard Contract Provisions

- Scheduling
  - Purchasers with allocations submit Delivery Commitment Schedules (DCS) identifying location and range of spent fuel 63 months before delivery
  - Purchasers may exchange delivery allocations up to six-months prior to delivery, subject to DOE approval
  - DOE has approved DCS's for approximately 2850 MTU
  - Depending on litigation outcome, approved DCS's could form the basis of 2010 operations

Operational Assumptions - Transportation Mode and Cask Fleet

The final environmental impact statement (FEIS) studied two transportation scenarios:

MOSTLY RAIL SCENARIO		
Summary of Estimated Number of Shipments for National Transportation		
	Truck	Rail
Proposed Action (24 years)	<1,100	<10,000 casks <3,300 trains*
Annual	≈45/yr	≈400 casks/yr <135 trains/yr*
Estimated Cask Fleet		
	Truck	Rail
Proposed Action	≈10	≈90

MOSTLY TRUCK SCENARIO		
Summary of Estimated Number of Shipments for National Transportation		
	Truck	Rail
Proposed Action (24 years)	<53,000	≈300 casks ≈100 trains
Annual	≈2,200/yr	12-13 casks/yr. <5 trains/yr.
Estimated Cask Fleet		
	Truck	Rail
Proposed Action	≈110	N/A

* Based on three rail casks per train shipment.

FEIS states preference for rail, both nationally and in Nevada.

Transportation Casks - Rail

RAIL SPENT FUEL TRANPORTATION CASKS

Model (Type)	Vendor	Capacity (MTU)[1]	No. Built	Part 71 COC (Expires)	ALLOWABLE CONTENTS
MP-187 (Canister)	Transnuclear	24P (10.56)	1	9255 Rev 6 (9/03)	PWR: B&W 15x15 assemblies, <3.43 w/o U-235 5 to 8 years cooled, 30 GWD/MTU 9 to 17 years cooled, 40 GWD/MTU PWR: WE 14x14 SStl clad assemblies, <4.05 w/o U-235 38 years cooled, 45 GWD/MTU
HI-STAR 100 (DP Canister)	HOLTEC International	24P/68B (10.56/12.53)	7	9261 Rev 1 (3/04)	Allowable contents are specified in a 26-page appendix to the CoC. Every type of standard fuel assembly can be transported. PWR: 7 to 10 years cooled, 24.5 GWD/MTU 15 years cooled, up to 44.1 GWD/MTU BWR: 8 years cooled, 24.5 GWD/MTU 15 years cooled, 39.1 GWD/MTU
TN-68 (DP Bare fuel)	Transnuclear	68B (12.53)	15	9293 Rev 1 (2/06)	BWR: 10 years cooled, 40 GWD/MTU, <3.7 w/o U-235 (29 more are on order for storage at Peach Bottom)
NAC-STC (DP Bare fuel) & (DP Canister)	NAC International	26P (11.43)	6	9235 Rev 4 (3/04)	PWR: 6.5 years cooled, 40 GWD/MTU, <3.7 w/o U-235 10 years cooled, 45 GWD/MTU, <3.7 w/o U-235 Max fuel assy length = 165" Yankee Rowe fuel: All types
TS-125 (DP Canister)	BNFL Fuel Solutions	21P/64B (10.56/11.24)	0	9276 Rev 0 (9/07)	PWR: 6 years cooled, 35 GWD/MTU, <4.6 – 5.0 w/o U-235 25 years cooled, 60 GWD/MTU, <4.6 – 5.0 w/o U-235 BWR: Limited to all types of Big Rock Point fuel.
MP-197 (Canister)	Transnuclear	61B (11.24)	0	9302 Rev 0 (7/07)	BWR: 6 years cooled, 27 GWD/MTU, <4.4 w/o U-235 15 years cooled, 40 GWD/MTU, <4.4 w/o U-235
NAC-UMS (DP Canister)	NAC International	24P/57B (11.43/10.50)	0	9270 Rev X (N/A)	Not certified. Currently being reviewed by NRC.

1. Average kgU per assembly based on discharges from standard reactors as given in 1994 RW-859: BWR = 184.3 PWR = 439.8.

Transportation Casks - Truck

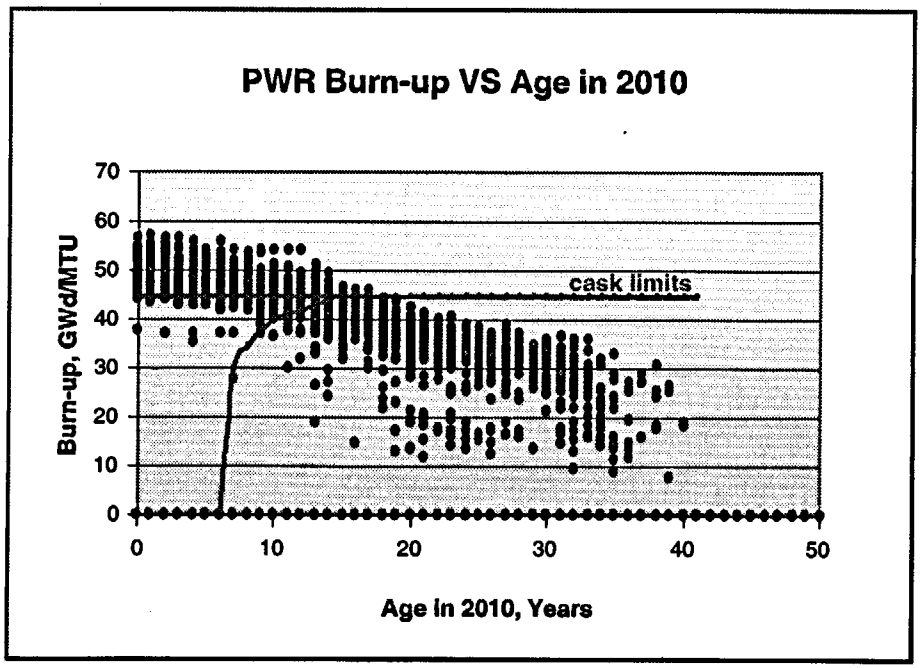
TRUCK SPENT FUEL TRANSPORTATION CASKS

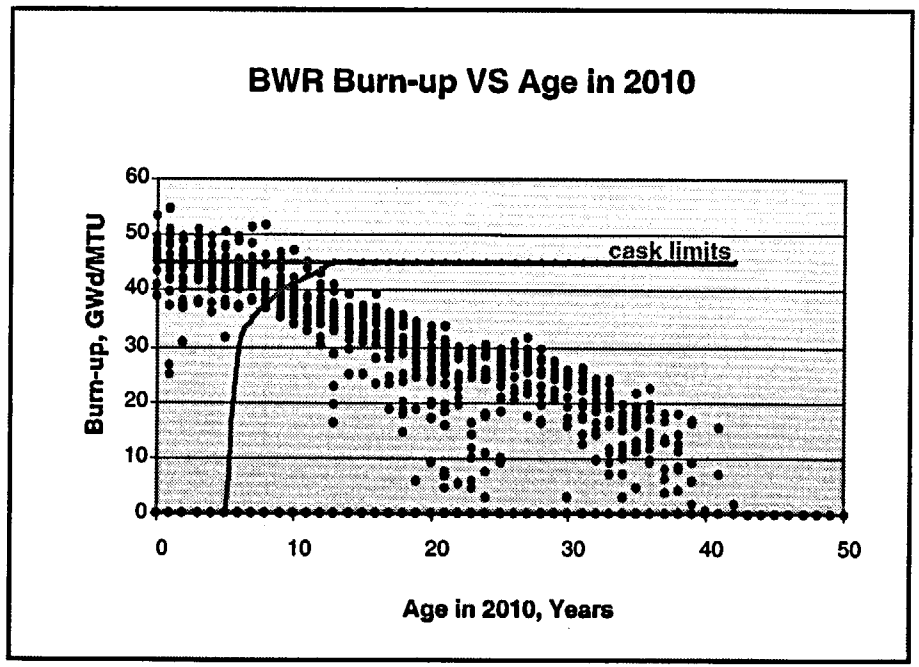
Model	Vendor	Capacity (MTU)[1]	Number Built	Part 71 COC (Expires)	ALLOWABLE CONTENTS
NAC-LWT	NAC International	1P/2B (.44/.37)	8	9225 Rev 31 (2/05)	PWR: 2 years cooled, 35 GWD/MTU, <3.5 – 3.7 w/o U-235 BWR: 2 years cooled, 30 GWD/MTU, <4.0 w/o U-235
GA-4	General Atomics	4P (1.76)	0	9226 Rev 1 (10/03)	PWR: 10 years cooled, 35 GWD/MTU, >3.0 <3.15 w/o U-235 15 years cooled, 45 GWD/MTU, no min <3.15 w/o U-235 Maximum decay heat per assembly: 0.617 kw (The GA-4 has been analyzed for partial loadings with higher decay heats. NRC approval has not been requested, but could be obtained.)
GA-9	General Atomics	9B (1.66)	0	9221 Rev X (N/A)	Not certified. NRC review is inactive.

1. Average kgU per assembly based on discharges from standard reactors as given in 1994 RW-859: BWR = 184.3 PWR = 439.8.

Pool Storage - Range of Fuel

Of the SNF projected to be in pool storage in 2010, approximately 67% of BWR fuel and 55% of PWR fuel could be accommodated in existing cask designs



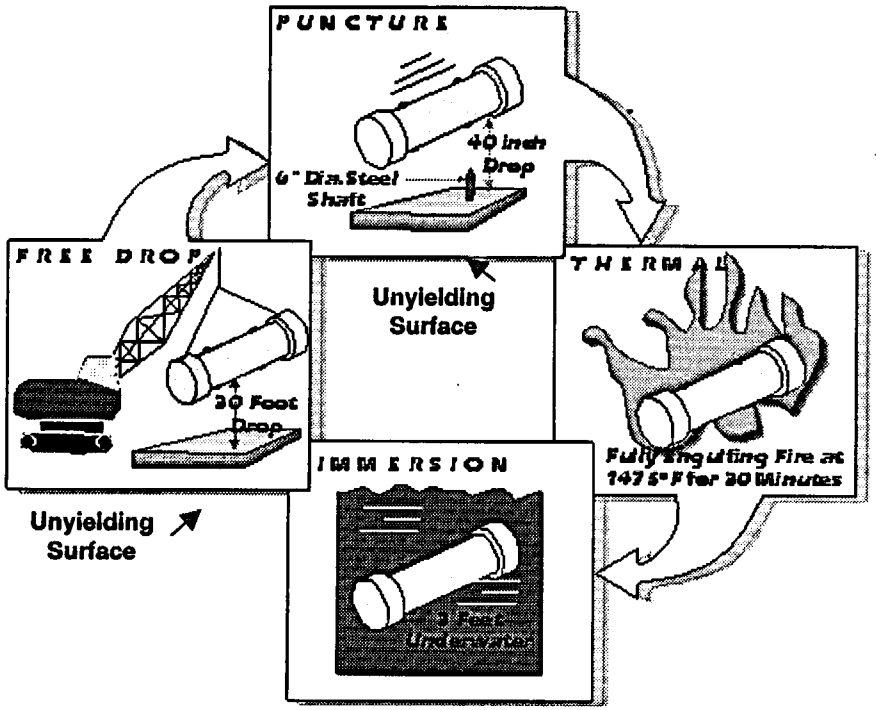


Transportation Equipment

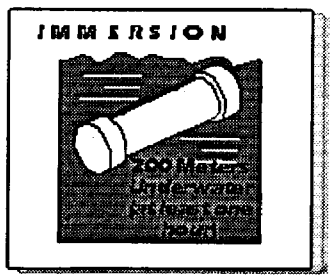
- DOE will use existing, certified casks to the extent practicable
- Existing casks may need to be enhanced to transport higher burn-up and higher enriched SNF
- Recent industry emphasis on large rail casks
- For a mostly truck scenario, additional technology development is required

NRC Cask Performance Requirements

Hypothetical Accident Conditions



Additional Test for SNF Casks



- **Regulations require demonstrations that casks meet performance requirements following accident tests**
  - **Demonstrations may be done by analysis or tests**
- **The regulatory accident tests cover over 99% of all accident conditions**
  - **NRC has analyzed the small fraction of extra regulatory accidents**
  - **NRC will perform tests to verify these analyses**
  - **OCRWM has requested funds to support these tests**

Requirements Documents - Cask Requirements

- CRWMS Requirements Document
  - Private industry will be used to the fullest extent practicable for transport
  - Design and operations planning will be compatible with transportation of SNF and HLW to the repository by rail, heavy haul vehicle, and legal weight truck
  - Transport standard, failed, and nonstandard commercial SNF
  - Transport in NRC-certified transportation casks, including:
    + Single-Purpose Casks
    + Canister Casks - MPC and DPC (not covered by contract)
    + Transportable Storage Casks (TSCs)
    + HLW Casks
    + Specialty Casks

Transportation of Single-Purpose Storage Casks

- Single-purpose storage casks will have to be opened and repackaged at the Purchaser site
  - Dry Transfer System Topical Safety Analysis Report (TSAR) submitted to NRC in 1996
  - NRC issued Assessment Report in 12/02
  - Transmittal of TSAR Revision 1 delivered to NRC on 1/23/03
- Some Purchasers may seek one-time transportation certification for their single purpose casks (storage)

Multi-Purpose Canisters (MPC) - Current Status

- OCRWM no longer directly funds development of MPC designs, but continues to support the concept
- OCWRM plans to:
  - consider the implementation of NRC-approved disposable canisters for the OCRWM program
  - share any attendant cost savings
  - provide data on performance-based disposal criteria related to the monitored geologic repository, including preliminary Waste Acceptance Criteria for commercial spent nuclear fuel in disposable multi-element canisters
- MPCs are planned for Naval SNF

Routing for OCRWM Shipments

- To date, no rail or highway routes have been selected
  - Preliminary routes will be determined in accordance with current DOE practice for rail and DOT regulations for highway approximately 3-5 years before shipments begin
  - OCRWM is committed to working with states and tribes and will consult with them in the selection of final routes

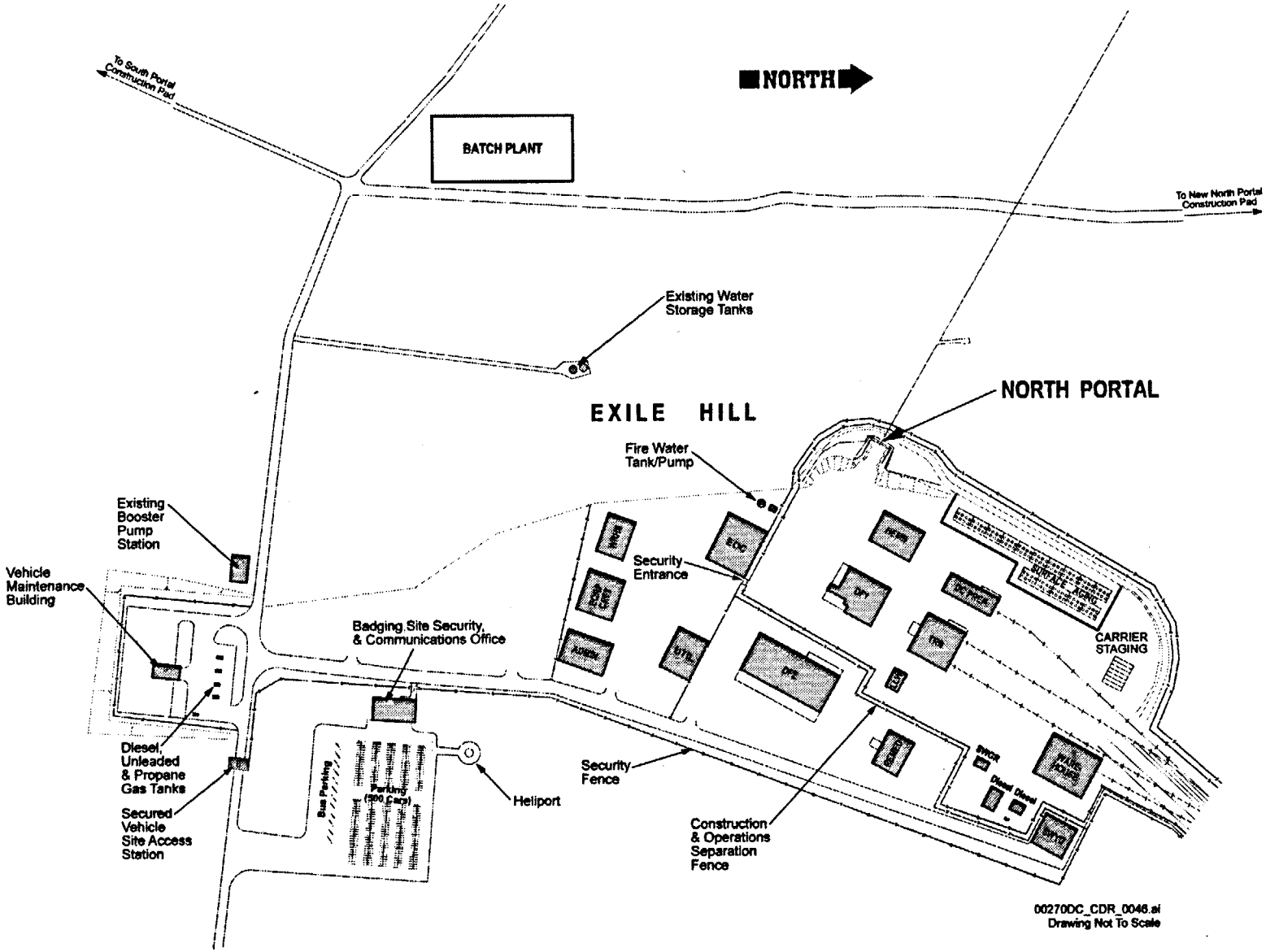
Route Selection

- Highway routing (DOT 49CFR397.101)
  - Carriers select routes to reduce time in transit
  - Vehicles transporting radioactive materials operate over preferred routes:
    - interstate highway system, including bypasses or beltways, are preferred routes
    - a state, tribe, or political subdivision may designate alternate routes consistent with DOT regulations in addition to or in lieu of the interstate highway system
- Rail routing
  - No Federal rail routing regulations exist
  - Current DOE practices:
    - minimize time, distance, number of carriers, and interchange points
    - maximize use of best track
    - use computer codes for route selection

Surface Facility

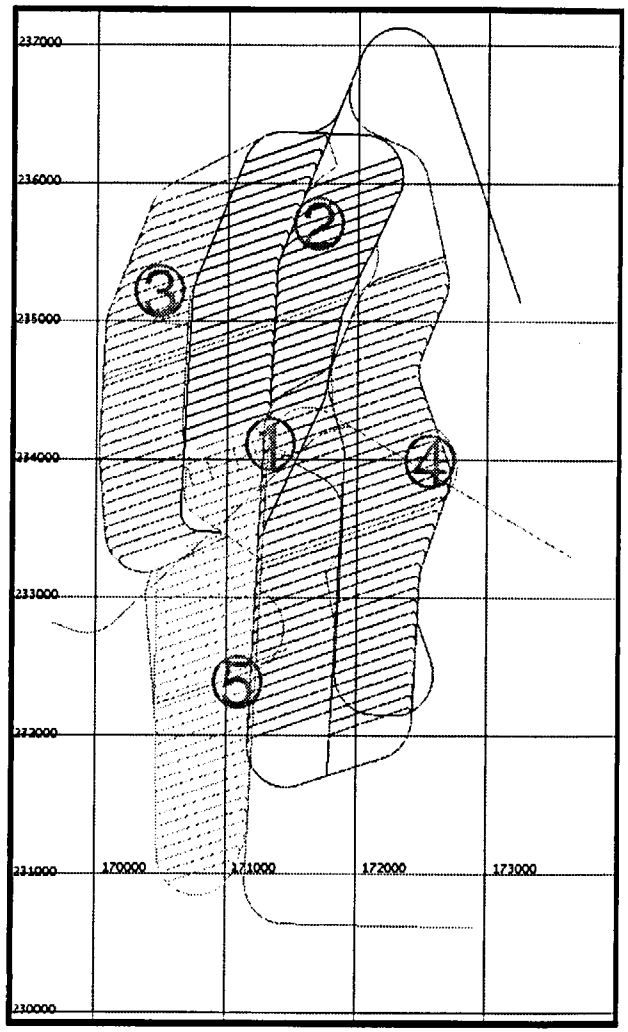
- Thermal management plans are finalized prior to each shipment
  - may include blending (mixing of hotter and cooler fuel assemblies)
  - may include surface storage to age SNF
- Casks are received, surveyed, spotted and unloaded
- Packaging
  - Disposal
    - bare fuel is loaded directly into waste package (blending may occur)
    - fuel in non-disposable canisters fuel is removed from canisters and loaded into waste package (blending may occur)
    - Navy MPC loaded directly into waste package
  - Storage
    - bare fuel most likely placed into storage casks (except if already in dual-purpose cask)
    - canistered fuel left in canisters and placed in concrete overpack for storage (except if already in dual-purpose cask)

Surface Facilities Layout

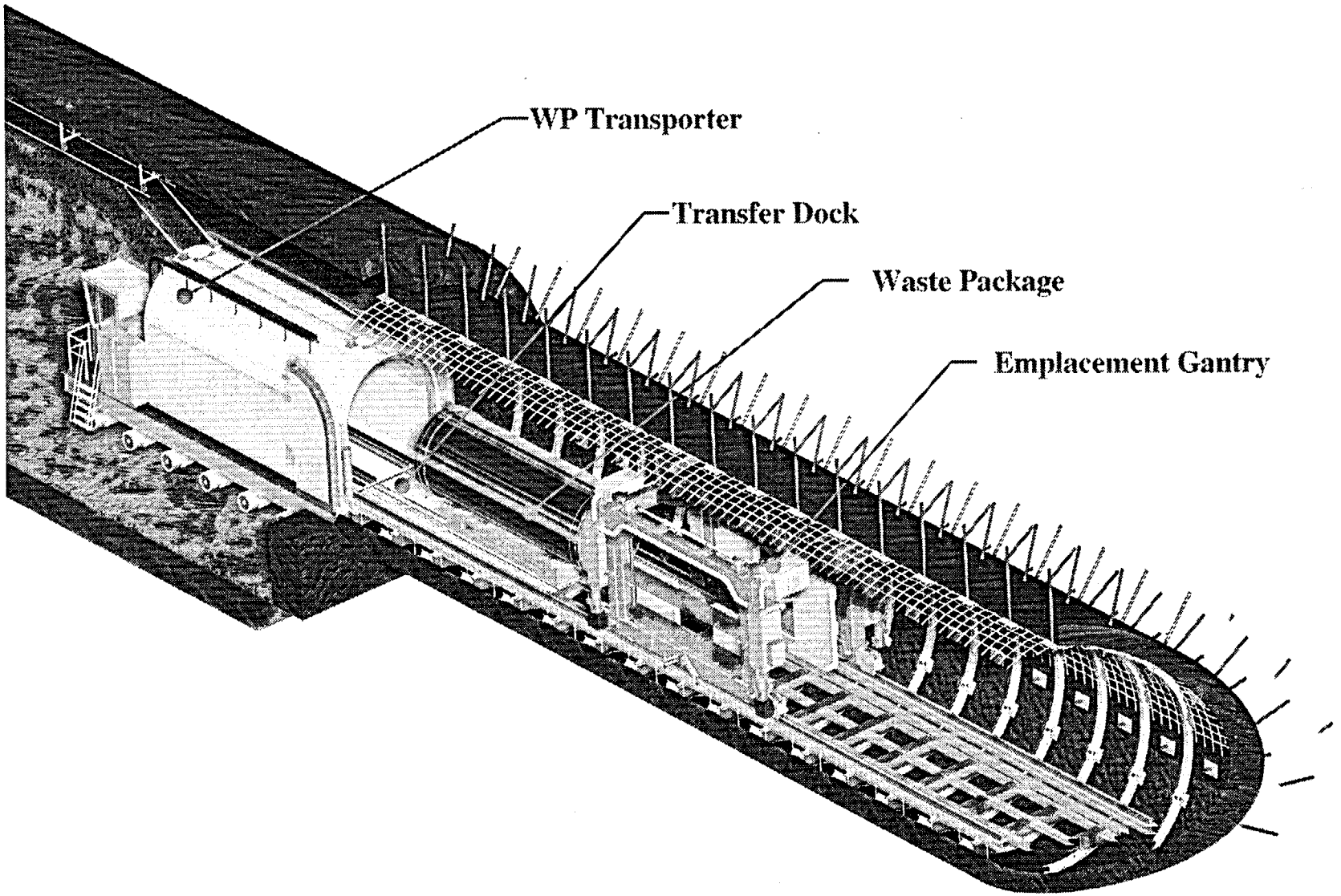


Potential Underground Layout

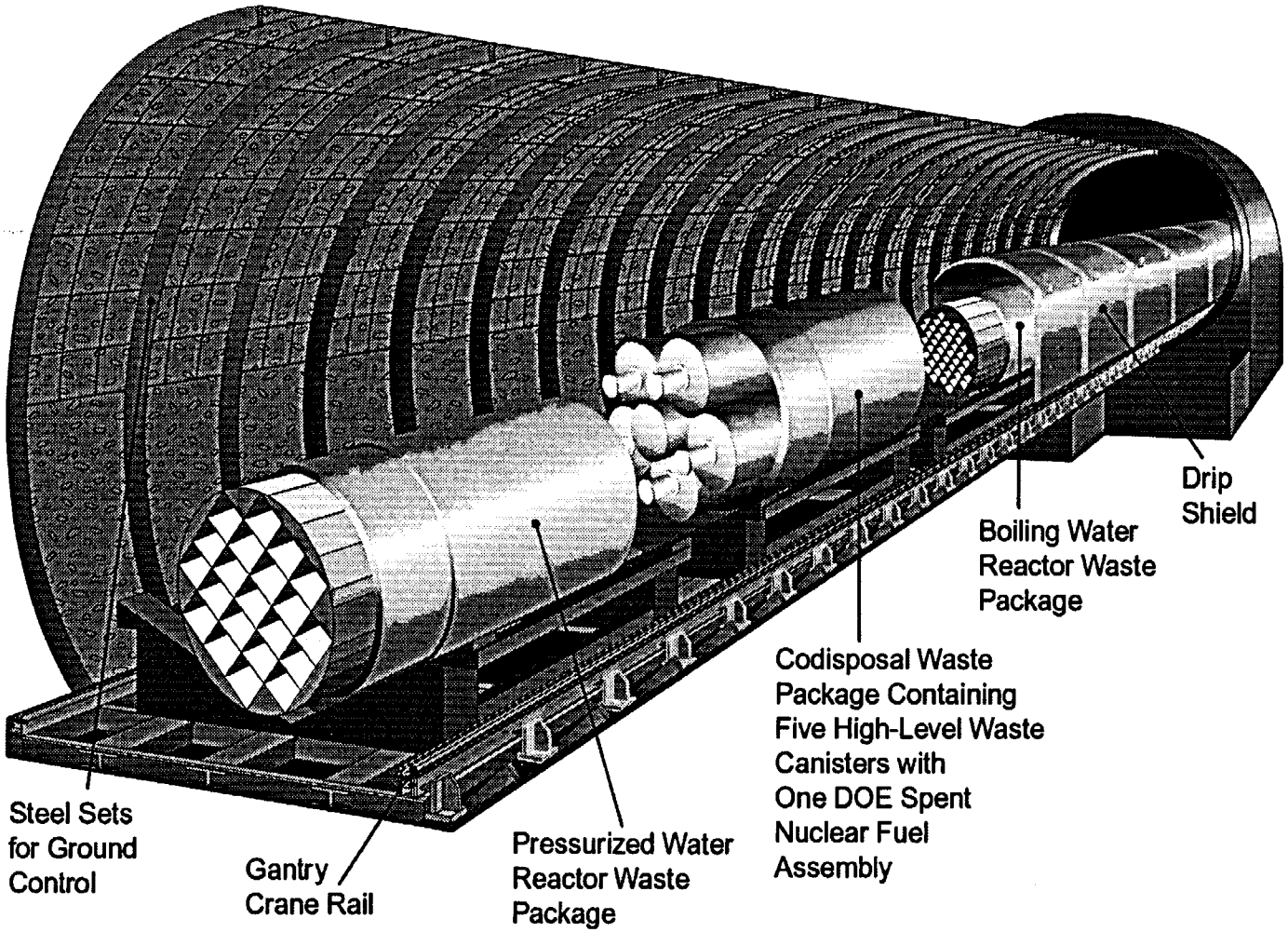
- **Modular panel layout**
  - Panels 1-4 sufficient for 70,000 MTHM at up to 2 meter Waste Package spacing
  - Contingency of approximately 25% with addition of Panel 5
  - Improved ventilation scheme
  - Adds optional 3rd access ramp
  - Modular development allows "adaptive staging" to applying lessons learned in one phase to the next
- **Utilizes ESF for construction of small initial emplacement Panel by 2010**
  - Use a portion of Panel 1 to acquire additional scientific and engineering testing
- **Construction schedule to first emplacement in Panel 1: approximately 27 months**



Emplacement Drift Transfer Dock



Cutaway of a drift with three types of waste packages



Drawing Not to Scale
00022DC-SRCR-V1S30-02c.ai

Summary

- Much work needs to be done to achieve a fully functioning Waste Management System by 2010
- Waste acceptance planning is difficult because of Purchasers' control of SNF selection
- Industry has developed and certified Storage and Transport technologies and is continuing to enhance capabilities
- DOE will use private industry to the extent practicable
- DOE will use existing, certified casks to the extent practicable and will support development of additional capabilities needed
- "Mostly Rail" is DOE's preferred mode
- Routes will be selected 3-5 years before shipments
- Surface facility operations may include blending and surface storage for thermal management purposes

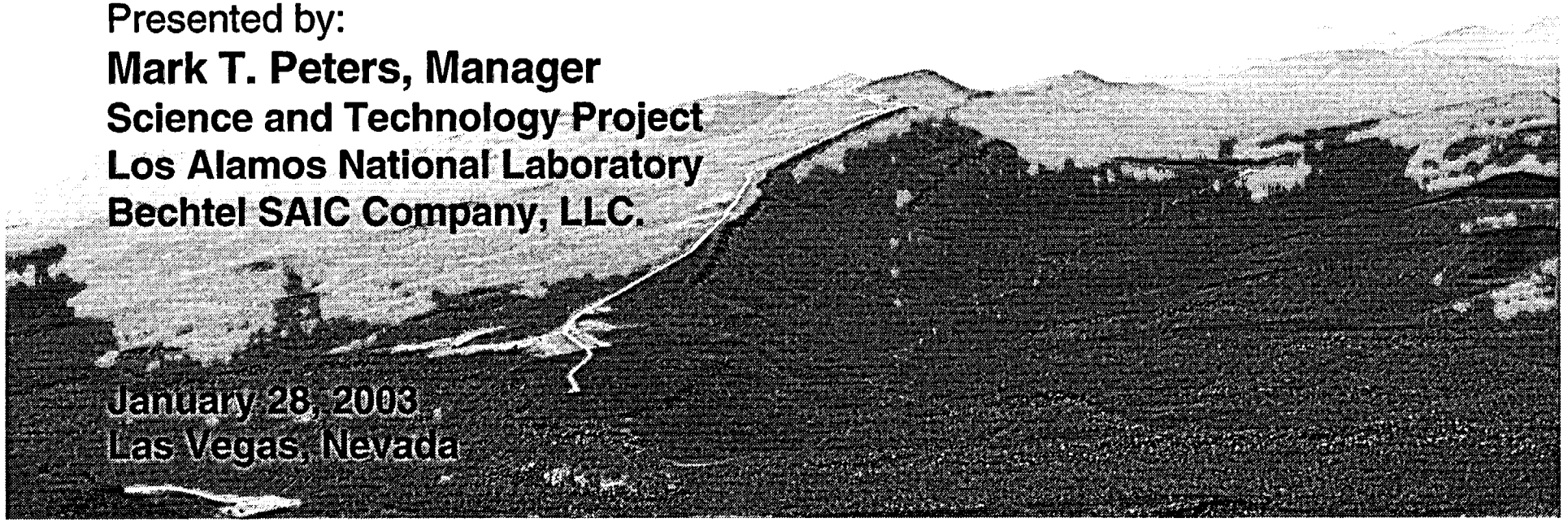
U.S. Department of Energy
Office of Civilian Radioactive Waste Management

YUCCA MOUNTAIN PROJECT

Science and Engineering Update

Presented to:
Nuclear Waste Technical Review Board

Presented by:
Mark T. Peters, Manager
Science and Technology Project
Los Alamos National Laboratory
Bechtel SAIC Company, LLC.



January 28, 2003
Las Vegas, Nevada

Overview

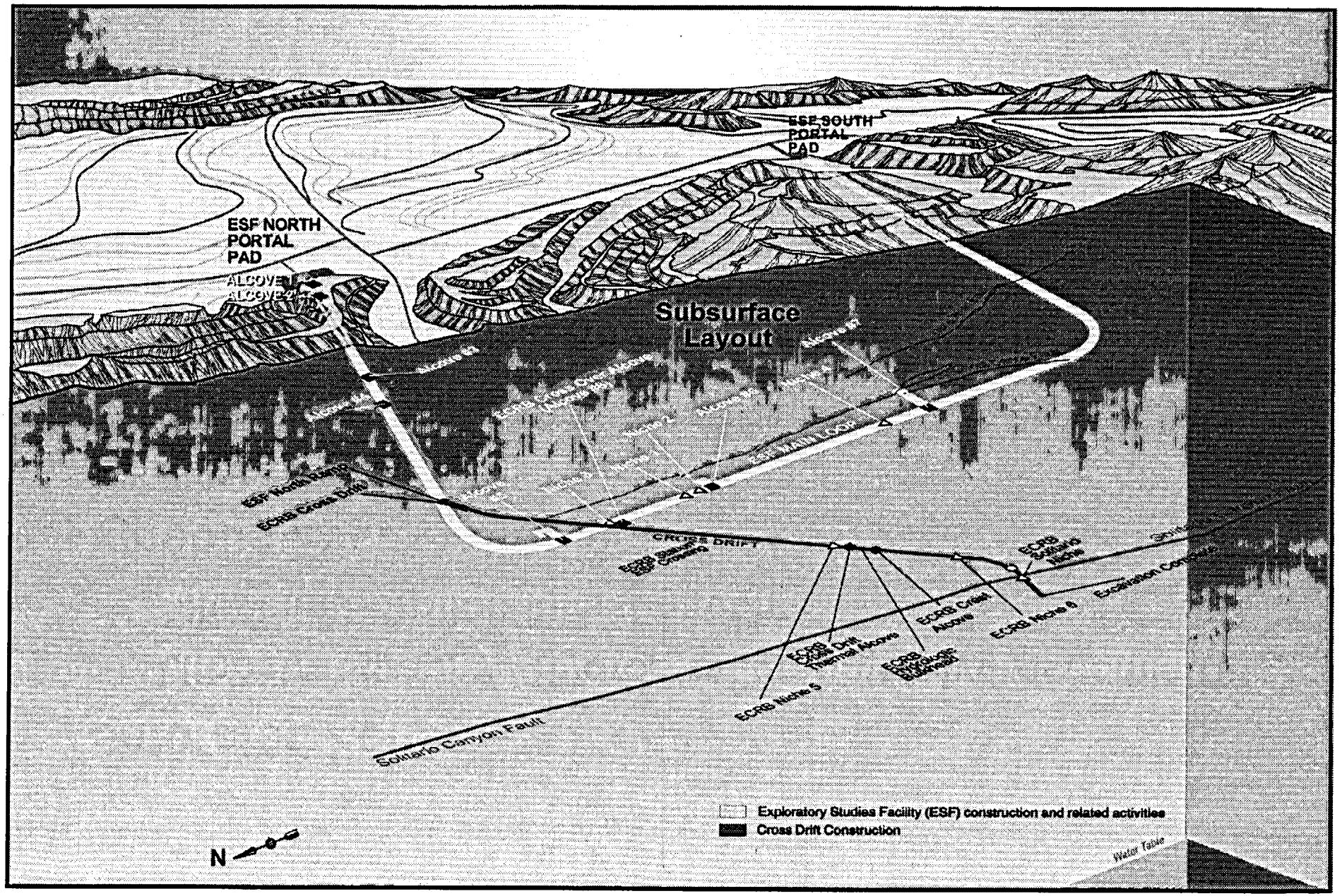
- Objective is to provide status on scientific and engineering data collection and testing program in support of natural and engineered systems process models and design
- Unsaturated Zone (UZ)
  - Exploratory Studies Facility (ESF) Studies
    - Drift Scale Test
    - 36Cl Validation
    - Secondary Fracture Minerals/Fluid Inclusions/Hydrochemistry
  - Cross Drift Studies
    - Lithophysal / Fracture Studies
    - Alcove 8 / Niche 3 (Crossover Alcove)
    - Niche 5 and Systematic Hydrologic Testing
    - Bulkhead Investigations
  - Busted Butte UZ Transport Test

Overview
(Continued)

- Saturated Zone
  - Lithostratigraphy / Hydrostratigraphy / Hydrochemistry
  - Alluvium Sorption Investigations
- Igneous Events Studies
- Engineered Barrier System
  - Thermal Properties Investigations
  - Thermal-Mechanical Rock Properties Investigations
  - Dust Investigations
  - Reactive Transport Studies
  - Waste Form Investigations
- Summary

The data and conclusions presented are preliminary, in various stages of Project review, and not yet all in controlled databases/reports.

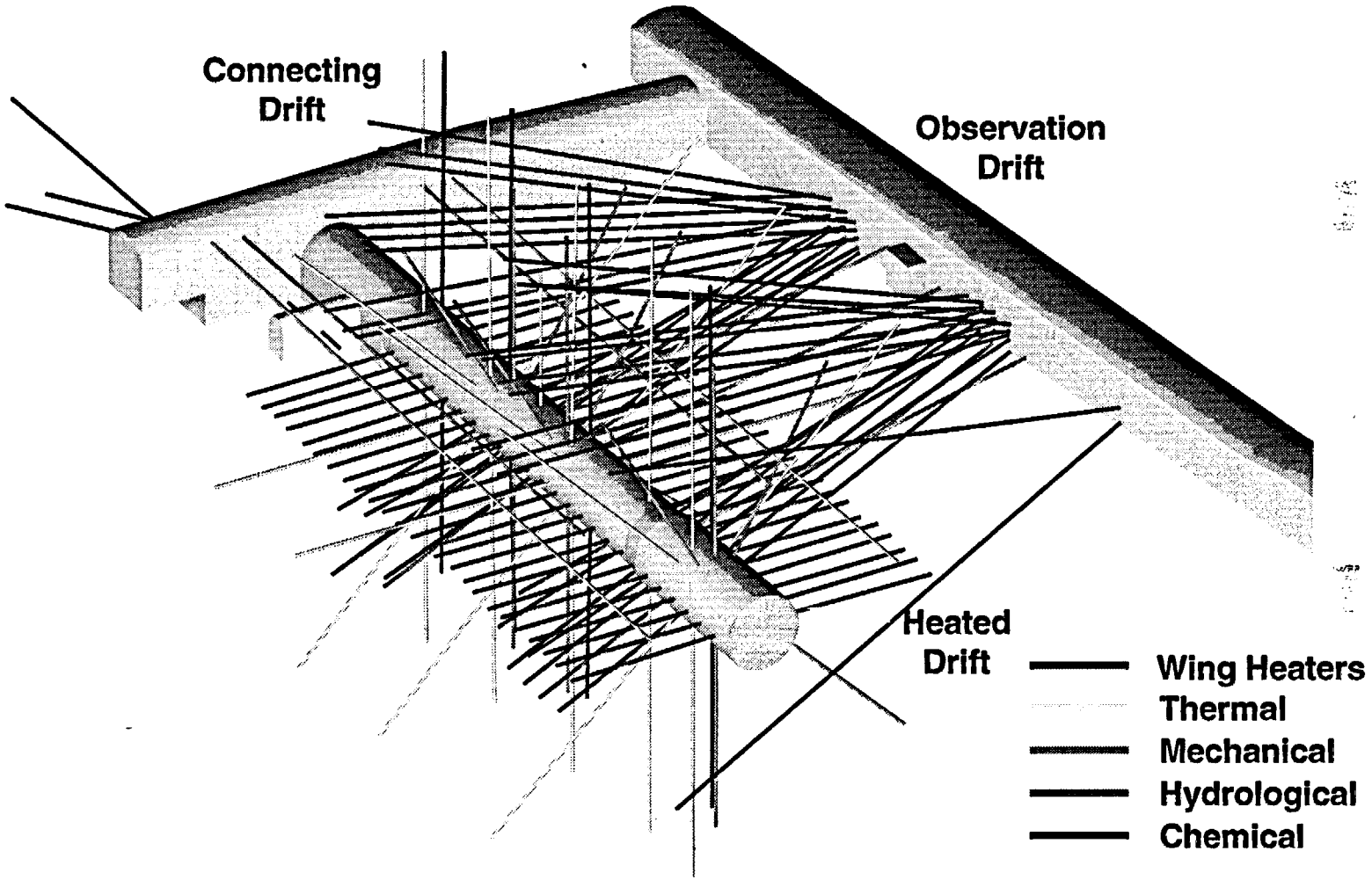
Exploratory Studies Facility and Alcoves



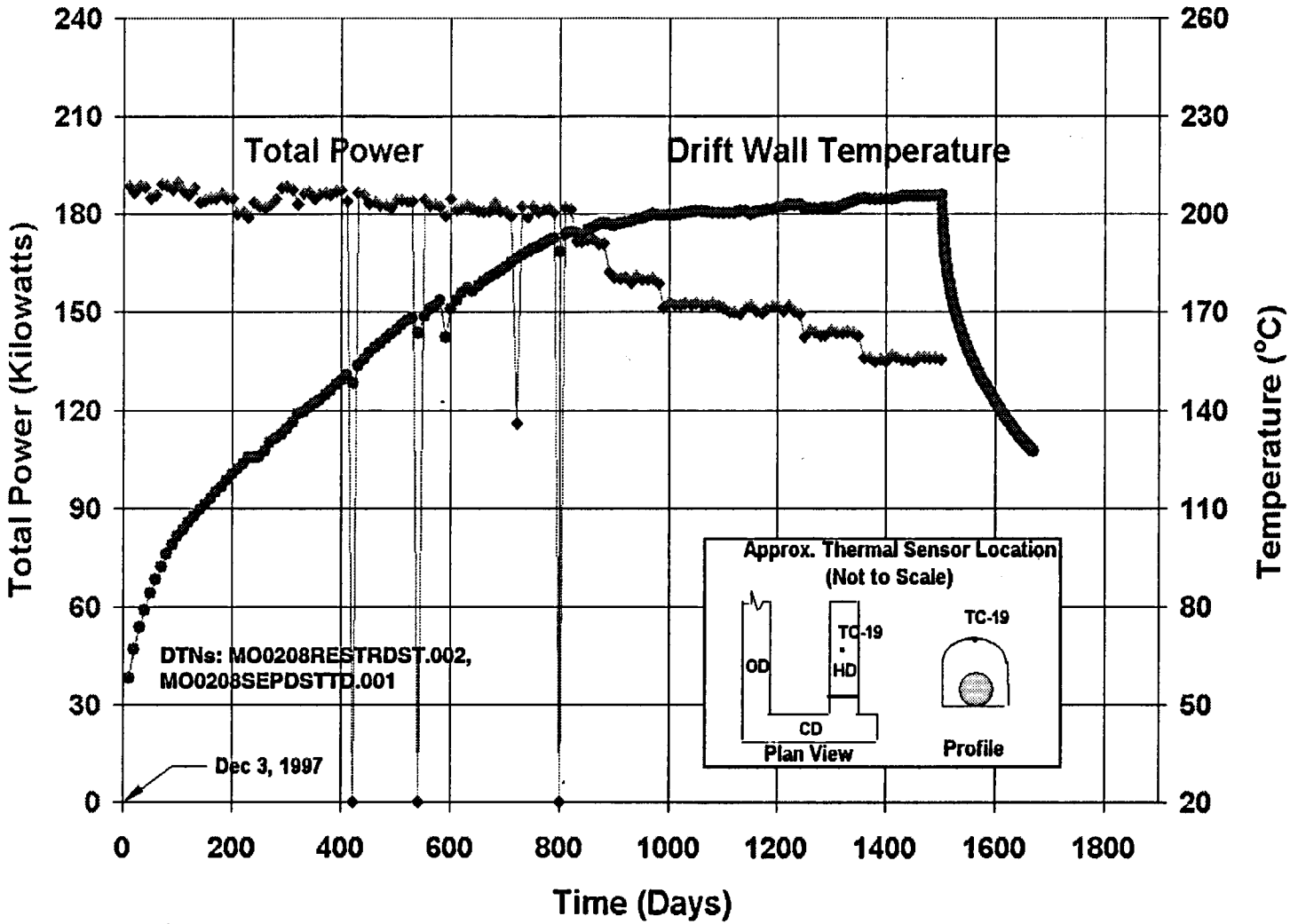
ESF_subsurface_01_03a.ai

Drift Scale Test

Evaluate thermally-coupled processes in potential repository horizon rocks at the field-scale in support of Coupled Process Models, Near-Field Environment Models, and Design



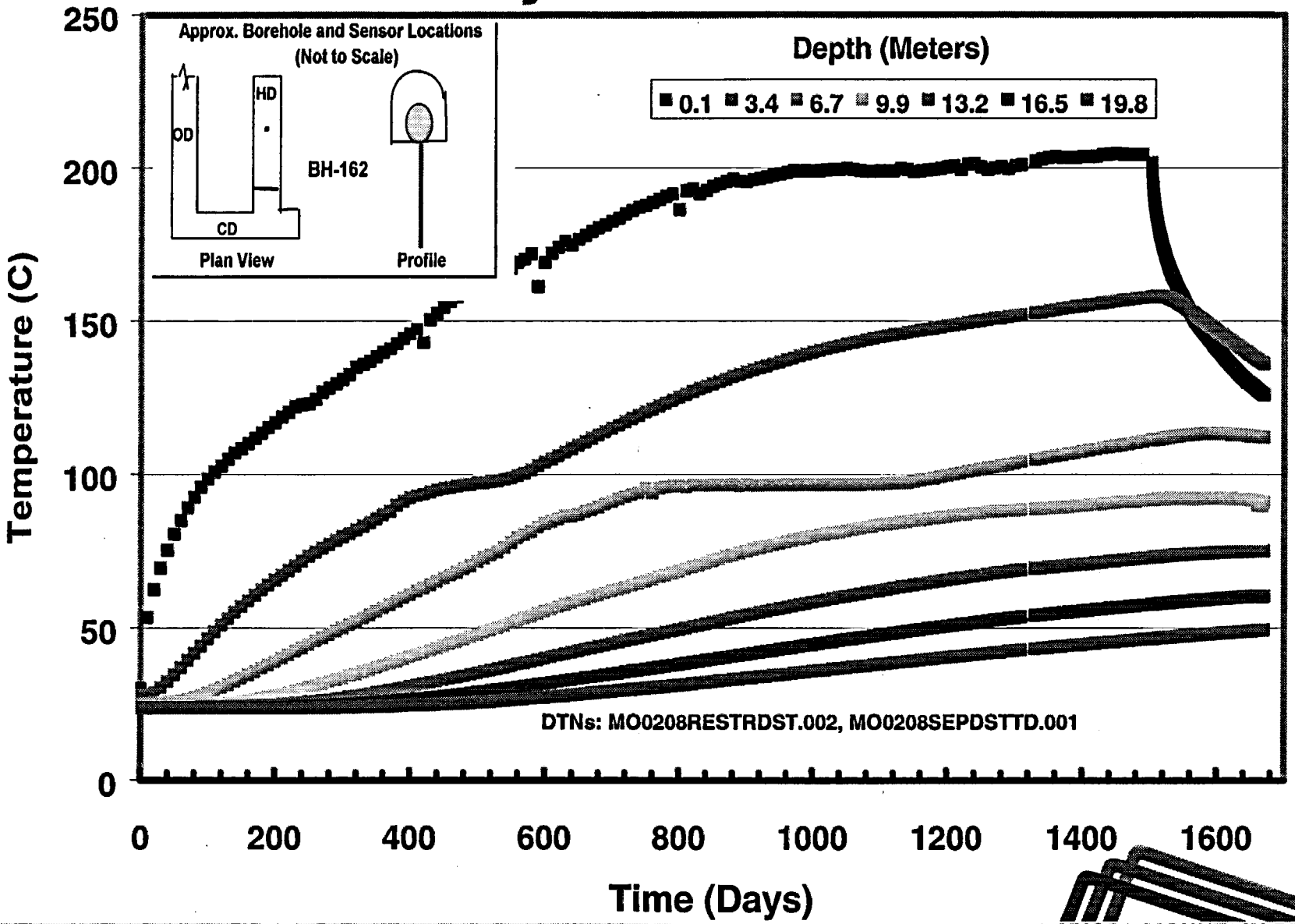
Drift Scale Test: Power and Temperature History



Drift Scale Test: TH, THC, and THM Model Predictions

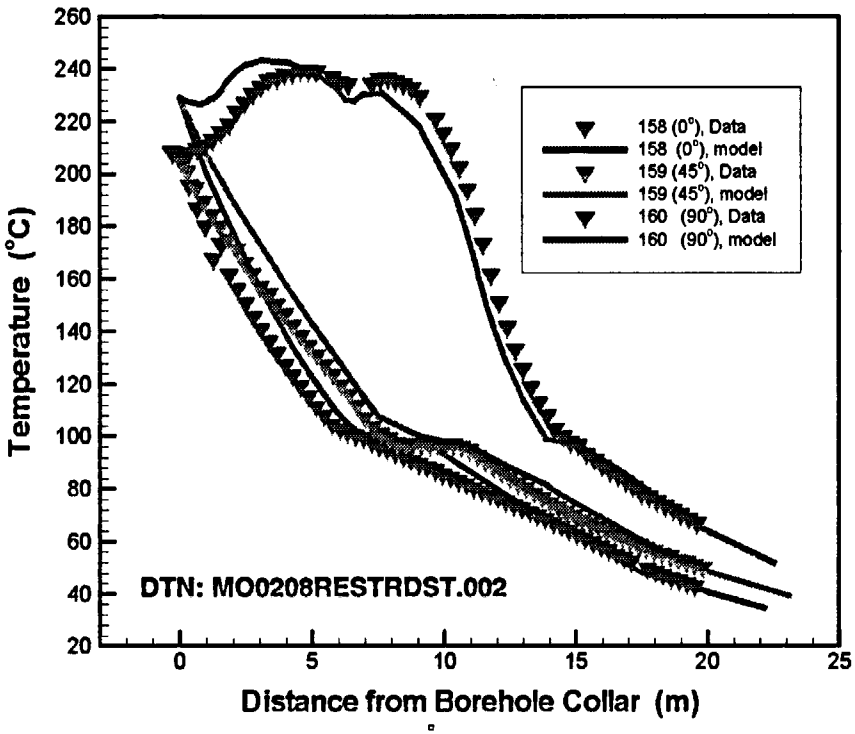
- Temperature in the test block away from the Heated Drift and the wing heaters continues to rise
- Heat-pipe signatures are not expected as temperature cools from above to below boiling
- CO_2 concentrations continue to change gradually in the rock during cooling phase - consistent with modeling
- Modeled fracture saturations indicate that little water is likely to be collected in boreholes during cooling - consistent with observations
- Air-permeability measurements confirm modeled predictions of TH processes (drying and wetting in fractures) and THM processes (closing and opening of fractures)

Drift Scale Test: Temperature Histories for Vertically Down Borehole

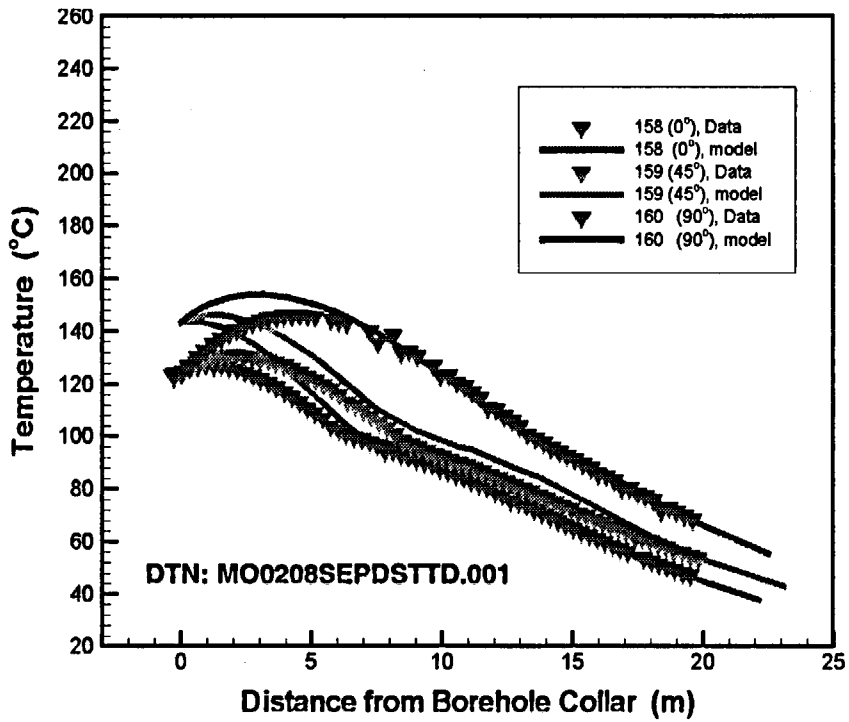


YUCCA MOUNTAIN PROJECT

Drift Scale Test: Disappearance of Heat-Pipe Signature During Cooling Phase as Water Drained and Vapor Diminished

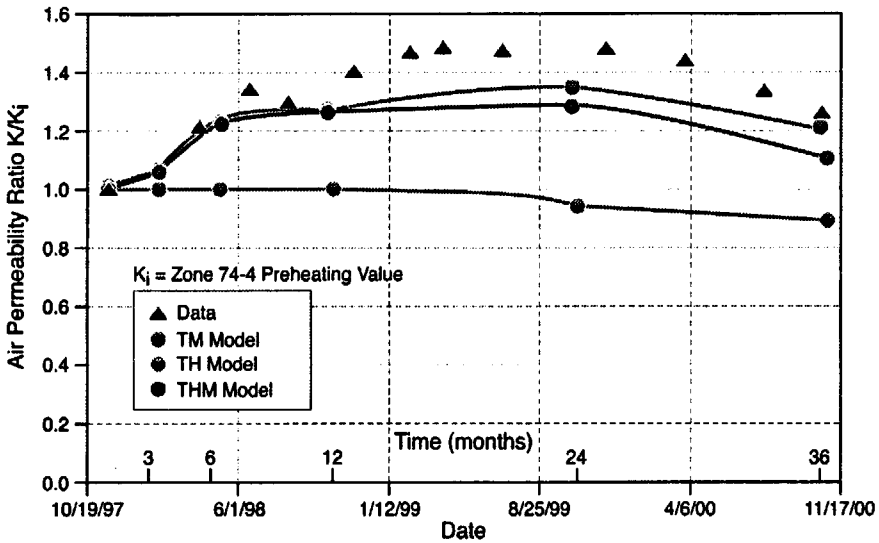


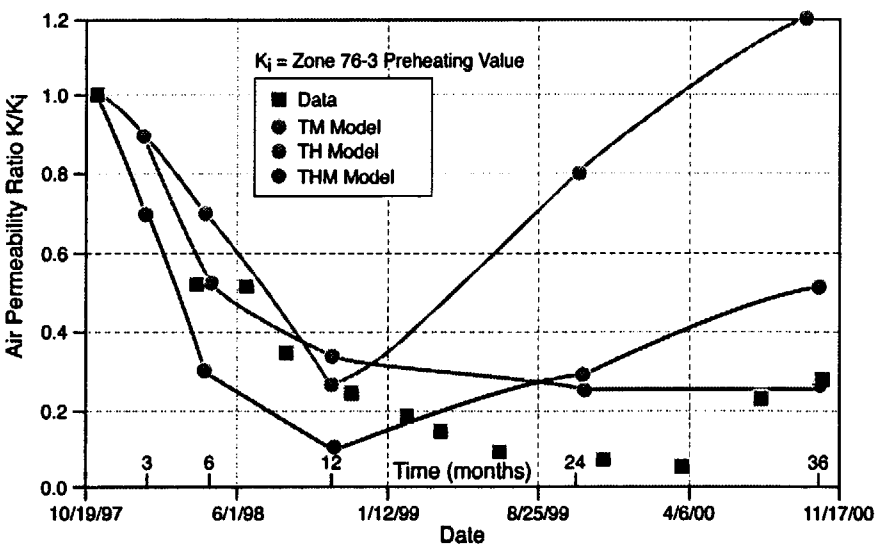
48 Months of Heating

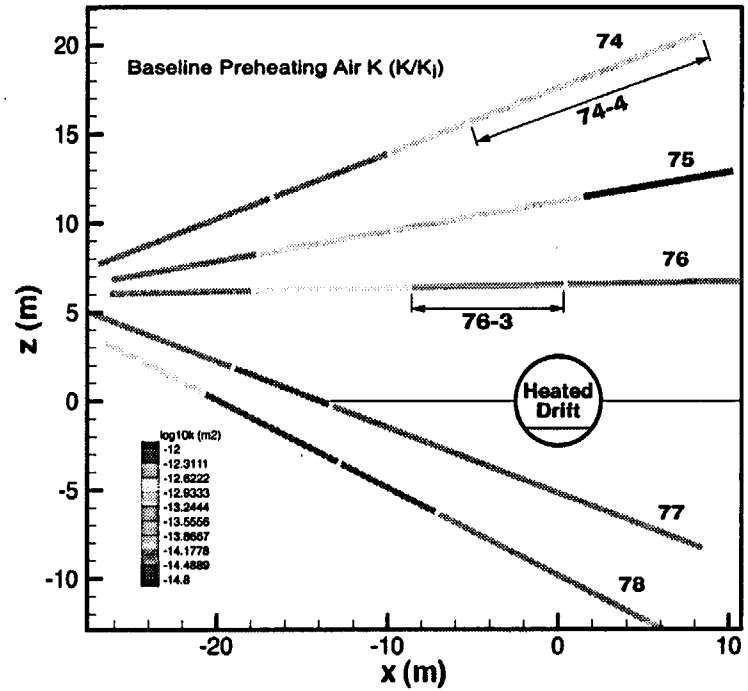


6 Months of Cooling

Drift Scale Test: Air-Permeability Data and TH and THM Modeling







- Due to its distance from anticipated drying and wetting regions, zone 77-4 air permeability data reflects mostly TM processes.
- Zone 76-4 air-k data reflects both TH and TM processes
- DTN: LB0208AIRKDSTH.001

Drift Scale Test: Water from Borehole 75 - Zone 2

- Abnormal water chemistry occurred in six samples (February 19th to June 26th, 2002) from one of 46 collection zones
- Water Sample Characteristics:
  - Samples were distinguished by a dark yellow color
  - Conductivity measured 10 to 100 times stronger than other Drift Scale Test (DST) waters
  - Relative to ambient pore water, samples contained unusually high amounts of Cr, Mn, Ni, Zn, Na, Ca, SO4 , and Cl
- Investigation included the following:
  - Literature search on neoprene thermal degradation
  - Complete chemical analysis of waters collected
  - Laboratory tests to determine possible sources of chloride and other water contaminants using hydrothermal reactor vessels loaded with packer materials
- Tests indicate that neoprene packer materials become unstable at temperatures exceeding 60°C

Drift Scale Test: Red Spot on Floor Heater

- Review of video from remote camera resulted in the following observations of the "red spot":
  - Located on the top of a floor heater approximately 32 meters from bulkhead
  - Also visible on floor and nearby power connection
  - Occurred between March 20th and September 18th of 2002
- Analyses of swipe sample indicate the "red spot" is mostly iron oxide with traces of alumina and silica
- Mostly likely source of the iron oxide, based on current investigations, is an overhead rock bolt
- Ongoing investigations include additional swipes, additional video from remote camera, and effect of rock bolt boreholes on thermal seepage

^{36}Cl Validation

- Validate occurrence of "bomb-pulse" ^{36}Cl at two locations in the ESF (Sundance Fault Zone and Drillhole Wash Fault Zone) in support of UZ Flow Model
- Update
  - Final USGS/LANL/LLNL report currently in progress - due date – June 2003
    - Will include a path forward (further experiments for consideration)
  - Conceptual model for UZ flow and UZ process and Total System Performance Assessment (TSPA) models do not rely directly on this data and will not be modified based on results to date
  - DOE is also pursuing an independent study of $^{36}Cl/Cl$ systematics - to be conducted by completely independent expert(s)

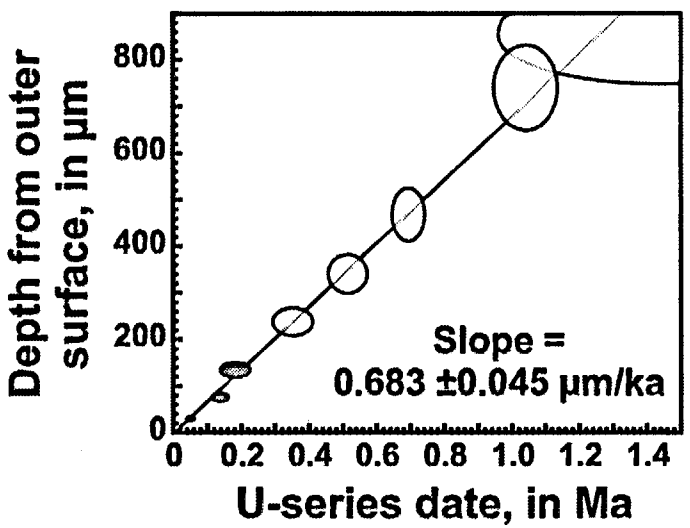
Secondary Fracture Minerals

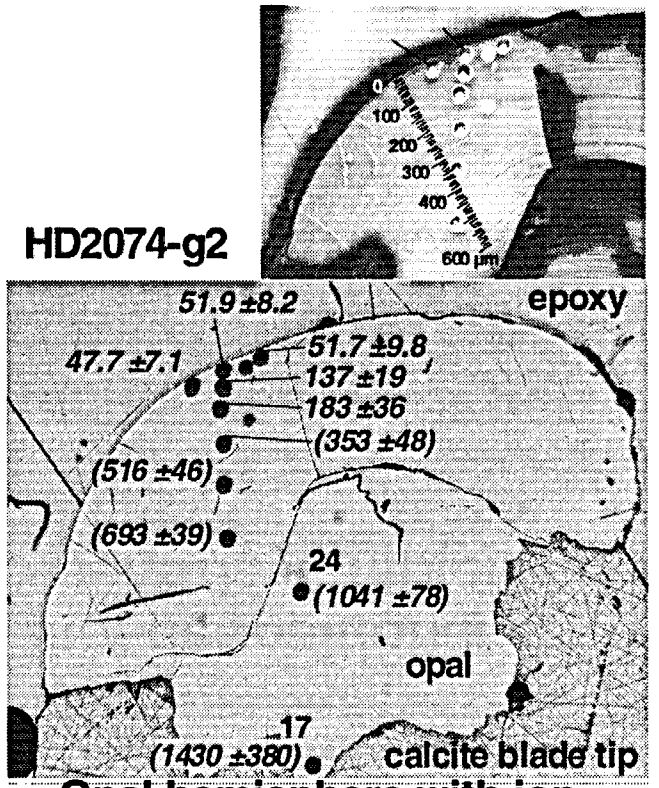
- Ongoing studies of fracture minerals
- Confirm slow mineral growth rates throughout the Quaternary
- Establish a linkage between climate variations and UZ percolation flux
- Add confidence to the UZ flow and transport models by integration of climate records

Secondary Fracture Minerals (Continued)

U-series Ion-Probe Dating of Unsaturated Zone Opal

- Ion-microprobe data using ~35 µm-diameter spots traversing several individual opal hemispheres
- U-series ages indicate uniform average growth rates of 0.5 and 0.7 µm/k.y. over the past ~1.5 million years - consistent with long-term average percolation fluxes





Opal hemisphere with ion-probe spots and resulting U-series ages (in ka)

- Slower Pleistocene growth rates (compared to 1-5 µm/k.y. Tertiary rates) may reflect decreasing moisture during the Quaternary

Thermal History of the Unsaturated Zone Fluid Inclusion Studies

- During 1999-2002, the U.S. Geological Survey (USGS) studied the timing and distribution of secondary-mineral-hosted fluid inclusions
  - fluid inclusions in calcite indicate that depositional temperatures have ranged from present-day ambient to as high as 90°C
  - Depositional temperatures are highest in the older parts of deposits
  - Calcite delta ^{18}O values correlate with and corroborate the fluid inclusion temperatures
  - Both the fluid inclusion and delta ^{18}O data indicate that calcite/opal deposition has been at or near present-day ambient temperatures for the past 2 to 4 m.y.

U-Series Delineation of Flow Paths

- Radioactive disequilibrium in the U-series decay chain is a consequence of water/rock interactions
- The degree of U-series disequilibrium in bulk-rocks
  - Is a function of hydrologic conditions
  - Is proportional to the amount of water flux
  - Integrates the effects of water/rock interactions throughout the Quaternary
- U-series disequilibrium in bulk rocks offers a geochemical test to build confidence in various aspects of the UZ flow and transport model

U-Series Delineation of Flow Paths

(Continued)

- **Recent Work**
  - Focused on demonstrating analytical feasibility using two contrasting underground hydrogeologic settings:
    - Proposed repository-level samples not associated with faulting
    - Near-surface samples at the Bow Ridge fault zone
  - Samples of deeper, unfaulted rock are expected to have
    - Smaller amounts of water/rock interaction
    - $^{234}U/^{238}U$ and $^{230}Th/^{238}U$ close to equilibrium (activity ratios ~1.0) - consistent with preliminary results from proposed repository horizon samples
  - Samples of shallower faulted rock are expected to have
    - Focused flow and greater water/rock interaction
    - Greater ^{238}U-^{234}U-^{230}Th disequilibrium - consistent with preliminary results from Bow Ridge Fault samples

Geochemistry of Pore Water

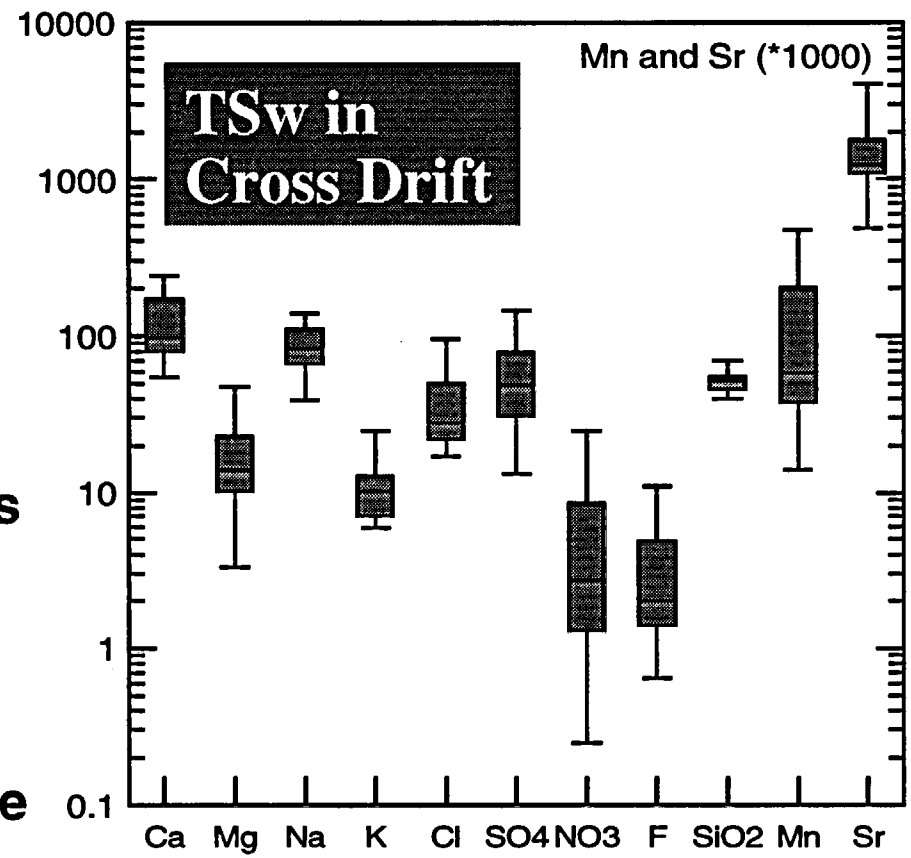
- Relevance of pore water compositions to the UZ hydrologic system
  - Tuffs contain several liters of water per m^3 of rock
  - Pore water may seep into drifts and contact waste packages
  - Evaporation of pore water on drift walls supplies salts to dust load
  - Pore water composition must be known to understand total hydrologic system

Geochemistry of Pore Water
(Continued)

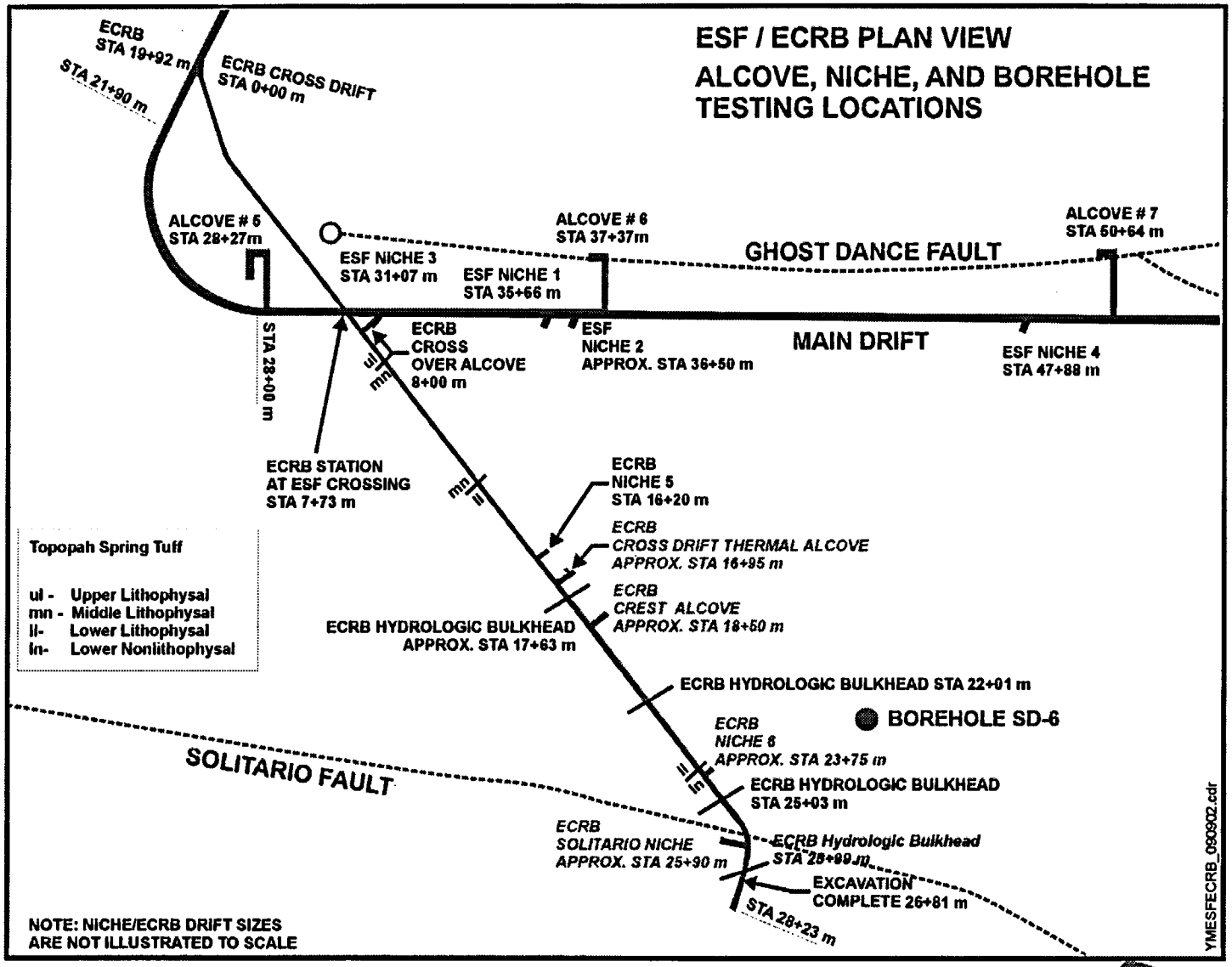
- Pore water is extracted from dry drilled core by
  - Compression of nonwelded tuffs and
  - Ultracentrifugation of welded tuffs in 150 gram batches
- Chemical (major and trace anions and cations) and isotopic (O, H, C, Sr, and U) analyses are conducted on extracted samples

Geochemistry of Pore Water
(Continued)

- **Compositional Variability (n=28)**
  - Variability at meter scale
  - Nitrate shows greatest variability
  - Silica shows least variability
  - Variability of alkaline earths is ±60 percent
  - Variability of alkalies is ±35 percent
  - Integrated with waste package environment and corrosion studies



Exploratory Studies Facility and Cross Drift



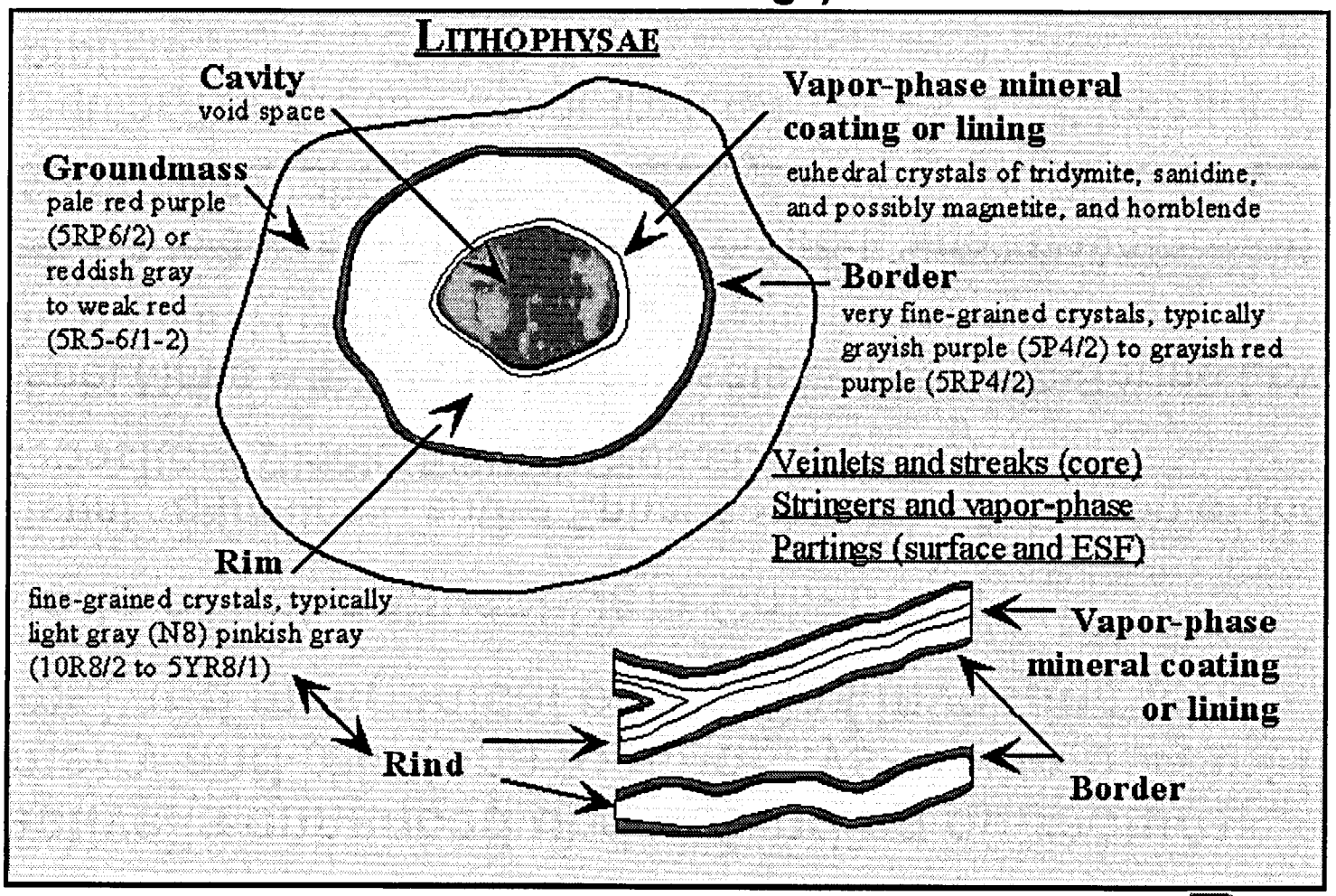
Lithophysal / Fracture Studies

- Objective is enhanced understanding of fracture geometry and relations to lithophysae -- important link to thermal and mechanical properties investigations
- Methods of Lithophysal Data Collection
  - Visual estimates – entire Enhanced Characterization of the Repository Block (ECRB) Cross Drift (1998)
  - Panel Maps – 1 X 3 m photomosaics - Topopah Spring Lower Lithophysal (Tptpll)
  - Tape Traverses – Physically measured "line" traverses on 5m centers throughout the Tptpll
  - Angular Traverses – Laser traverses at selected locations in the Tptpll
  - Large Lithophysae Survey – Locating only lithophysae >50 cm in size in upper Tptpll

Lithophysal / Fracture Studies (Continued)

Lithophysae, Spots, and Vapor Pathways

(spots are the same as lithophysae, but do not have cavities and vapor-phase mineral coatings)

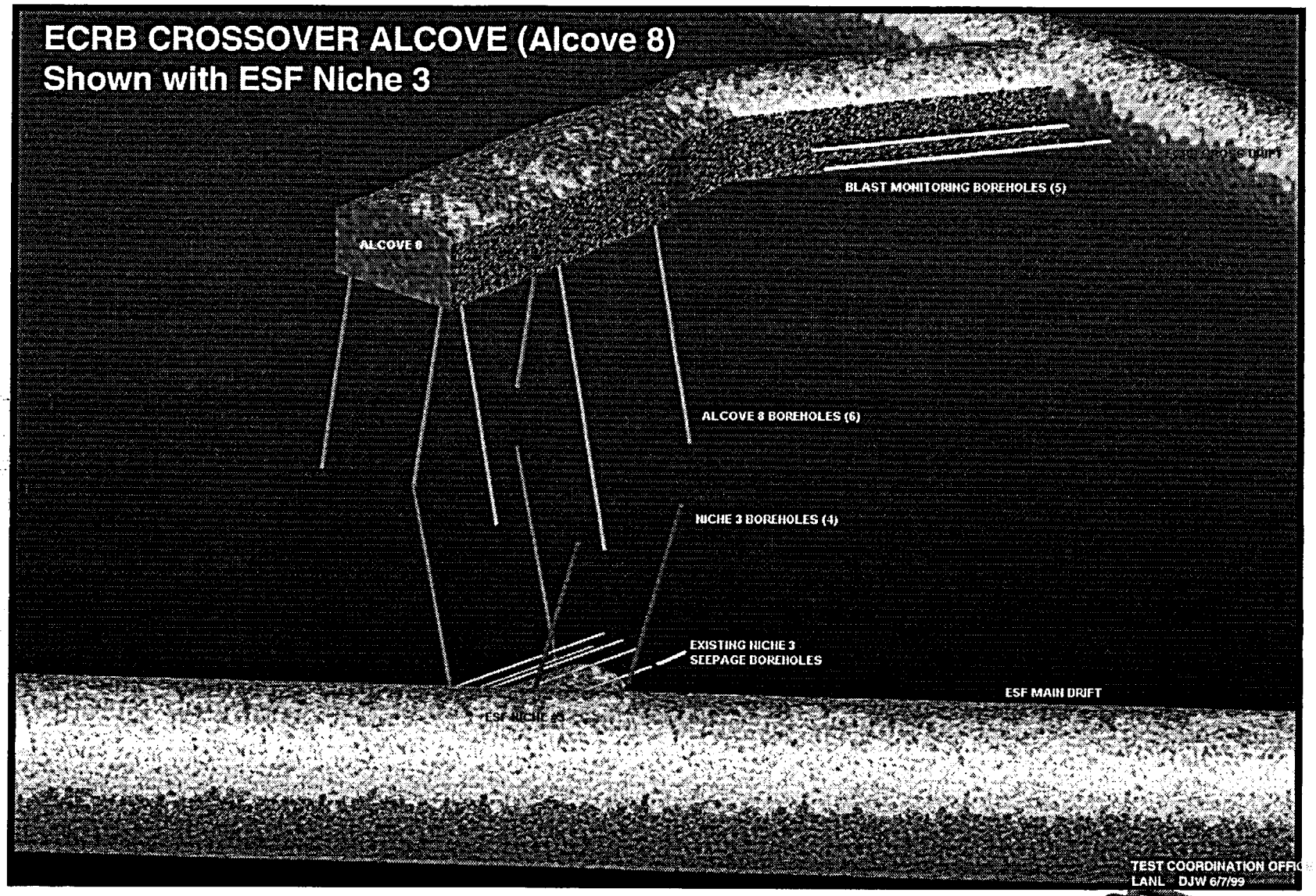


Cross Drift Studies

- Alcove 8 / Niche 3 (Crossover Alcove) (Station 8+00 meters)
  - Evaluate flow and seepage processes in potential repository horizon rocks at scale of tens of meters
  - Supports UZ Seepage and Transport models

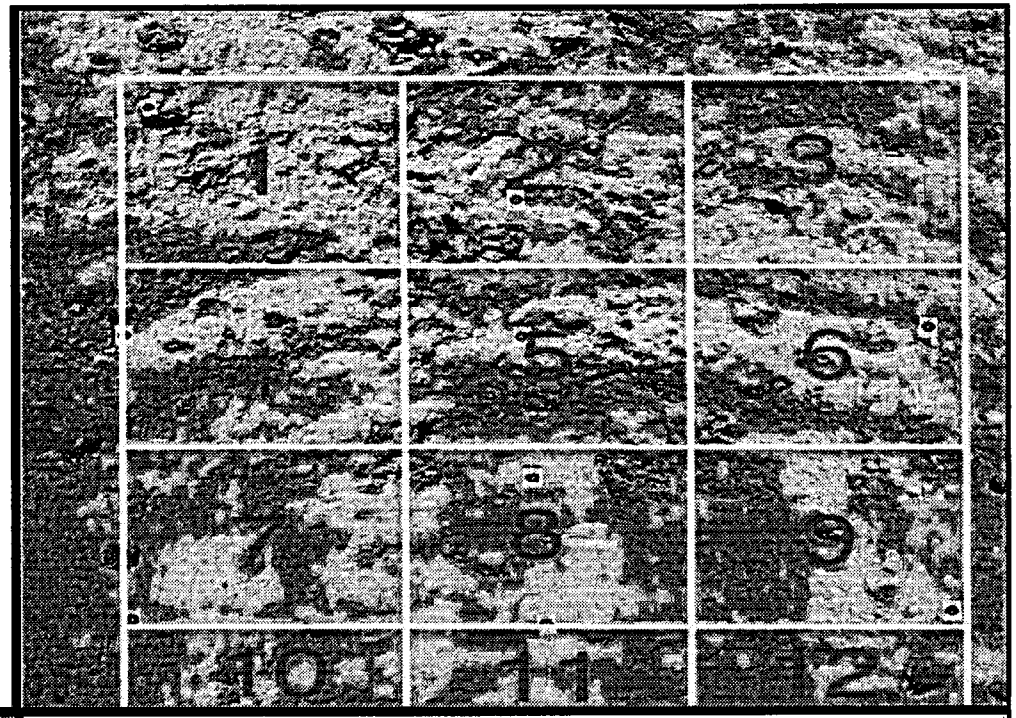
Cross Drift Studies

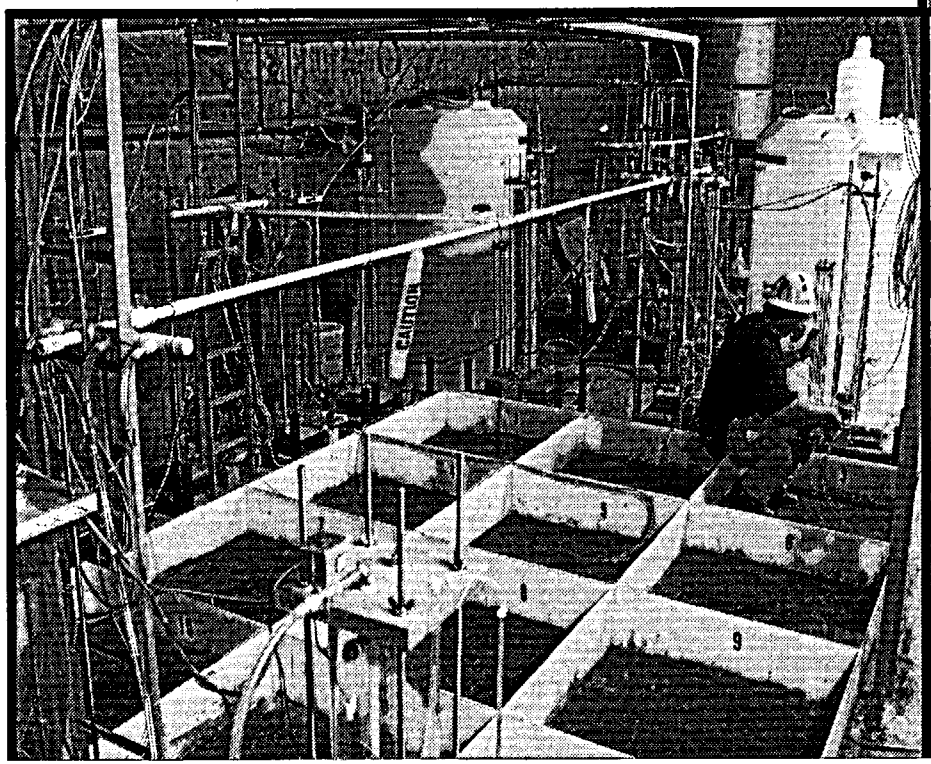
(Continued)

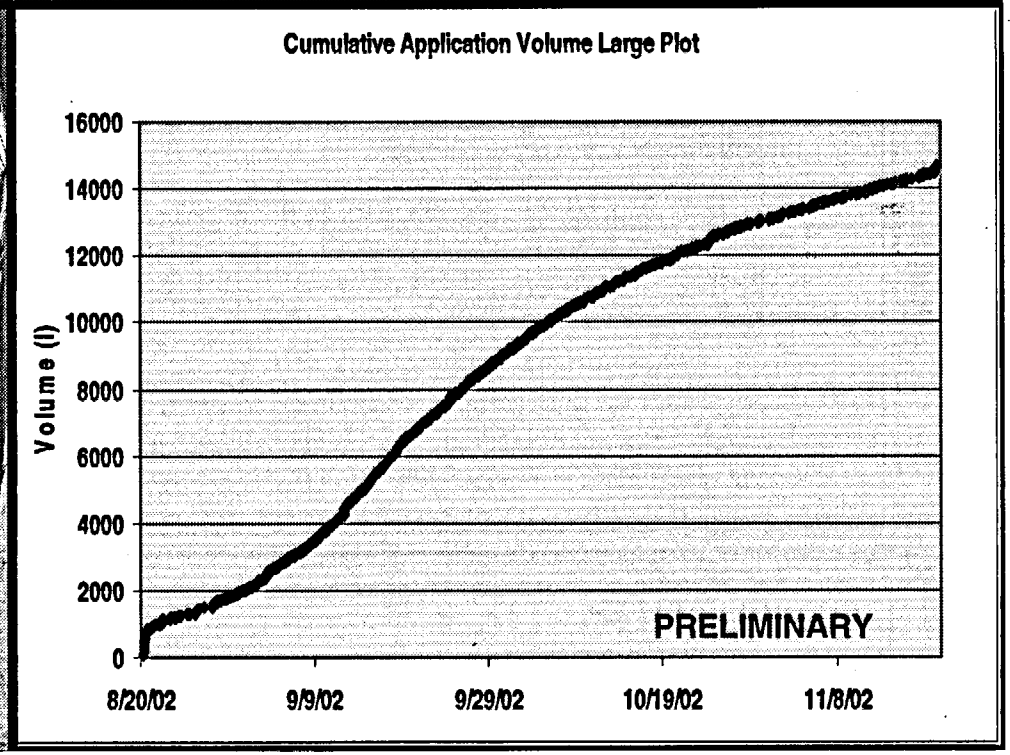


YUCCA MOUNTAIN PROJECT

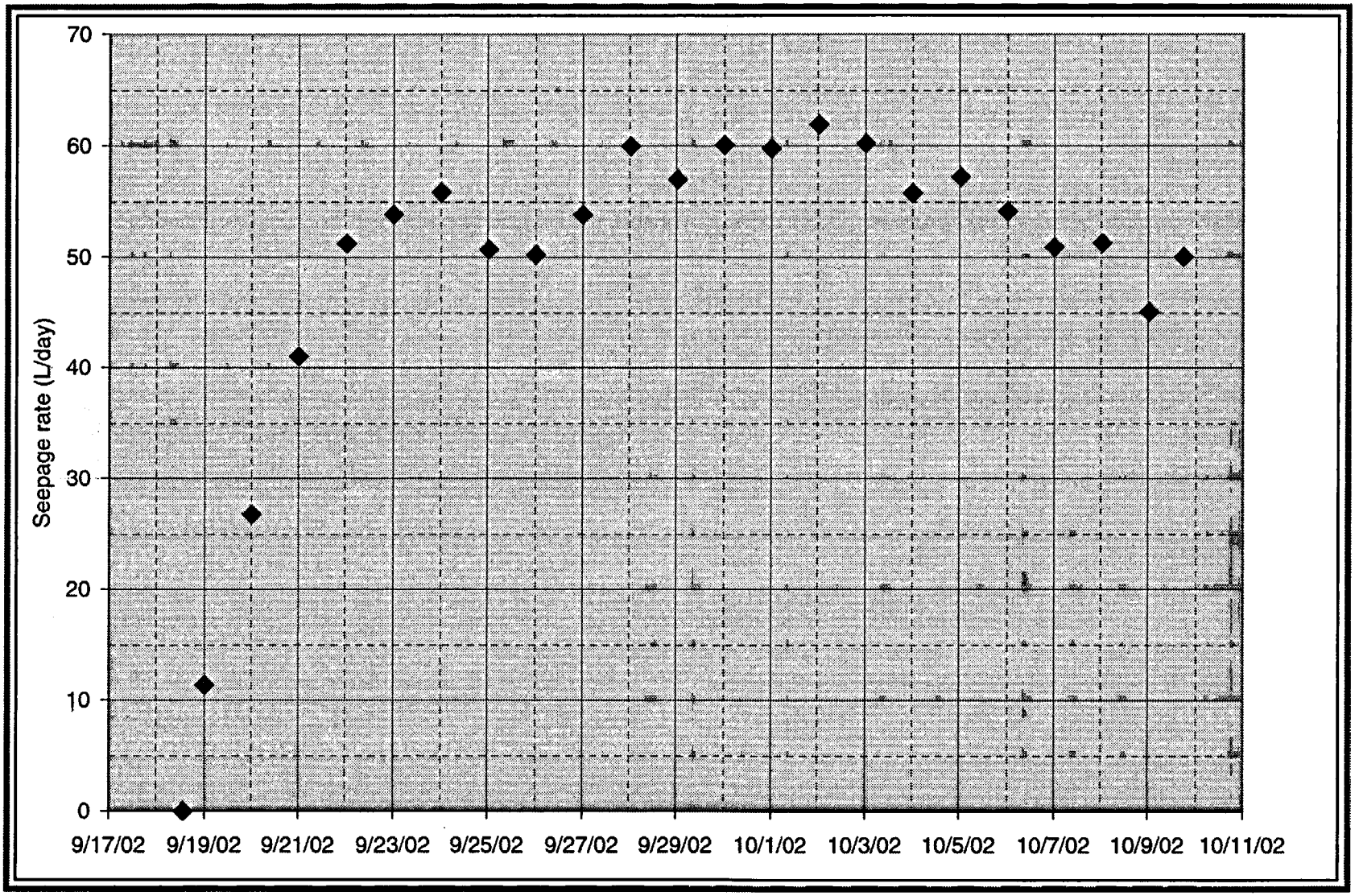
- **LARGE PLOT EXPERIMENT**
  - Saturated application began on 8-20-02 and continues.
  - Three zones of water application, Z1 = 1,2 Z2 = 3,4,5,6,7,8,9 Z3 = 10,11,12
  - Infiltration rate of fast zone 3.20 cm/day





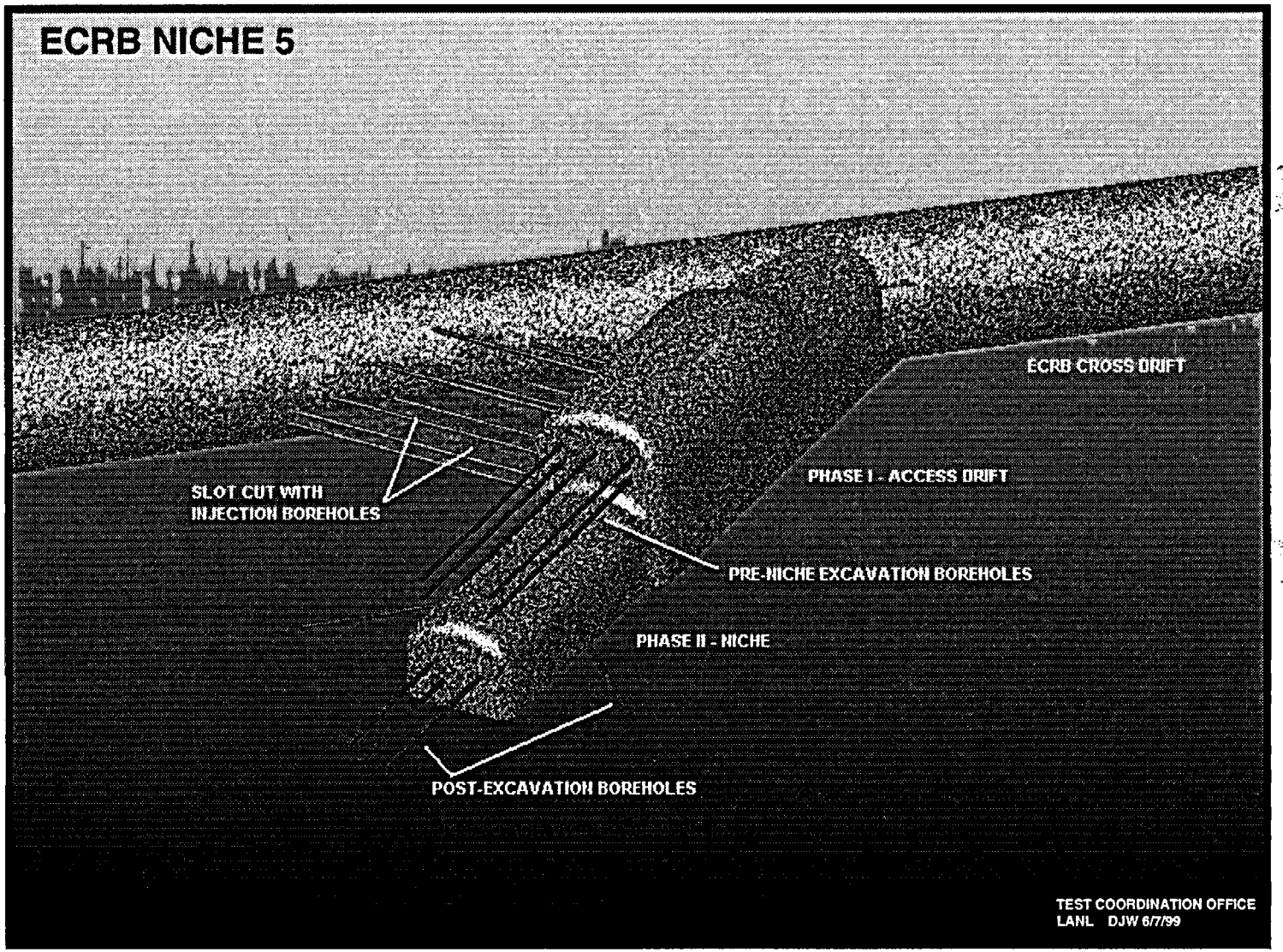


Seepage rates measured in Niche 3 following liquid release in large block in Alcove 8 on August 20, 2002



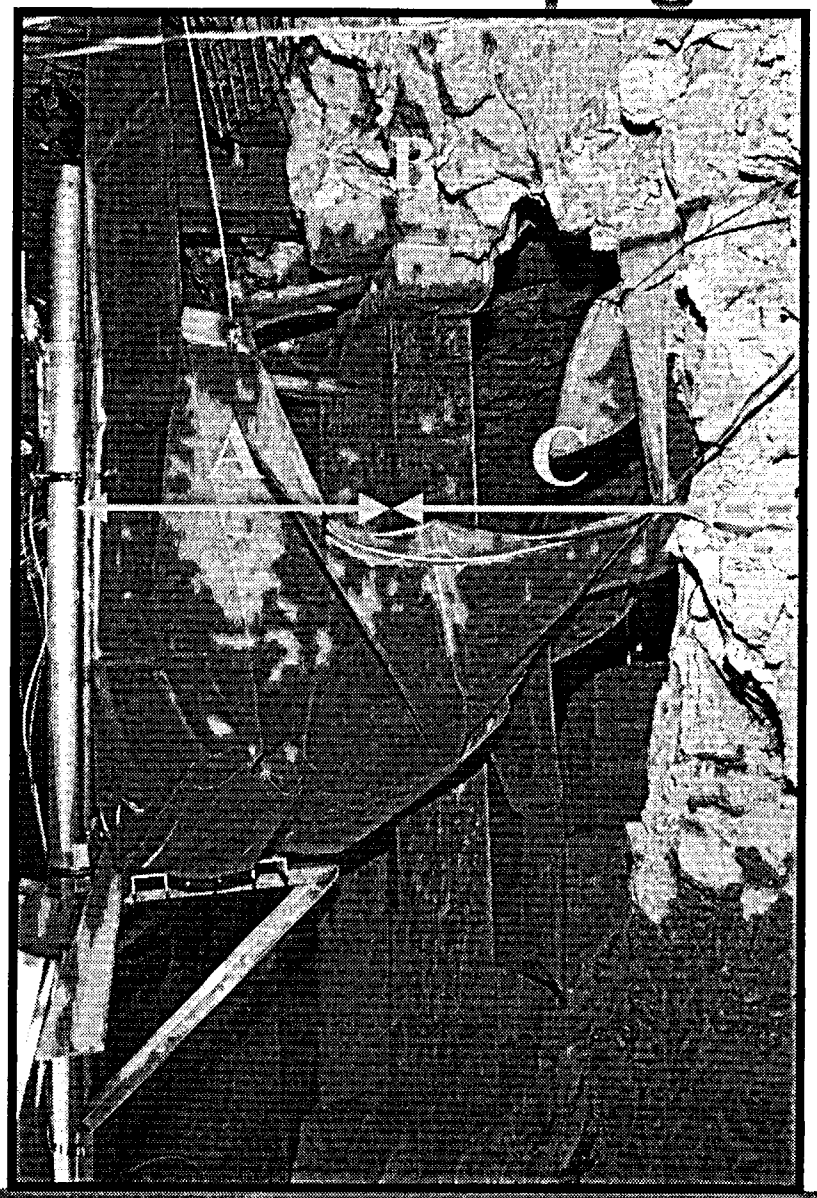
Cross Drift Studies

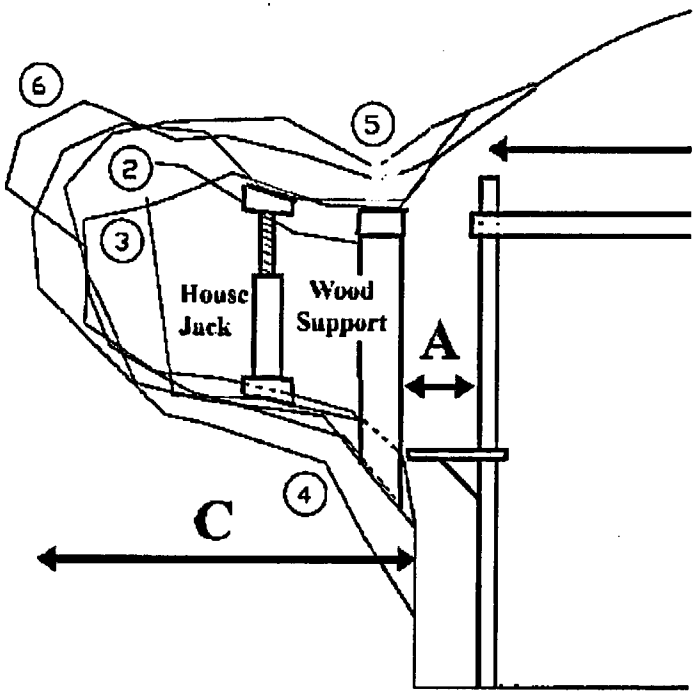
Niche 5 — Supports UZ Seepage Models — Evaluate Seepage in Lower Lithophysal Unit



Niche 5 (Continued)

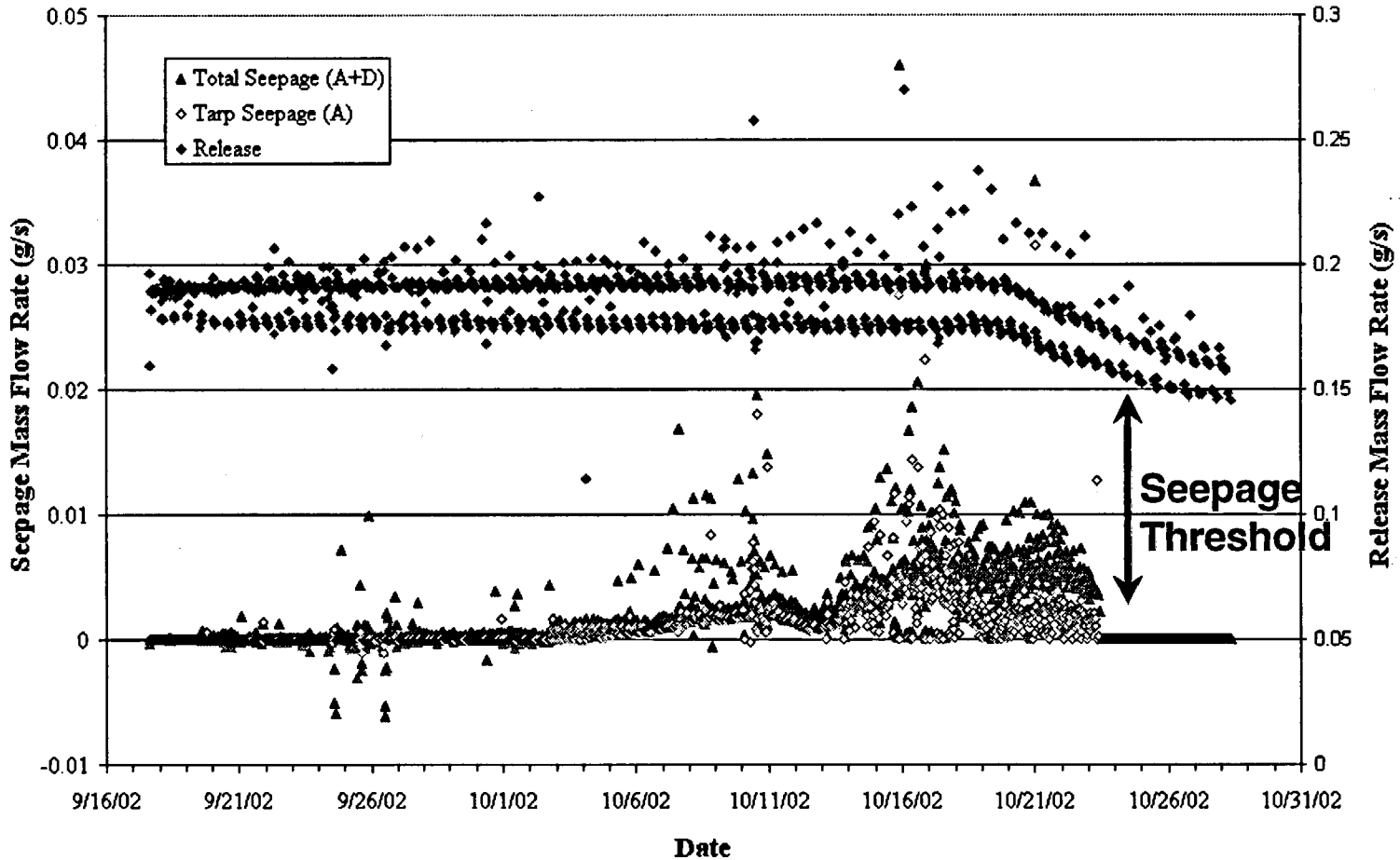
Seepage Collection





Niche 5 (Continued)

Release and Seepage Mass Flow Rates Test #2 9-17-02

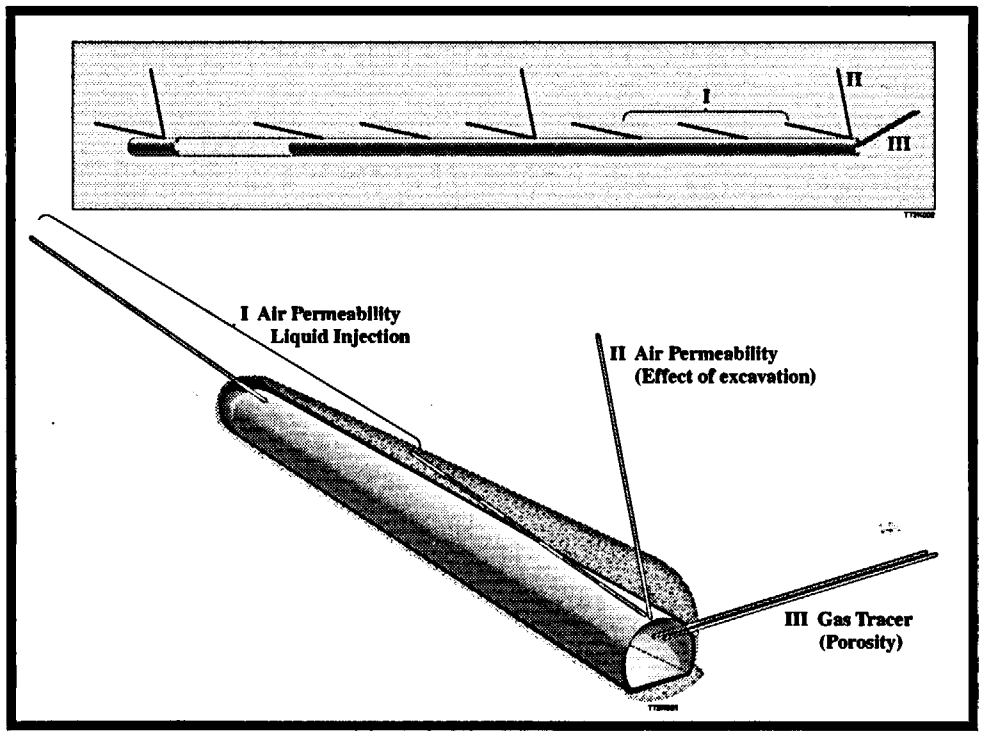


Niche 5 (Continued)
Objectives / Results

- Data being used to calibrate and validate the drift-scale seepage model
- Demonstrated that a capillary barrier and seepage threshold exist in the Tptpll
- Could not definitively show that lateral flow occurred into slot by visual inspection
  - However, photographic evidence indicates liquid released above the ceiling reaches the niche wall

Cross Drift Studies Systematic Hydrological Testing in the Topopah Spring Lower Lithophysal Unit

- Supports UZ Seepage Model - Heterogeneity of fracture characteristics, permeability, and seepage
- Perform hydrological tests in 20-m long boreholes drilled at regular intervals (every 30 meters) along the Cross Drift regardless of specific features (fractures, lithophysal cavities etc.)
- Equipment systems (for air-k and liquid release tests) fitted on flatcar units are moved from one borehole station to another



Systematic Hydrologic Testing (Continued)

Systematic Approach Designed to Evaluate Spatial Heterogeneity

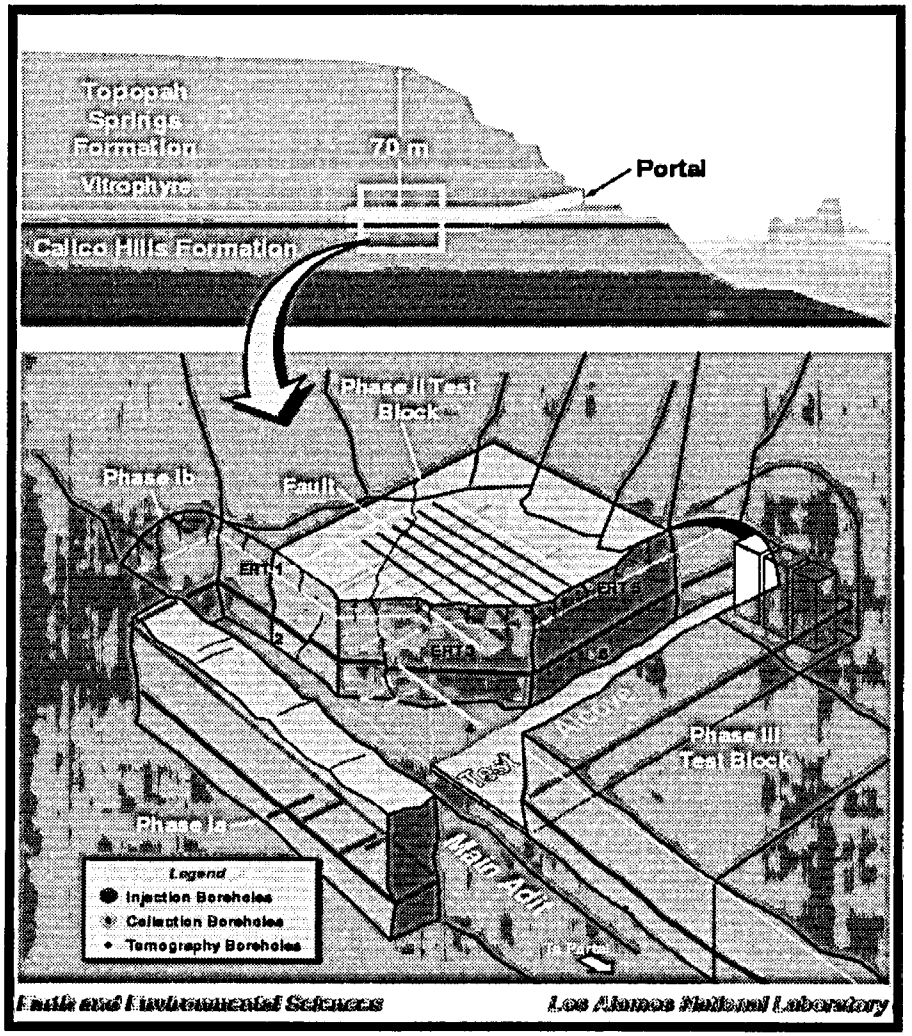
- Variability in formation response at different locations
  - Some of the test locations do not let any water enter the formation; all introduced water returned in overflow
  - Some locations show complete diversion of all water from entering the drift regardless of uptake rate
  - Most test zones show partial diversion of introduced water from entering the drift
- Flow characteristics common to all locations
  - Small fractures and lithophysal cavities connect to provide discrete, preferential flow paths
  - Participation of lithophysal porosity in liquid flow paths is small
- This variability is being addressed within the drift-scale seepage model

Cross Drift Studies (Continued)

Bulkhead Investigations

- Evaluate flow and seepage processes in potential repository horizon rocks and Solitario Canyon Fault Zone in support of UZ Flow and Seepage Models
- Terminal 918m of the Cross Drift isolated from ventilation to observe in situ drift conditions and re-wetting after closing bulkheads
- Monitor for free liquid water from either seepage or condensation
- Multiple lines of evidence (e.g., water chemistry, moisture distribution) suggest condensation is dominant
- Ongoing and planned testing and analysis program in place to address observations

Busted Butte Unsaturated Zone Transport Test



- Evaluate influence of heterogeneities on flow and transport
- Evaluate other aspects of site, including fracture/matrix interactions and permeability contrast boundaries
- Consider colloid migration in unsaturated zone
- Test use of laboratory sorption data at field scale
- Calibrate and validate site-scale UZ flow and transport model
- Address scaling issues

Busted Butte Unsaturated Zone Transport Test

(Continued)

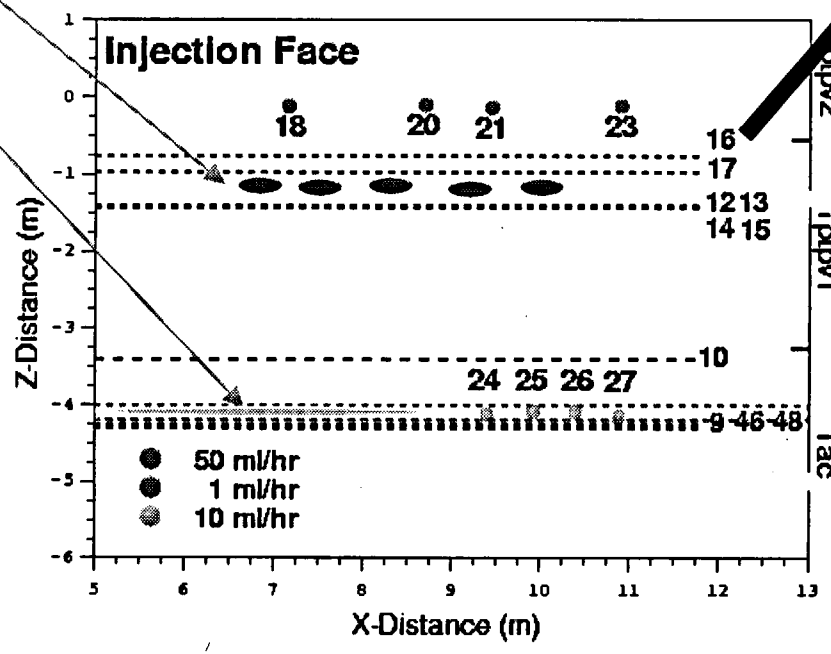
Modeling Goals

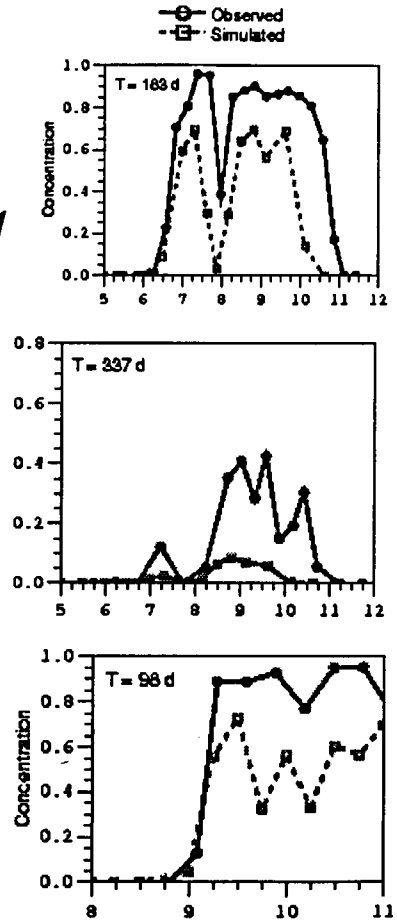
- Apply model used in site-scale predictions to small-scale test at Busted Butte
- If model accurately predicts small-scale field behavior, our confidence in site-scale predictions is increased

Busted Butte Unsaturated Zone Transport Test
(Continued)

Permeability Contrast Results: Phase 2

- **Thin interfaces found during mineback affected breakthrough**
  - **Pumice**
  - **Ash layer**





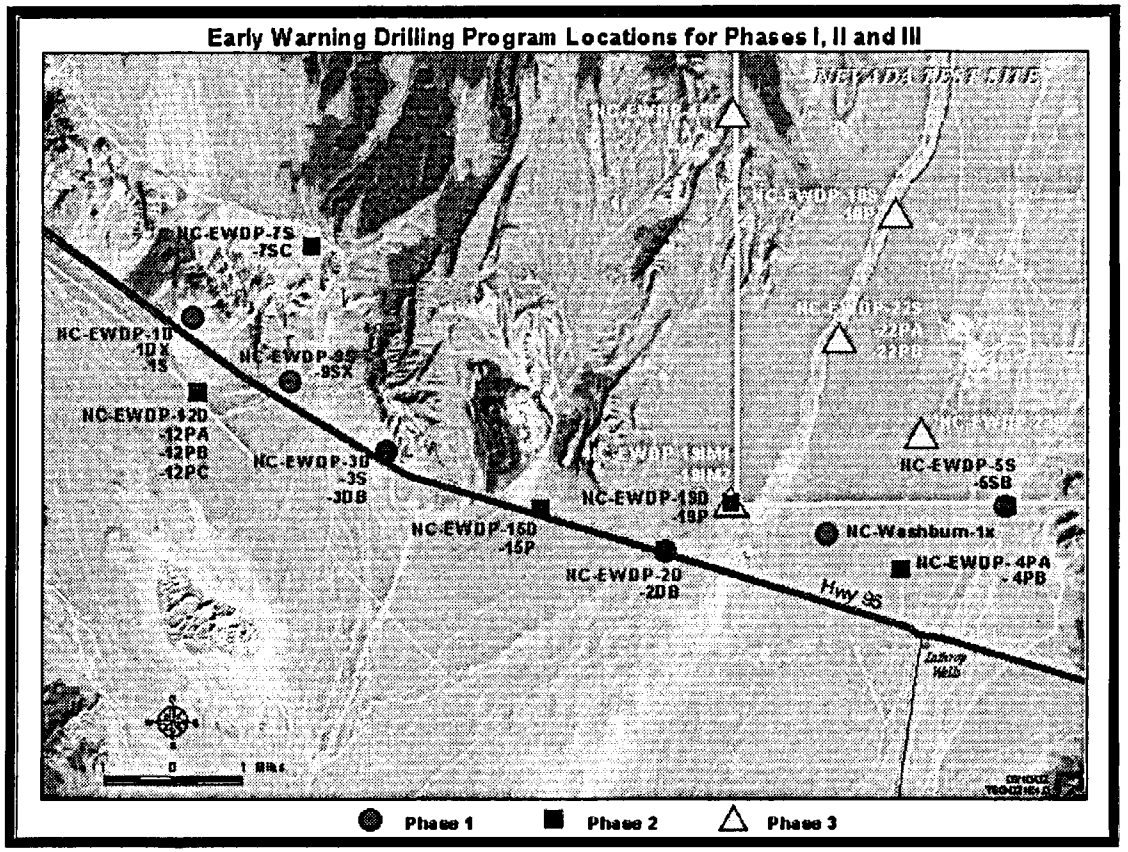
Busted Butte Unsaturated Zone Transport Test

(Continued)

Conclusions

- Busted Butte shows that rocks in the field behave in a manner similar to rocks in the laboratory with respect to capillary forces
- Permeability contrasts and unit boundaries appear to be more important for transport than fractures, at the flow rates used
- Busted Butte is consistent with the current conceptual model
- Busted Butte provides support for modeling parameters used in the site-scale flow model

Saturated Zone
Nye County Early Warning Drilling Program

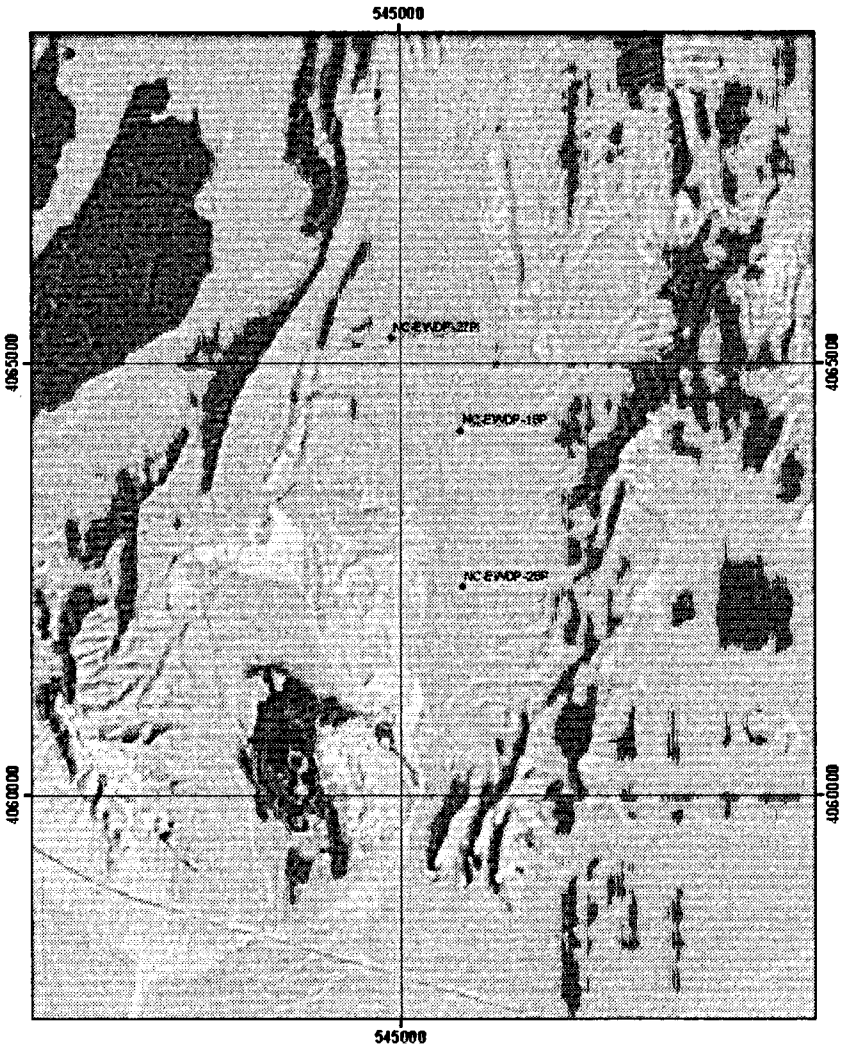


Site-Scale Data Being Collected in support of the SZ Flow and Transport Model:

(1) Lithologic data into the hydrogeologic framework model
(2) Water-level data for flow field calibration
(3) Hydraulic testing data for flow and transport models
(4) Laboratory sorption measurements (^{237}Np, ^{129}I, and ^{99}Tc) on alluvium for process models and TSPA
(5) Hydrochemistry data for flow field calibrations
(6) Eh/pH data for use in flow and transport models
(7) Hydraulic and transport testing of alluvial aquifer for flow and transport models

Saturated Zone (Continued)

Nye County's Phase IV Drill Hole Locations

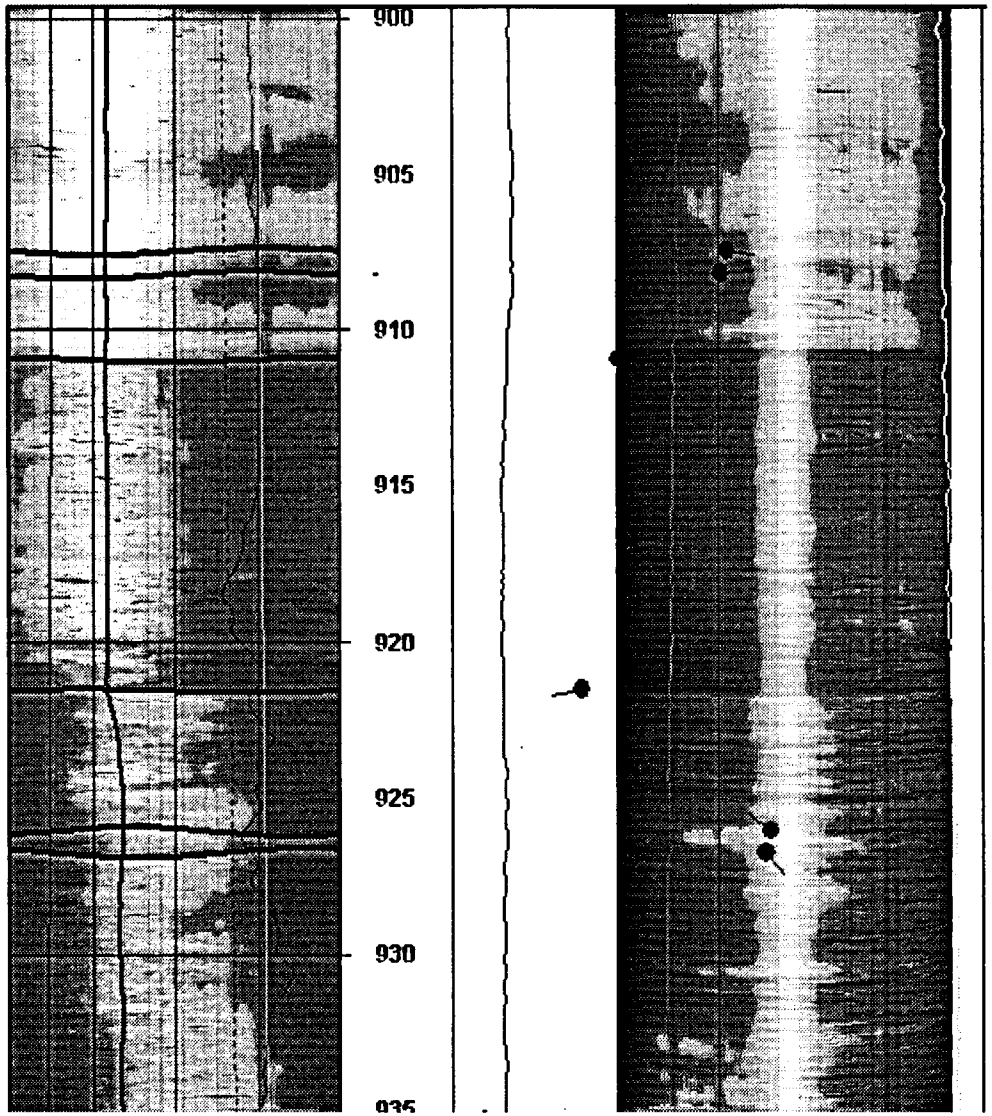


Cross Sections Nye-1, Nye-2, and Nye-3

- Cross sections Nye-1, Nye-2, and Nye-3 have been revised to include phase III drill hole data
- Three new deep boreholes have been drilled as part of Phase IV drilling
- Samples from Nye County Phase IV drilling are currently being processed

Lithostratigraphy (Continued)

Where possible, digital images of borehole walls of Nye County drill holes are being collected using state-of-the-art technology



Selected interval from NC-EWDP-27P

Saturated Zone (Continued) Hydrochemistry Objectives

- Identify and map hydrochemical facies in Yucca Mountain region
- Identify potential flow paths from Yucca Mountain to accessible environment
- Assess interaction and mixing among different facies, including transition from volcanic to alluvial aquifer downgradient from Yucca Mountain
- Improve understanding of compositional variability in the third dimension

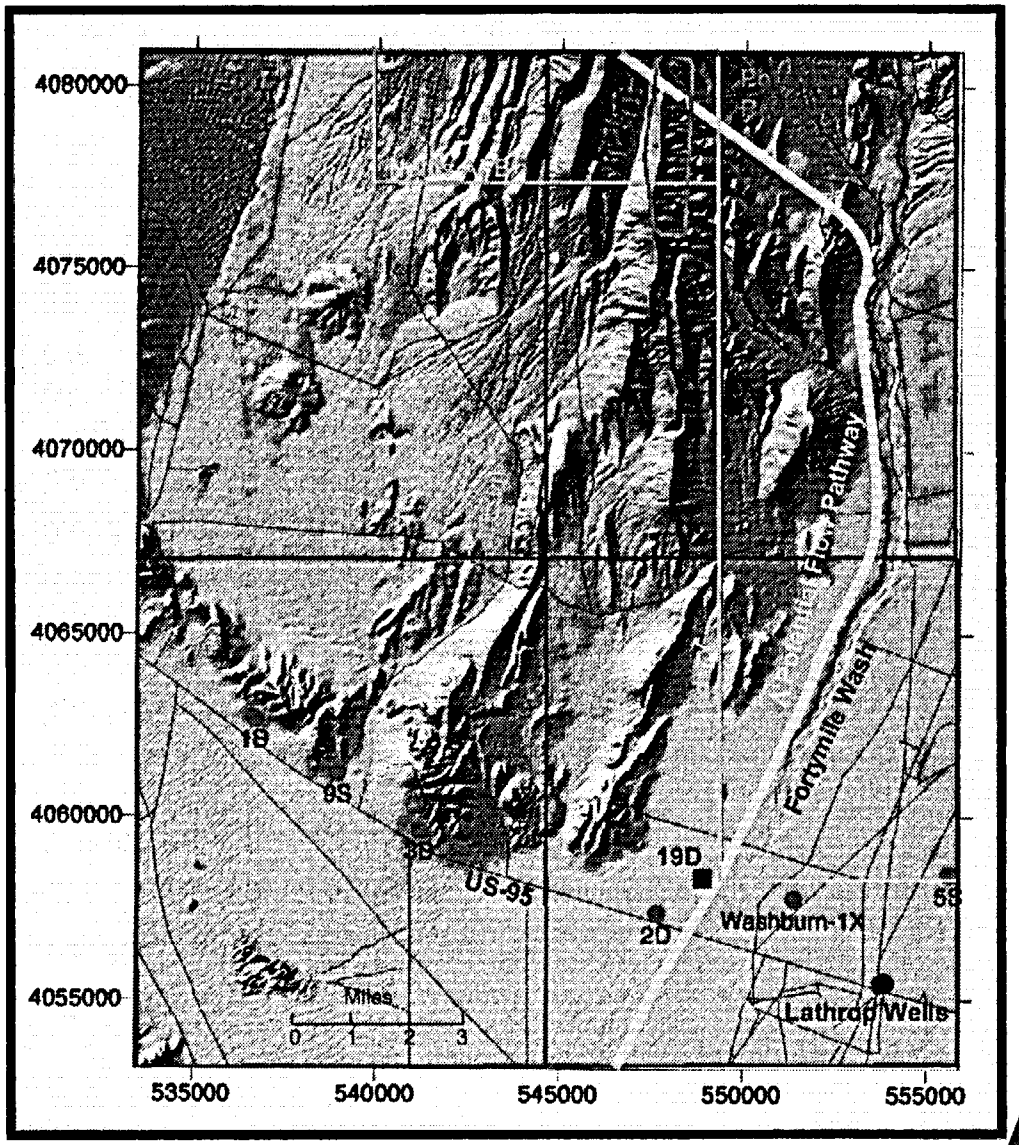
Saturated Zone Hydrochemistry (Continued)
Current Activities

- Continue sampling of Nye County wells
- Sample Inyo County wells when drilled
- Other sampling—Nevada Test Site, Bond Gold monitor wells, domestic wells in Amargosa

Saturated Zone Hydrochemistry (Continued)
Hydrochemical Facies

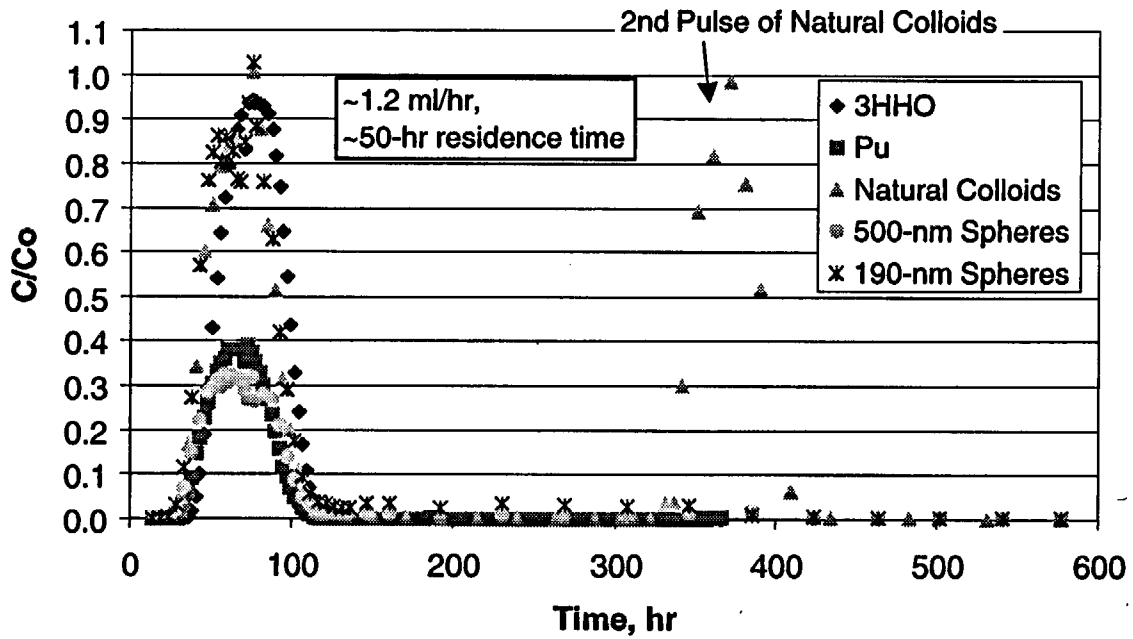
- Yucca Mountain—Eastern Crater Flat
  - Volcanic aquifer, zeolitized tuffs influence water chemistry
- Fortymile Wash
  - Alluvial/volcanic aquifer
- Bare Mountain
  - Similar to regional carbonate waters
- Amargosa River
  - Isotopically influenced by Precambrian rocks
- Eastern Amargosa Valley
  - Transitional from volcanic to alluvial aquifers

Saturated Zone (Continued)
Alluvium Sorption Investigations



Alluvium Colloid and Colloid-Facilitated Transport Experiments

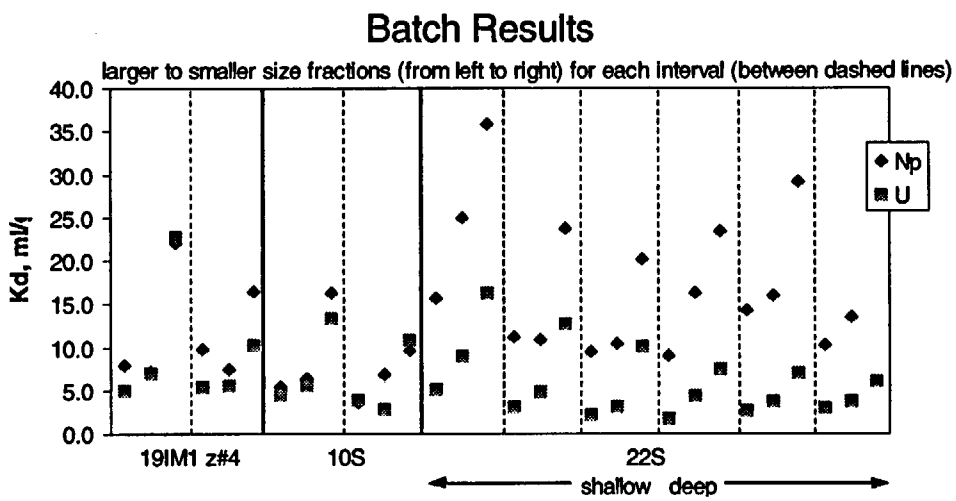
- 4 experiments; 2 different flow rates in 2 columns packed with EWDP-19D alluvium
- Pu(V) sorbed onto natural colloids collected from 19D
- 2 different sizes of carboxylate-modified latex microspheres
- Breakthrough curves for tritium, Pu, natural colloids, and microspheres

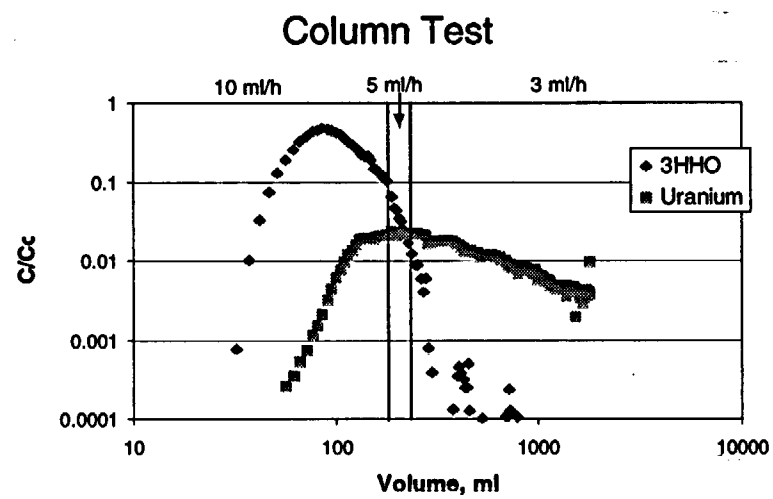


- Conclusions:
  - Natural colloids basically unretarded in these experiments
  - Almost all Pu sorbed onto colloids going into columns was recovered
  - No soluble Pu recovered
  - 190-nm microspheres behave similar to natural colloids; 500-nm microspheres quite attenuated

Uranium and Neptunium Sorption and Transport Experiments in Alluvium

- Numerous batch sorption experiments onto Alluvium from 19IM1, 10S, and 22S
- Np and U column experiments using 19IM1 alluvium





PRELIMINARY

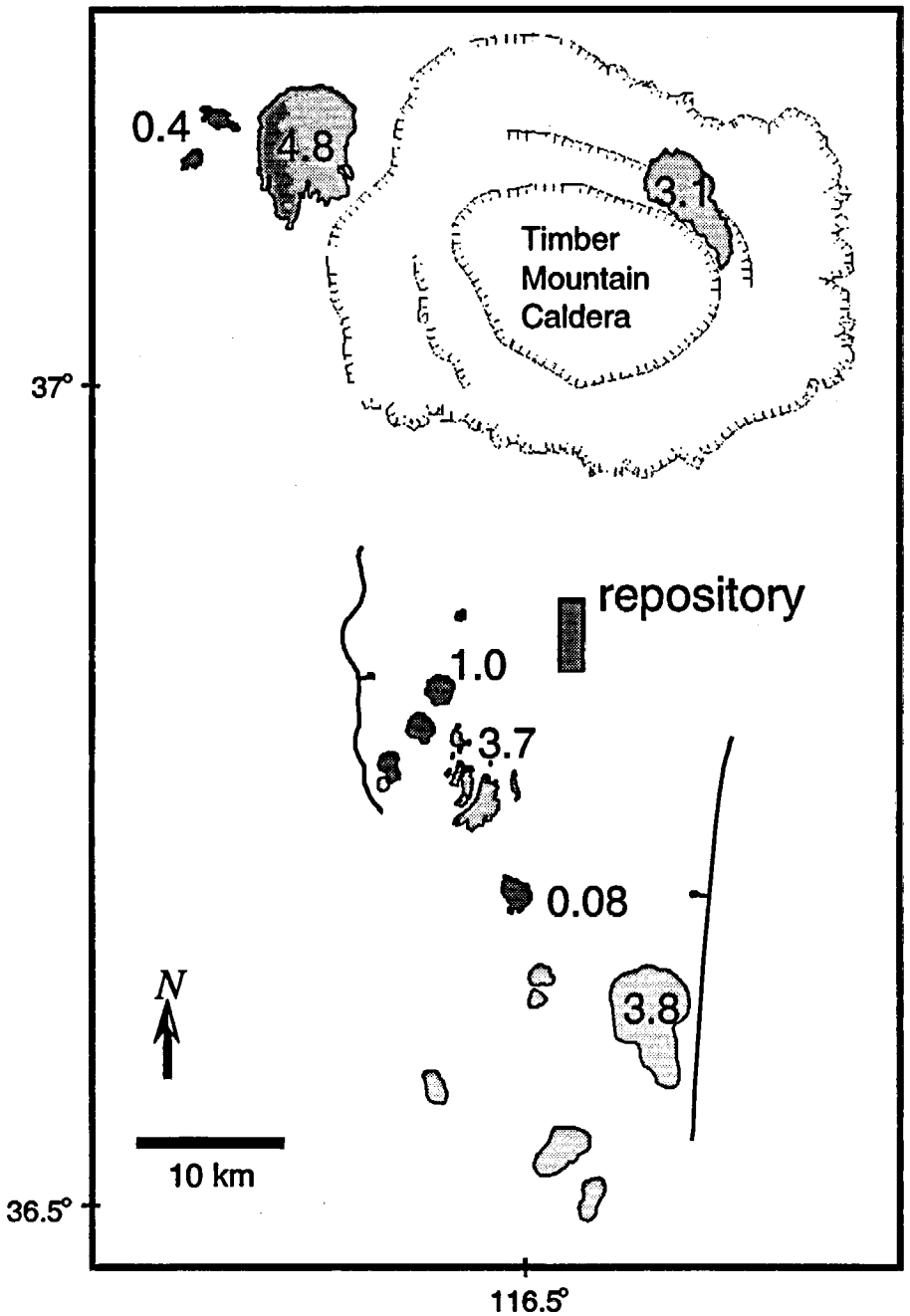
- Conclusions:
  - Np slightly more strongly sorbed than U to alluvium in most batch experiments
  - Column experiments suggest a wide distribution of Kd values.
  - Small fraction of radionuclide mass has smaller Kd values than in batch experiments, but a significant fraction have larger values. Kinetics may play a role as well

Igneous Events Studies Support Igneous Disruptive Events Analyses and Models

- Evaluating igneous consequence scenarios including
  - Modeling dike propagation through proposed repository
  - Modeling extrusive event through proposed repository
  - Completing Igneous Consequences Peer Review
    - Evaluate current technical basis to analyze consequences
    - Assess adequacy of the analysis and modeling program and recommend any augmentation of planned work
- Evaluating aeromagnetic data for identification of potential buried volcanic centers
- Evaluating probability of intersection based on aeromagnetic data

Igneous Events Studies
(Continued)

Buried Volcanoes are Part of the Geologic Record



- Buried volcanoes are potentially a factor contributing to the uncertainty in the recurrence rate
- At time of Probabilistic Volcanic Hazard Assessment (PVHA), known geologic record included presence of seven inferred (from geophysics) or known (from drilling) buried basalt centers

aeromagnatic anomaly

YUCCA MOUNTAIN PROJECT

Residual Magnetic Anomalies near Yucca Mountain

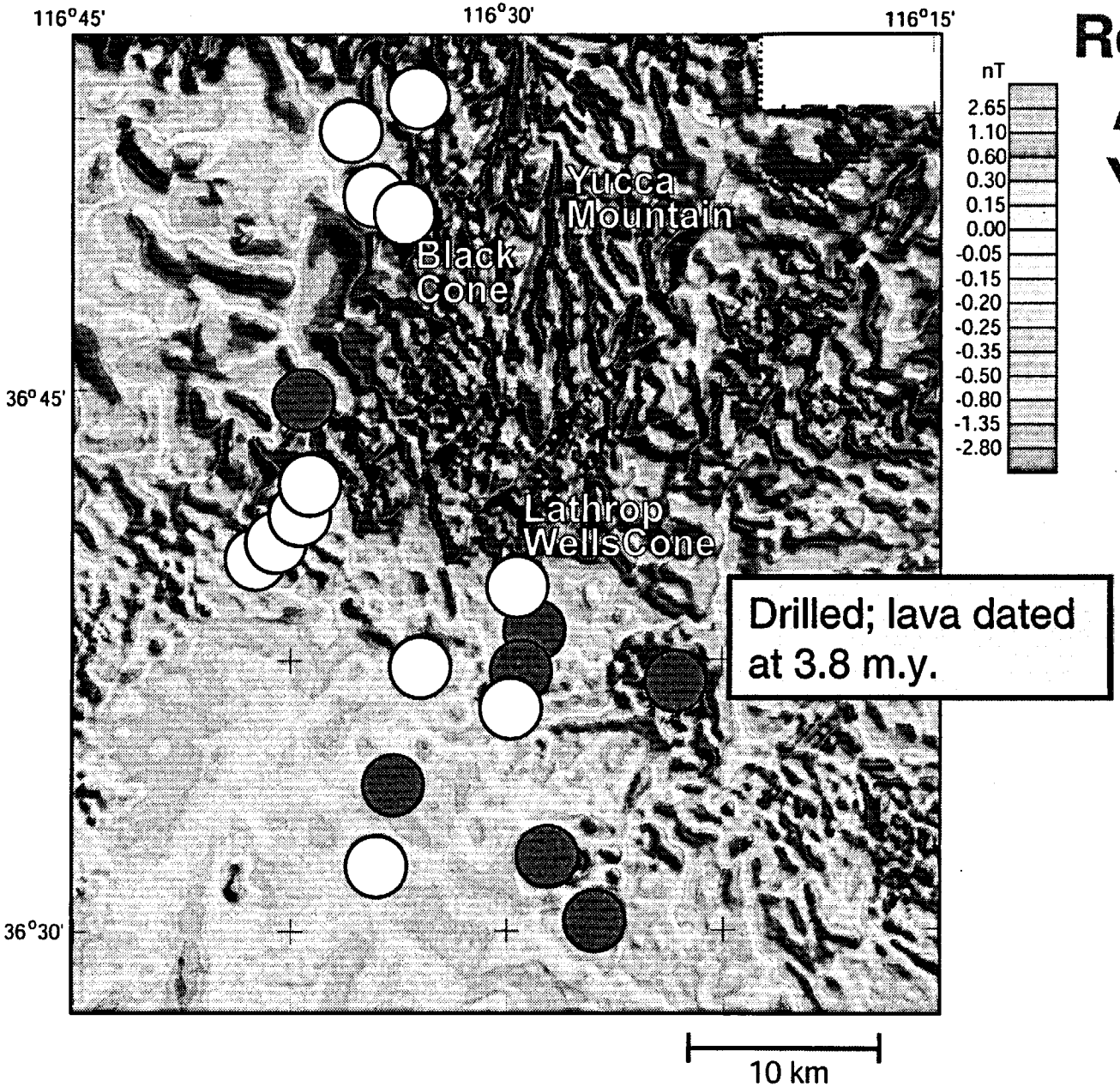


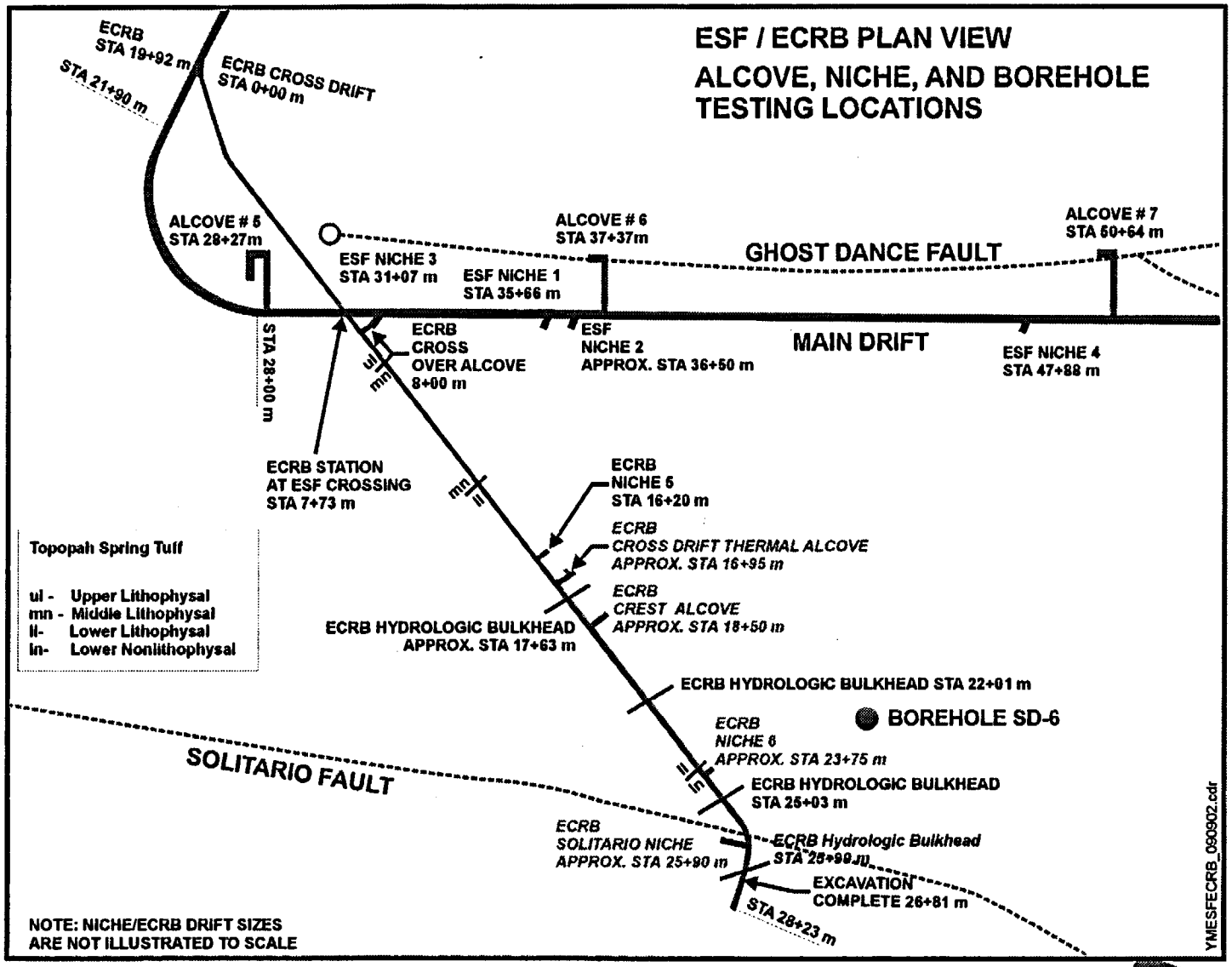
Figure 4 of O'Leary et al. (2002), USGS Open-File Report

Builds on earlier work from Langenheim (1995) and Blakely et al. (2000)

Engineered Barrier System Studies Thermal Properties Investigations

- Supports coupled process models, engineered barrier system (EBS) process models, and design
- Laboratory Testing Program on Tptpll. Status: 144 new tests completed; results presented September 2002
  - Oven-Dried Specimens
  - Saturated and Oven-Dried Specimens – Including matched pairs
  - Specimens containing both natural and artificial porosity
- Field Tests
  - One test completed, two nearly completed.
  - Two additional tests are planned for FY03: Tptpll and Tptpul

Exploratory Studies Facility and Cross Drift



Thermal Properties Investigations (Continued)
Field Data: Implications for Model

Model predictions given in: Thermal Conductivity of the Potential Repository Horizon Model Report, MDL-NBS-GS-000005. Model values account for moisture and lithophysal porosity

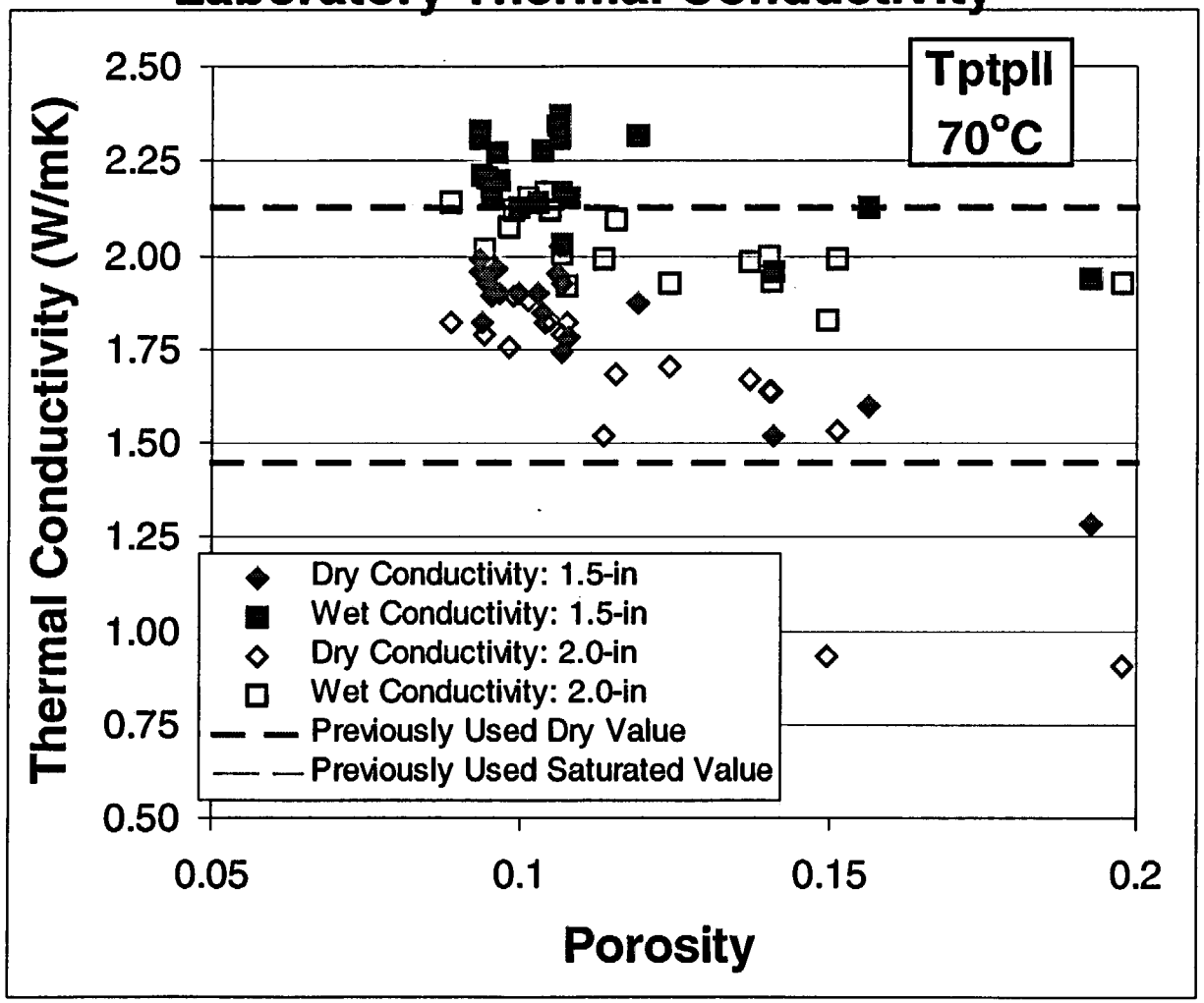
	Field Thermal Conductivity		Model Report (W/mK)
	Wet (Stg1) (W/mK)	Dry (Stg2) (W/mK)	
Test 1 (2-Hole Test)	1.74	---	1.66 ± 0.25
Test 2 (6-Hole Test)	2.03 – 2.18	1.59 –1.63	---
Test 3 (3-Hole Test)	1.73 – 1.76	1.47	1.62 ± 0.25

Wet field values of thermal conductivity are above model values but well within one standard deviation

Thermal Properties Investigations (Continued)

Comparison of Field and Laboratory Topopah Springs Lower Lithophysal Data

Laboratory Thermal Conductivity



Field Thermal Conductivity

Wet: 1.7 – 2.2 W/mK

Dry: 1.5 – 1.6 W/mK

Laboratory data obtained on matrix specimens without lithophysae.

Field and laboratory data are consistent.

Engineered Barrier System Studies(Continued)

Thermal-Mechanical Rock Properties Investigations

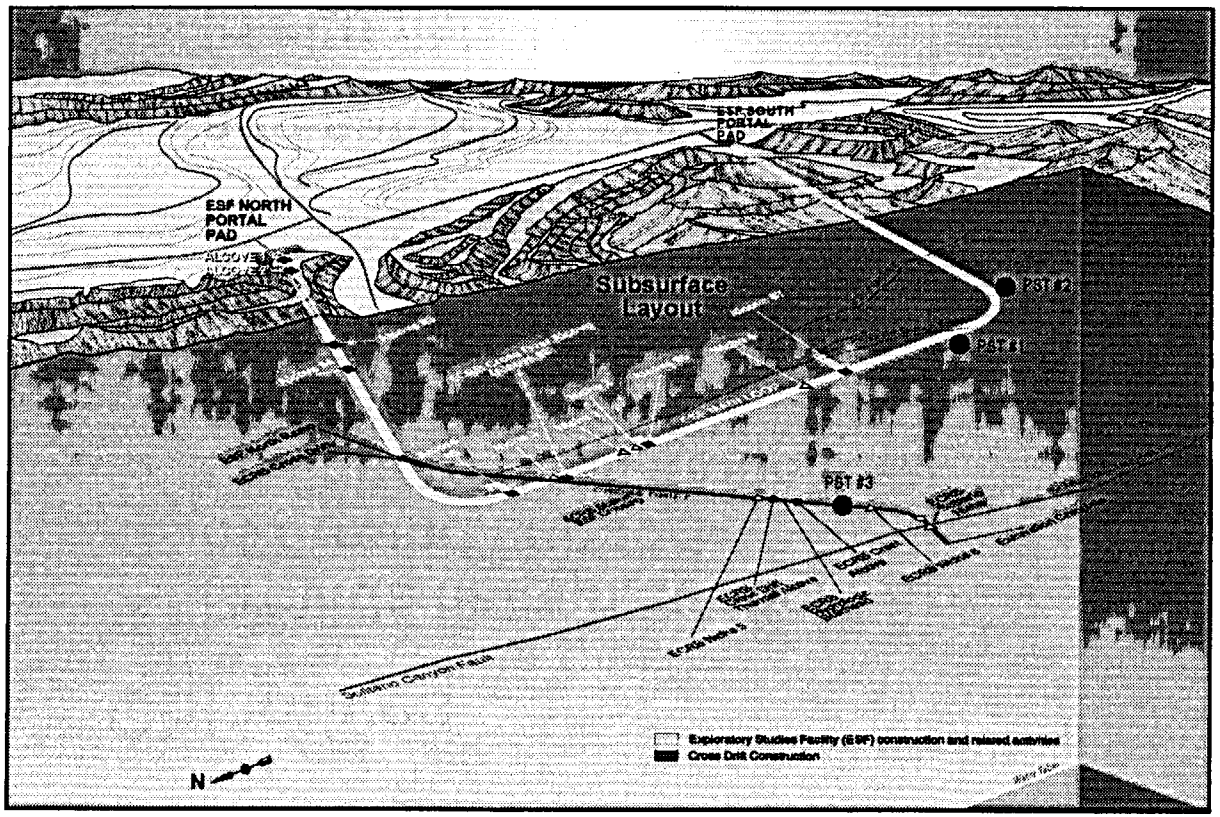
- **Objectives**
  - Provide data in support of ground support design, rockfall models, and thermal models
- **Status**
  - Large diameter coring and sampling ongoing
  - In situ field tests complete
  - Laboratory measurements ongoing

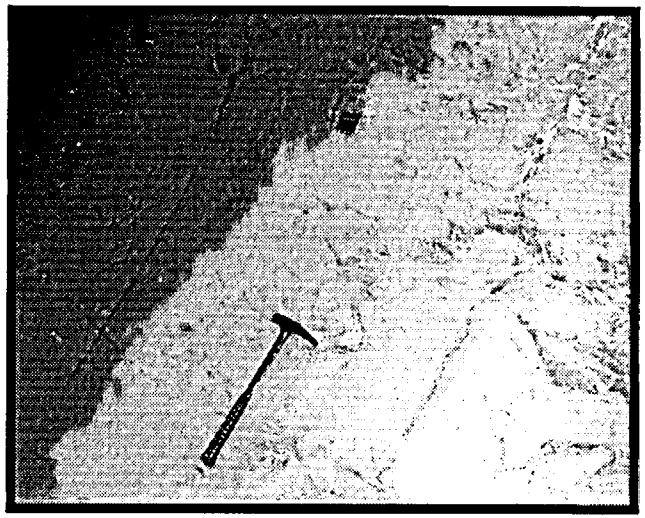
YUCCA MOUNTAIN PROJECT

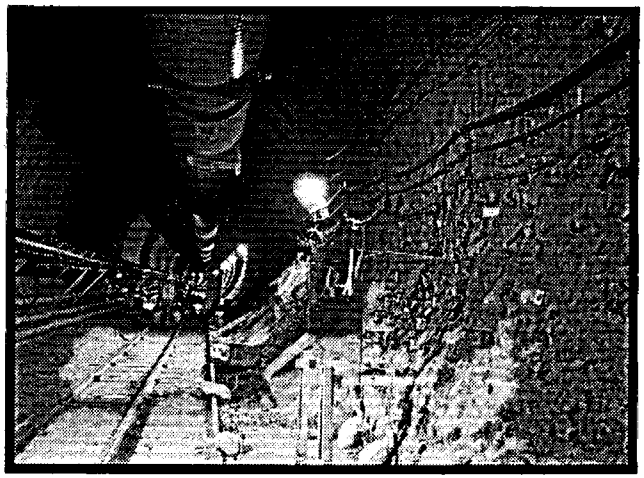
Thermal-Mechanical Rock Properties Investigations
(Continued)

Pressurized Slot Test Locations

Exploratory Studies Facility and Alcoves







PST #1 – Station 57+77 of ESF, Tptpll (Completed)
PST #2 – Station 63+83 of ESF, Tptpul (Completed)
PST #3 – Station 21+25 of Cross Drift, Tptpll (Completed)

Thermal-Mechanical Rock Properties Investigations

(Continued)

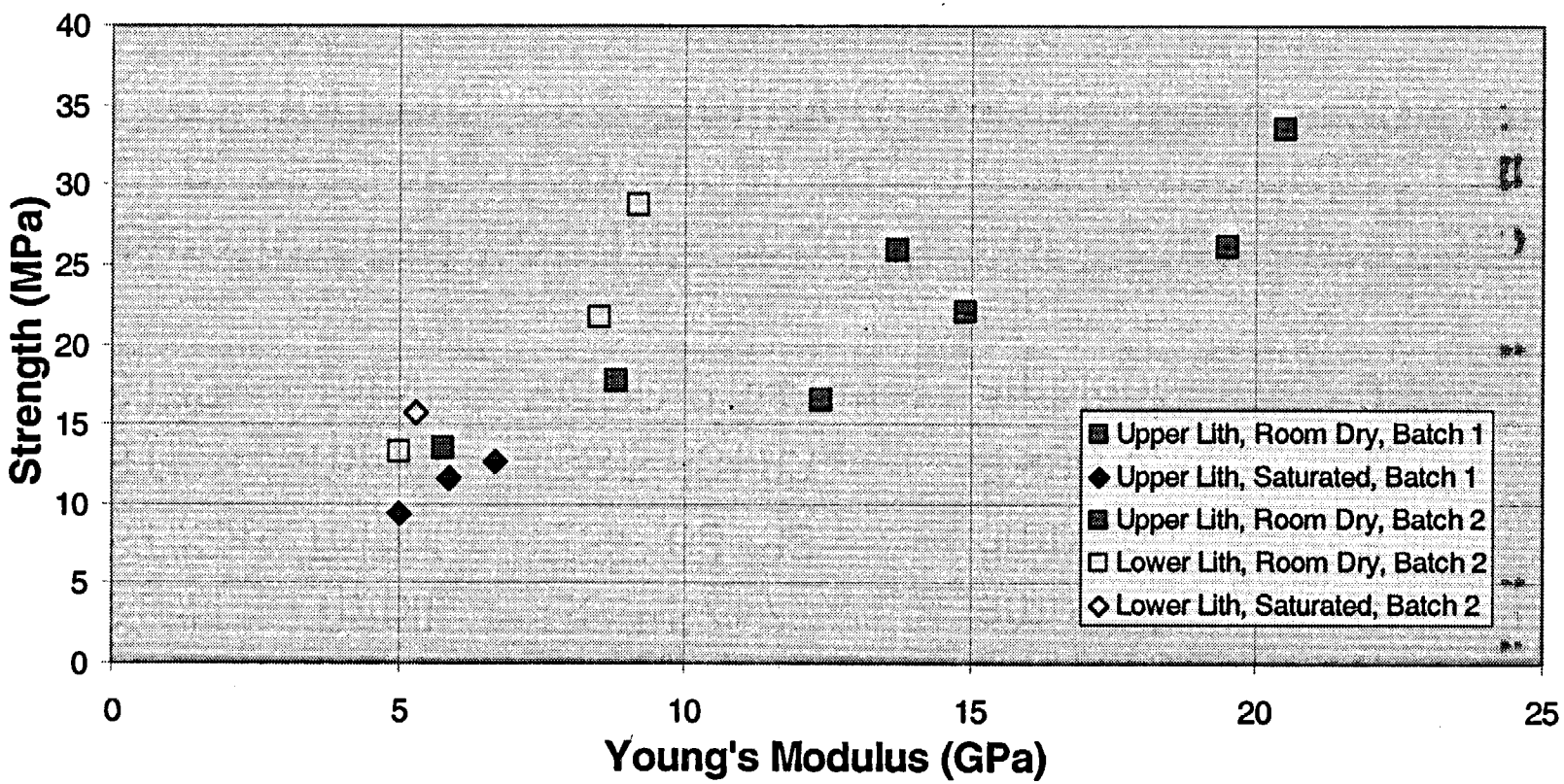
Pressurized Slot Test Results

Test	T-M unit	Location	Temperature	E (GPa)	ν
PST #1	Tptpll	ESF 57+77	ambient	0.5	0.2
PST#2	Tptpul	ESF 63+83	ambient	3.0	0.2
PST#2	Tptpul	ESF 63+83	T>80°C	1.5	0.2
PST#3	Tptpll	ECRB 21+25	ambient	0.7	0.3

- **The estimated Young's modulus of Tptpll and Tptpul is only a fraction of the value of Tptpmn modulus measured in the Thermal Test Facility (0.5~3.0 GPa vs. 20 GPa)**
- **It appears that the effects of lithophysae on mechanical properties of Tptpll are more significant than anticipated**
- **Results are being incorporated into drift degradation models**

Thermal-Mechanical Rock Properties Investigations
(Continued)

Laboratory Experiments on Large Samples of Topopah Spring Lithophysal Tuff at Room Temperature

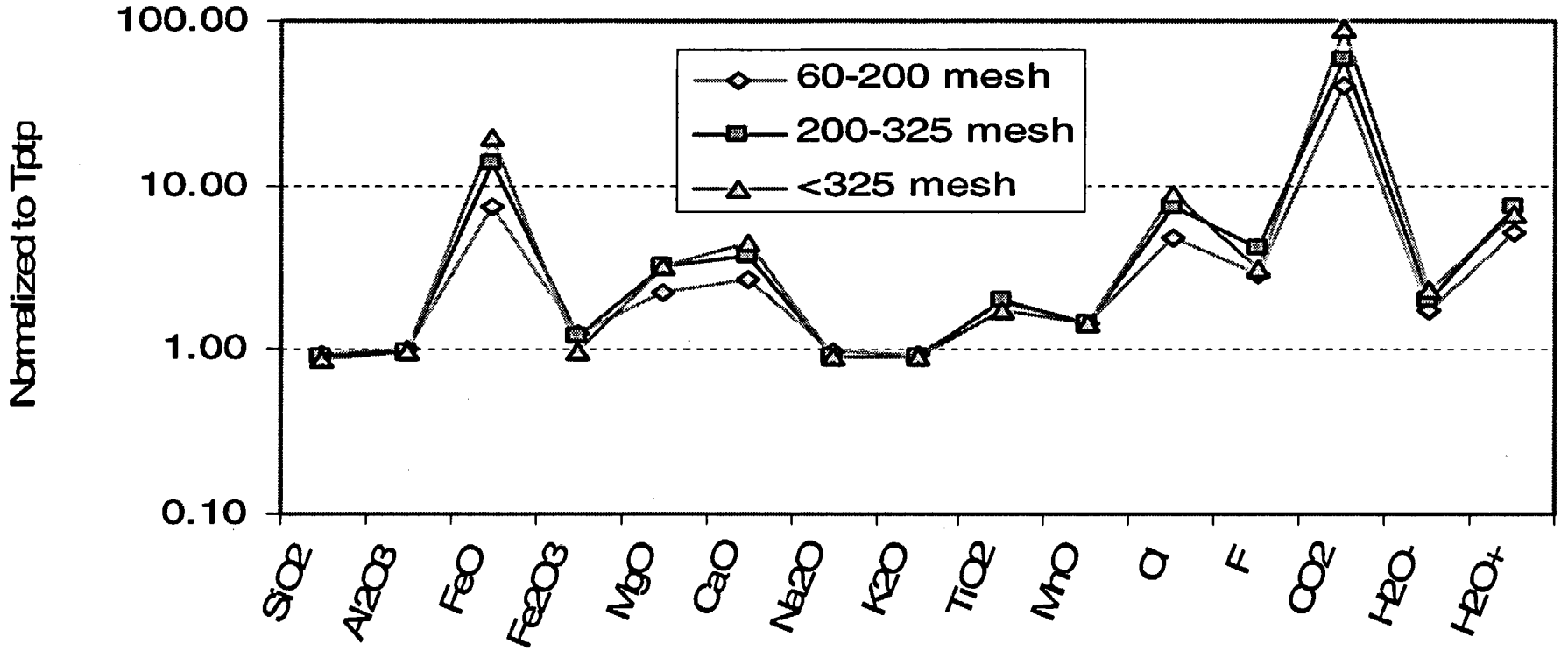


Dust Investigations
Chemistry of Dust in the Exploratory Studies Facility

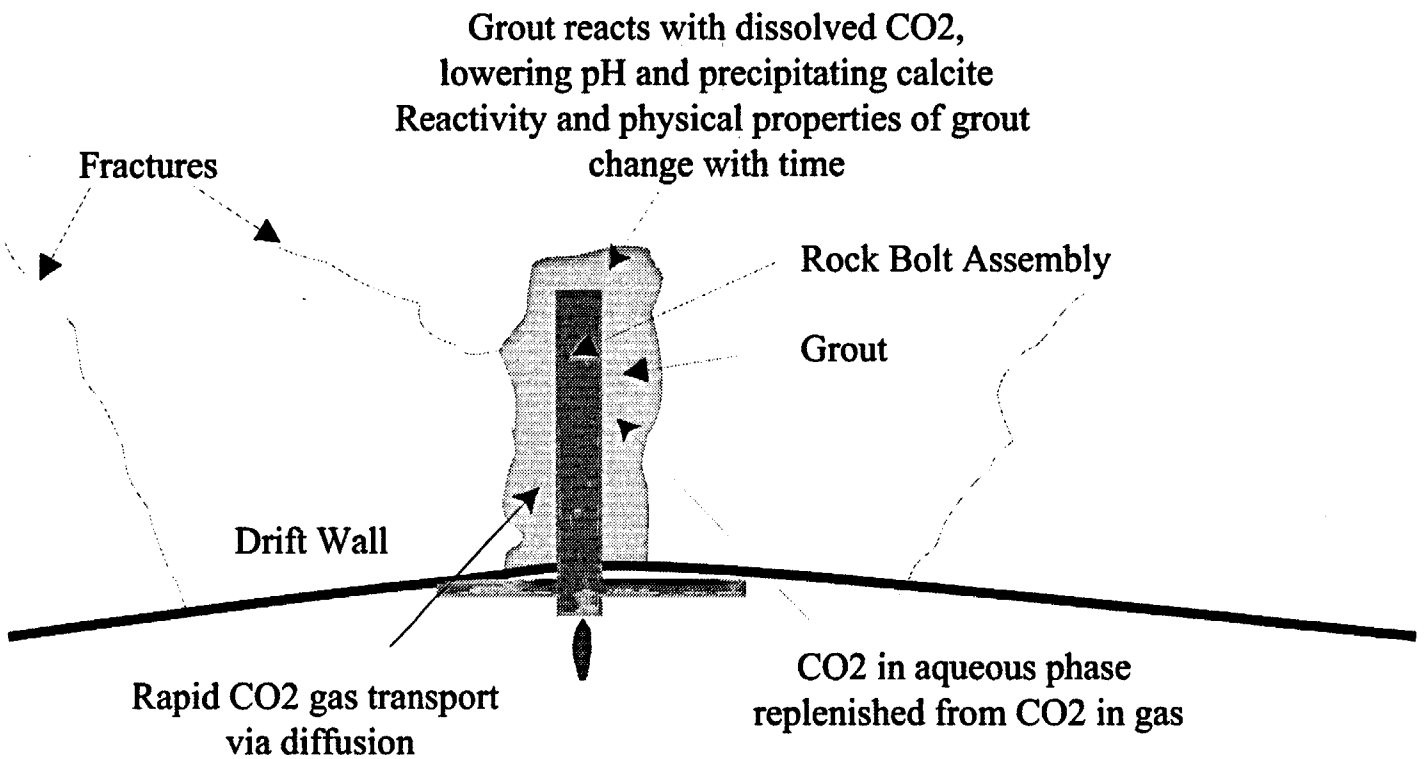
- **Why is dust chemistry important?**
  - Dust will accumulate on waste packages
  - Soluble fractions will dissolve in water dripping on canisters or deliquesce in variable relative humidity environments to form brine droplets or films
  - Potential effects on environment on waste package surface
- **What is the source of dust?**
  - Construction activities
    - Rock dust
    - Anthropogenic dust
  - Ambient atmospheric dust

Dust Investigations (Continued)

Chemistry of Dust in the Exploratory Studies Facility Comparison with Mean Rock Composition Shows Major Element and Oxide Enrichment in Dust



Reactive Transport Experiments Grout-Seepage Water Interaction



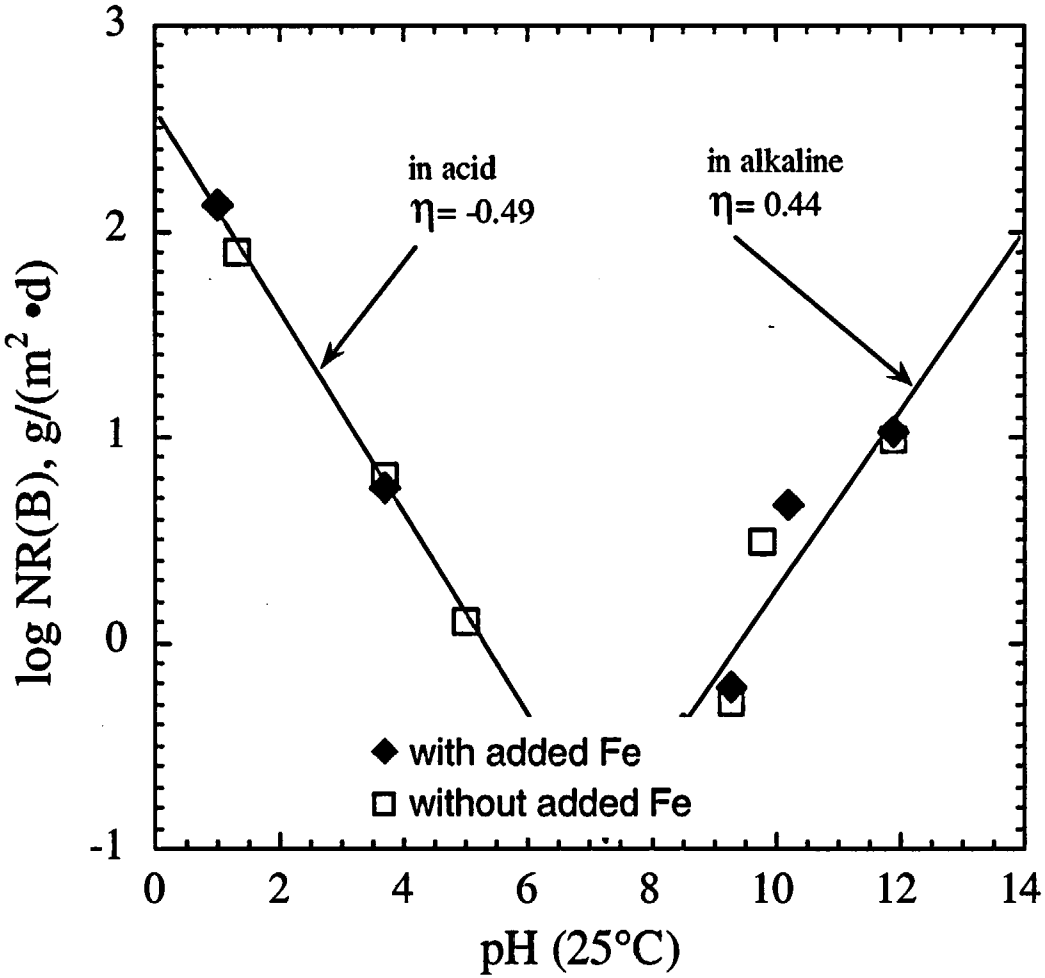
Reactive Transport Experiments (Continued)
Conclusions to Date

- Neutralization of hyperalkaline drip takes place on time scale of hours to days at atmospheric CO_2 concentrations
  - Time scale of 1 to 2 hours for a 1 mm drip
  - Presence of gas phase with CO_2 important in attenuating hyperalkaline plume
- Portlandite dissolves faster than Ca-silicate phases, thus controlling solution chemistry
- Steam-autoclaved grout with 5% silica fume still shows high pH (portlandite not all consumed)—high silica cement needed to reduce pH
- Carbonation via calcite precipitation reduces reactivity of grout
- These data are being used in the in-drift chemistry model

Engineered Barrier System Studies

Waste Form Investigations — Support Waste Form Degradation Models and Design

Tests Show No Effect of Iron Corrosion Products on Glass Dissolution Rate



Tests at 90°C show no effect of iron (added as $FeCl_3$, FeOOH, Fe_3O_4, or Fe_2O_3) on glass dissolution rate. (addresses KTI issue)

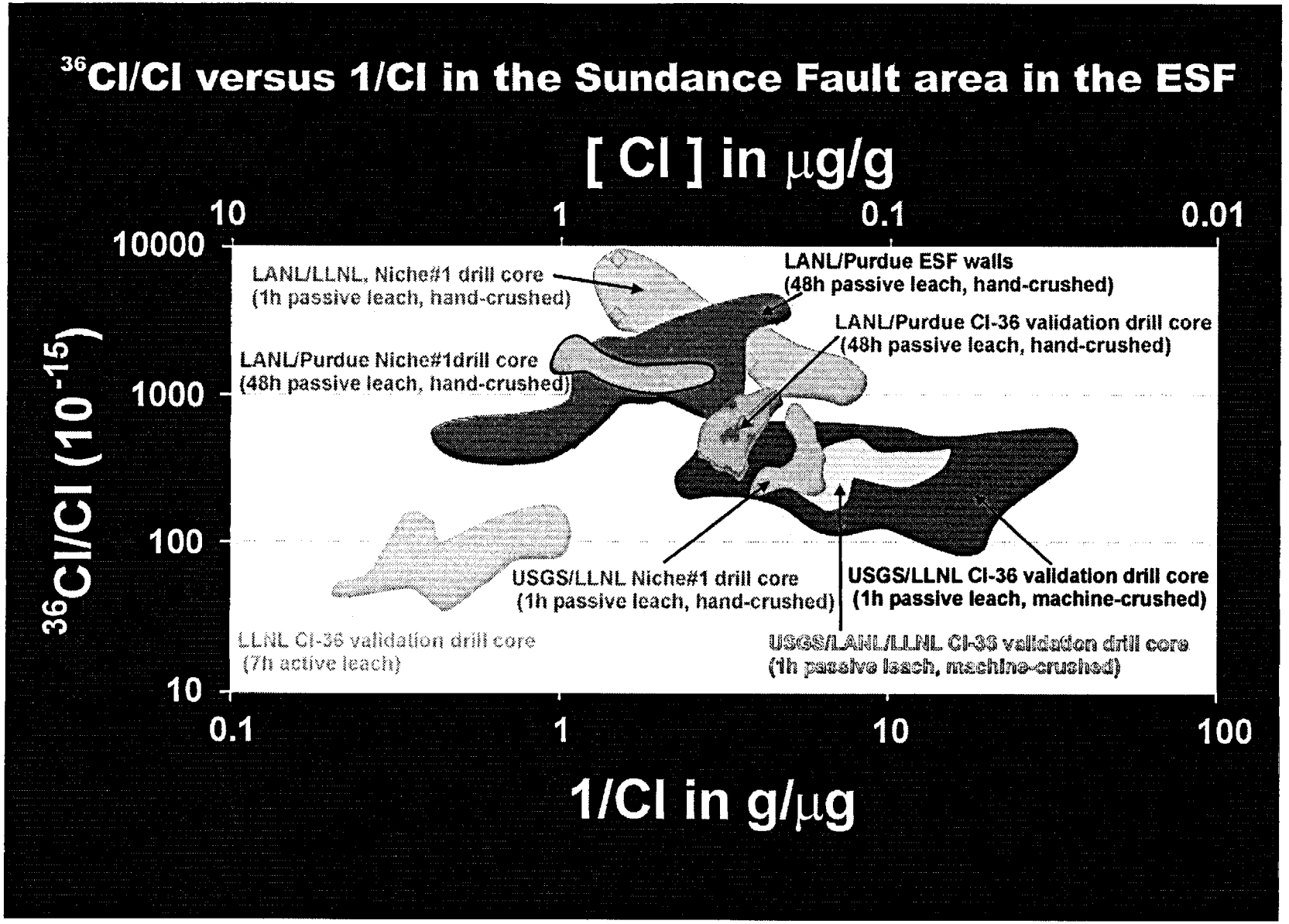
Tests provide measure of pH-dependence (η) for glass degradation model at 90°C.

Summary

- Ongoing data collection and testing in ESF, Cross Drift, and laboratories continue to address uncertainties and provide additional confidence in natural and engineered systems analyses and models and design in support of License Application

Backup

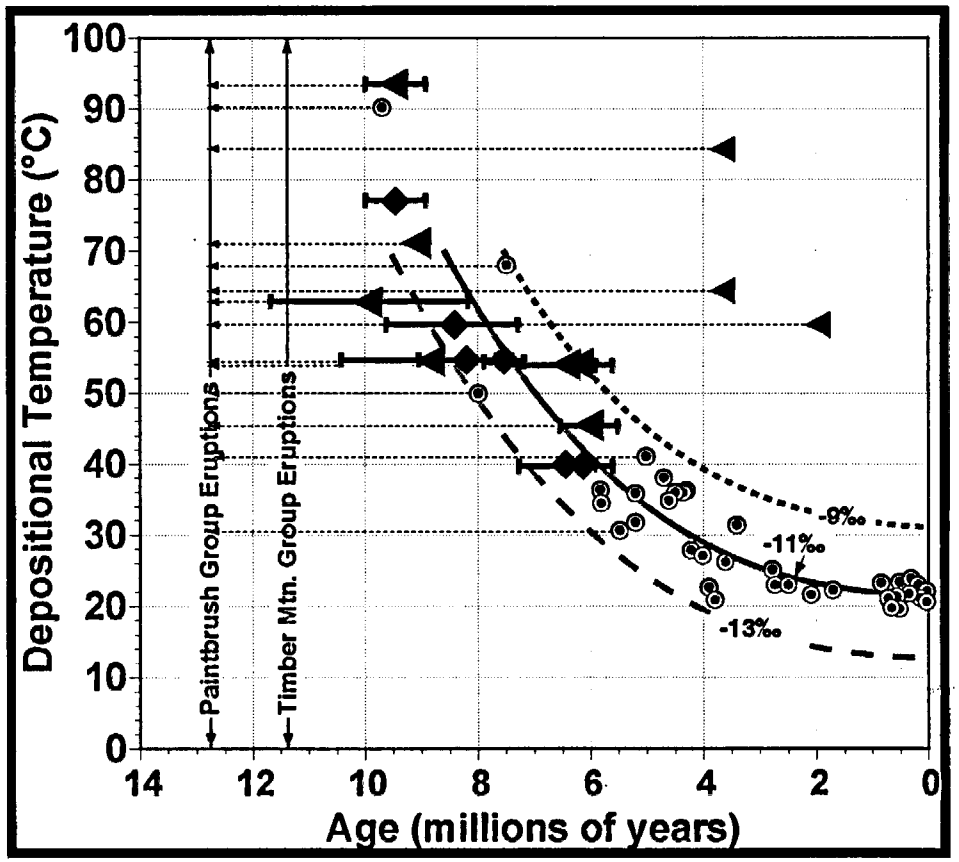
Comparison of Previous Los Alamos National Laboratory and Cl-36 Validation Project Data



PRELIMINARY

Temperature vs. Time in the Unsaturated Zone

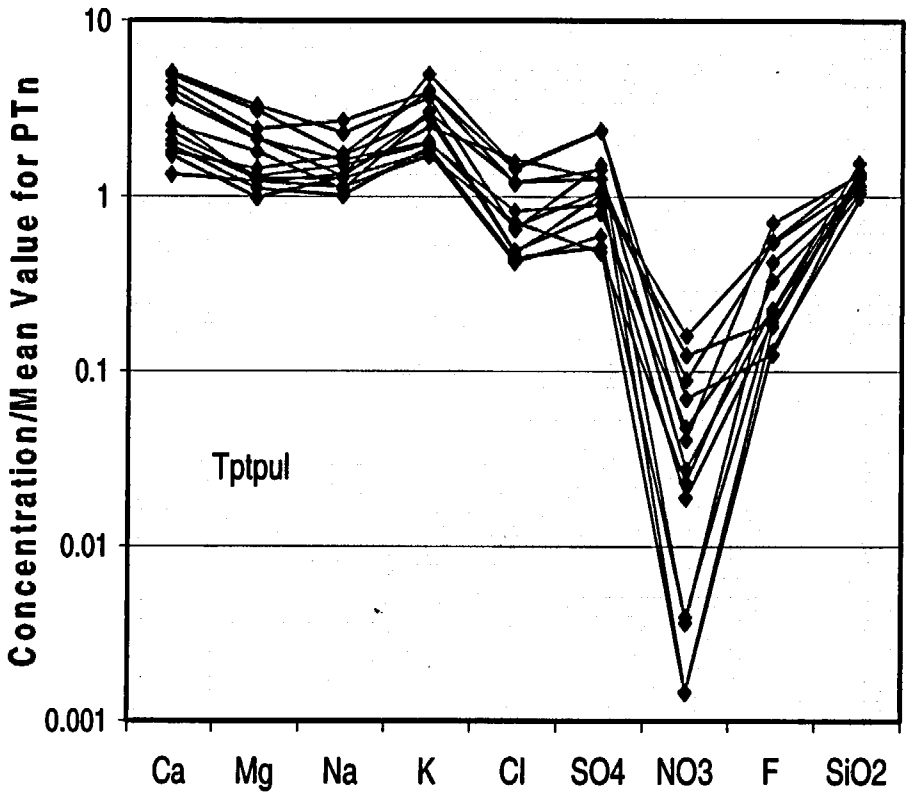
- Age of calcite deposition can be constrained by associated opal or chalcedony U-Pb or U-series ages
- Dated silica overlying calcite provides a minimum age; true calcite age falls along the dashed lines and may be substantially older
- Temperatures can also be calculated from calcite delta ^{18}O values, assuming a delta ^{18}O for the depositing water of –11‰ (shown as circled dots)
- Curves shown are best-fit regressions to the calcite delta ^{18}O temperatures for waters having a delta ^{18}O value of -13, -11, and -9‰, similar to present-day meteoric water, and demonstrating



- The gradual cooling is consistent with heat provided by the formation and cooling of the batholith-scale upper crustal magma body that produced the 15 to 10 m.y.-old volcanic tuffs and alteration of the tuffs below the water table 11 to 9 Ma

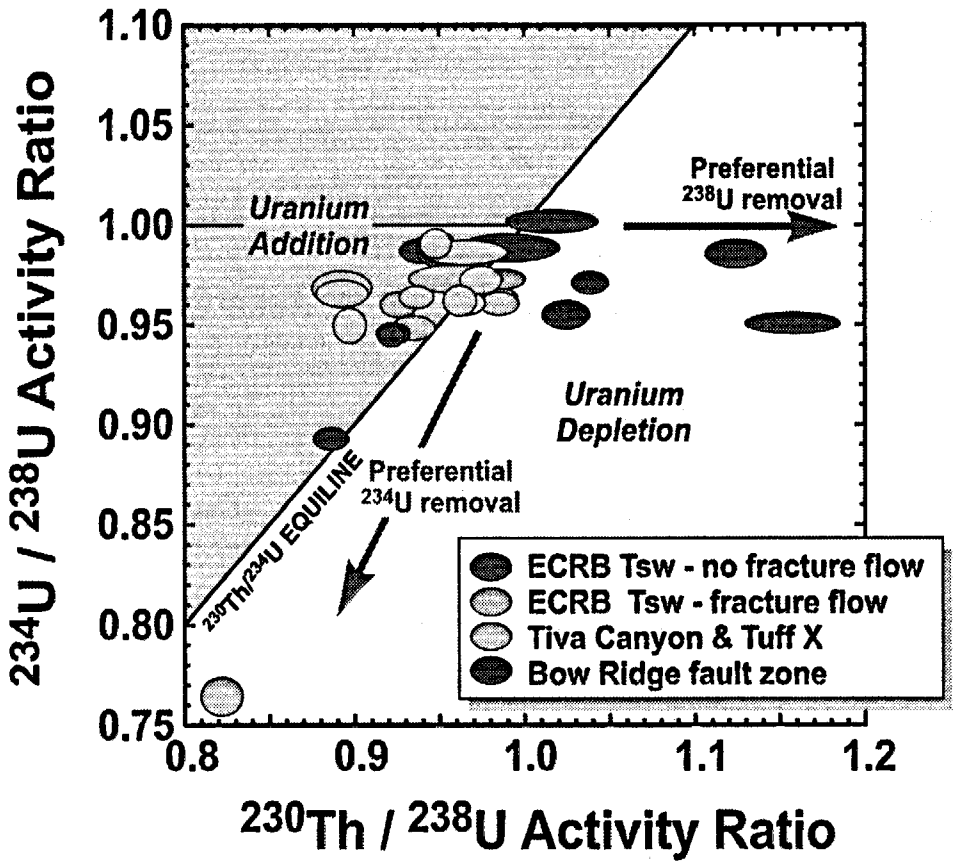
Geochemistry of Pore Water

- Dissolved-ion concentrations in pore water change systematically from PTn into TSw
- Decrease in NO_3^{-1} suggests microbial denitrification
- Microbial activity also suggested by presence of organic acids in pore water
- SiO_2 at saturation—no change

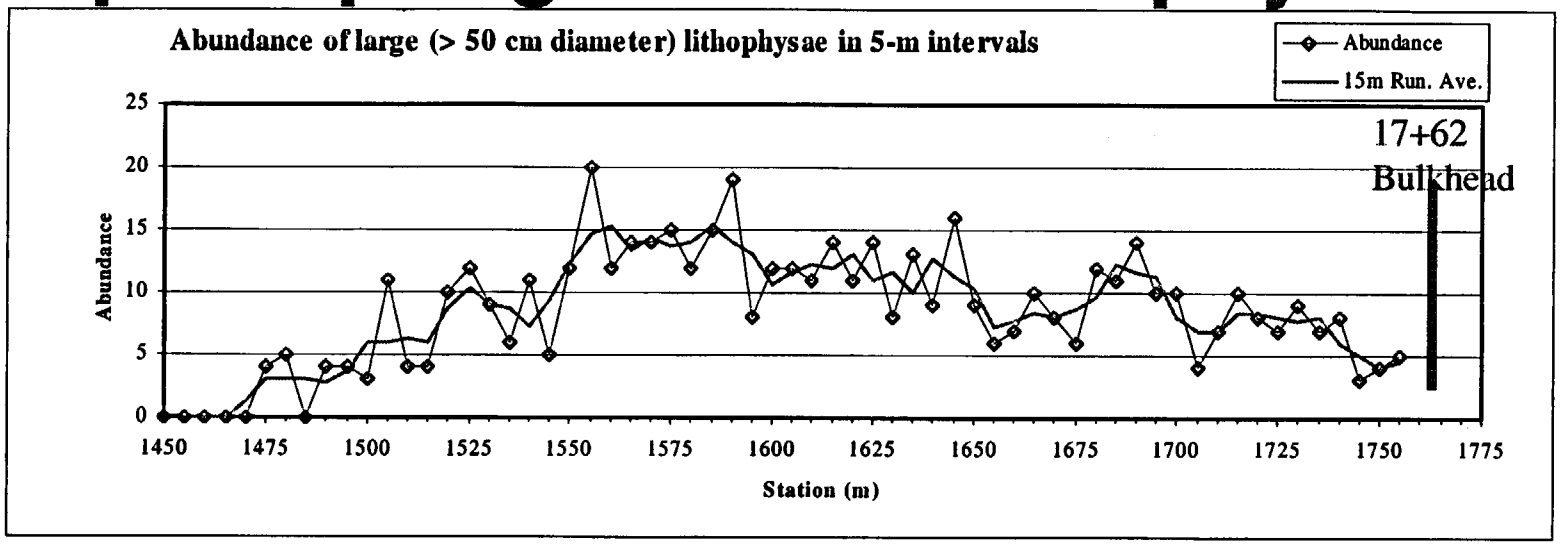


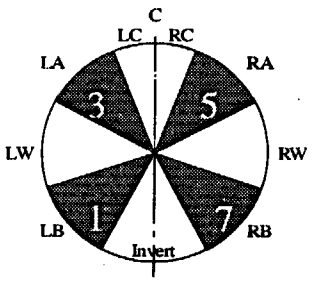
U-Series Delineation of Flow Paths

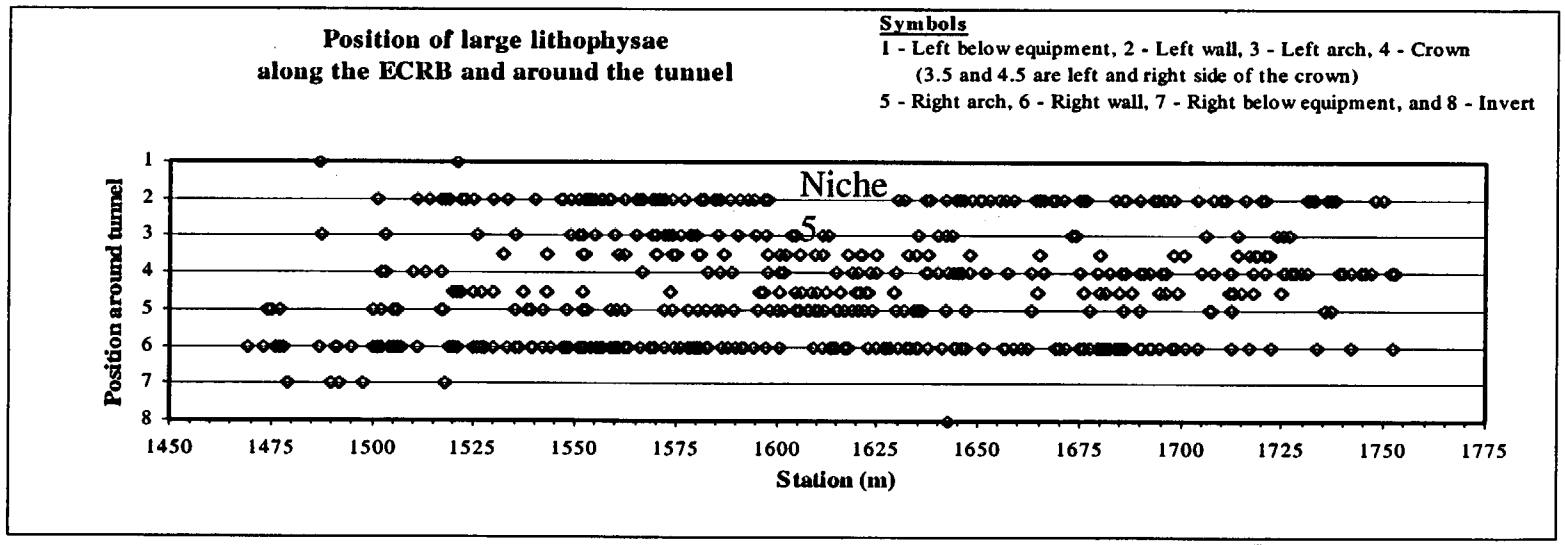
- **Recent results showed method applicability:**
  - Greatest disequilibrium observed within Bow Ridge fault zone (zone of focused flow)
  - Least disequilibrium observed in TSw samples from repository horizon
  - Intermediate values reflect variable, but low, amounts of water/rock interaction



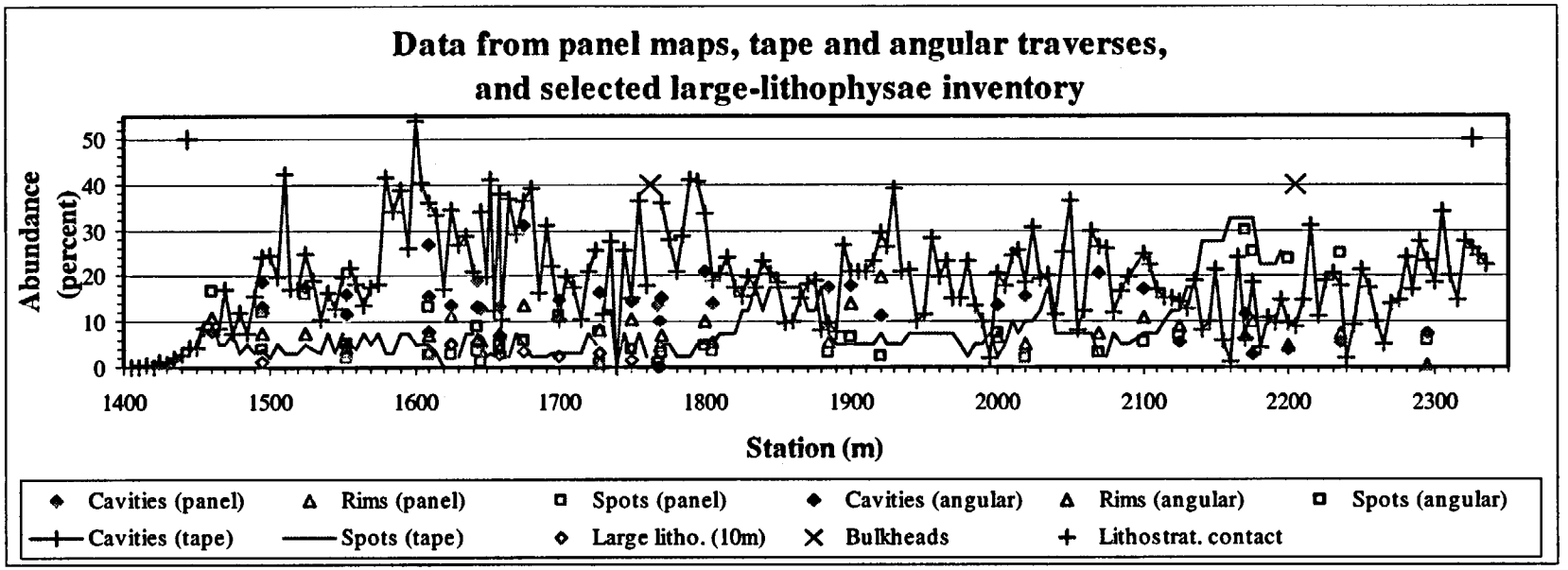
Large Lithophysal Inventory in the Topopah Springs Lower Lithophysal

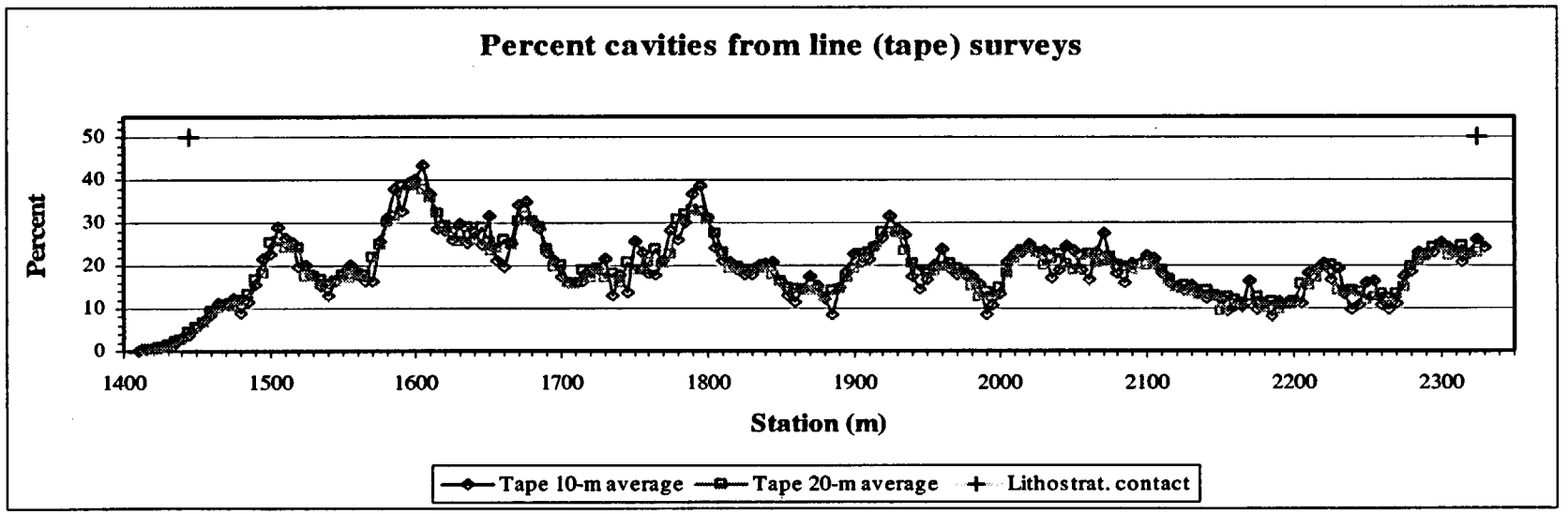






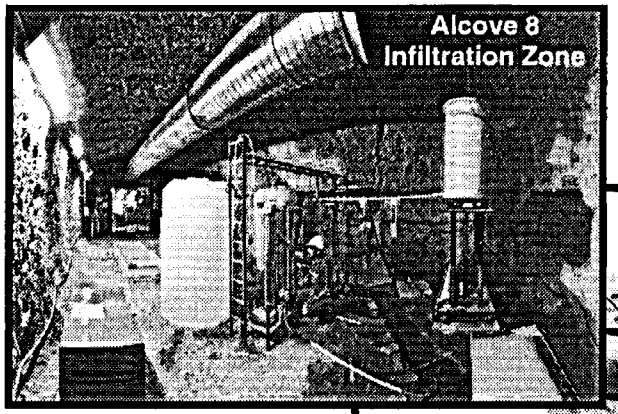
Lithophysal / Fracture Studies



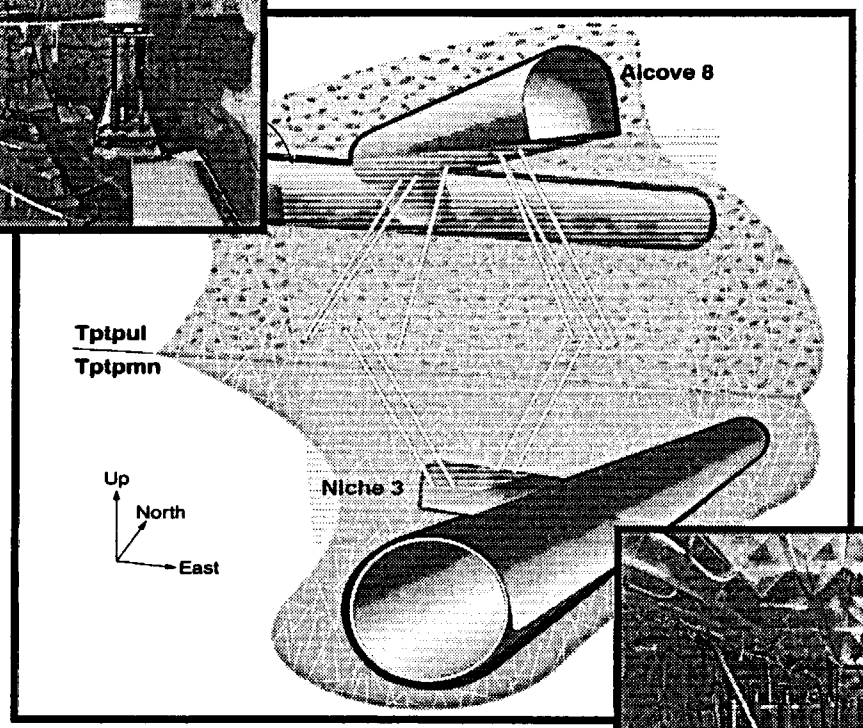


PRELIMINARY

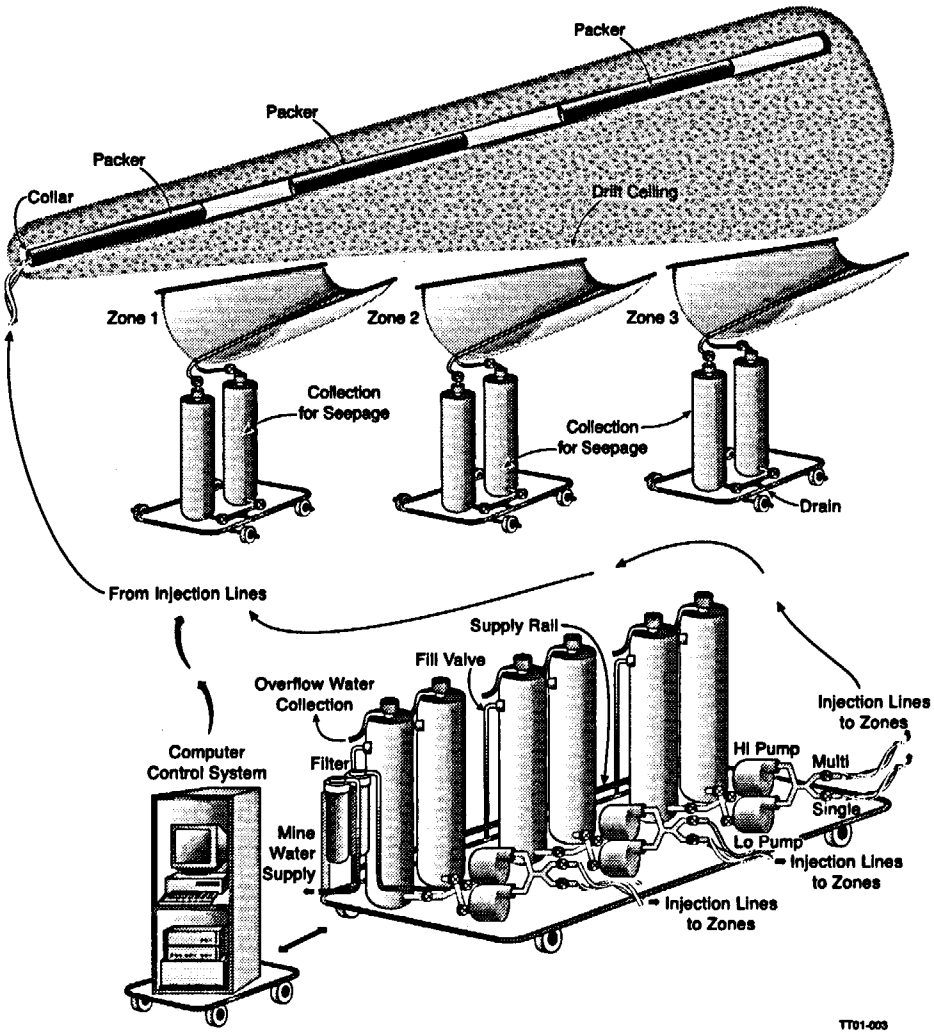
Alcove 8 / Niche 3 Fault Test

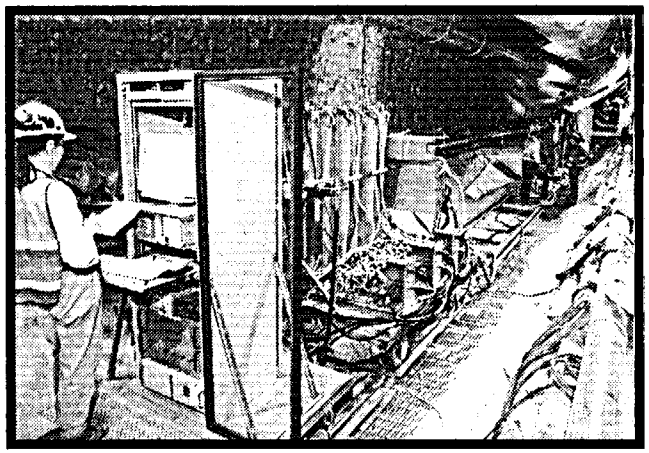


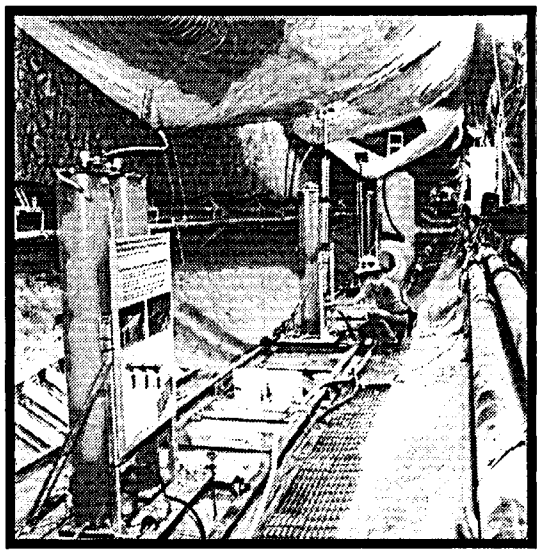
The Testbed



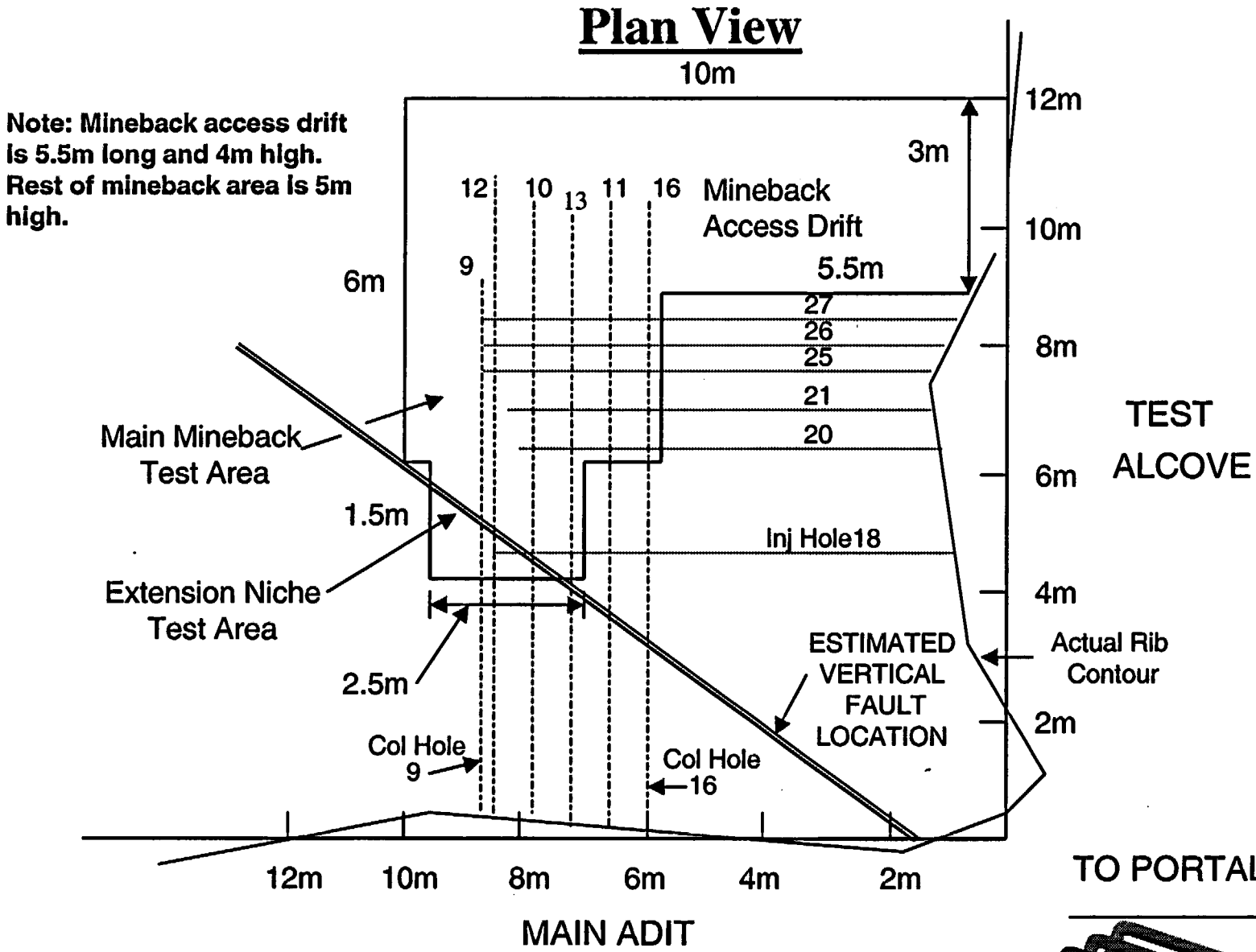
Systematic Hydrologic Testing
Equipment System: Schematics and Actual Field Deployment







Busted Butte Phase 2 Post-test Mineback Program

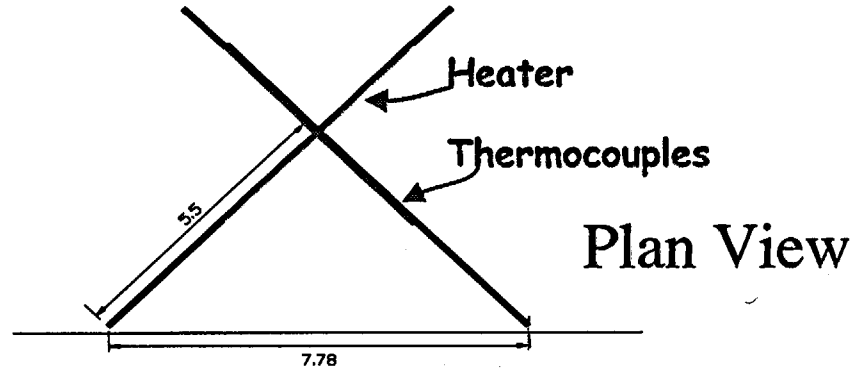


Thermal Properties Investigations Overview of Field Test Program in Tptpll

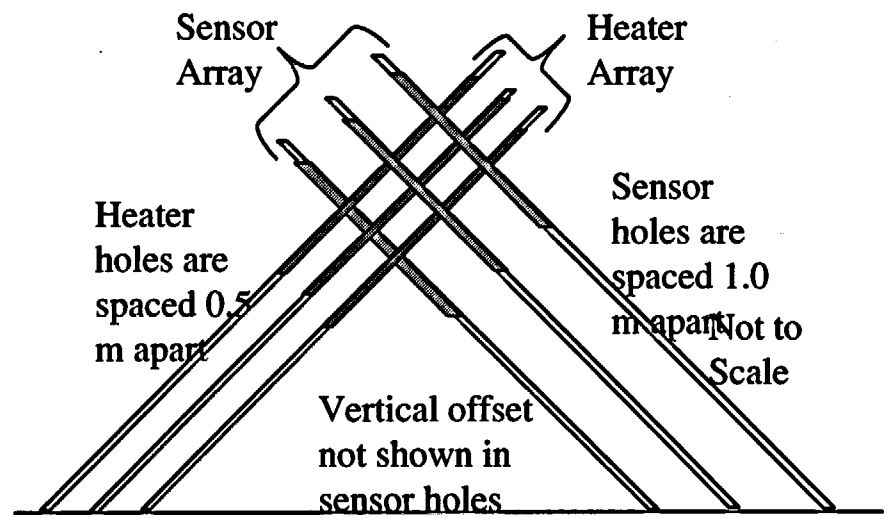
- **Test 1**: Single heater and single instrumentation borehole, run at temperatures below 100°C. ***Status: Completed.***

- **Test 2**: Three heaters and 3 instrumentation boreholes sample larger test volume, provide control of temperature distribution. Measure thermal properties at temperatures below 100°C (phase 1), and also after the test area has been dried out (phase 2). ***Status: At end of Stage 2.***

- **Test 3**: Sample 3rd location. Single heater with instrumentation holes both above and below it to measure effects of convection on temperature distribution. Measure thermal properties at temperatures below 100°C (phase 1), and also after the test area has been dried out (phase 2). ***Status: In cooling phase.***

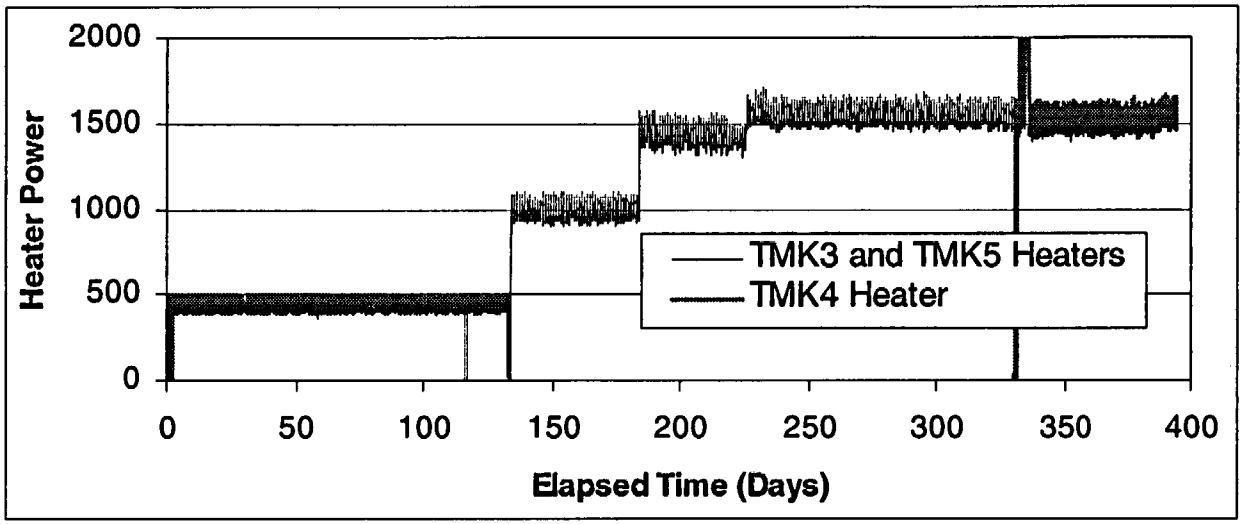


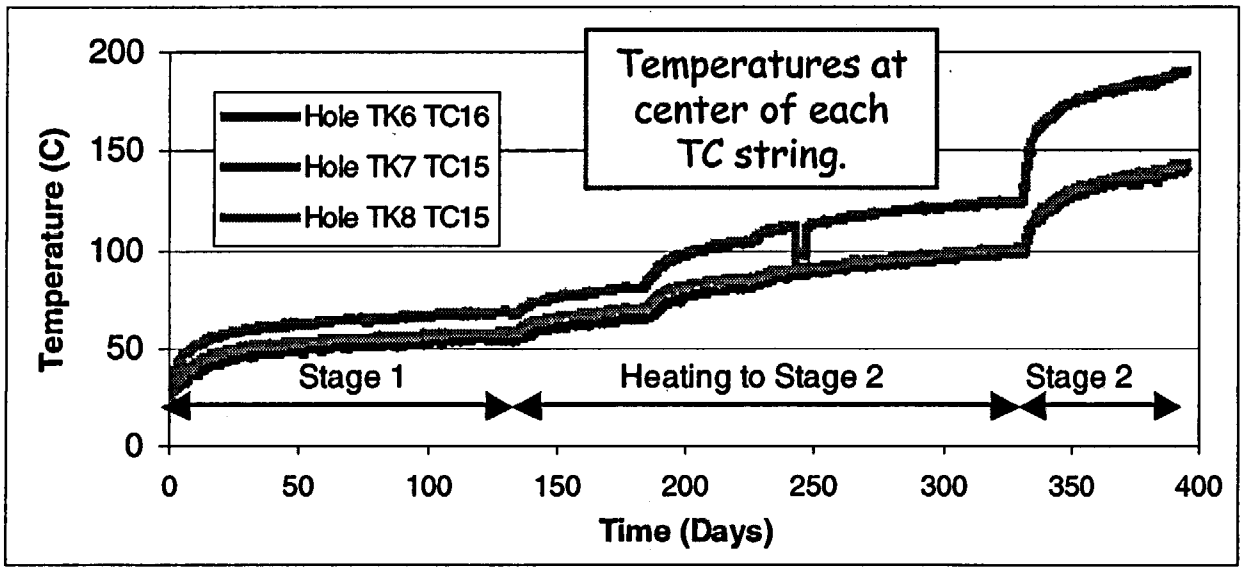
Geometry for Tests 1 and 3



Geometry for Test 2

Test 2: 6-Hole Test History
(Data through January 1, 2003)



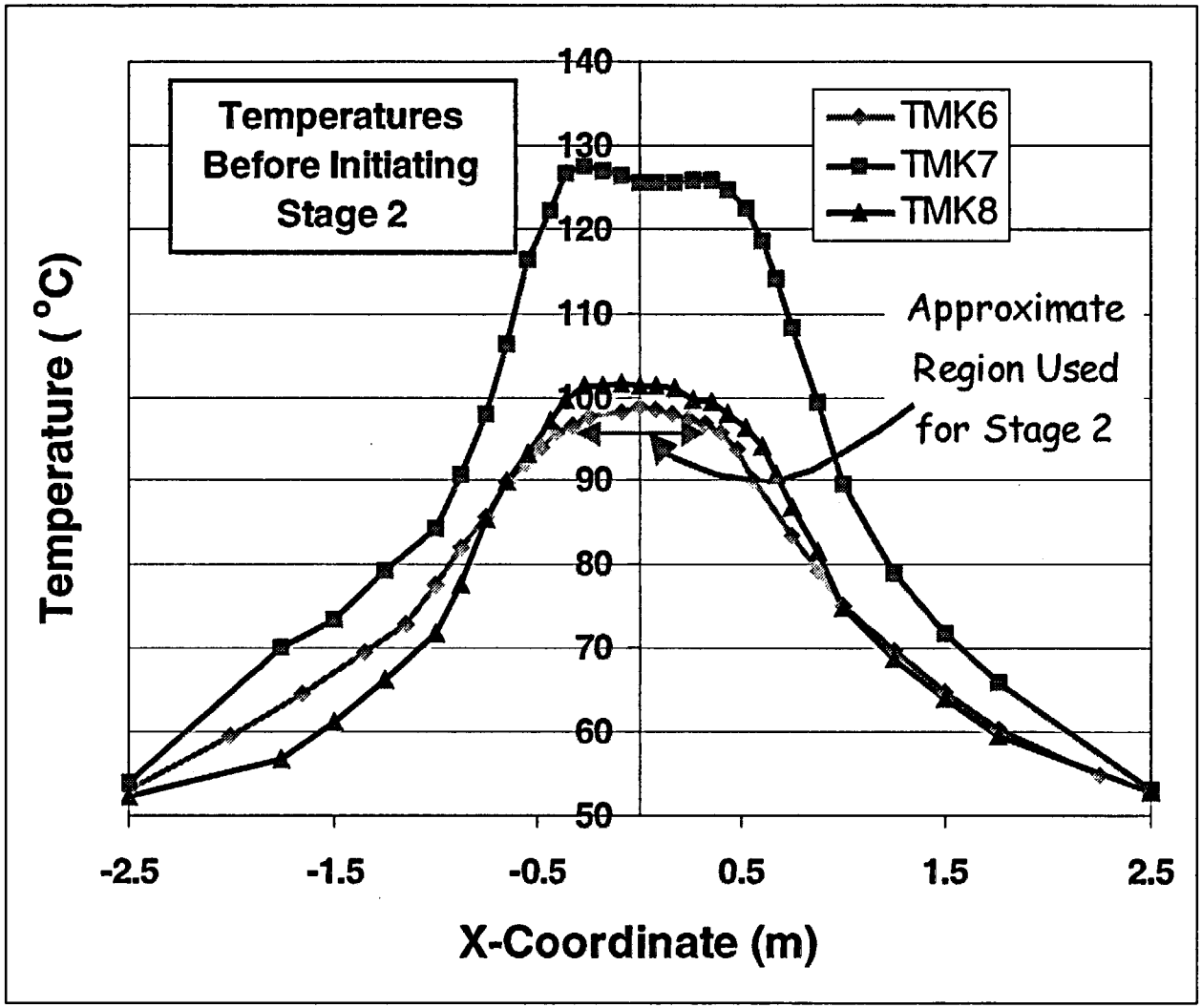


Stage 1: Plots show all heaters at 500W for Stage 1. Maximum temperatures (at center of each TC string) smoothly increase.

Heating to Stage 2: Center heater (TMK4) was shut down on Day 133. Outer heater powers were then stepped up, bringing central region to above boiling.

Stage 2: Central heater was reconnected on Day 330, initiating Stage 2.

Test 2
Temperature Profiles Before Initiation of Stage 2



Relatively flat temperature profiles in central region.

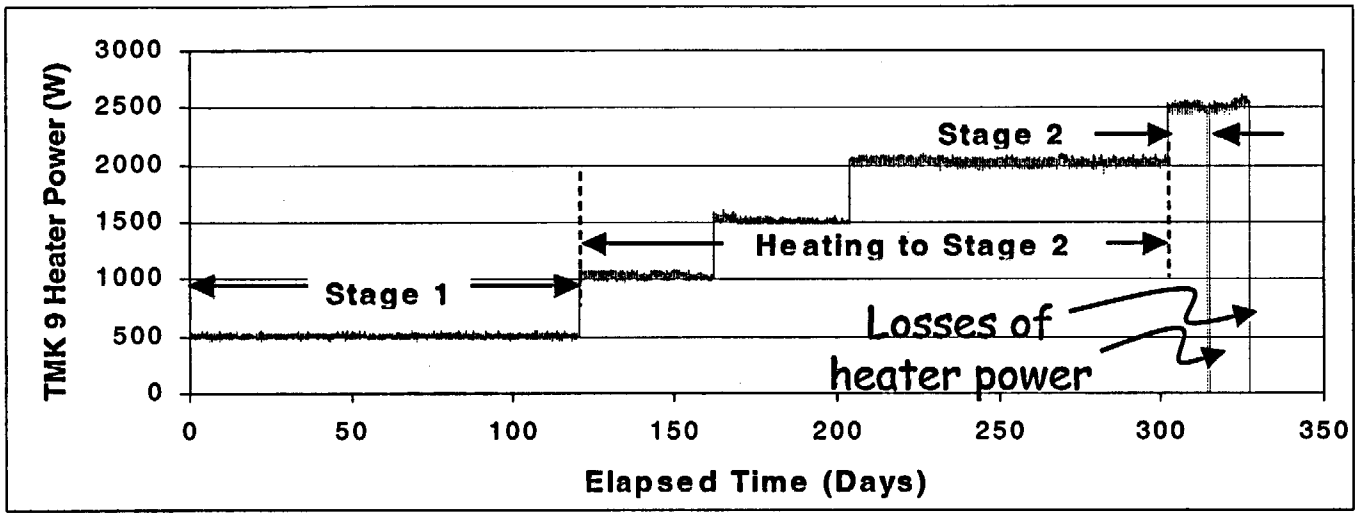
Heating rates below ~0.1C/day. (Not shown on this plot)

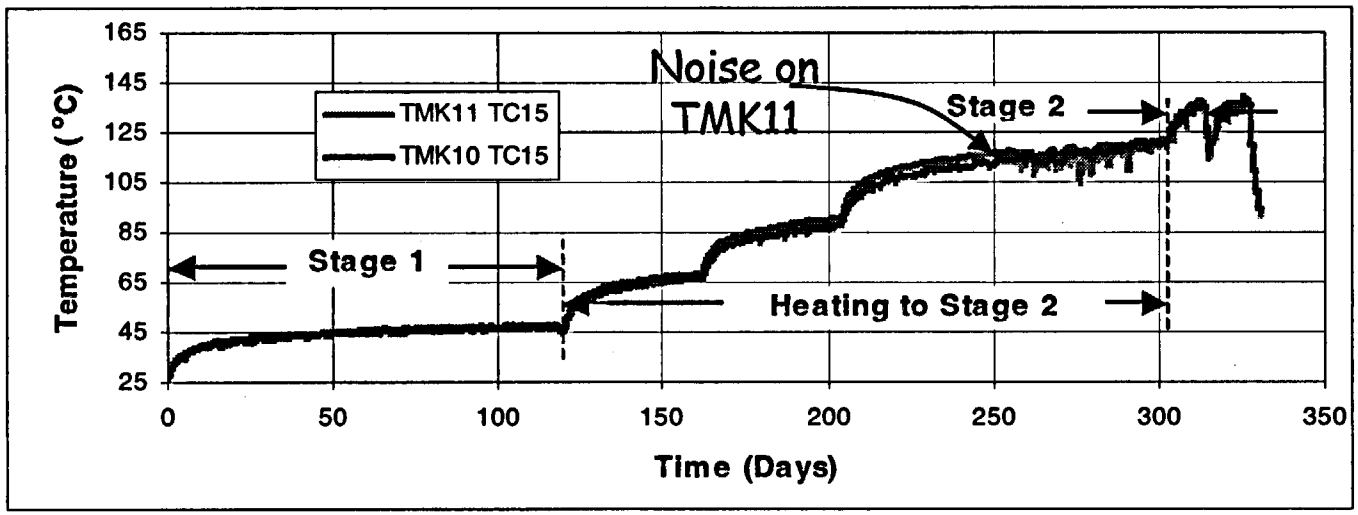
Thermal Properties for Test 2

Borehole Thermocouple String	Thermal Conductivity (W/mK)	Thermal Diffusivity m^2/s	Volumetric Heat Capacity (J/m^3K)
Stage 1: All Thermocouples			
TMK006	2.18	1.10×10^{-6}	1.97×10^{6}
TMK007	2.09	1.07×10^{-6}	1.95×10^{6}
TMK008	2.03	8.83×10^{-7}	2.30×10^{6}
Stage 1: Central Thermocouples (In Dried-Out Region), NQ			
TMK006	2.09	8.28×10^{-7}	2.53×10^{6}
TMK007	2.10	1.18×10^{-6}	1.77×10^{6}
TMK008	2.10	1.19×10^{-6}	1.78×10^{6}
Stage 2: Central Thermocouples (In Dried-Out Region), NQ			
TMK006	1.59	7.37×10^{-7}	2.16×10^{6}
TMK007	1.66	7.86×10^{-7}	2.11×10^{6}
TMK008	1.63	6.71×10^{-7}	2.43×10^{6}

Test 3:

3-Hole Test (Data through January 1, 2003)





Stage 1: Heater at 500W. Maximum temperatures (at center of each TC string) smoothly increase.

Heating to Stage 2: Heater power stepped up, bringing central region to above boiling.

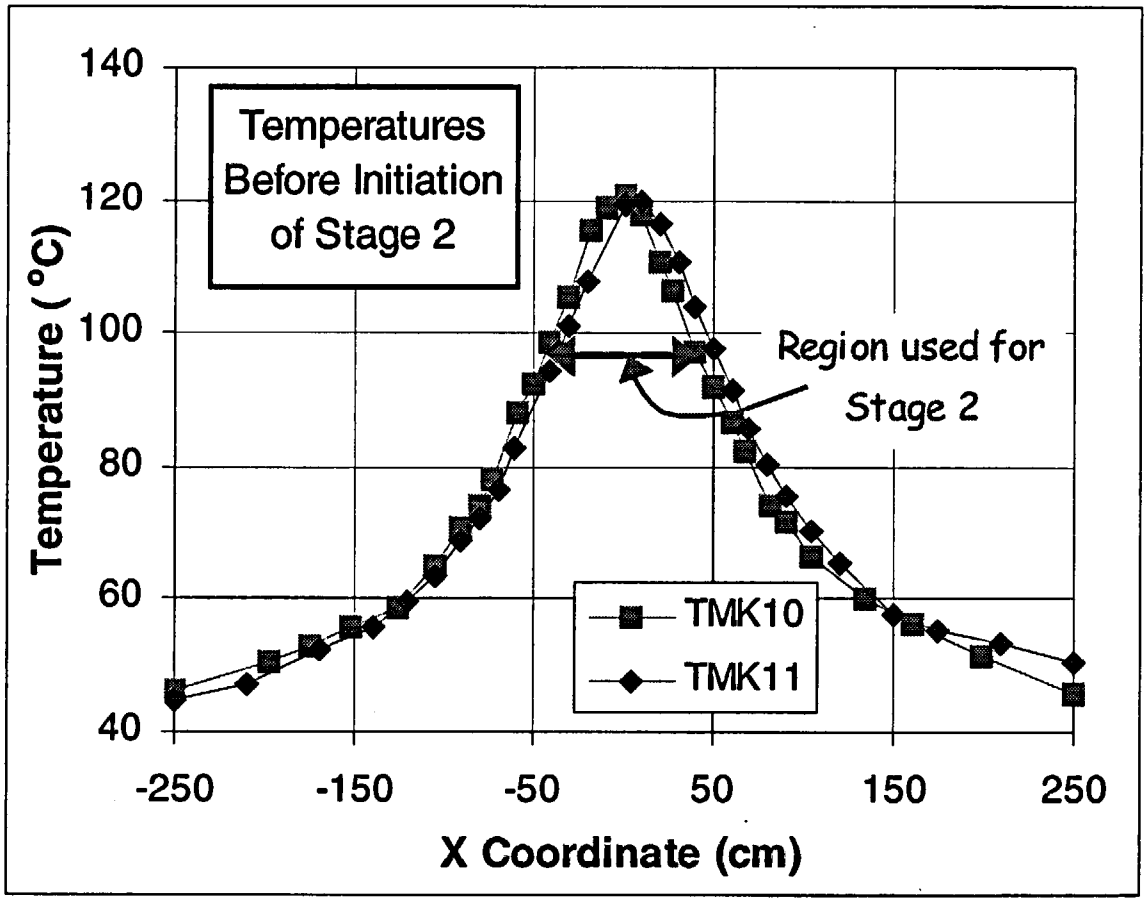
Stage 2: Heater power increased.

Test 3 (3-Hole Test) Temperature Data

Temperature profiles are the same above (TMK11) and below (TMK10) the heater. Implies impact of moisture convection on heat transport is not evident.

Central region of TC strings reached above boiling temperatures.

Heating rates of less than 0.5 °C/day before initiation of Stage 2 (Not shown on plot.)

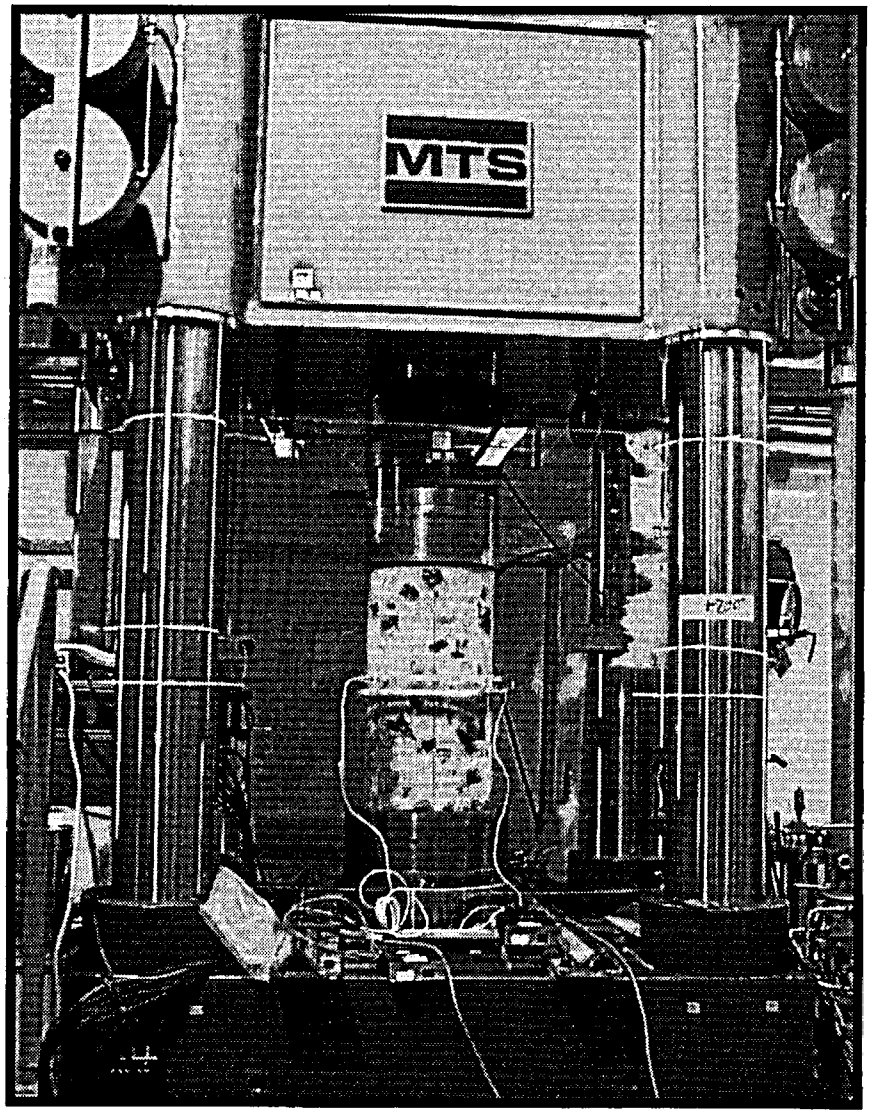


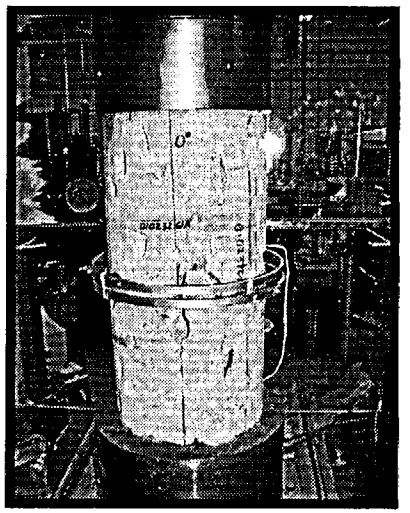
Thermal Properties for Test 3

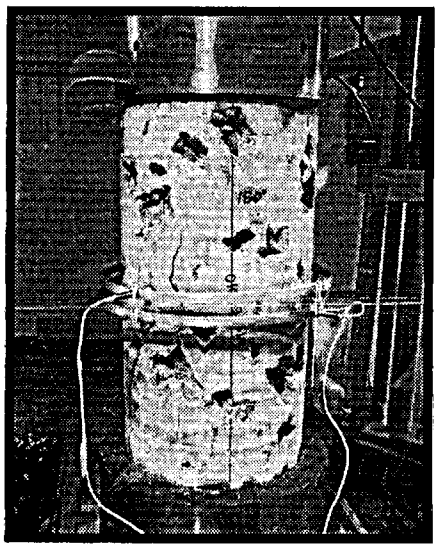
Borehole Thermocouple String	Thermal Conductivity (W/mK)	Thermal Diffusivity m^2/s	Volumetric Heat Capacity (J/m^3K)
Stage 1			
TMK10	1.73	8.92×10^{-7}	1.94×10^{6}
TMK11	1.76	8.75×10^{-7}	2.01×10^{6}
Stage 1: Central Thermocouples, NQ			
TMK10	1.78	1.13×10^{-6}	1.57×10^{6}
TMK11: Packer Failure?			
Stage 2: Central Thermocouples, NQ			
TMK10	1.47	1.14×10^{-6}	1.30×10^{6}
TMK11: Packer Failure?			

Thermal-Mechanical Rock Properties Investigations

Rock Properties Testing at Sandia National Laboratories

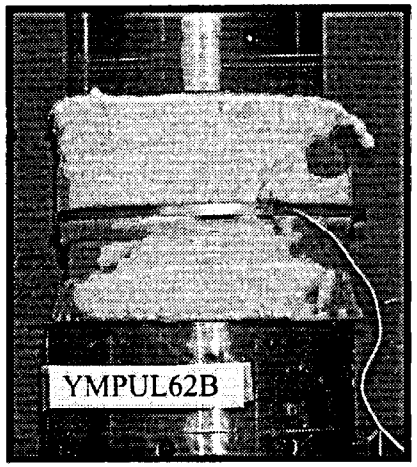




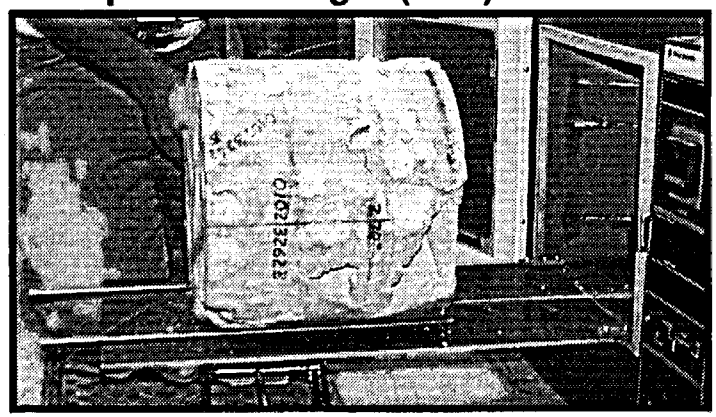


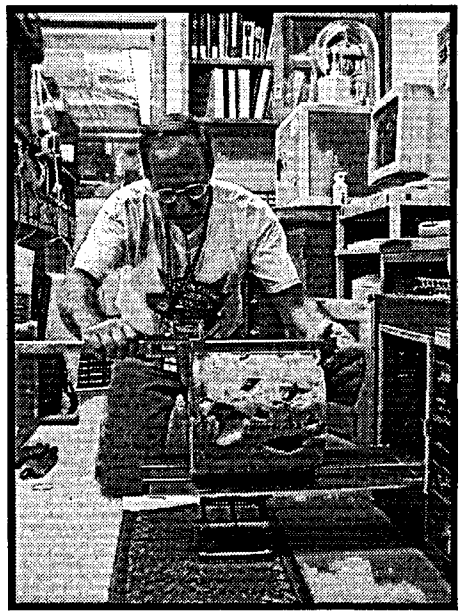
Uniaxial Compression Tests of the 11.5" diameter upper lithophysae samples (7-8/02)

Thermal-Mechanical Rock Properties Investigations
Rock Properties Testing at Sandia National Laboratories



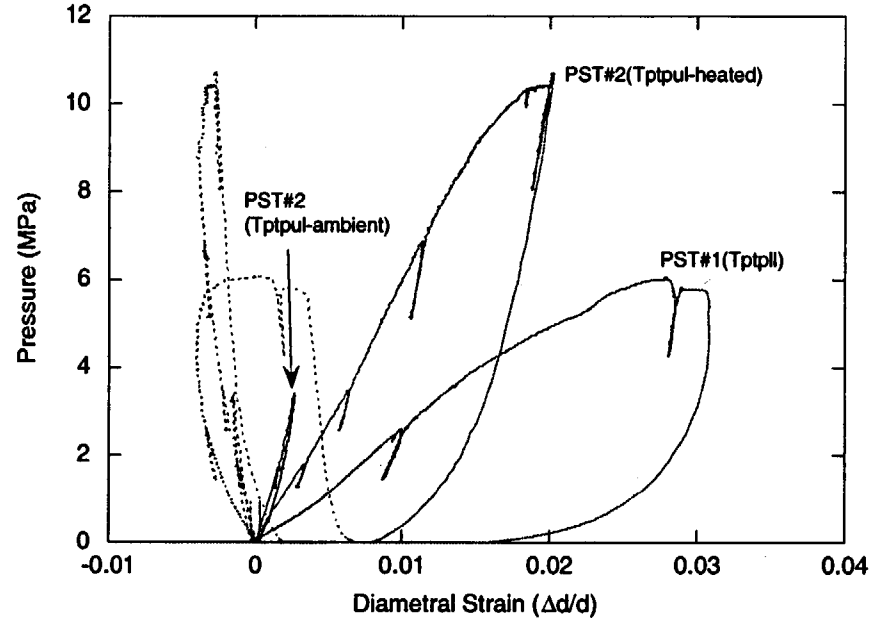
Uniaxial Compression Test on a Sample at 200 deg C (8/02)

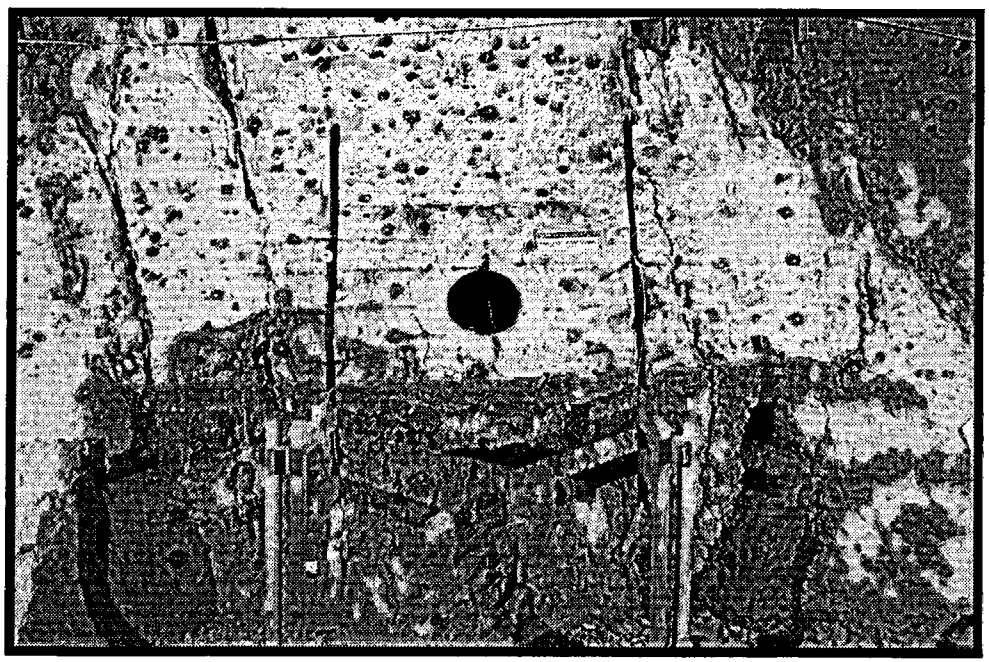


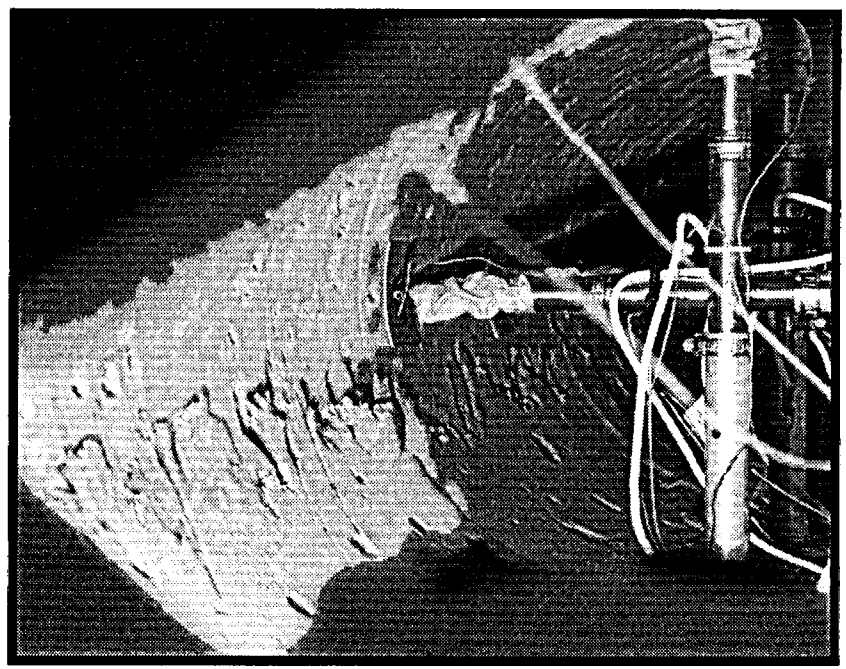


Thermal Expansion Test Sample (8/02)

Pressurized Slot Tests







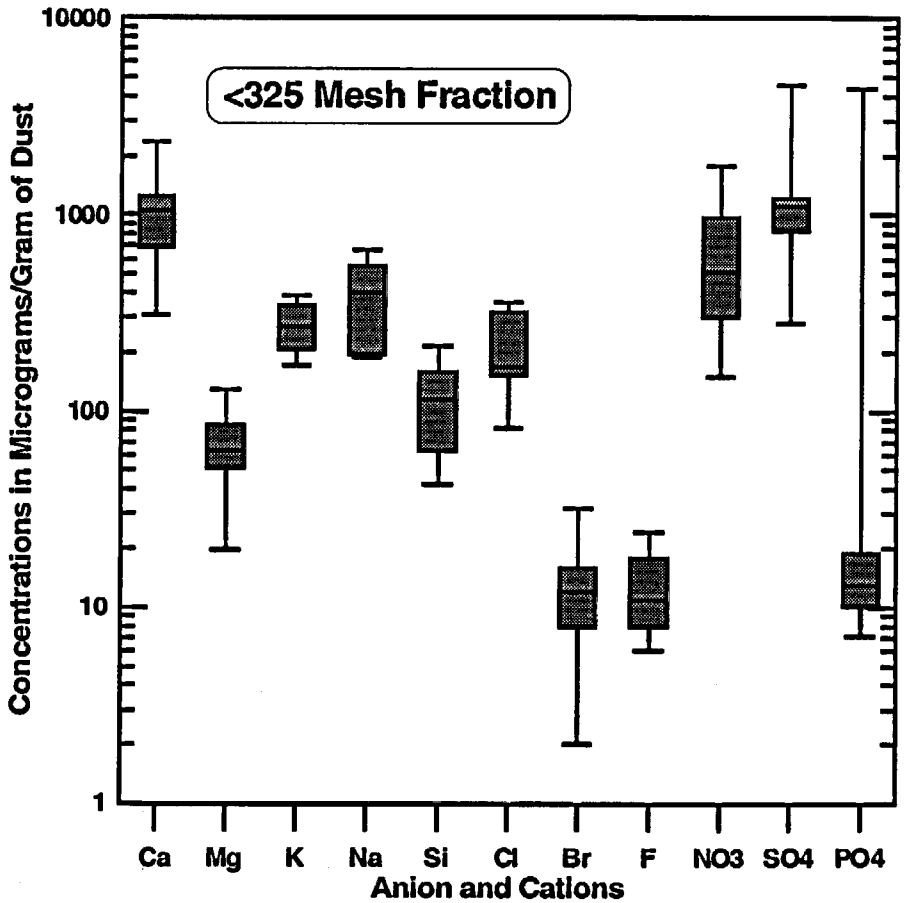
PRELIMINARY

Chemistry of Dust in the Exploratory Studies Facility

- **Analytical Approach**
  - Collect 200 to 400-gram samples from tunnel walls by vacuuming (mean accumulation of 0.017 grams/cm2)
  - Classify by size (~50% <325 mesh)
  - Chemical analyses (both total dissolution and water soluble components) of three size fractions (60-200 mesh, 200-325 mesh, <325 mesh)

Chemistry of Dust in the Exploratory Studies Facility
Water-Soluble Cations and Anions in Dust

- Plot shows medians, 2nd and 3rd quartiles (red boxes), and ranges (whiskers) of water-soluble anions and cations in dust
- Salts will form when the soluble fraction of dust dissolves and evaporates on canisters
- Cl/Br ratios indicate significant but variable amounts of salts derived from construction water



YUCCA MOUNTAIN PROJECT

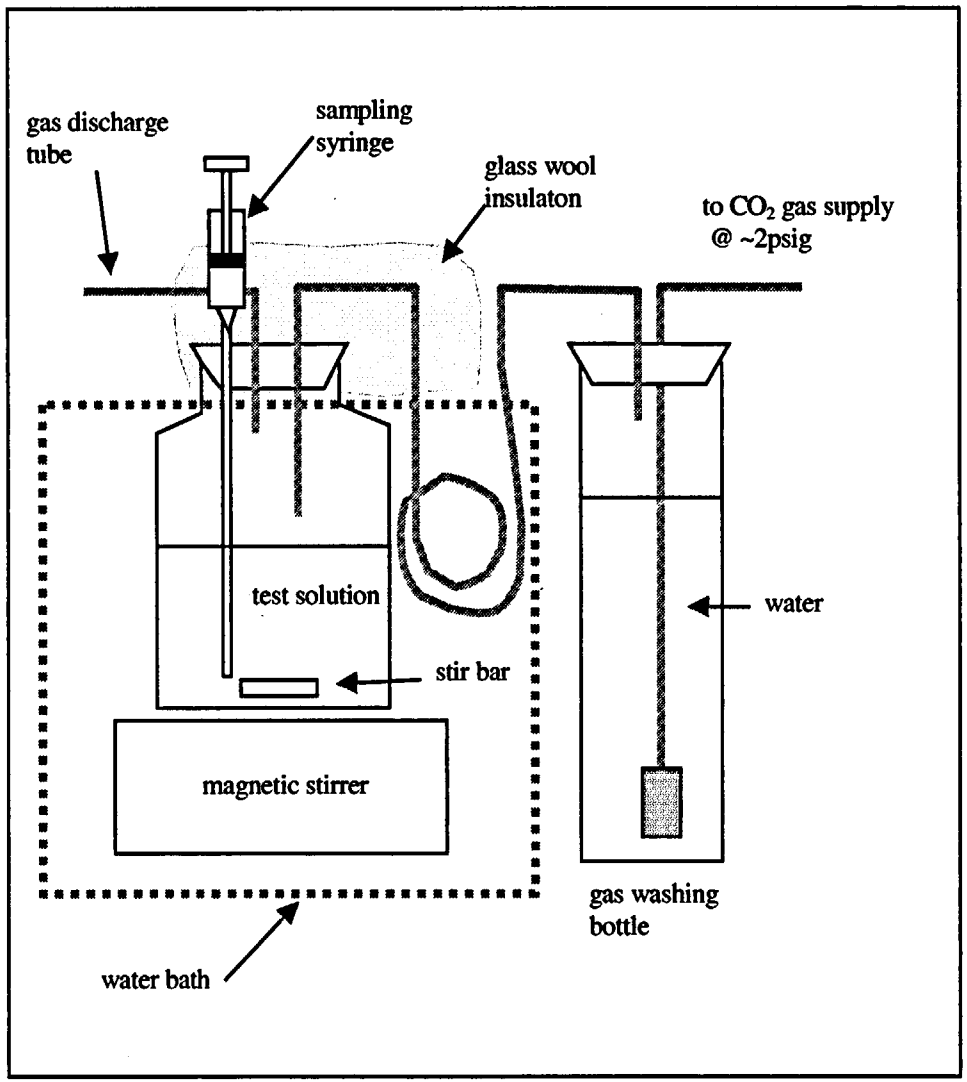
Chemistry of Dust in the Exploratory Studies Facility
Water-Soluble Anions and Cations
(in micrograms of ions or elements per gram of dust)

	60-200 mesh		200-325 mesh		-325 mesh	
	Mean	*SDOM*	Mean	*SDOM*	Mean	*SDOM*
Ca^{+2}	380	*87*	686	*123*	1079	*171*
Mg^{+2}	37	*6*	45	*5*	68	*10*
K^{+1}	231	*21*	237	*30*	273	*24*
Na^{+1}	215	*24*	311	*52*	402	*54*
Si^{+4}	114	*22*	105	*26*	117	*18*
Cl^{-1}	102	*9*	171	*31*	209	*29*
Br^{-1}	8	*2*	16	*5*	13	*3*
F^{-1}	13	*2*	10	*3*	13	*2*
NO_3^{-1}	184	*24*	358	*53*	645	*155*
SO_4^{-2}	402	*68*	732	*121*	984	*111*
PO_4^{-3}	28	*17*	12.1	*2.0*	13.0	*1.6*
Pb	0.0027	*0.0004*	0.0031	*0.0004*	0.0019	*0.0002*
As	0.051	*0.008*	0.056	*0.012*	0.073	*0.013*

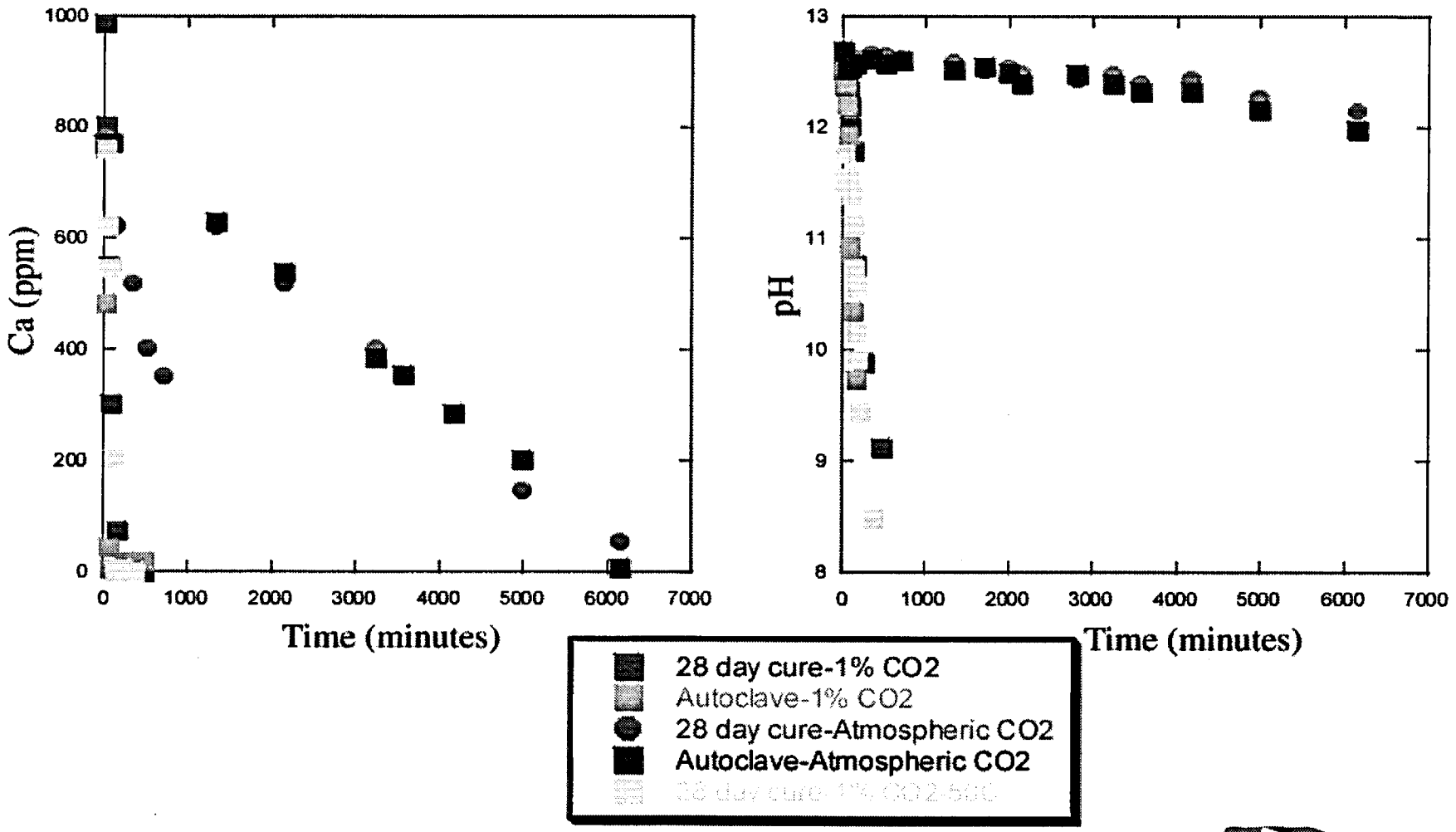
Reactive Transport Studies
Relevant Processes

- Interaction of water with cement to produce high pH values
  - Highest pH values due to interaction with portlandite
  - Lower but still high pH values due to interaction with various CSH phases (amorphous CSH, crystalline CSH, tobermorite, ettringite, etc)
- Carbonation (calcite precipitation) may lead to passivation of cement
  - Carbonation may take place either in the liquid phase (fully saturated conditions), or under unsaturated conditions

Reactive Transport Studies (Continued)
Carbonation of Hyperalkaline Fluid

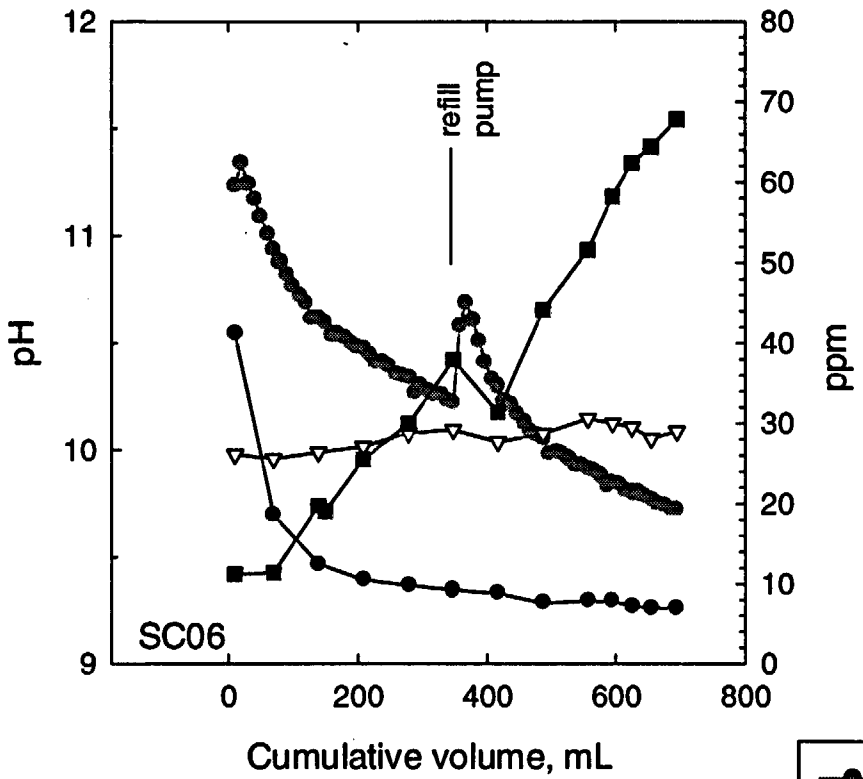


Reactive Transport Studies (Continued)
Carbonation of Hyperalkaline Fluid

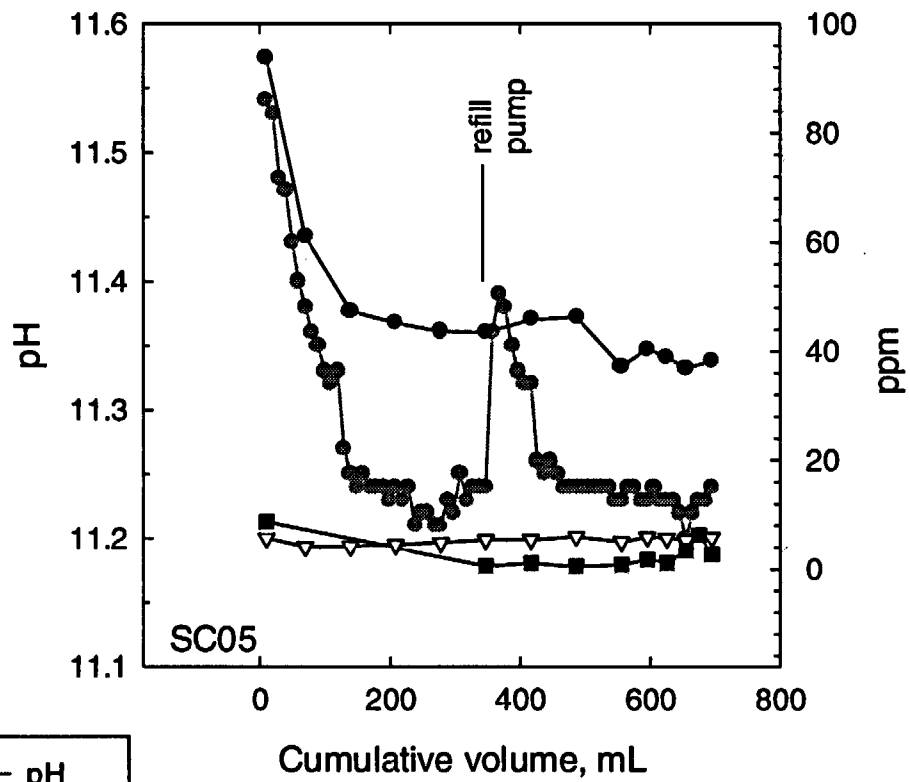


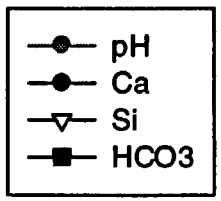
Reactive Transport Studies (Continued)
Flowthrough Stirred Cell Kinetic Results

Synthetic J-13



NaCl





Near-Field Environments and Corrosion

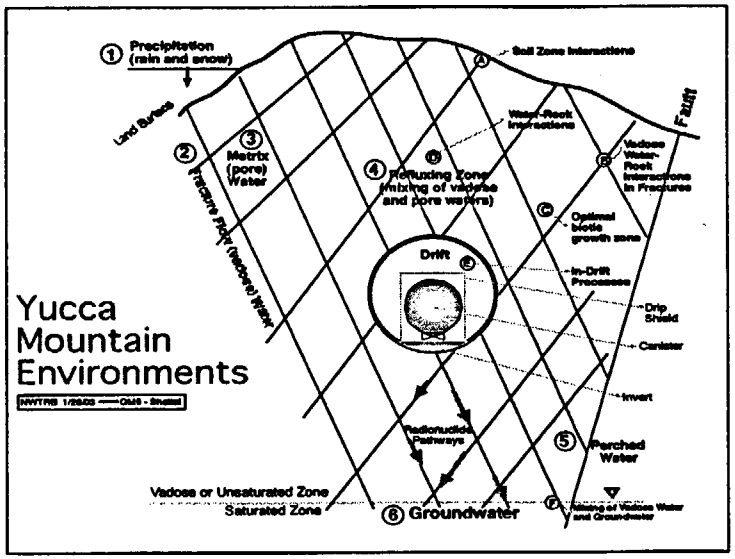
presented to the

U.S. Nuclear Waste Technical Review Board

by

Don L. Shettel, Ph.D.
(consultant to the State of Nevada)
Geosciences Management Institute, Inc.
1000 Nevada Way, Suite 106
Boulder City, NV 89005
702-294-3064; fax -3065
www.geomil.com
dls@geomil.com

28 January 2003



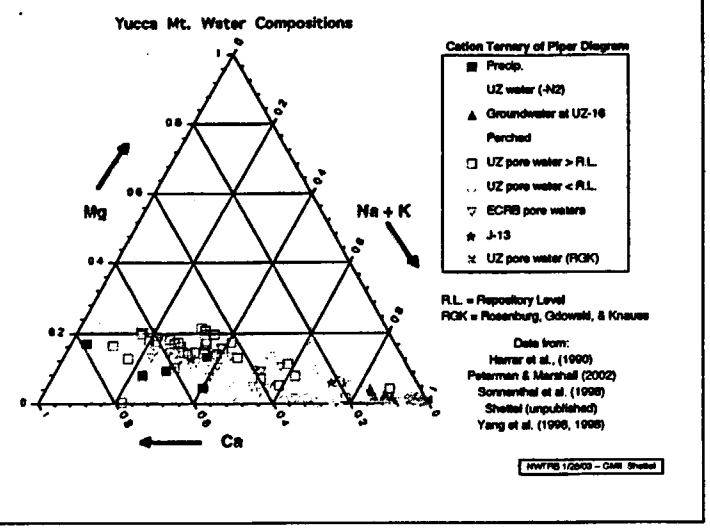
Yucca Mt. Water Types

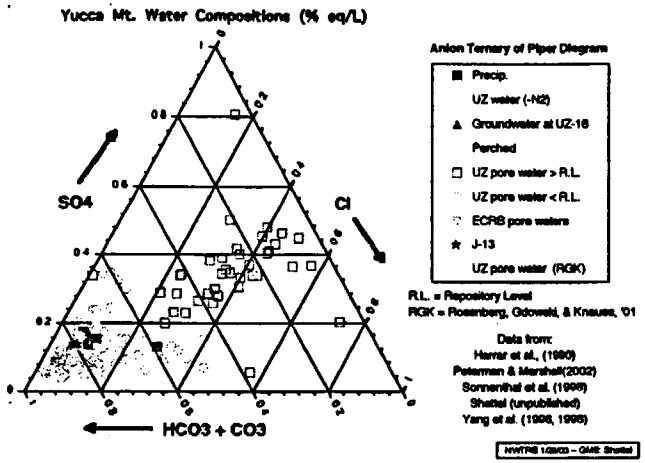
1. Precipitation (rain and snow)
   dilute: Ca - HCO_3
   (NO_3 similar to SO_4 and Cl)
2. Fracture flow (vadose) water
   3 shallow samples: Na - HCO_3
   Composition is generally unknown
3. Matrix (pore) water in Vadose Zone
   shallow (above Repository Level): Ca - SO_4 + Cl
   deep (below Repository Level): Na - HCO_3
4. Refluxing Zone
   Heated mixtures can evolve
   Mixtures of most types (except GW & perched)
   (from concentrated solutions to dilute condensates)

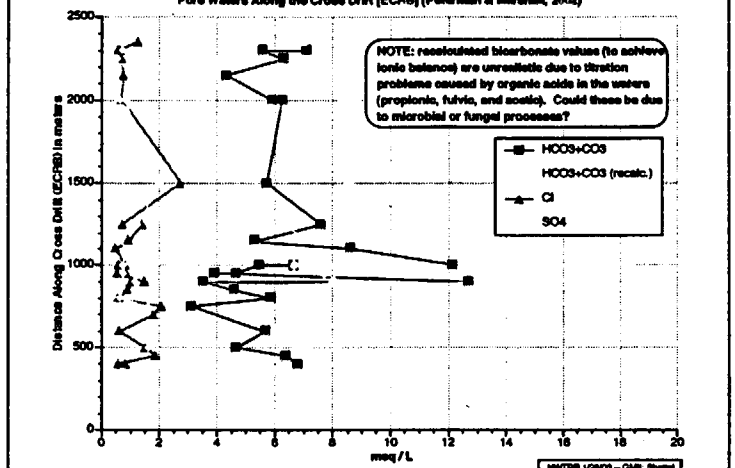
---

5. Perched Water
   Variable, but generally: Na - HCO_3 (similar to groundwater)
   (dead-end fracture water comp. unknown)
6. Groundwater
   Generally: Na - HCO_3

NWTRB 1/28/03 —— GMI - Shettel





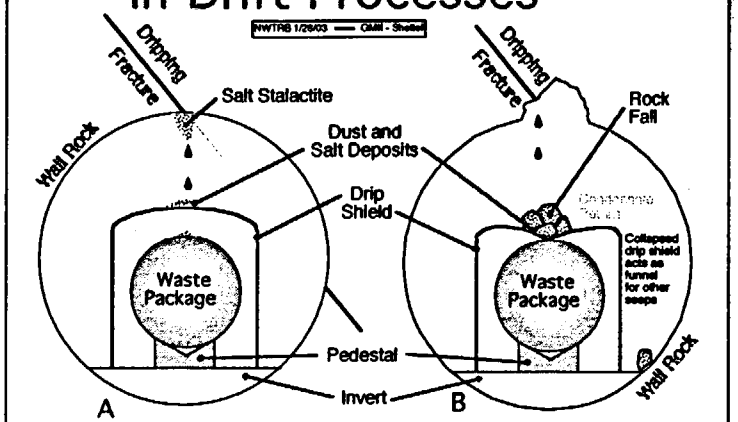


Yucca Mt. Environments

A. Soil Zone Interactions -
   Nitrifying bacteria, evaporative concentration
B. Vadose Water-Rock Interactions in Fractures -
   Silica, carbonates, and Mn-Pb-minerals coating fractures
C. Optimal Biotic Growth Zone -
   Wet and warm conditions promote maximum bacterial and algal growth (loss of NO_3 and PO_4)
   Dynamic - follows temperature changes (~45°C)
D. Refluxing Zone -
   Mixing of any vadose waters and pore waters
   Precipitation of minerals in boiling zone
   Dissolution of minerals in condensation zone
   Heated water-rock interactions
   Dynamic position with temperature
E. In-Drift Processes -
   Dripping / flowing vadose waters from fractures
   Relative humidity & temperature variations
   Dust and evaporative salt build-up on surfaces
   Rockfalls, radiolysis, other man-made materials
   Acid volatilization, hydrolysis of salts

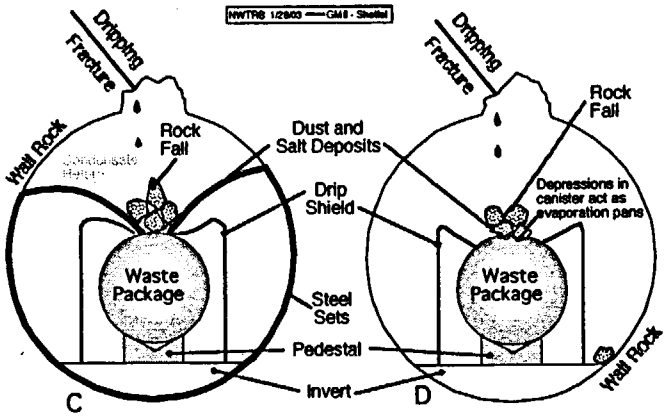
NWTRB 1/28/03 — GMR - Shettel

In-Drift Processes



Cross Section of Emplacement Drifts

In-Drift Processes



Cross Section of Emplacement Drifts

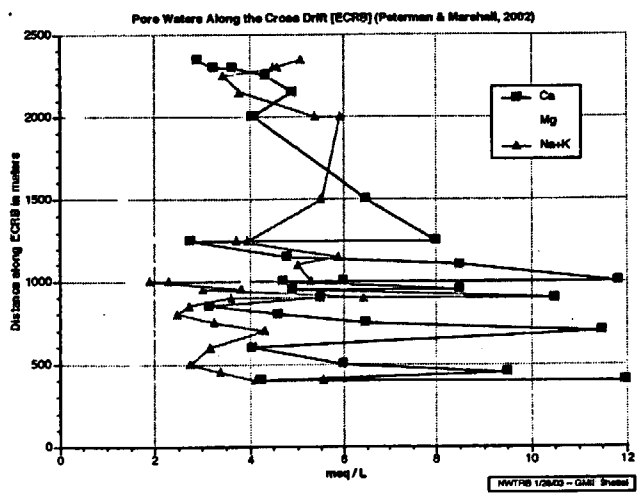
Conclusions

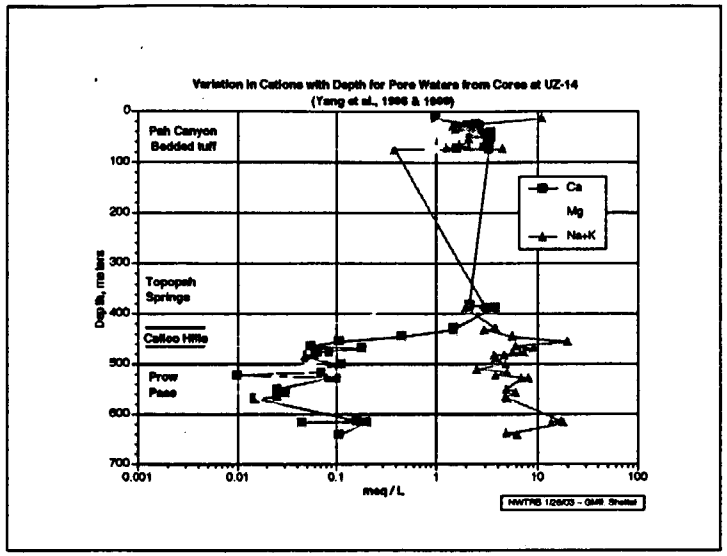
1. Pre-emplacement waters (precipitation, soil, vadose, matrix, perched, and groundwater) are unevenly characterized chemically.
2. Vadose-Zone Matrix (pore) Waters are extremely variable:
   Ca-rich waters predominate above repository level
   Na-rich waters predominate below repository level
   Above Rep. Level: highest SO_4 + Cl, highest & most variable NO_3
3. Cross drift (ECRB) pore waters have been affected by man: microbiological activity produces organic acids?
4. Post-emplacement waters evolve from mixtures of above Repository Level pre-emplacement waters modified by:
   Biotic Growth Zone (loss of NO_3 and PO_4, SO_4 reduction),
   Refluxing Zone (heated mixtures of waters reacting with Topopah Springs tuff), and in-drift processes.
5. Importance to Corrosion: Post-emplacement waters cannot be sampled nor analyzed; therefore, cannot be characterized. Modeled?
6. Corollary: sub-boiling, immersion testing of EBS materials in groundwater is BOTH unrealistic and non-conservative.

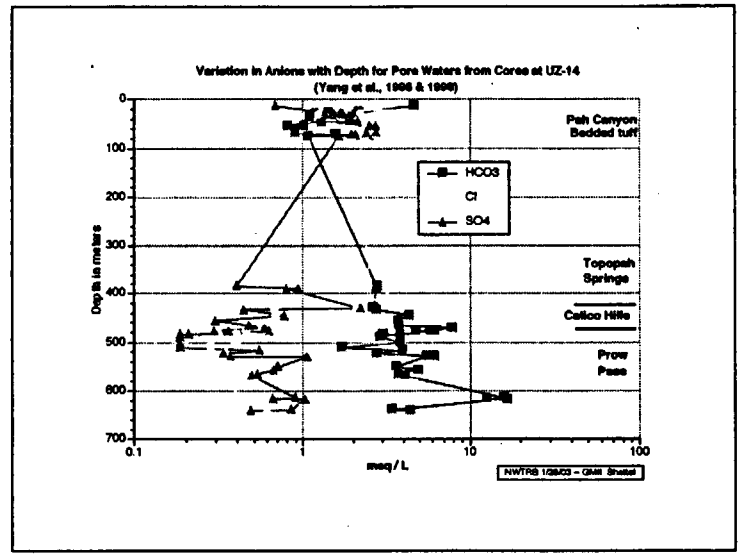
NWTRB 1/28/03 — GMII - Shettel

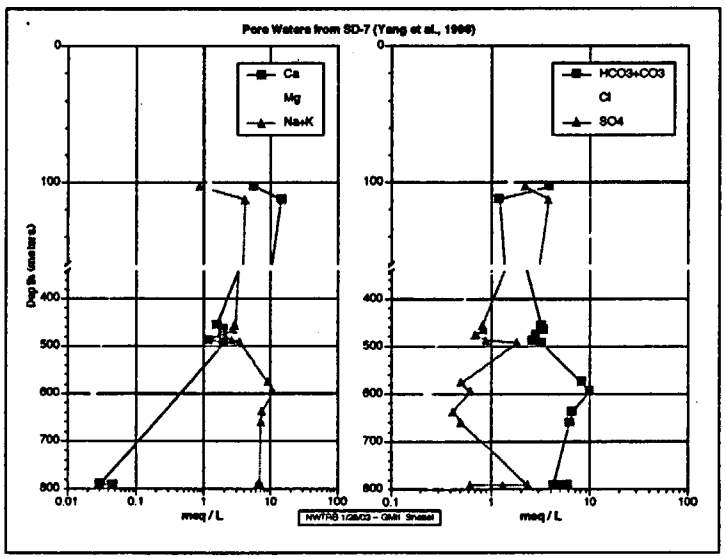
Back Up Slides

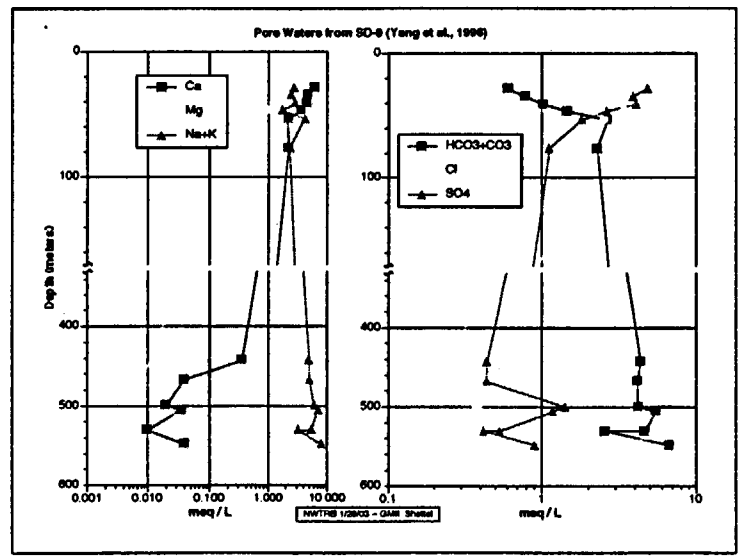
For D.L. Shettel's
Presentation to the
U.S. N.W.T.R.B.
1/28/03




Variation in Cations with Depth for Pore Waters from Cores at UZ-14
(Yang et al., 1996 & 1998)
Pah Canyon
Bedded tuff
Topopah
Springs
Calico Hills
Prow
Pass
Ca
Mg
Na+K
Depth, meters
meq / L
NWTRB 1/28/03 - GMR Shelled


Variation in Anions with Depth for Pore Waters from Cores at UZ-14
(Yang et al., 1996 & 1998)
Pah Canyon
Bedded tuff
Topopah
Springs
Calico Hills
Prow
Pass
HCO3
Cl
SO4
Depth in meters
meq / L
NWTRB 1/28/03 - GMR Shelled


Pore Waters from SD-7 (Yang et al., 1998)
Ca
Mg
Na+K
HCO3+CO3
Cl
SO4
Depth (meters)
meq / L
NWTRB 1/28/03 - GMR Shelled


Pore Waters from SD-9 (Yang et al., 1998)
Ca
Mg
Na+K
HCO3+CO3
Cl
SO4
Depth (meters)
meq / L
NWTRB 1/28/03 - GMR Shelled

CONTINUING INVESTIGATIONS OF LOCAL ENVIRONMENTS ON WASTE CONTAINER SURFACES

Presented by the State of Nevada

Contributors on Behalf of the State of Nevada

Dr. April Pulvirenti, Catholic University of America
Dr. M. A. Adel-Hadadi, Catholic University of America
Professor Aaron Barkatt, Catholic University of America
Dr. Charles Marks, Dominion Engineering
Dr. Jeffrey A. Gorman, Dominion Engineering
Dr. Roger W. Staehle, Adj. Prof., University of Minnesota (Presenting)

Presented at

Nuclear Waste Technical Review Board Meeting
Las Vegas, Nevada
January 28, 2003

ENVIRONMENTAL CONSIDERATION FOR ASSESSING INTEGRITY OF CONTAINER FOR RADIOACTIVE WASTE

- **Should determine the local surface environments before designing and choosing material.**

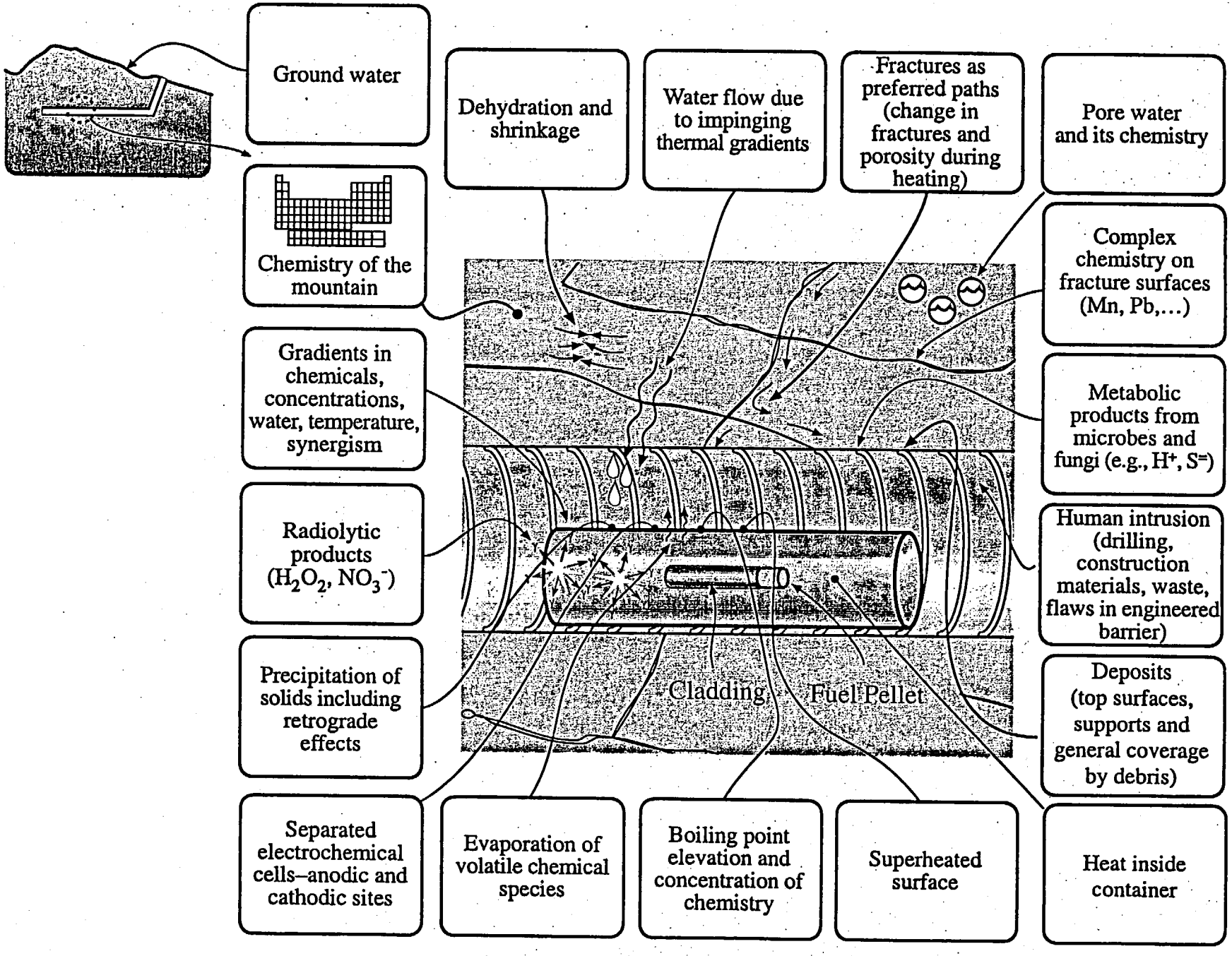
- **Corrosion processes are dominated by the local environments that are directly on the surface of containers.**

- **Local environments on surfaces are products of all surroundings and of multiple interactions, and can change over time.**

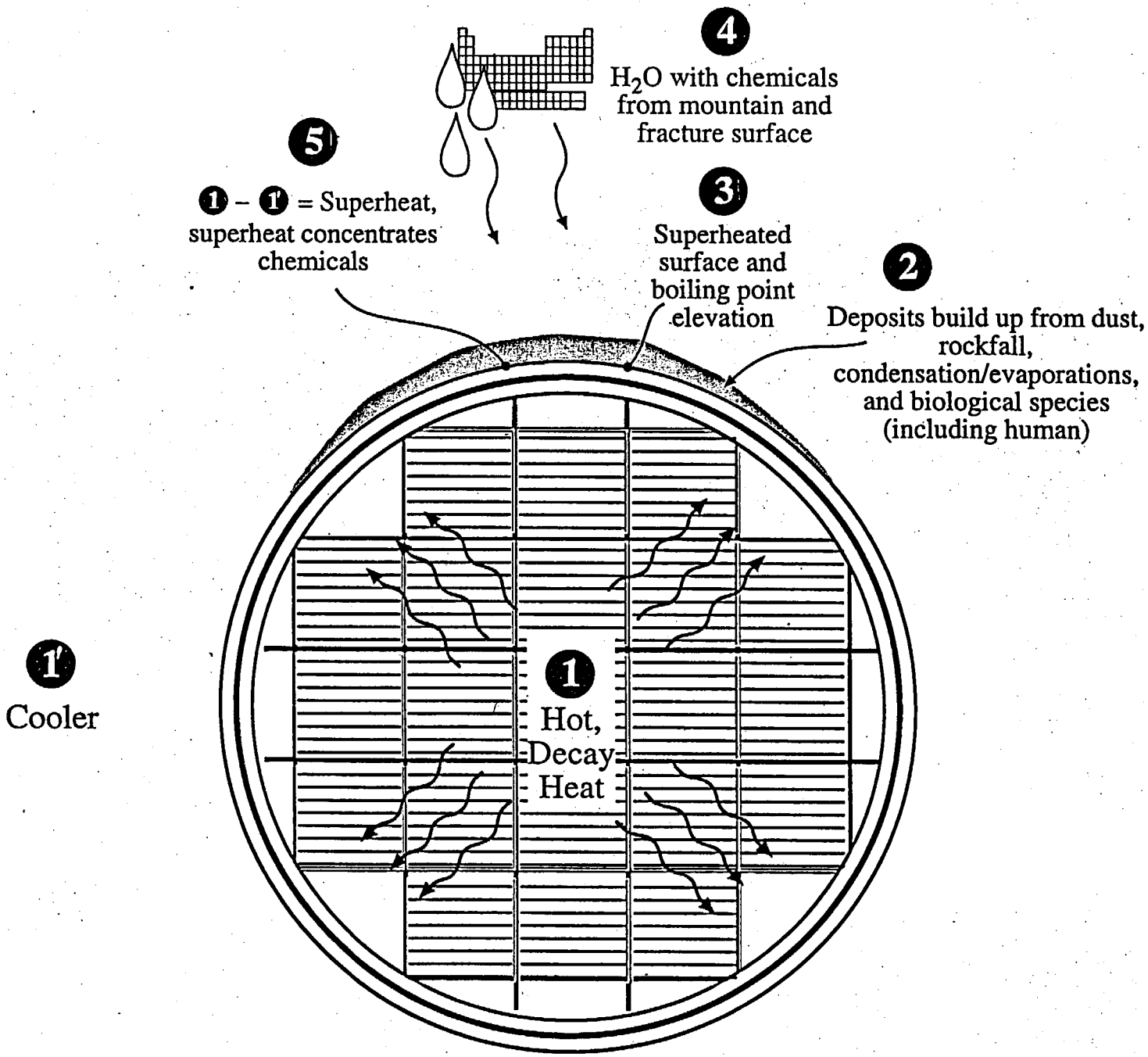
- **Local environments on the surface are affected primarily by:**
  - **Multiple aqueous chemistries that arrive at the surface from both local and wide ranging sources.**
  - **Decay heat from inside the container.**
  - **Presence and composition of insulating deposits.**
  - **Location and time.**

- **Surface environments cannot be predicted readily, not can they be simply bounded based on the relatively narrow ranges of conditions in which corrosion occurs on specific alloys. For example, although bulk environments of nuclear PWR steam generators are well defined, the local environments within heat transfer crevices have not been quantified, and can vary widely.**

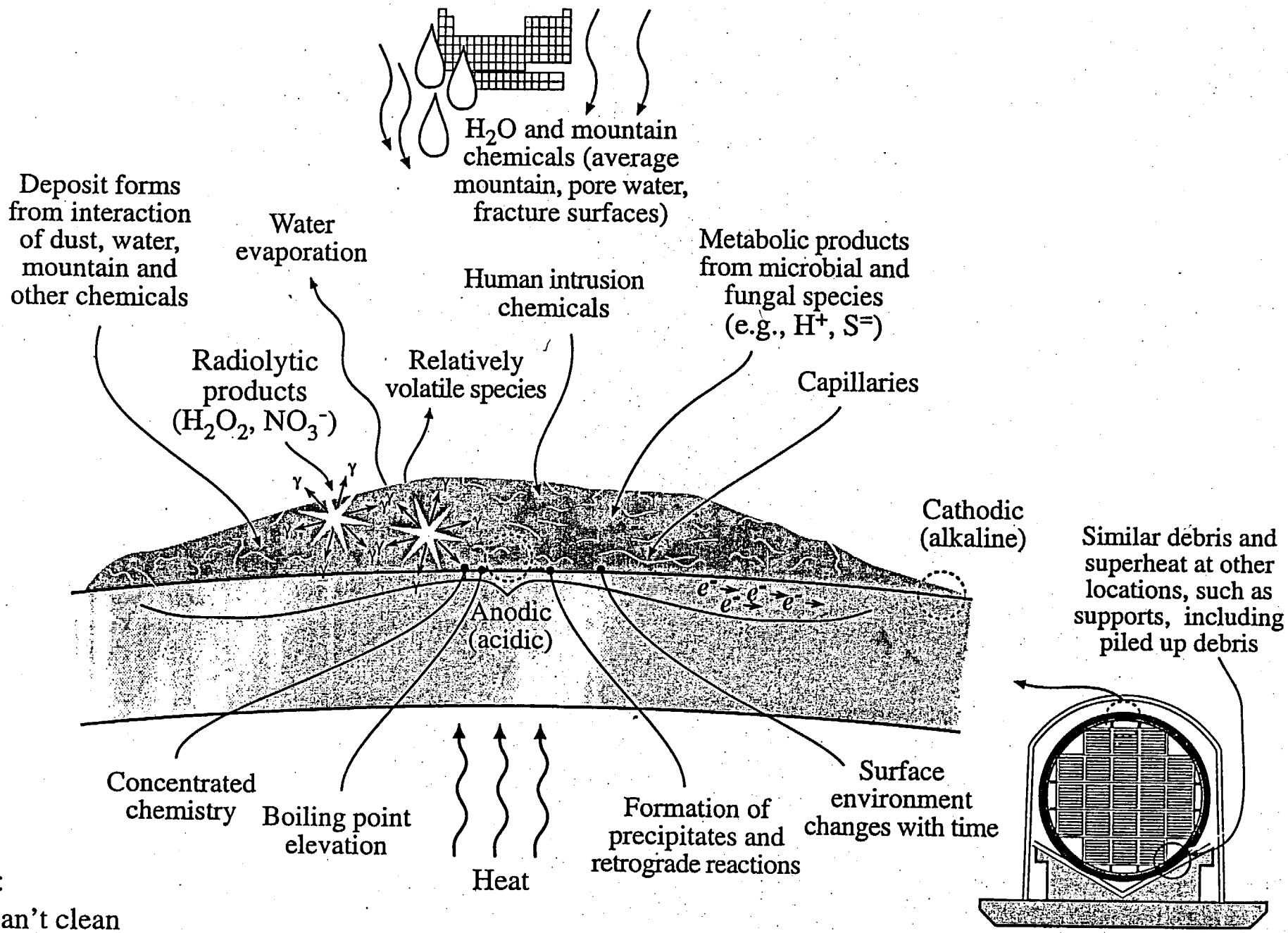
Factors Producing Corrosive Environment



Superheated Processes at Waste Package



Surface Processes at Superheated Deposits



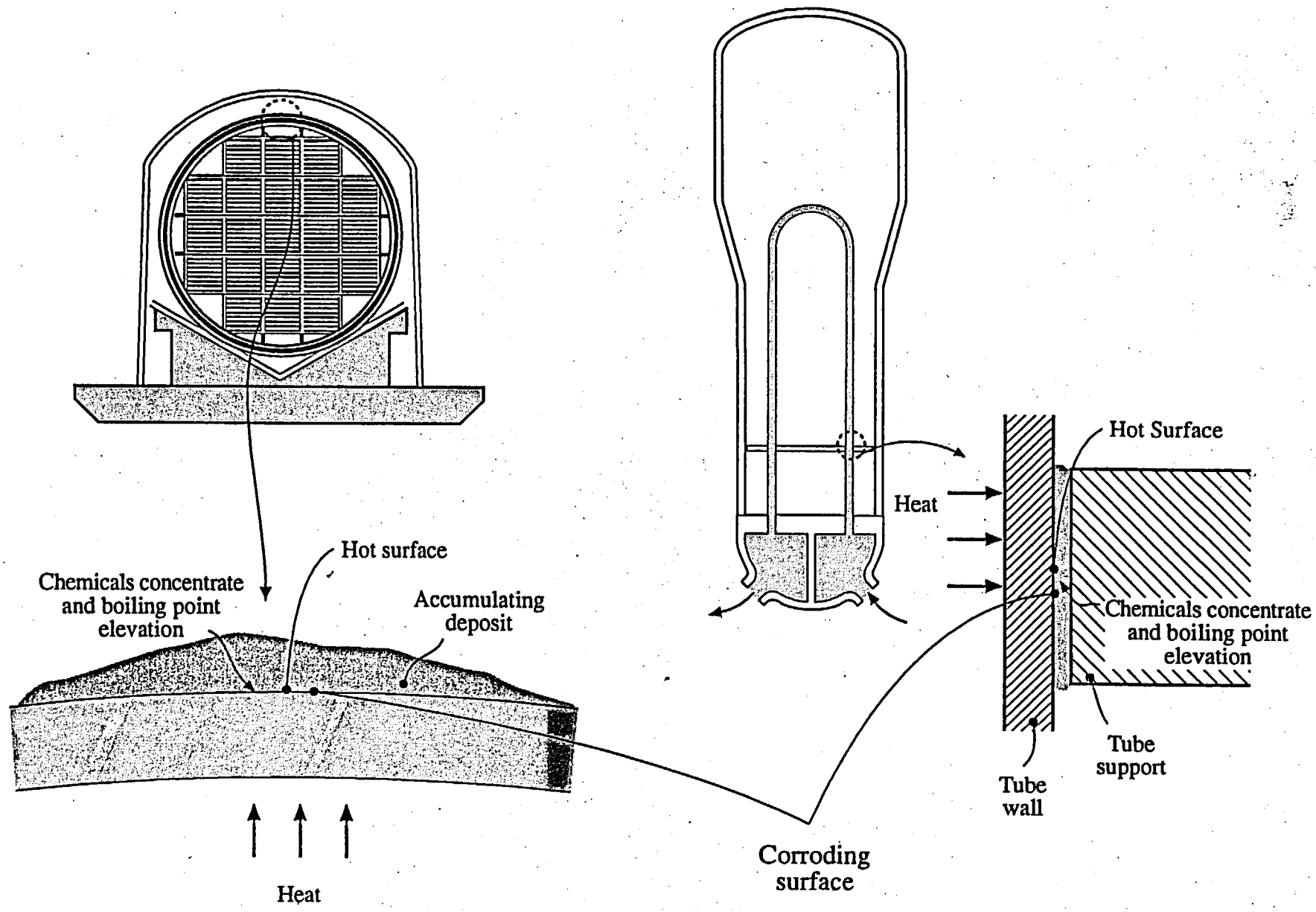
Note:

Can't clean

Hot Surfaces Concentrate Chemicals: Similarities

Yucca Mountain

Commercial Steam Generators



EXPERIMENTAL APPROACH

1. Characterize possible local environments as they develop with time on a hot surface of the container.

2. Emphasize a subset of aqueous environments that results from water originating from or passing through the unsaturated zone above the container.

3. Assess both the evaporated environment and the residual environments after evaporation occurs.

4. Start with concentrated solution that had been identified by LLNL (Rosenberg, Gdowski, and Knauss in 2001) from the unsaturated zone and continue concentration by boiling.

5. Measure instantaneous pH of condensed vapor during evaporation.

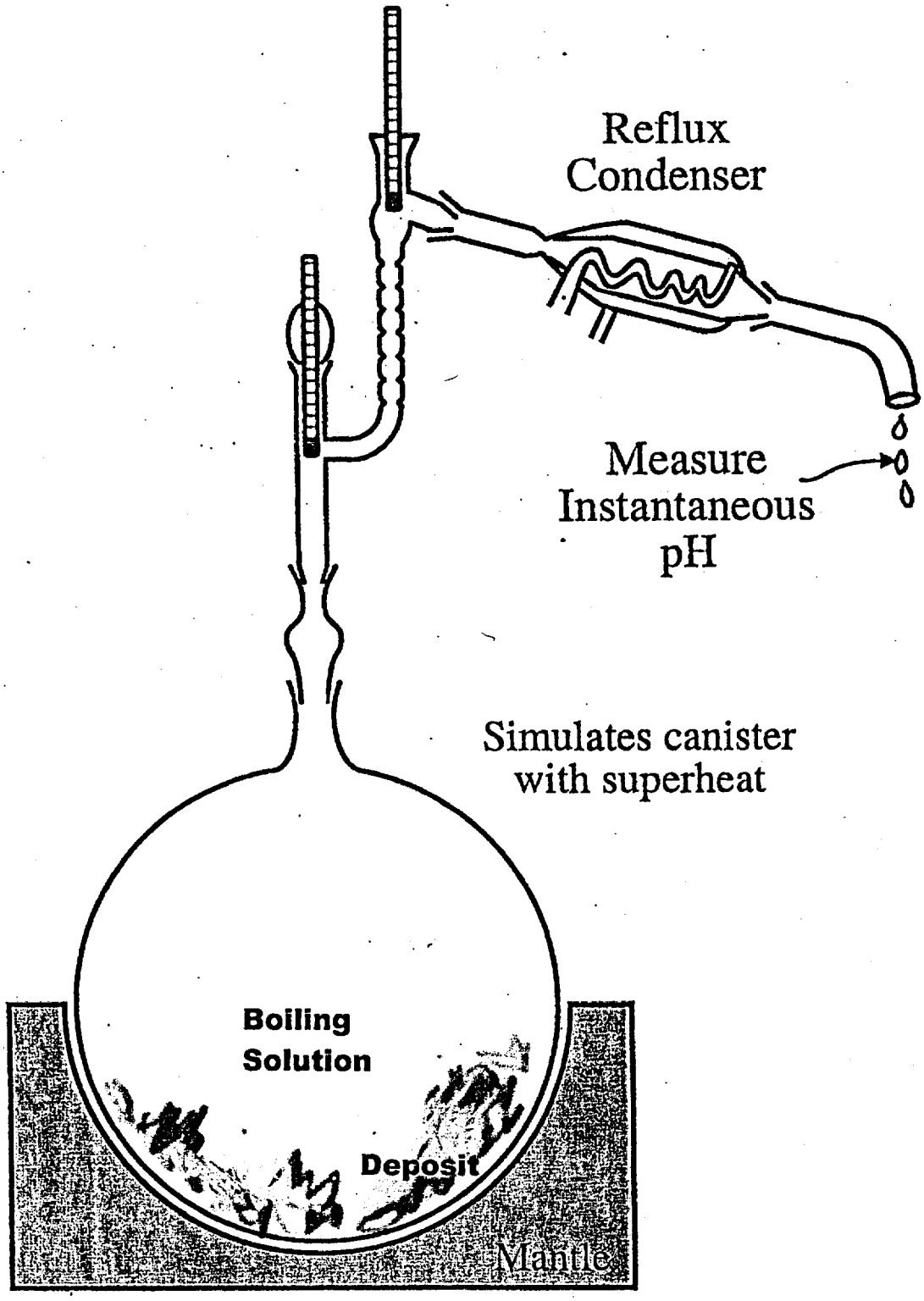
6. Measure corrosion rate in condensed solutions and in residual solutions by immersed coupon tests.

STARTING CONCENTRATIONS FOR DISTILLATIONS*

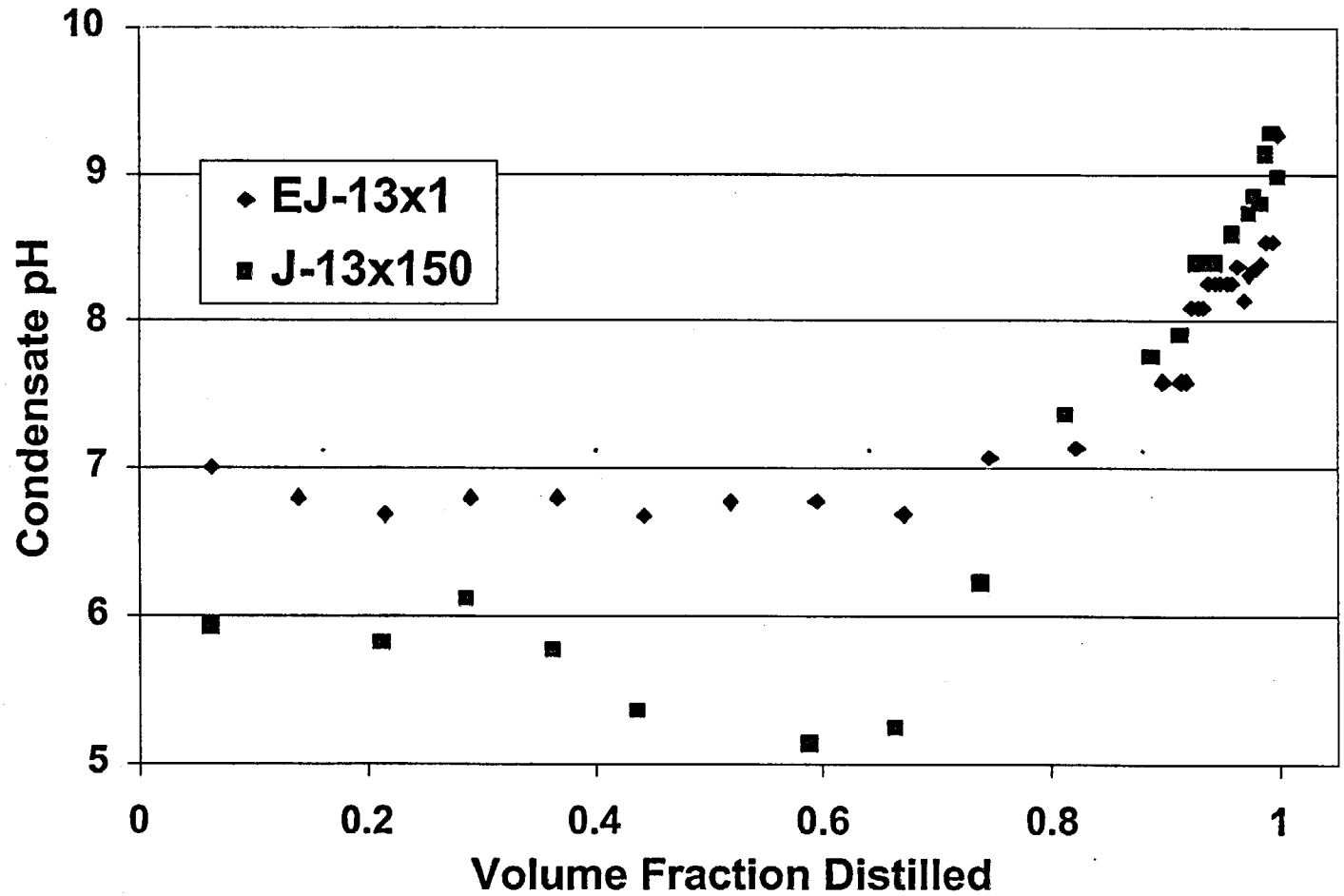
ppm ion	Saturated Zone Water (J-13)		Unsaturated Zone water (UZ)		
	1x	150x	1x	62x	1243x
Na^+	45.2	162.2	8.56	476.8	6223
K^+	5.2	592.8	4	268.4	2644
Mg^{2+}	2.1	1.12	11.8	550	5546
Ca^{2+}	5.8	0.06	57.3	1713	15643
SiO_2	10.4	1040	10.4	503.36	540.8
HCO_3^-	105.0	4410	20.3	9.95	44.66
SO_4^{2-}	18.5	2109	83.9	1543	2097.5
Cl^-	7.2	813.6	76.6	4259	52165
NO_3^-	7.9	1034.9	10.7	591.7	2578.7
F^-	2.3	236	2.16	38.2	432
pH	**8.07**	**10.18**	**7.55**	**7.65**	**6-6.5**

**from Rosenberg, Gdowski, and Knauss in 2001*

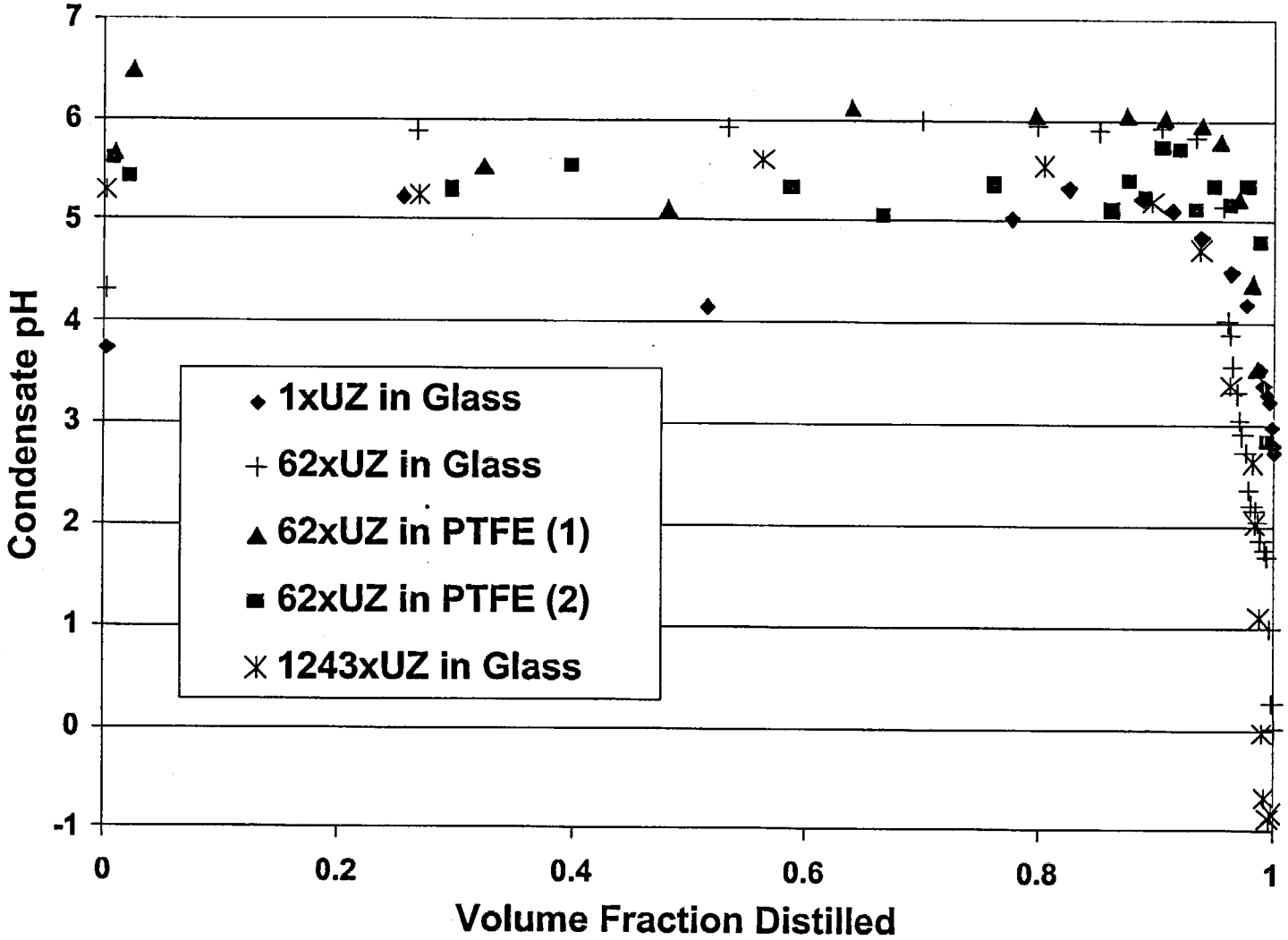
DISTILLATION EXPERIMENTS



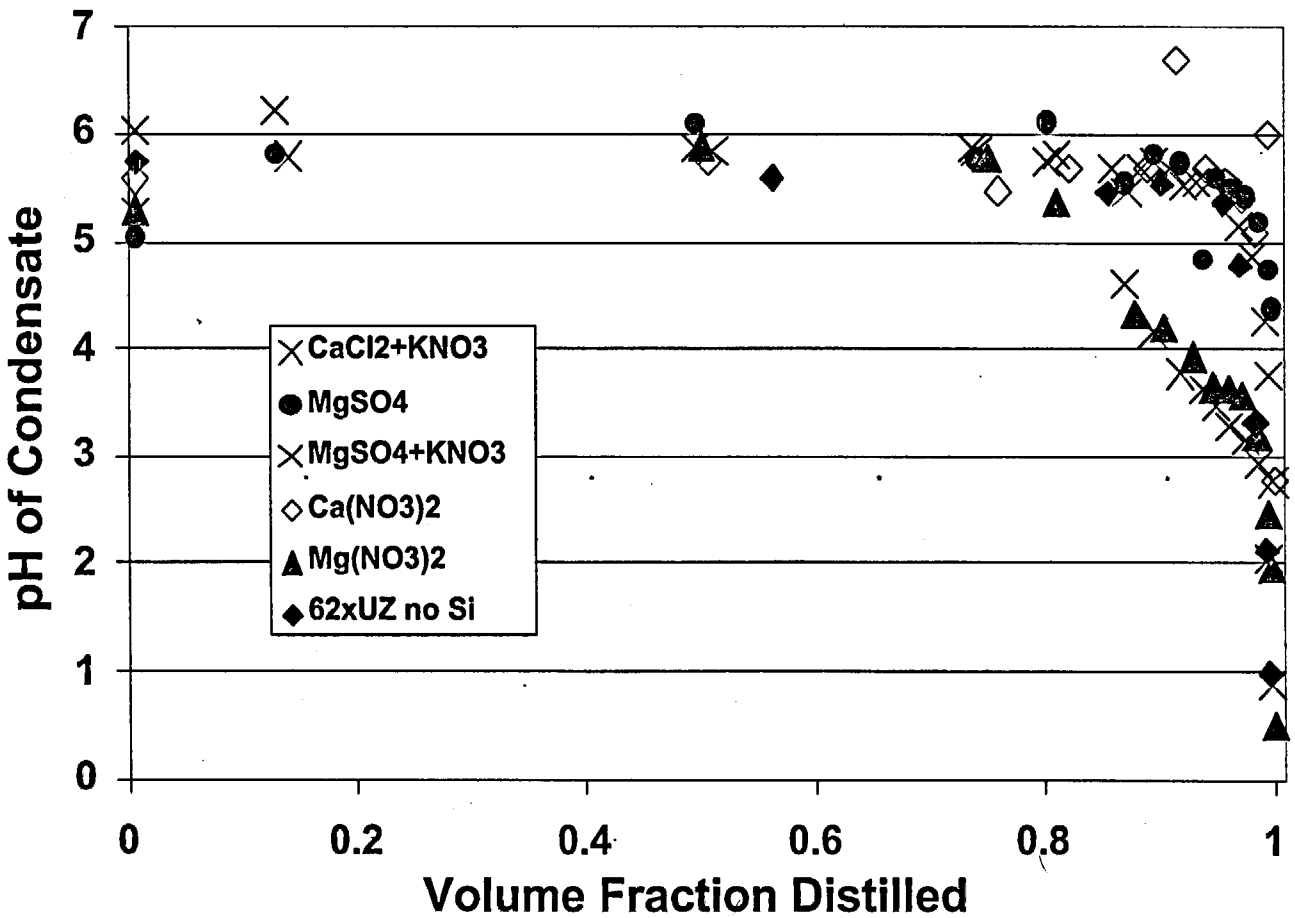
DISTILLATION OF J-13



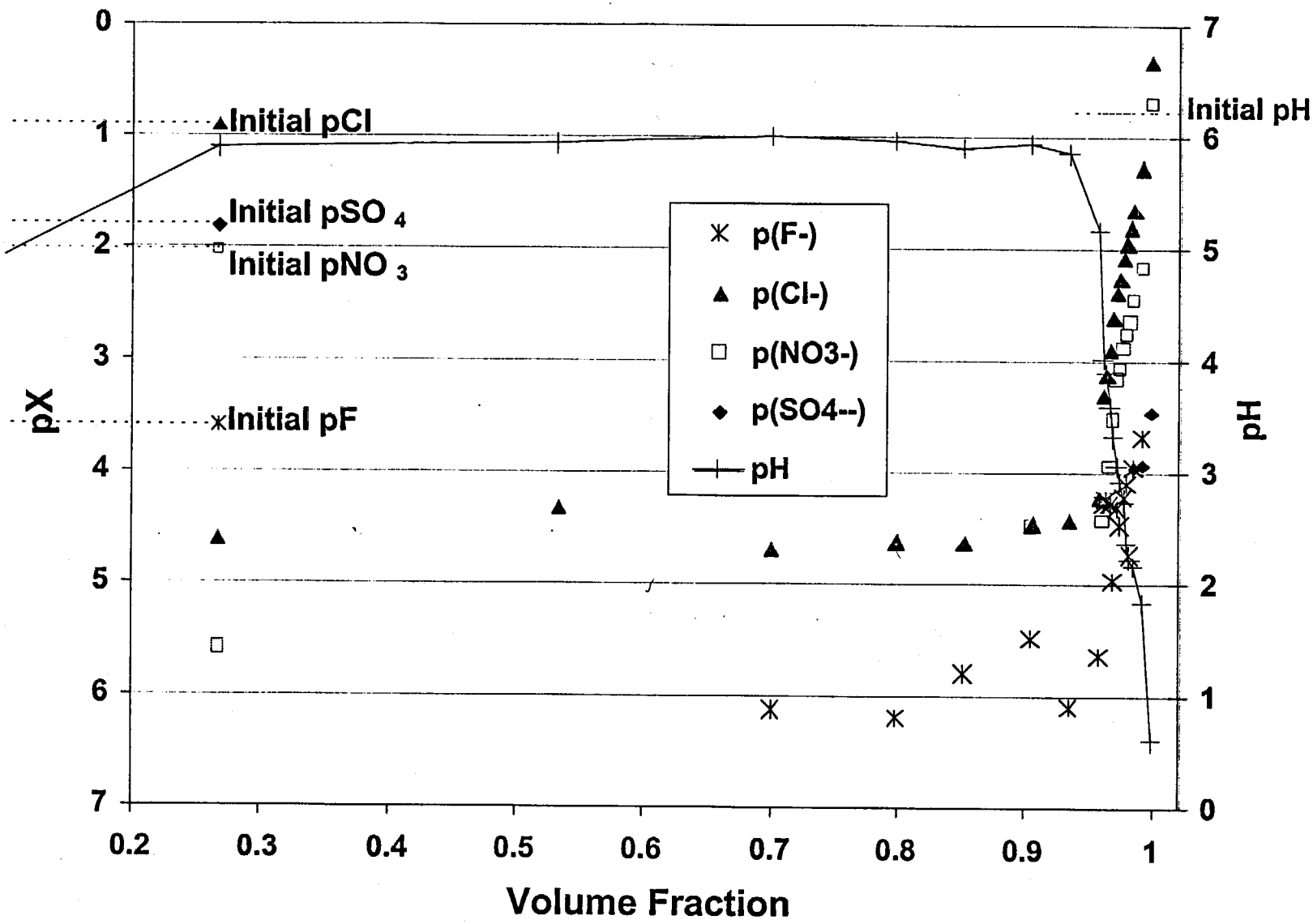
DISTILLATION OF UZ PORE WATER



DISTILLATION OF COMPONENTS OF PORE WATER



ANION CONCENTRATIONS vs. VOLUME FRACTION



CHEMISTRY OF THE CONDENSATES

In flask:

$$Mg(NO_3)_2 \cdot xH_2O_{(l)} \circledR Mg(OH)_2 \cdot nMg(NO_3)_{2(s)} + H^+ + NO_3^-{}_{(aq)}$$

In condenser:

$$H^+_{(aq)} + \begin{matrix} NO_3^-{}_{(aq)} \\ Cl^-_{(aq)} \\ F^-_{(aq)} \end{matrix} \longrightarrow \begin{matrix} HNO_{3(g)} \\ HCl_{(g)} \\ HF_{(g)} \end{matrix} \xrightarrow{\text{condensed } H_2O} \begin{matrix} HNO_{3(aq)} \\ HCl_{(aq)} \\ HF_{(aq)} \end{matrix}$$

- **H_2SO_4 is not volatile, and therefore SO_4^{2-} does not appear in condensed vapor.**

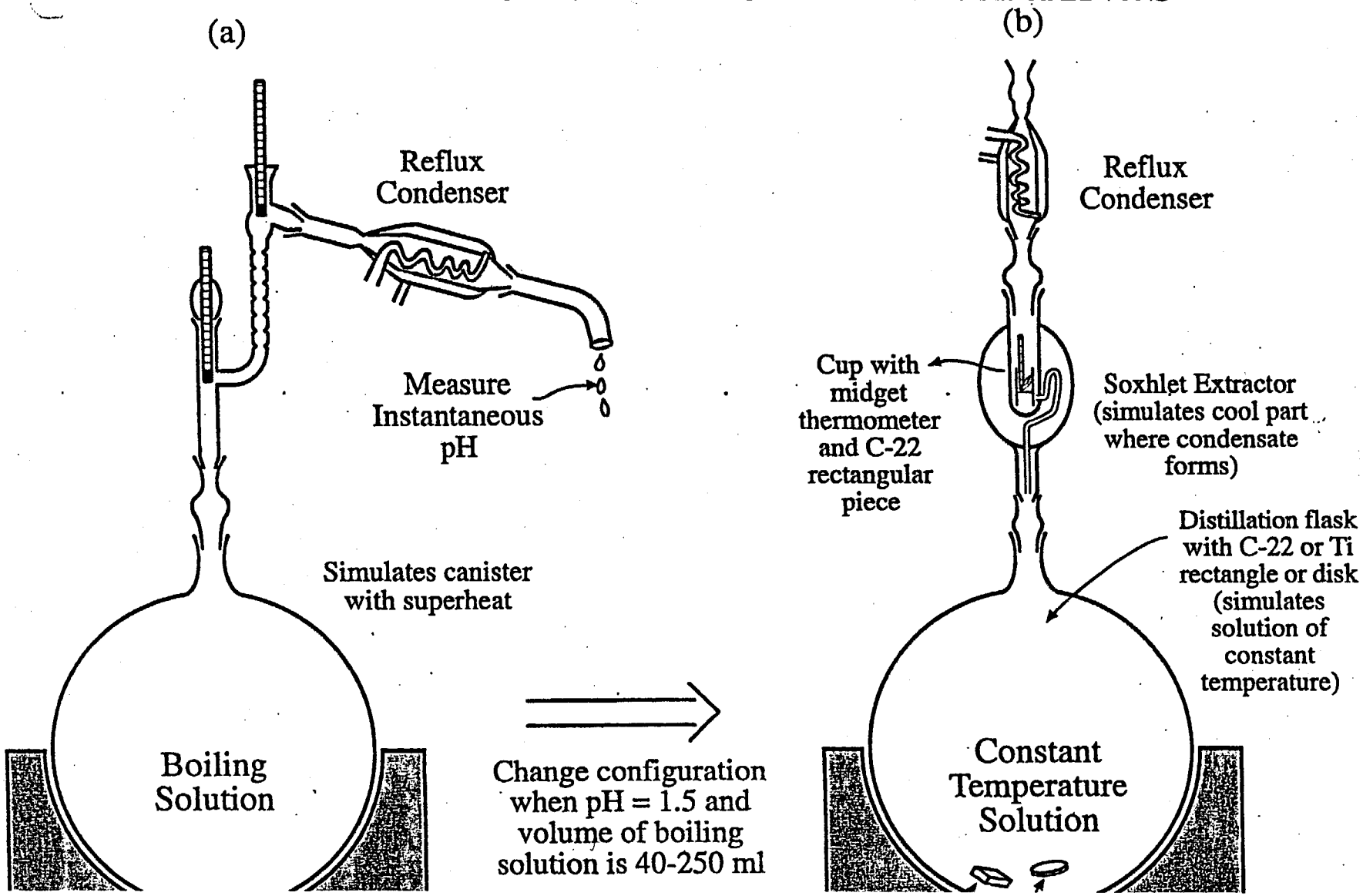
- **$Ca(NO_3)_2xH_2O_{(l)}$, $CaCl_2xH_2O_{(l)}$, and $MgCl_2xH_2O_{(l)}$ decompose to give acid, but to a lesser extent at these temperatures.**

CORROSION TESTING OF ALLOY 22 IN CONDENSATES*

Original Solution	Condensate type	Measured pH	Test temp °C	Corrosion rate†
62xPore	Next-to-last 30 mL	1.62	130	15
62xPore	Final 30 mL	0.59	130	406
1243xPore	Next-to-last 30 mL	0.02	90	52
1243xPore	Final 30 mL	-0.54	90	603

*30 day immersion test
†Based on weight loss, in µm/year

DISTILLATION / REFLUX EXPERIMENTS



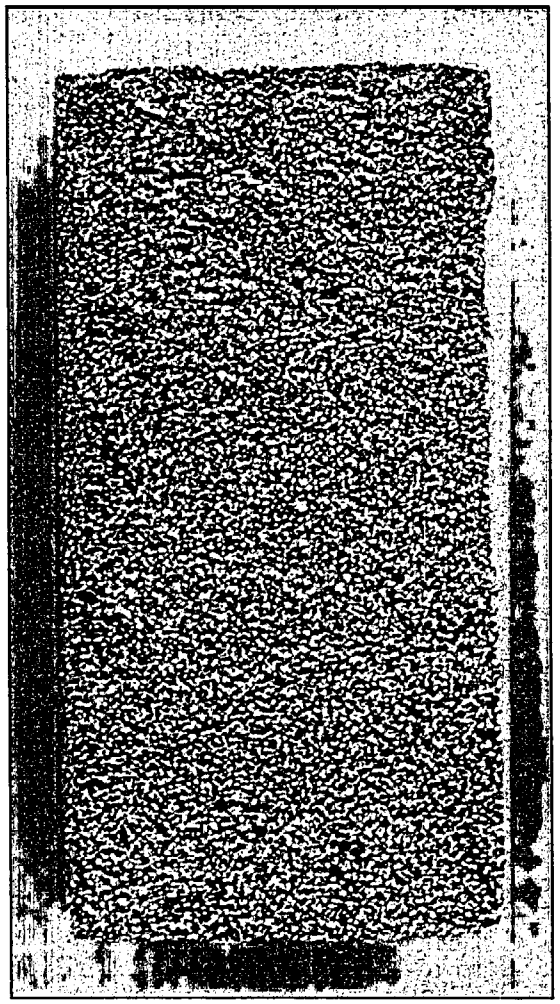
DISTILLATION / REFLUX EXPERIMENTS*

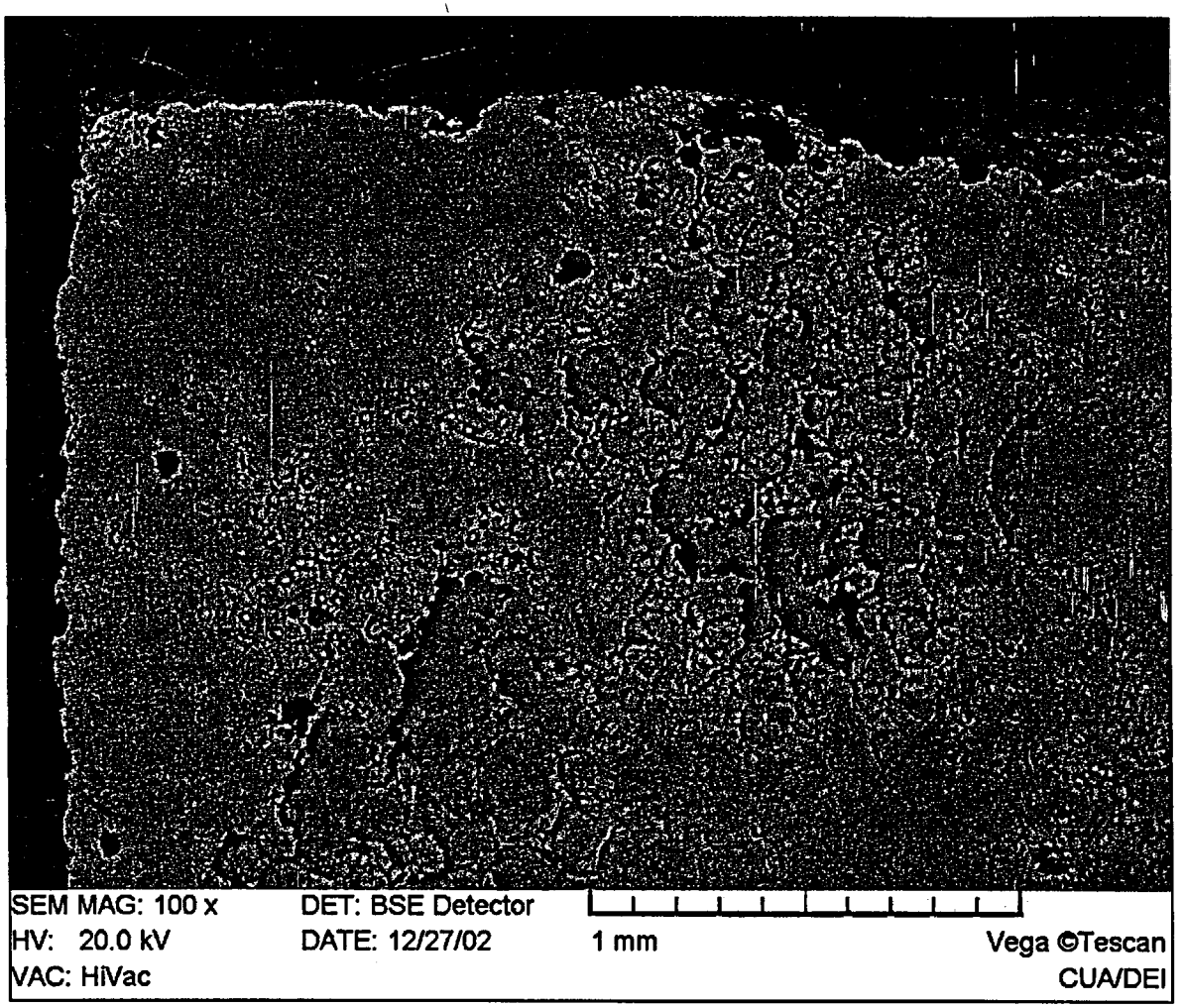
Metal	Original Solution	Sample environment	pH	Temp °C	Corrosion rate†
C-22	62xPore	Residual Paste	2.63	144	134
C-22 (#21)	1243xPore	Clear residual solution	0.22	144	10943
C-22 (#21)	1243xPore	Soxhlet cup	0.18	78	14
C-22 (#34)	1243xPore	Residual Paste	2.21	144	678
C-22 (#34)	1243xPore	Embedded in Residual solid	2.21	144	30
C-22 (#34)	1243xPore	Soxhlet cup	-0.48	77	938

*22-29 day test

†Based on weight loss, in μm/year

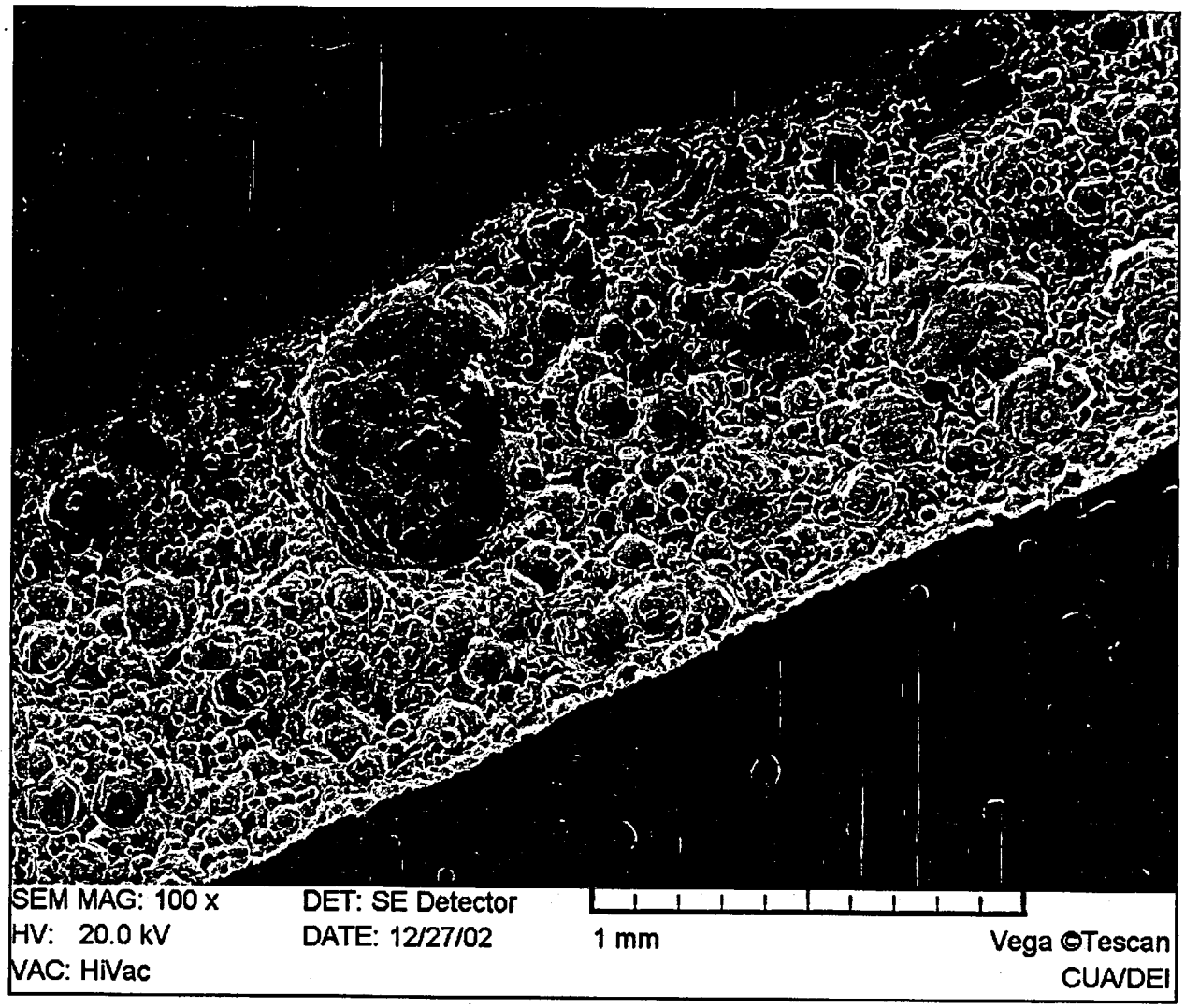
DISTILLATION / REFLUX EXPERIMENTS





C-22 #34 IN SOXHLET CUP (78°c, 29 DAYS)

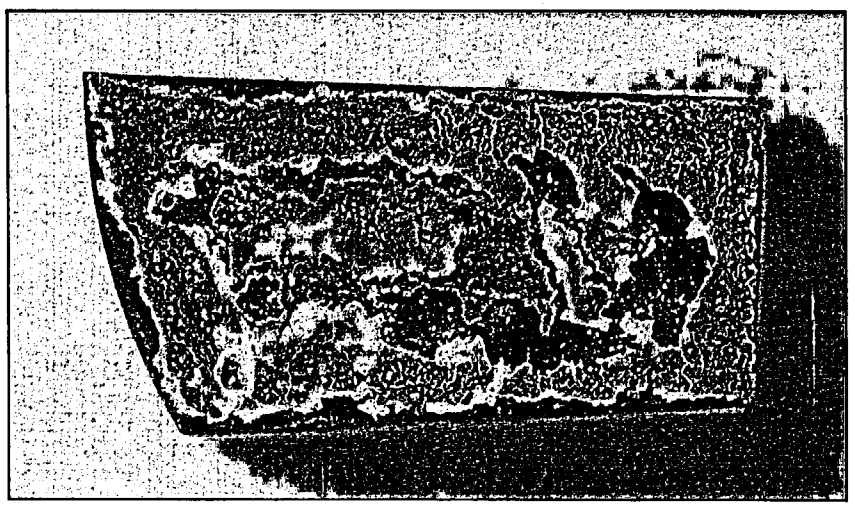
DISTILLATION / REFLUX EXPERIMENTS



C-22 #21 IN CLEAR RESIDUAL SOLUTION (144°c, 28 DAYS)

DISTILLATION / REFLUX EXPERIMENTS

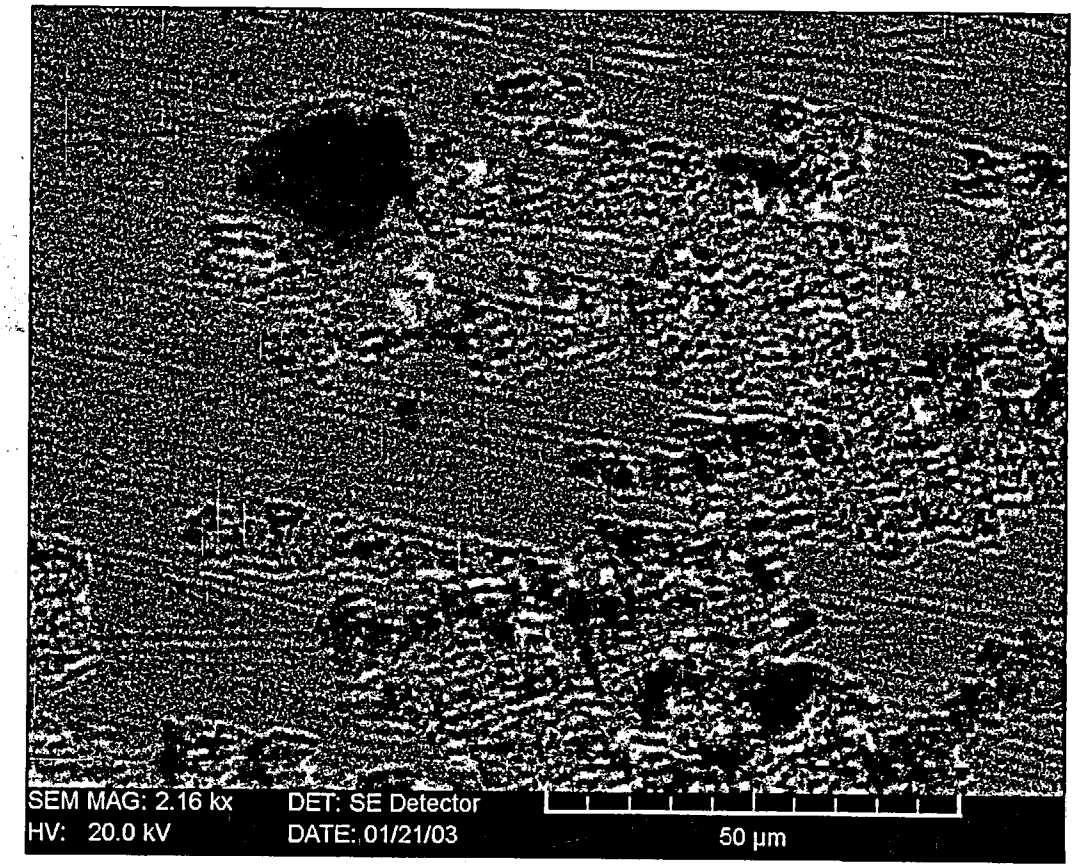
Metal	Original Solution	Sample environment	pH	Temp °C	Corrosion rate†
Ti-7	1243xPore	Residual Solution	1.60	144	969
Ti-7	1243xPore	Residual Solid	1.6	144	36
T-7	1243xpore	Soxhlet cup	-0.88	78	114



Ti-7 in Residual solution

DISTILLATIONS – IMPORTANCE OF THE SOLIDS

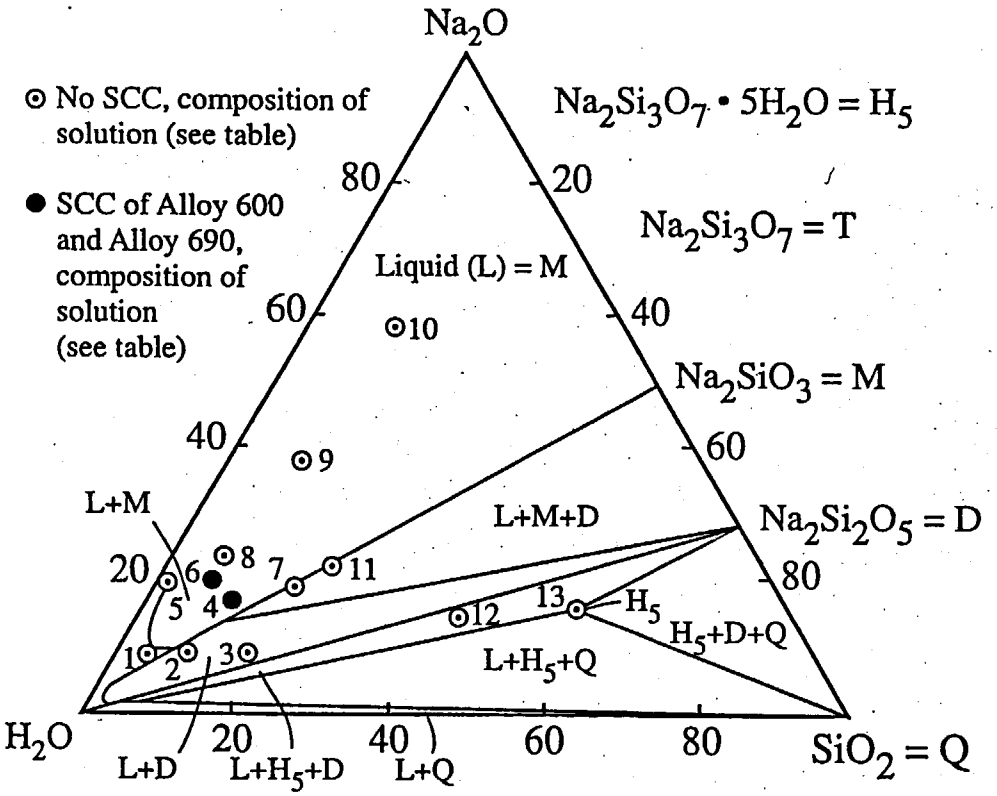
The solids that precipitate during distillations, including halite (NaCl), tachyihydrite ($CaMg_2Cl_6 \cdot 12H_2O$), and basic Mg oxy salts, are porous and heterogeneous. When allowed to deliquesce as a paste, may become aggressive as well.



A sample of C-22 embedded in a moist paste of residual solids from an distillation of 1243xPore water showd signs of tarnishing after 8 weeks at room temperature.

Corrosion of Hastelloy C, Alloys 600 and 690 in Concentrated Sodium Silicate Solutions (From the literature)

(a)



(b)

Composition of Test Solutions, mol % Test Results from Alloy 600 and 690 at 315°C in $H_2O + N_2O + SiO_2$ Solutions

Soln. No.	Na_2O	SiO_2(2)	Alloy 600 Test duration, hrs.	Alloy 600 U-bends (cracked/ total)	Alloy 600 Deepest crack, mm	Alloy 690(1) Test duration, hrs.	Alloy 690(1) U-bends, (cracked/ total)
1	8.2	4.5M	175	(0/6)	-	-	-
2	8.2	9M	175	(0/6)	-	-	-
3	8.2	17(3)M	175	(0/6)	-	-	-
4	16	12M	175	(2/6)	1.3	175	(6/6)
			343	(3/6)	2.1	-	-
5	19	2M	343	(0/6)	-	-	-
6	19	7M	175	(1/6)	0.05	175	(6/6)
7	19	17(3)M	175	(0/6)	-	-	-
8	23	7M	343	(0/6)	-	-	-
9	37	10M	175	(0/6)	-	-	-
10	58	12.5M	175	(0/6)	-	-	-
11	22	16M+6D	175	(0/6)	-	-	-
12	14	42T	175	(0/6)	-	-	-
13	19	55T	175	(0/6)	-	-	-

(1) Alloy 690 as received. Exhibited SCC.

(2) M = monomer, D = Dimer, T = timer

(3) This solution was made up as monomeric Na_2SiO_3 but is in a regime where some dimer should be present.

(c)

It is of note that the Hastelloy C wire (0.8 mm diameter) used to support the U-bends was observed to have broken in solution No. 4. After a solution No. 6 run that was aborted after 76 hrs., SCC was noted in several places in the Hastelloy C wire. No conclusion can be drawn as to whether solution No. 6 is as aggressive toward Alloy C276 as it is toward Aloy 600. This is due to an undefined increase in concentration (caused by a leak) as well as the unknown stress in the wire. *Ref. C.R. Bergin Corrosion Journal, p. 85, 1985*

CONCLUSIONS

1. Continued evaporation of concentrated aqueous UZ pore water solutions produce significant acidity in both residual and condensed environments. Similar evaporations of J-13 well water produce generally alkaline environments.

2. The acidity of the evaporated UZ environments relative to that of the J-13 results from the relatively higher combined concentrations of Mg^{2+}, NO_3^-, and Cl^-.

3. Residual and evaporated environments are significantly corrosive to both C-22 and Ti-7. Corrosion rates in the range of 0.1 to 1.0 mm/year were observed, with rates as high as 10 mm/year.

4. The environments studied represent a small subset of many that can result from water passing through the UZ, reaching the containers, evaporating, and interacting with the heated surface and other deposits.

5. Future work will consider the chemistry of the precipitated solids, and the possibility of stress corrosion cracking.

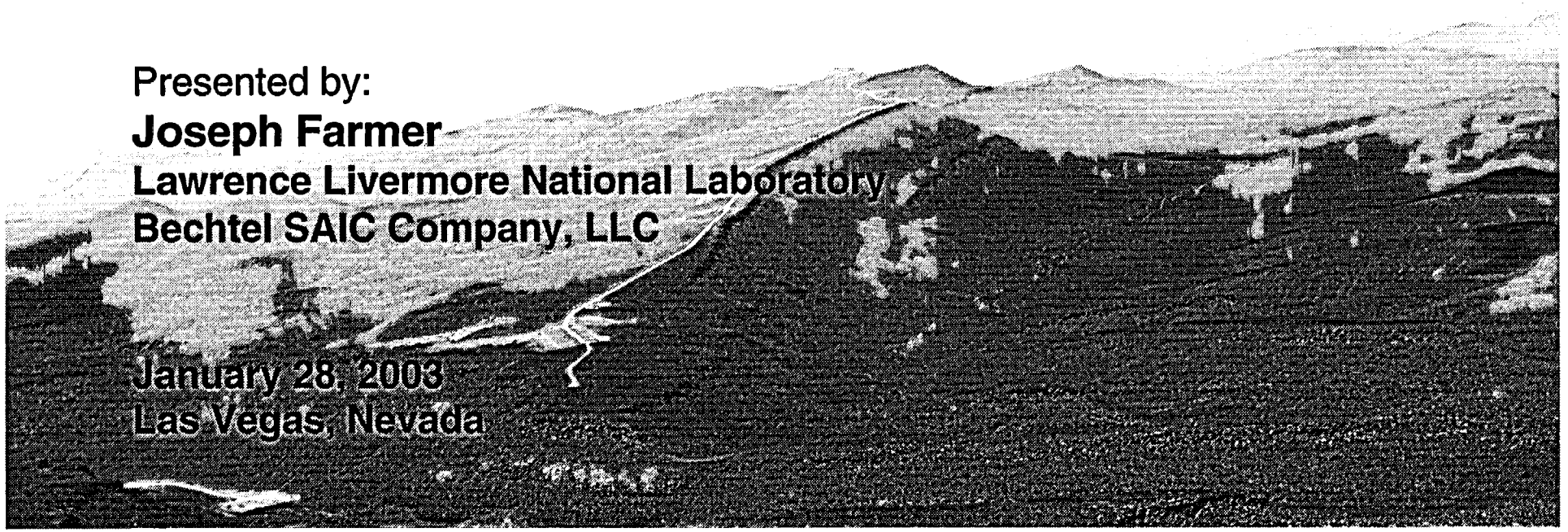
6. The combination of a wide range of chemistries in the surroundings, the surfaced heated by radioactive decay, and the formation of surface deposits over time will produce a range of corrosive conditions on the surfaces of container that cannot be readily quantified nor their effect on corrosion predicted.

U.S. Department of Energy
Office of Civilian Radioactive Waste Management

YUCCA MOUNTAIN PROJECT

Chemical Environment Evolution on Alloy 22

Presented to:
Nuclear Waste Technical Review Board



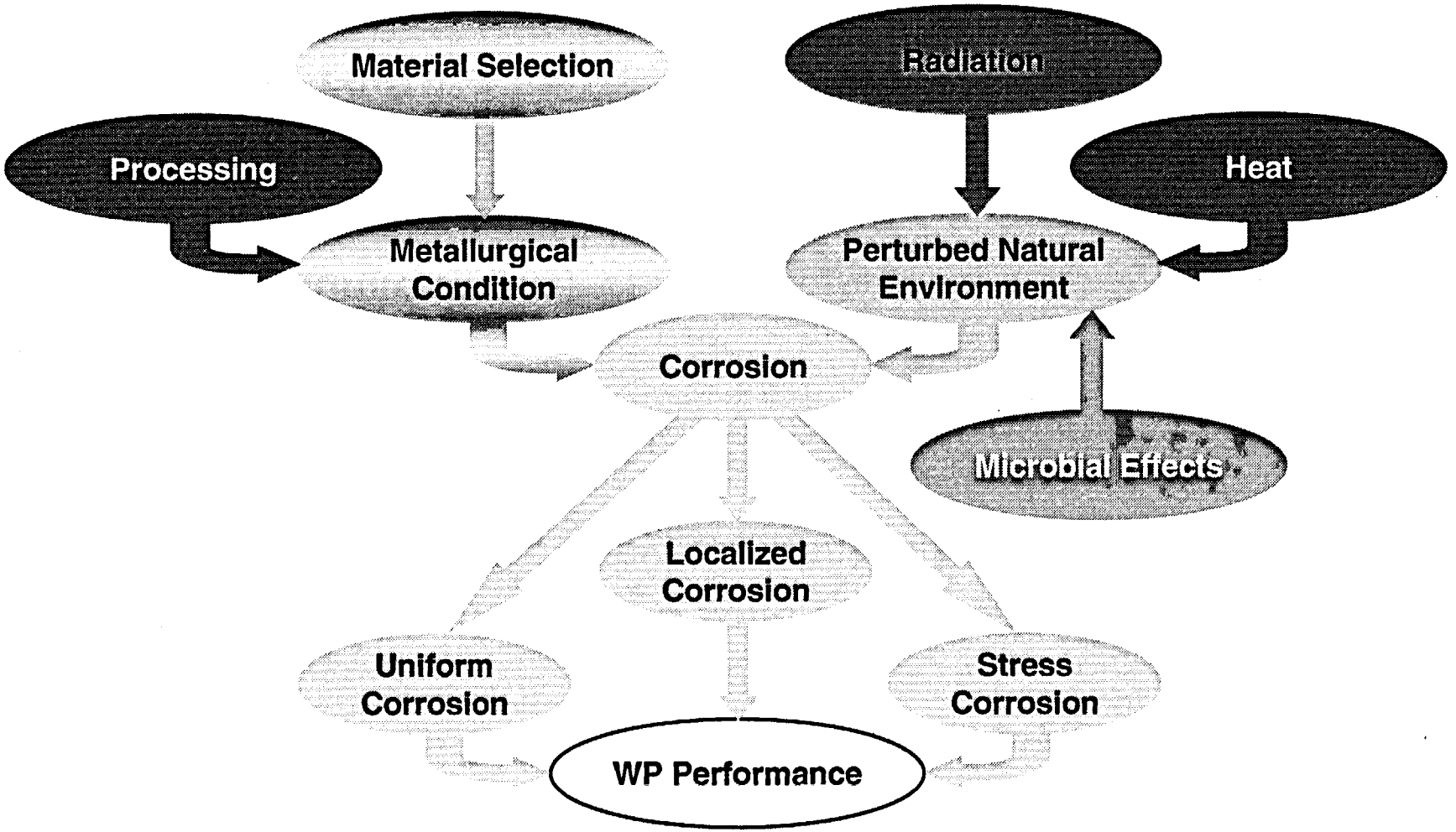
Presented by:
Joseph Farmer
Lawrence Livermore National Laboratory
Bechtel SAIC Company, LLC

January 28, 2003
Las Vegas, Nevada

Outline

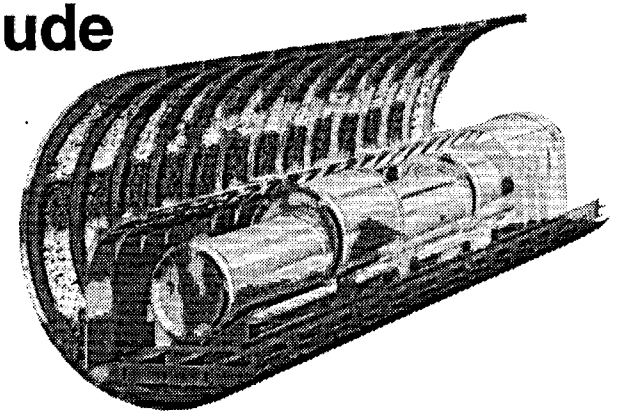
- In-Drift Environment
- Deliquescence Brines
- Seepage Brines
- $CaCl_2$ Brines
- Environment-Surface Interactions
- Heat Transfer Through Scale
- Summary

In-Drift Environment – Impact on Corrosion



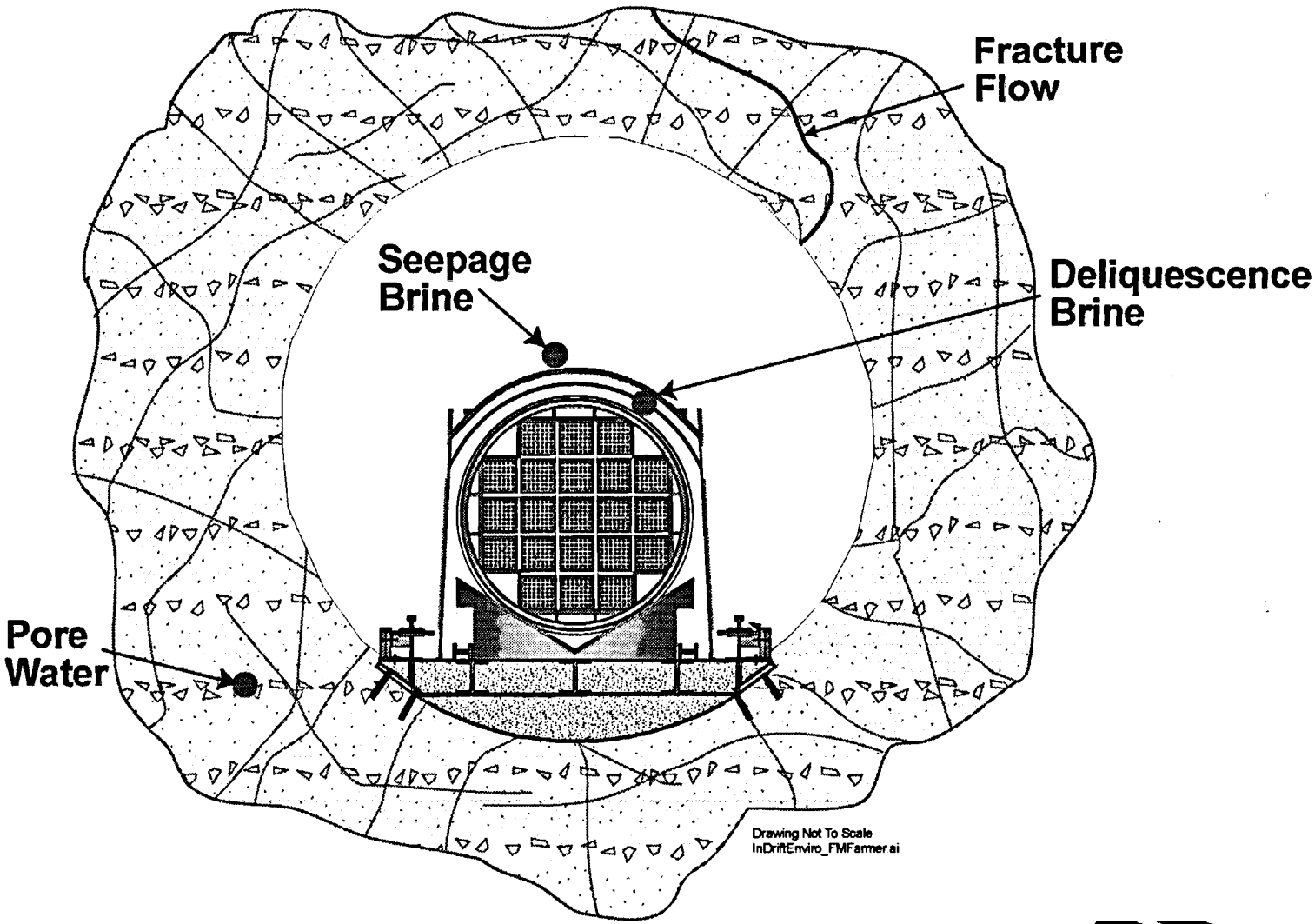
In-Drift Environment

- The evolving in-drift environment will determine the long-term performance of the waste package (WP) and drip shield (DS)
  - Drifts are in an unsaturated zone of highly fractured rock
  - They comprise an open system that will permit gas exchange with rocks and the surface
- Important in-drift characteristics include
  - Temperature (T)
  - Relative humidity (RH)
  - Chemistry of aqueous solutions
  - Interactions with metal substrates

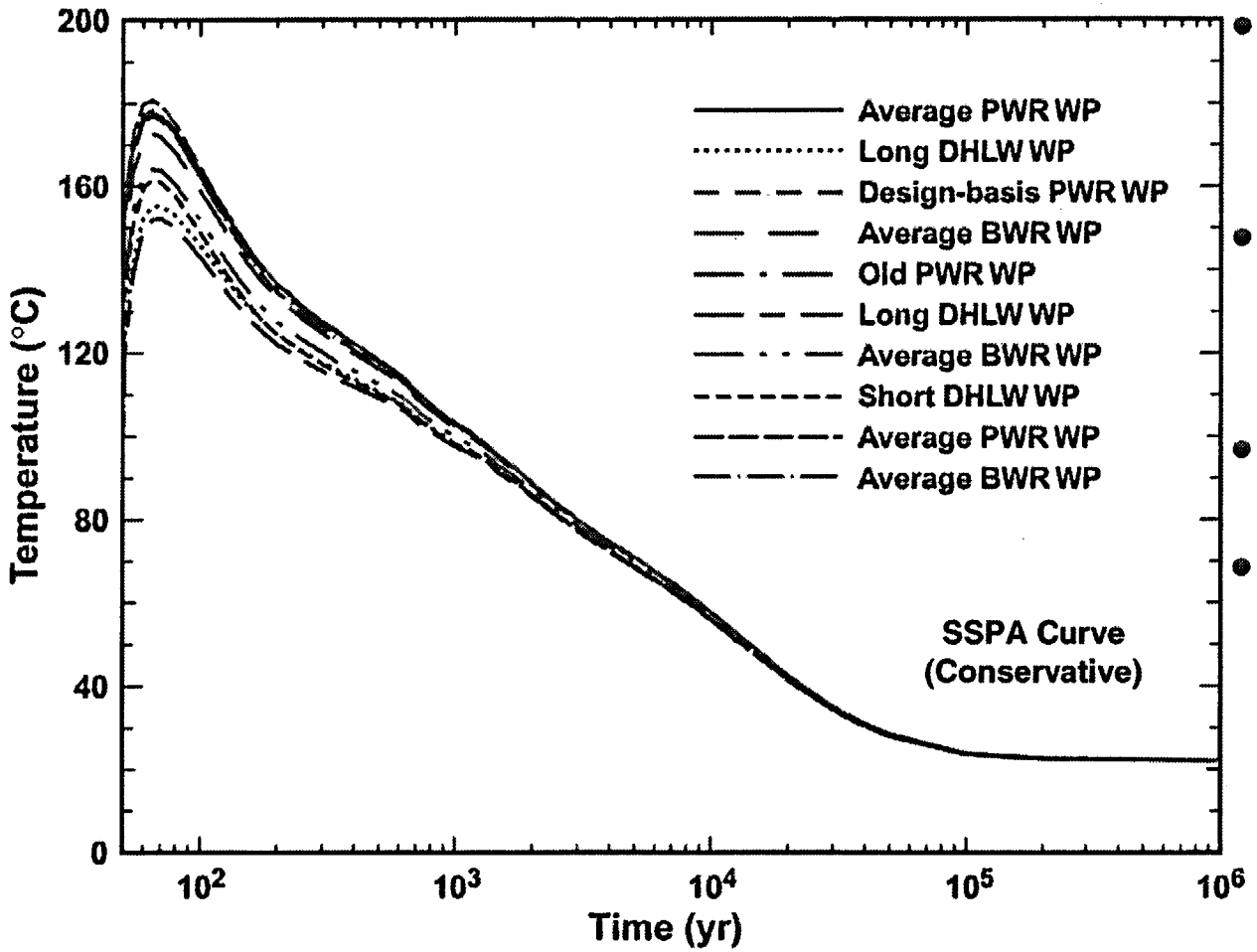


- Decay heat results in T elevation & RH reduction at WP & DS surface (relative to surrounding environment)
- Aqueous solutions may eventually contact WP & DS

In-Drift Environment

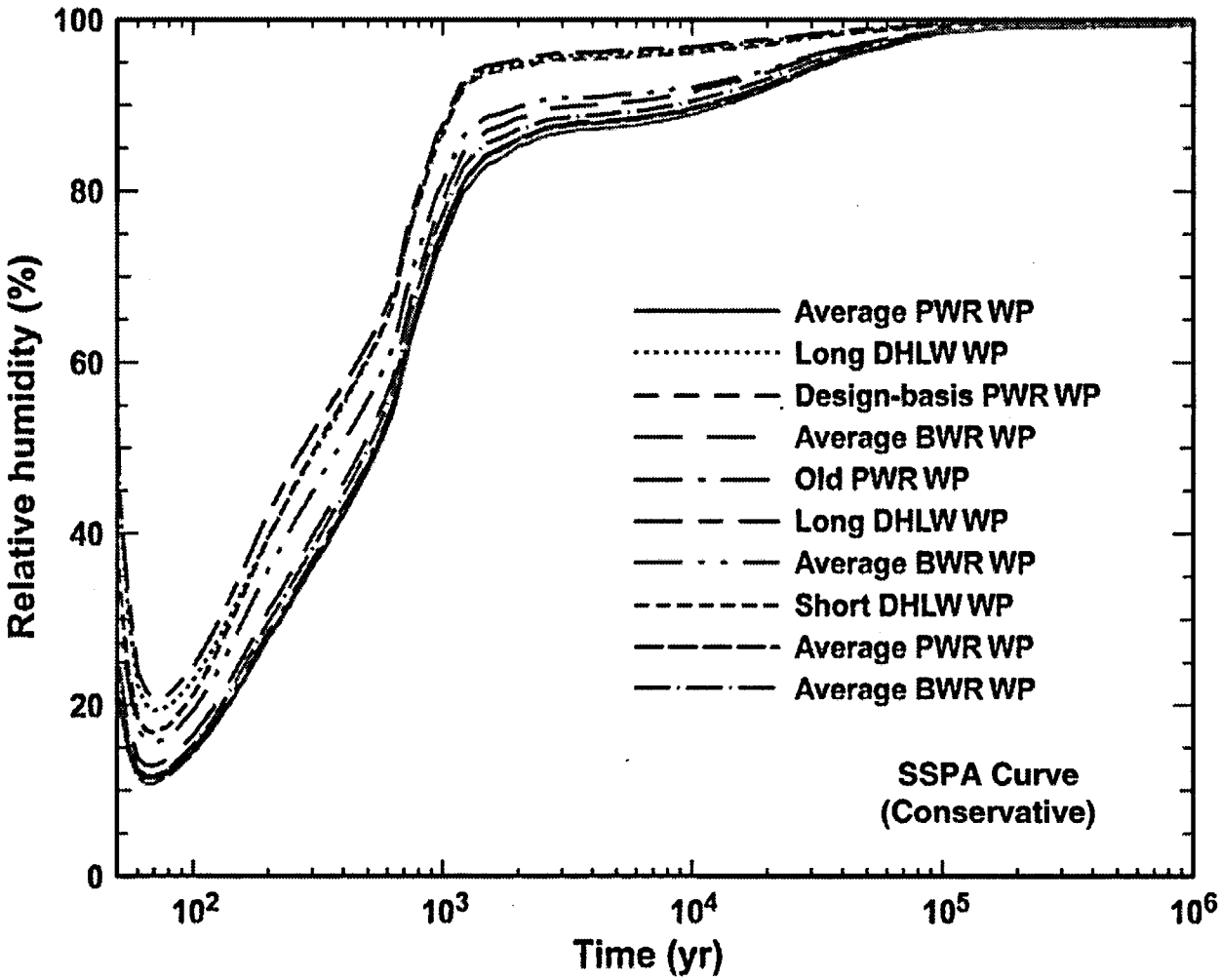


In-Drift Environment – Temperature



- Analysis from Supplemental Science and Performance Assessment (SSPA)
- Predictions for waste packages (WPs) at center of repository (hottest)
- Assumes all WPs are instantly emplaced
- A more realistic sequential emplacement process will lower WP temperatures by approximately 30°C

In-Drift Environment – Relative Humidity



- Analysis from FY01 Supplemental Science and Performance Assessment analysis (SSPA)
- Represents waste-packages at the center of the repository (hottest)
- Waters that are in contact with WPs will be brines because of the low to moderate RHs, other solutions unstable

Categories of Water at Yucca Mountain

- Precipitation (Rain & Snow)
  - Water at Surface of Mountain
- Vadose (Fracture) Water
  - Possible Source of Seepage Into Drifts
- Matrix (Pore) Water
  - Held in Pores of Rock by Capillary Forces
  - Extraordinary Effort (Centrifugation) Required for Removal
- In-Drift Chemistry – Possible Contact with Waste Package
  - Deliquescence Brines from Dust-Water Interaction (Expected)
  - Seepage Brines from Fracture Flow (Expected)
  - Calcium Chloride Brines from Pore Water (Unlikely)
  - Acid Gas Evolved from Calcium Chloride Brines (Unlikely)
- Perched Water & Ground Water

In-Drift Chemistry

- Deliquescence Brines from Dust-Water Interaction (Expected)
  - Low-to-Neutral pH ($6 < pH < 9$)
  - Salt mineral assemblages pertinent to real dusts are more complex and include many different anions
  - Present on waste package surface in very small amounts ...
- Seepage Brines from Fracture Flow (Expected)
  - High pH from Grout Interactions ($9 < pH < 12.5$)
  - These brines are also complex and include many different anions
  - Volumetrically more important than deliquescence brine ...
- Calcium Chloride Brines from Pore Water (Unlikely)
  - No known mechanism for getting pore water from rock to the waste package surface

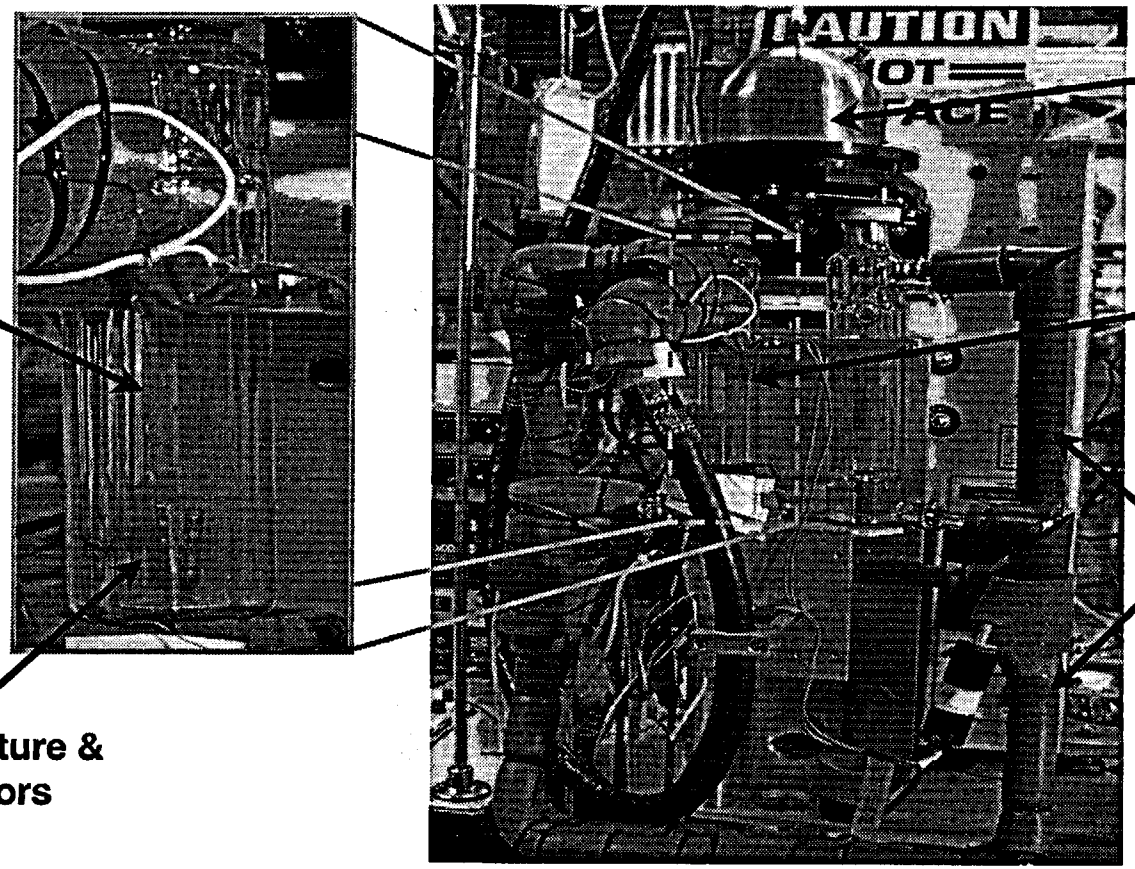
In-Drift Chemistry

- Acid Gas (Unlikely)
  - Produced by thermal decomposition of calcium chloride brines based on evaporative concentration of synthetic pore waters
  - These acid gases can be condensed in artificial conditions to form low to moderate pH solutions
  - Volatility is dependent on temperature and chemical species
    - $CO_2 > HF > HCl > HNO_3$
  - The pH in residue left behind would actually rise due to loss of hydrogen ion (electroneutrality and conservation of charge)
    - Solubility of aqueous components may change
  - Any volatile species entering drift air will be distributed and greatly diluted ... species would be adsorbed and diluted

Deliquescence Brines – Testing Program

- **Objective of Studies**
  - Characterization of aqueous films that may form on the WP surface due to deliquescence
  - Quantification of associated modes of corrosion
- **Test Conditions**
  - Fixed relative humidity (RH) and temperature (T)
  - Deposits of $CaCl_2$ and $CaNO_3$ salts
- **Measurements**
  - In situ measurement of weight change of samples with custom environmental thermogravimetric analyzer (TGA)
  - Surface analysis of specimens after exposure

Deliquescence Brines – TGA



Alloy 22 or 825 Sample

Temperature & RH Sensors

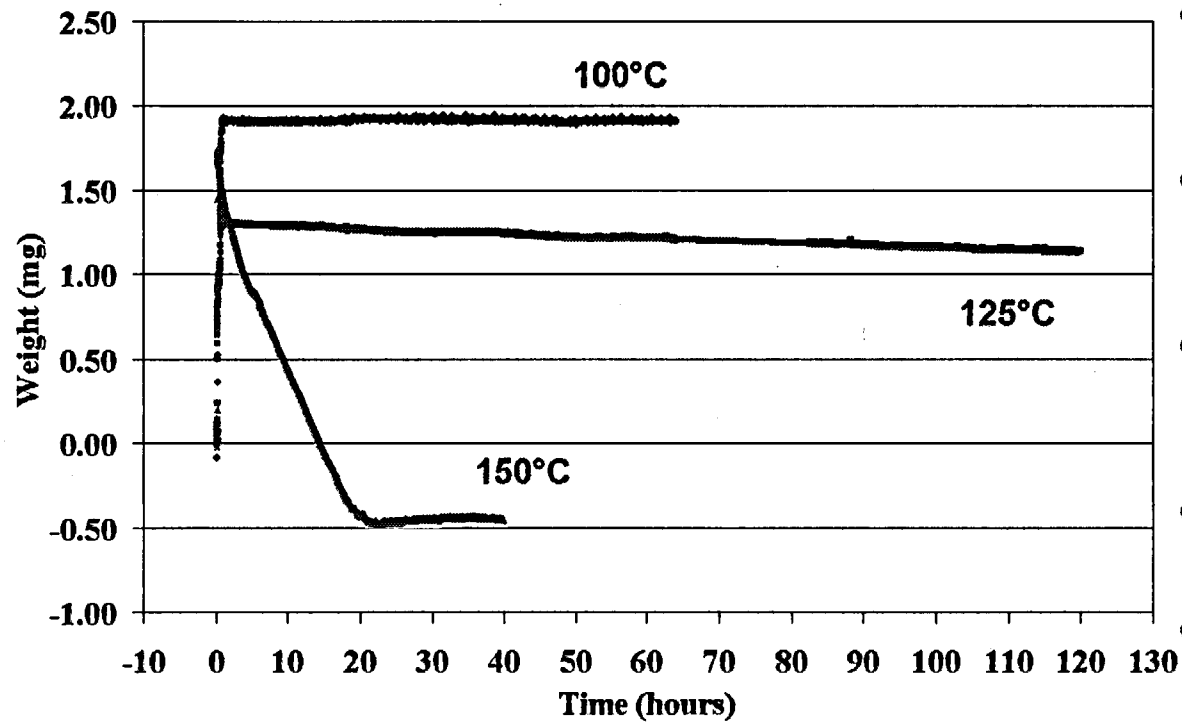
Micro Balance Housing

Sample Chamber

Heating Fluid Lines

- Apparatus is sensitive to weight changes of the order of tens of micrograms
- Operation up to 150°C

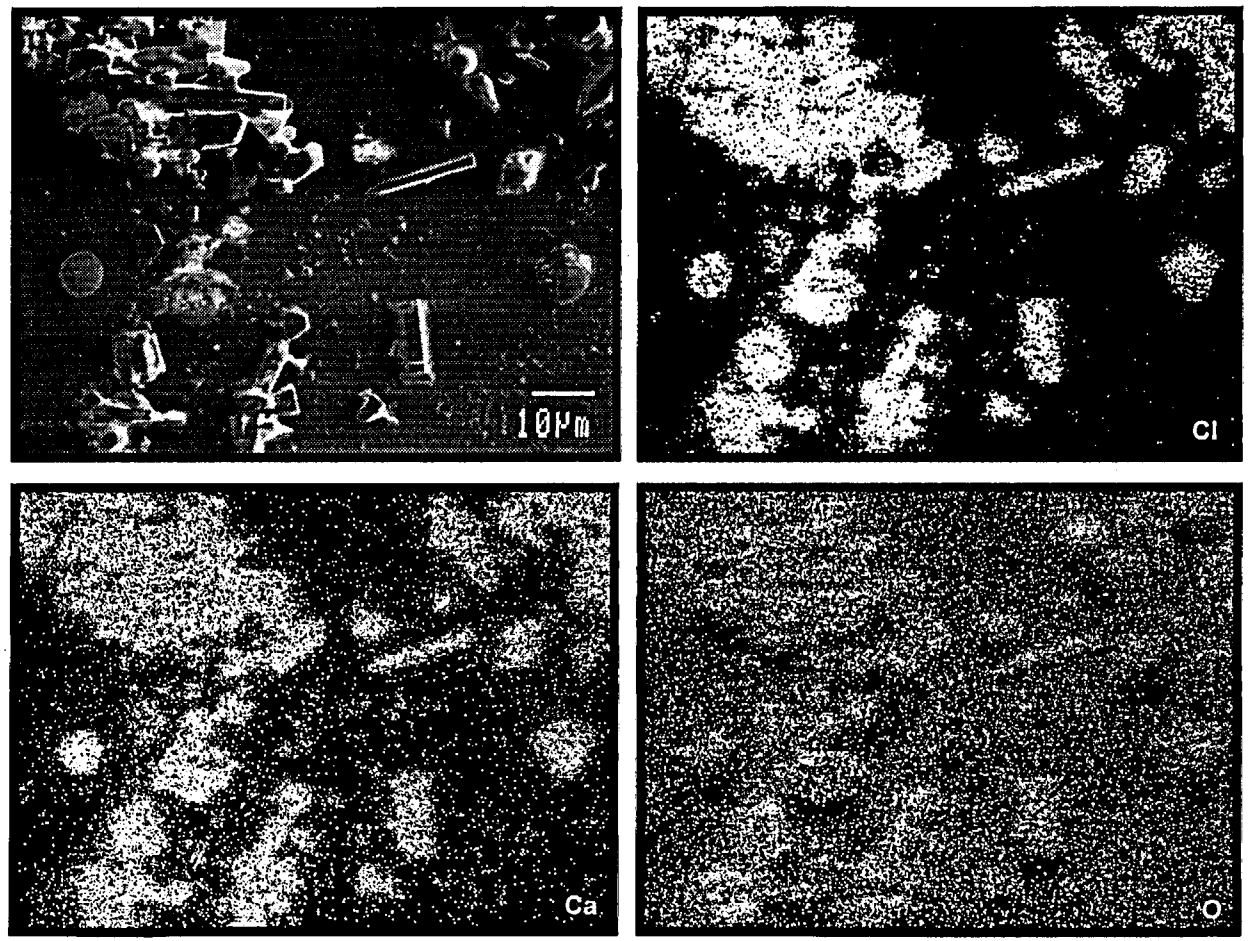
Deliquescence Brines – Deposit Formation



Alloy 22
22.5% RH
$CaCl_2$ initially deposited

- 100°C: $CaCl_2$ aqueous films are stable for duration for test
- 125°C: solution evolves slowly, forming insoluble precipitates
- 150°C: solution evolves rapidly, forming insoluble precipitates & acid gas
- No detectable Alloy 22 degradation
- Precipitates from 150°C and 125°C tests are similar
- Solution properties to be modeled in order to understand evolution

Deliquescence Brines – Deposit Formation



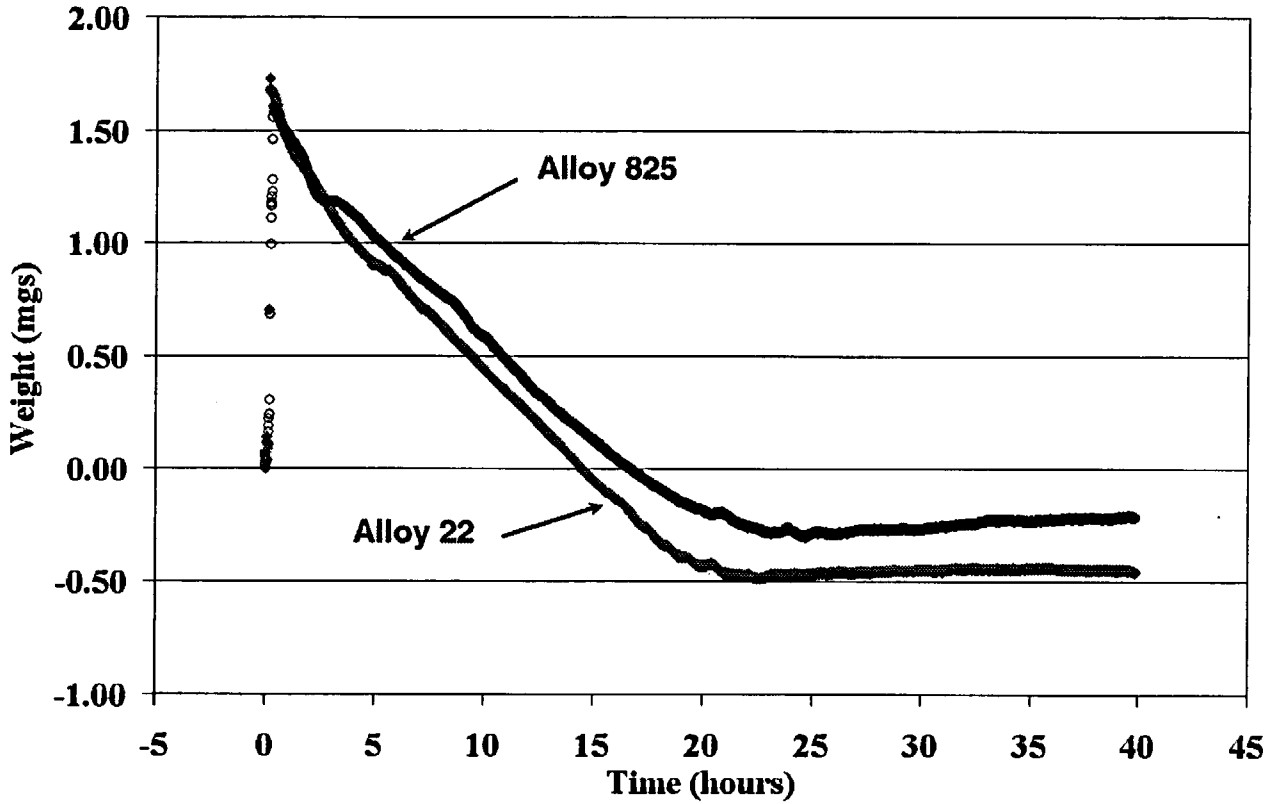
- EDS analysis indicates precipitates contain Ca, Cl, and O
- EDS & wet-chemical analyses indicate a loss of Cl relative to Ca (HCl volatilization)
- Raman spectroscopy indicates that precipitates are not $Ca(OH)_2$ or $CaCO_3$
- Precipitates are possibly a Ca(OH)Cl

Deliquescence Brines – Alloy 22 vs. 825

- Alloy 22 was shown to be resistant to localized attack under representative deliquescence brines (aqueous films)
  - Alloy 22 is identified as UNS # N06022
  - 55.5 Ni – 22 Cr – 13 Mo – 3 W – 4 Fe – 2.5 Co
- Alloy 825 is a less corrosion-resistant material and was tested in parallel to provide insight into localized modes of attack
  - Alloy 825 is identified as UNS # N08825
  - 42 Ni – 22 Cr – 3 Mo – 0.9 Ti – 2.2 Cu – 1 Mn – 28.9 Fe

Deliquescence Brines – Alloy 22 vs. 825

(Continued)



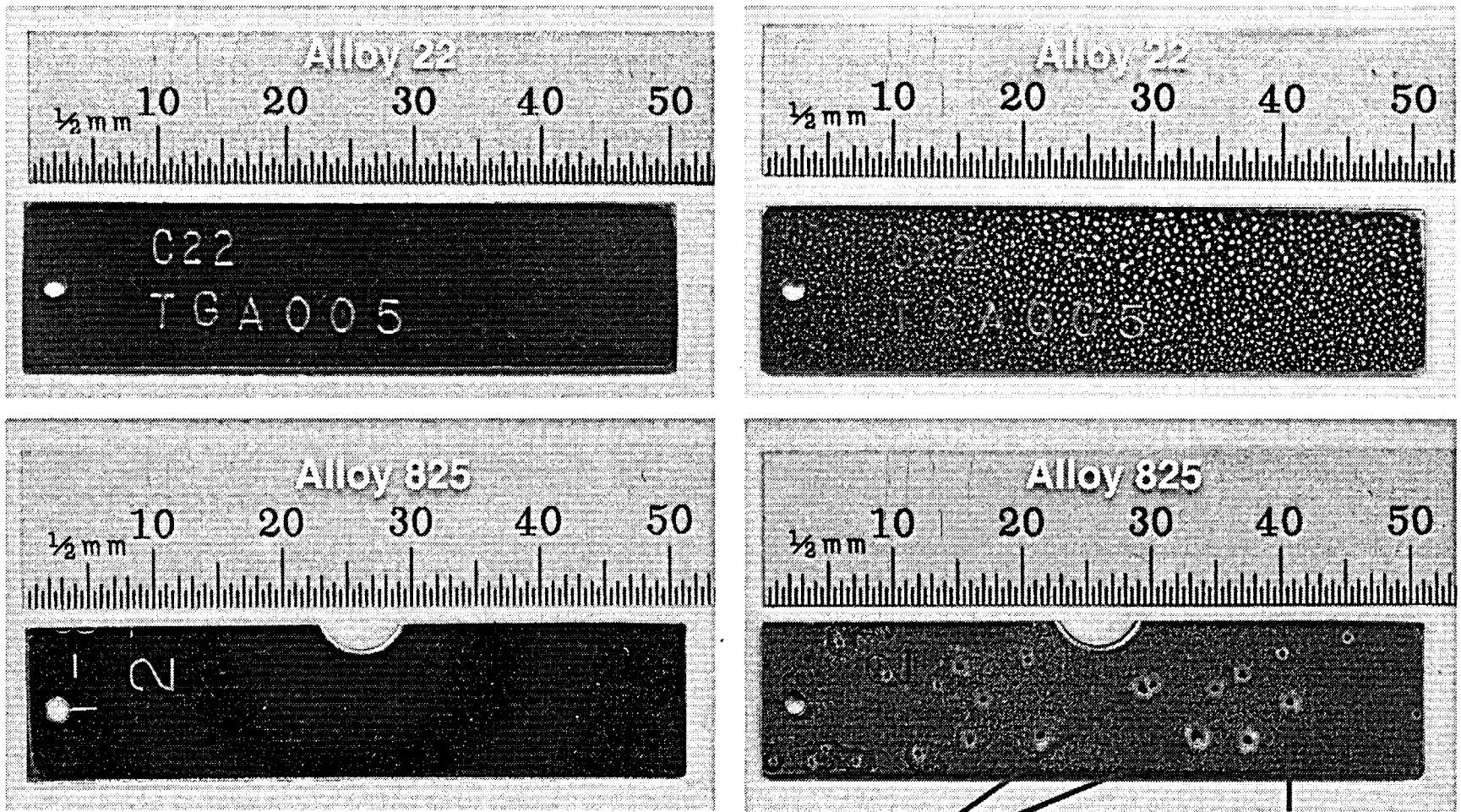
150°C
22.5% RH
$CaCl_2$ deposited

- Insoluble precipitates formed on Alloy 825
- White precipitates similar to those on Alloy 22
- In addition, reddish-brown precipitates formed on Alloy 825
- In contrast to Alloy 22, there was localized attack on Alloy 825

Deliquescence Brines – Alloy 22 vs. 825

(Continued)

Pre-Test Specimen | **Post-Test Specimen**



Ca-rich precipitates (light)

Precipitates containing Fe (dark)

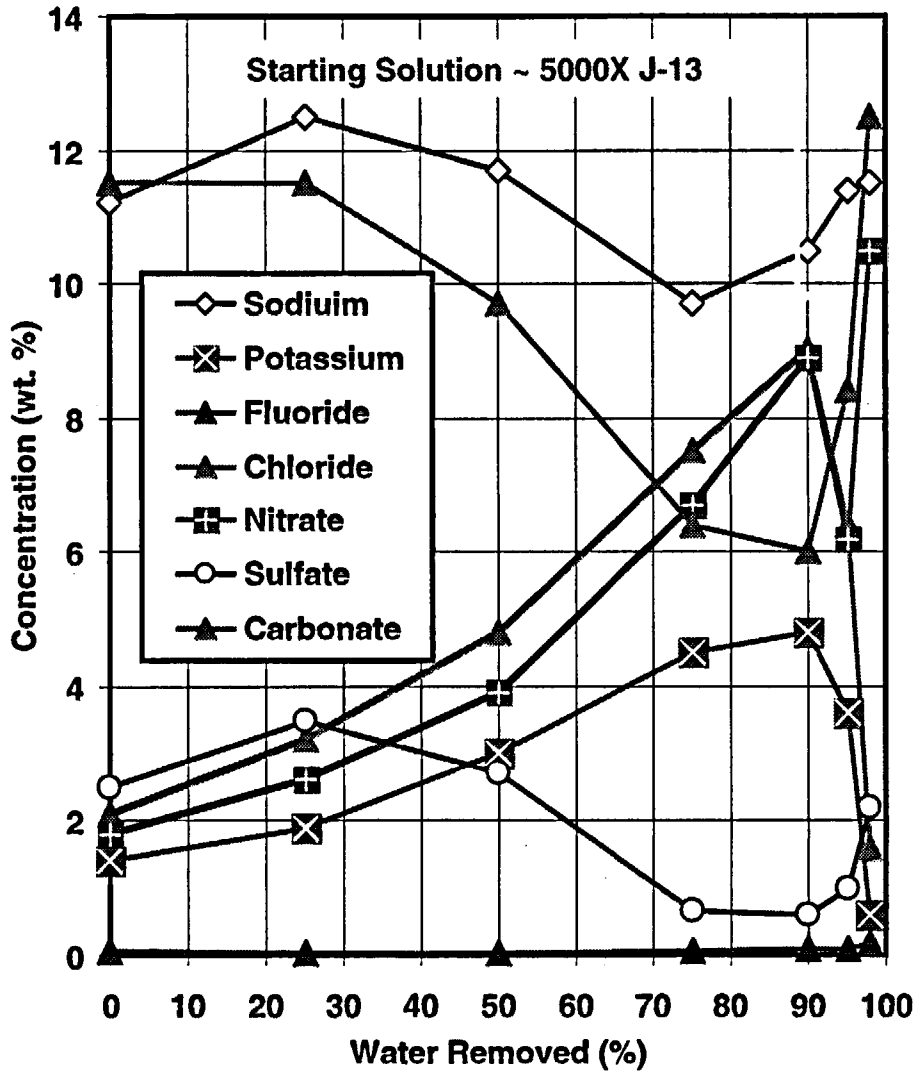
YUCCA MOUNTAIN PROJECT

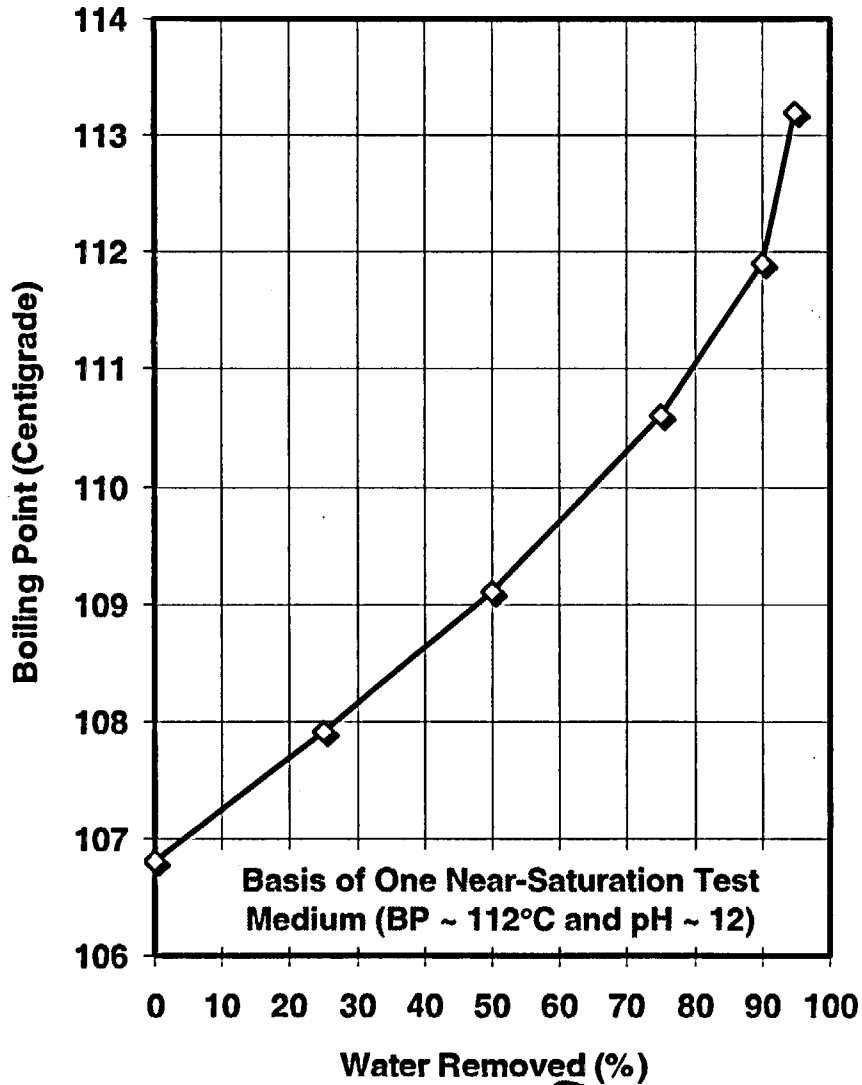
Deliquescence Brines – Alloy 22 vs. 825

(Continued)

- **Formation of Insoluble Precipitates at 125-150°C**
  - Precipitates are distributed across metal surface
  - Contains Ca, Cl, and O
  - Possibly a Ca(OH)Cl species
- **Corrosive Attack**
  - No detectable degradation of Alloy 22 based on surface analysis
  - Substantial localized attack of Alloy 825
  - Attack arrested due to formation of precipitates
- **Evidence of acid gas formation**
  - Chloride was lost from surfaces during tests
- **Precipitation of insoluble Ca species slowed by the presence of nitrate**
  - Mechanism may involve dilution effect

Seepage Brines – Evaporative Concentration

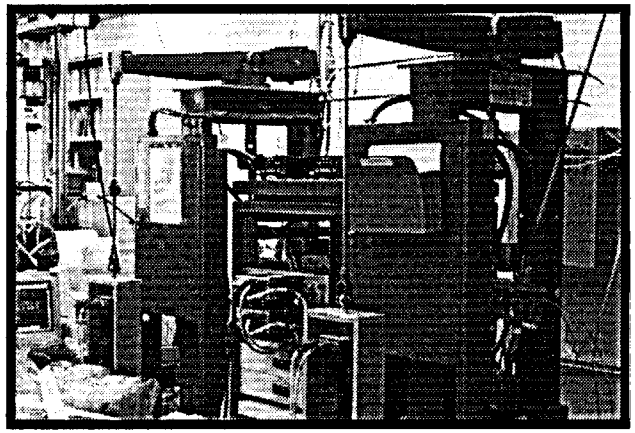




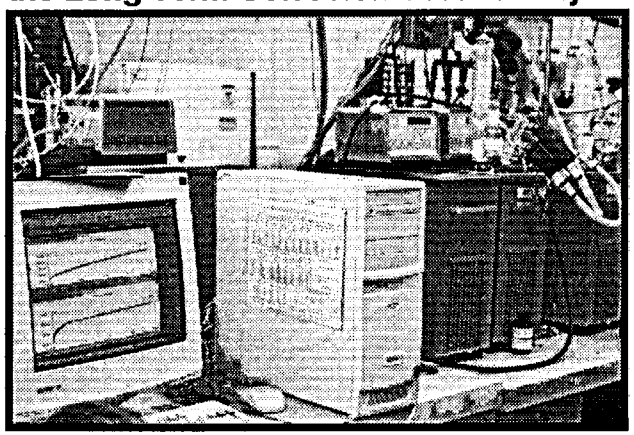
Note: Chloride Nitrate ratios close to 1:1

Seepage Brines – Testing Program

Thousands of waste package samples are exposed to repository-relevant conditions in the Long Term Corrosion Test Facility



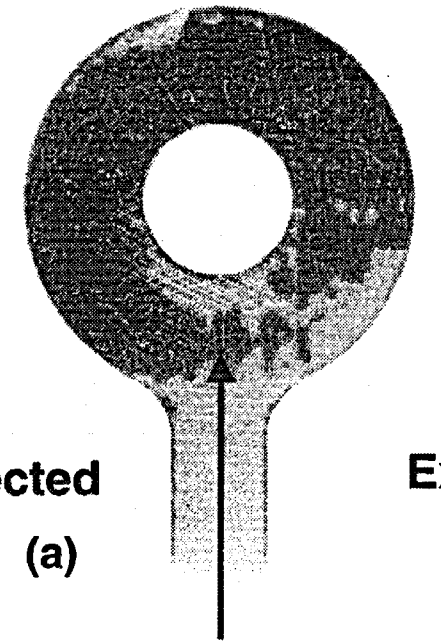
Propagation of stress corrosion cracks (SCC) is monitored *in situ* with the Reverse DC Technique



Arrays of potentiostats are used to measure threshold potentials for localized corrosion & the time-evolution of the corrosion potential

Seepage Brines – Crevice Corrosion

Alloy 22 Crevices
Ceramic Washer
Ramped to 550 mV
~ 100°C BSW

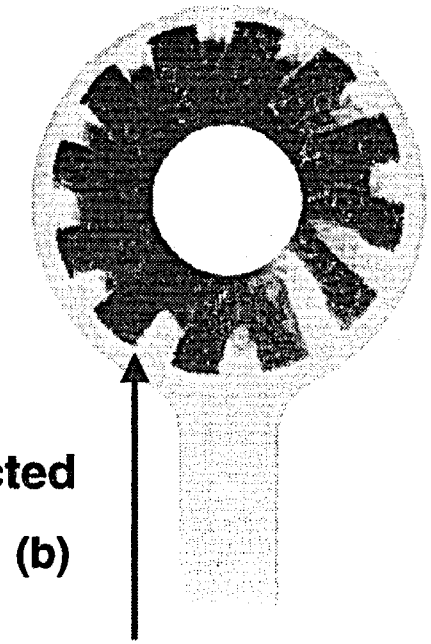


Expected

(a)

No crevice attack

Alloy 22 Crevices
Teflon Washer
Ramped to 800 mV
~ 110°C BSW

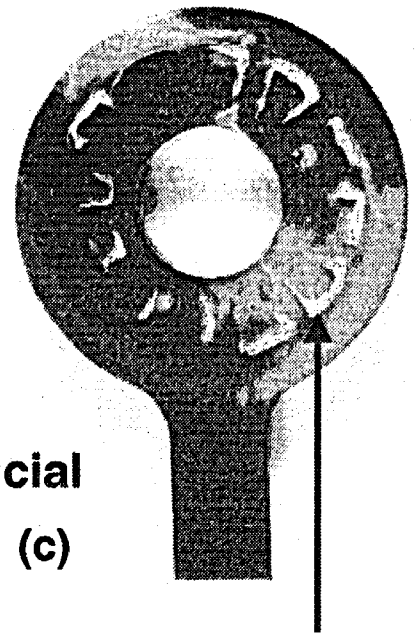


Expected

(b)

Stain but no crevice attack in BSW

Alloy 22 Crevices
Ceramic Washer
350 mV for 2 hours
~ 100°C 4M NaCl



Artificial

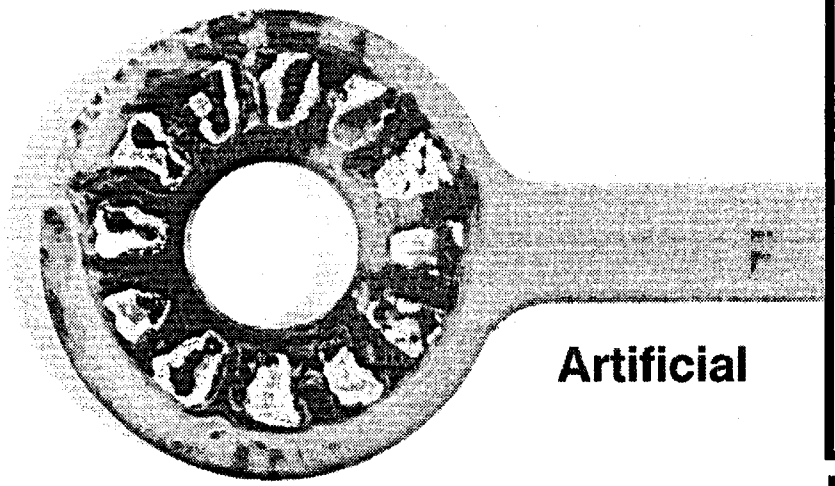
(c)

Severe crevice attack of sample

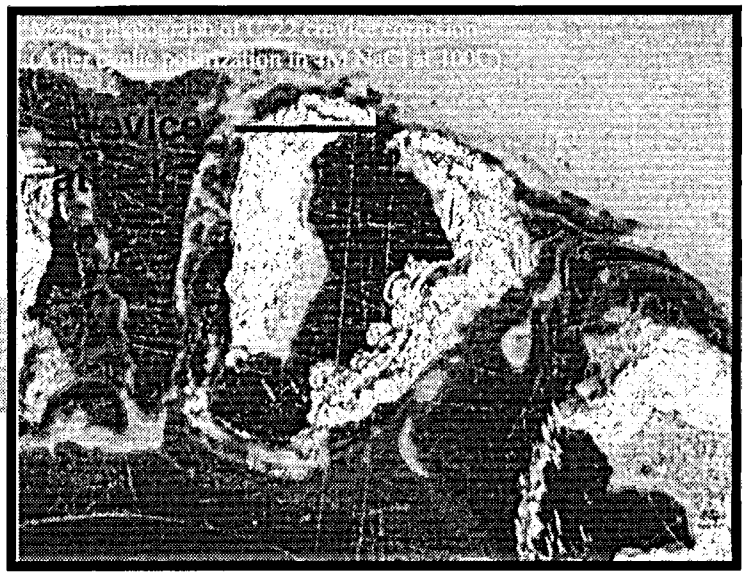
In the case of (a) and (c) above, the potential was increased until a current density of 5 mA cm^{-2} was achieved.

Inhibitor Ions Prevent Crevice Corrosion in Expected Environment

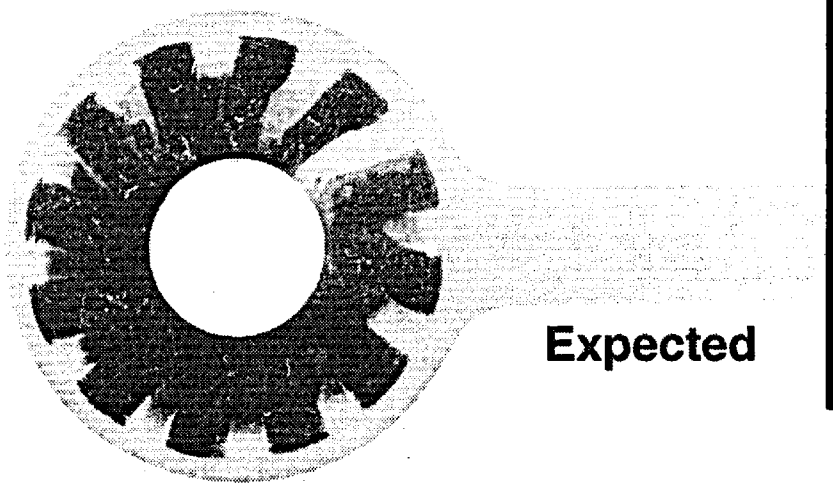
Alloy 22 Crevices - Ceramic
~ 100°C 4M NaCl: Cyclic Polarization



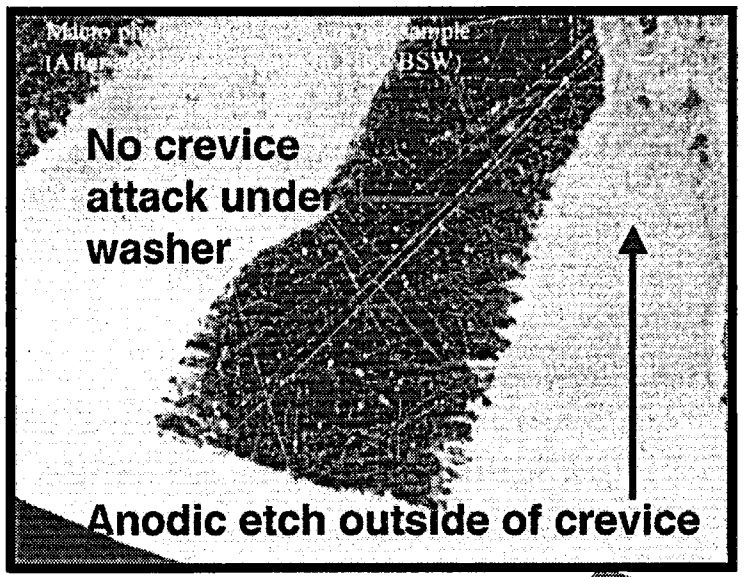
Artificial



Alloy 22 Crevices - Teflon
~ 110°C BSW: Ramped to 800 mV



Expected



$CaCl_2$ Brines – Localized Corrosion

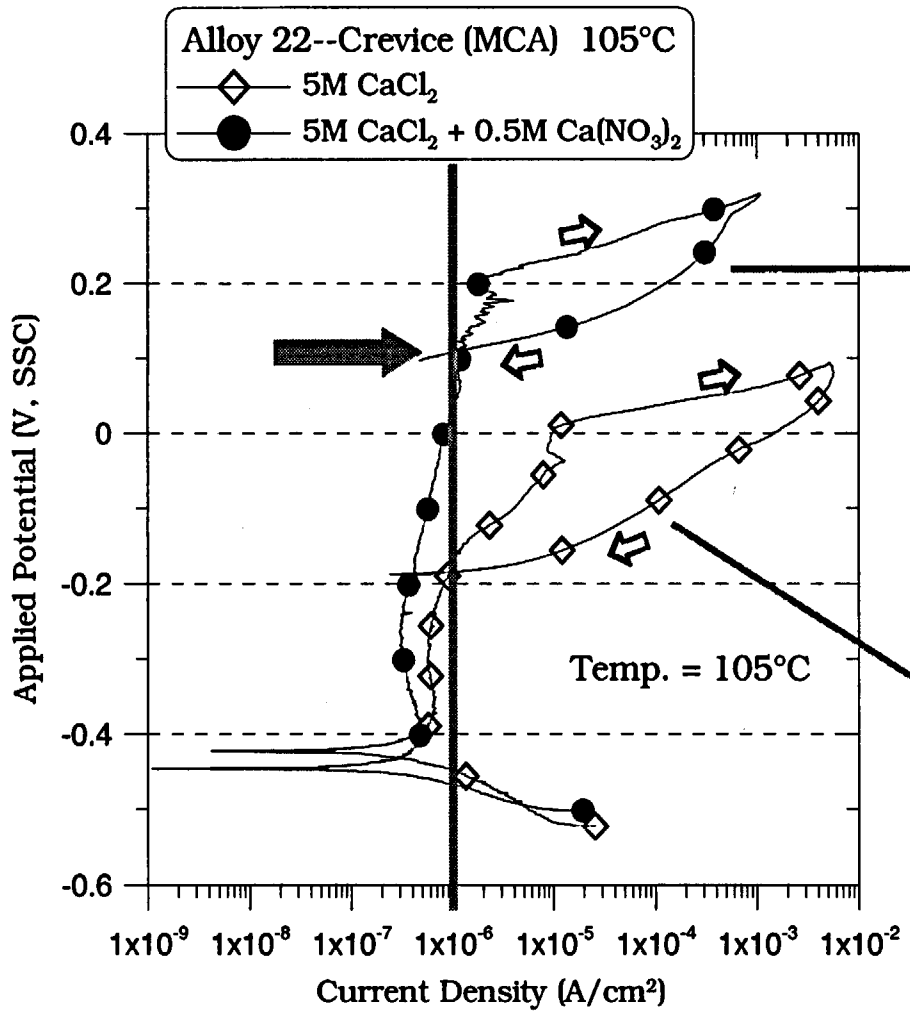
- **Objective of Study**
  - Quantify the threshold for localized corrosion in aqueous solutions
- **Test Conditions**
  - Chloride Concentrations: 10 to 18 Molar (near saturation)
  - Inhibitor Level: NO_3^-/Cl^- = 0.0 & 0.1
  - Temperature Range: 45 to 160°C
- **Measurements**
  - Cyclic polarization in temperature controlled electrochemical cell
  - Alloy 22 samples: disks and multiple crevice assemblies
  - Surface analysis of specimens after exposure

$CaCl_2$ Brines – Localized Corrosion

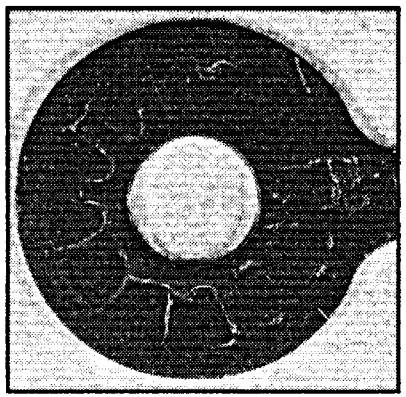
(Continued)

- **Determination of Threshold Potential for Localized Attack**
  - E_{corr} is the stable open-circuit corrosion potential ...
    - Achieved after monitoring the sample for 24 hours
    - Not taken from the cyclic polarization curve
  - E_{R1} is the repassivation potential ...
    - Defined as the potential at which the current density drops to levels indicative of passivity during the reverse scan ... where the hysteresis loop intersects the forward going scan
    - The passive current density is approximately 1 $\mu A/cm^2$
    - Repassivation of the active surface is assumed to occur when the current density drops to this level
  - The threshold for localized corrosion is defined in terms of ΔE
    - Localized corrosion occurs when $\Delta E \leq 0$ ($E_{corr} \geq E_{R1}$)
    - $\Delta E = E_{R1} - E_{corr}$

CP of Alloy 22 in $CaCl_2$ Brines at 105°C

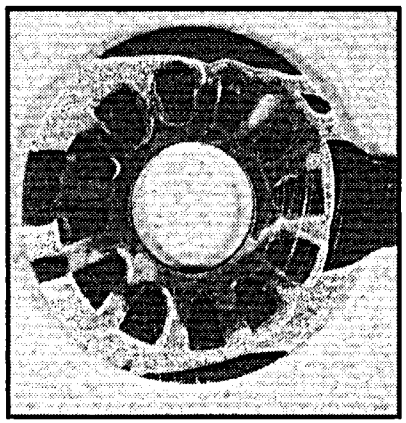


5M $CaCl_2$ + 0.5M $Ca(NO_3)_2$



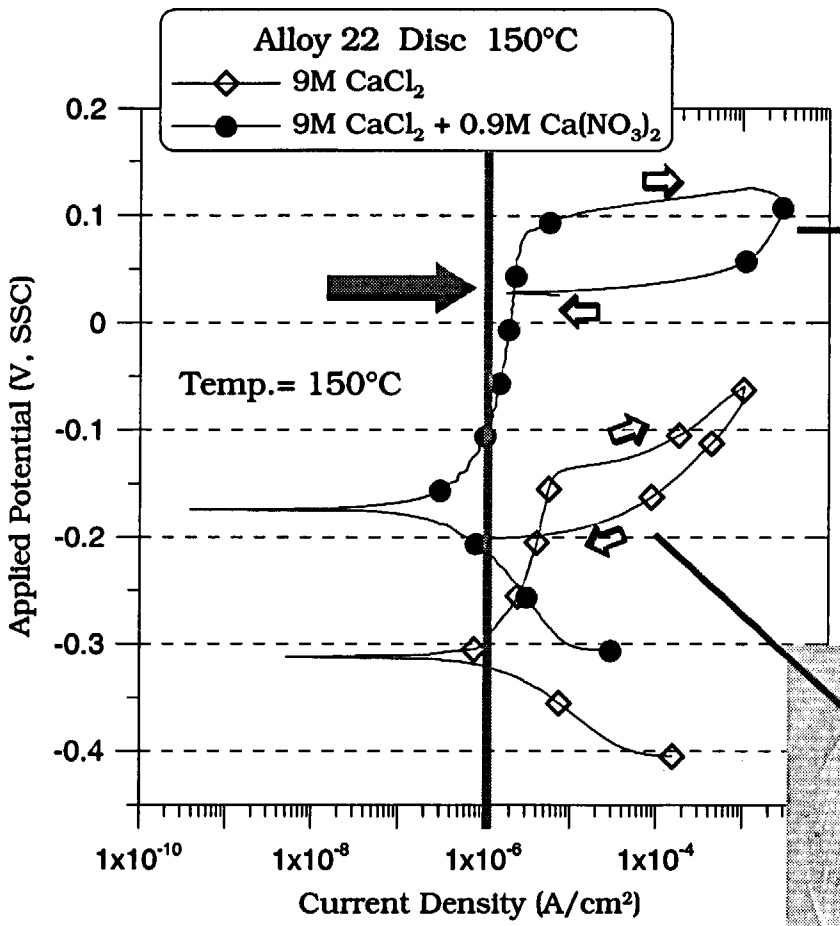
Top

5M $CaCl_2$

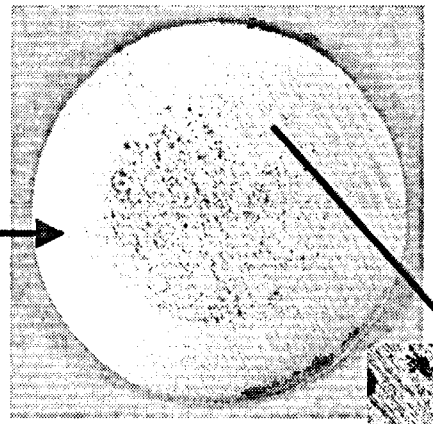


Top

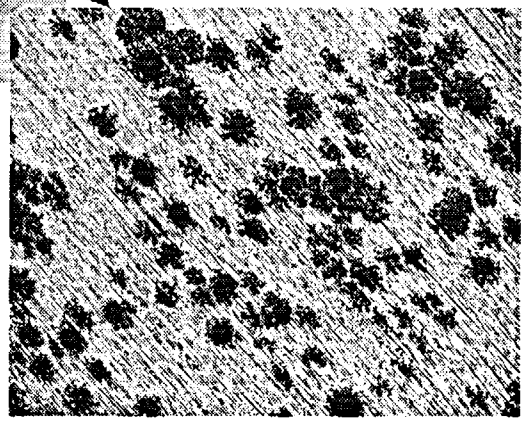
CP of Alloy 22 in $CaCl_2$ Brines at 150°C



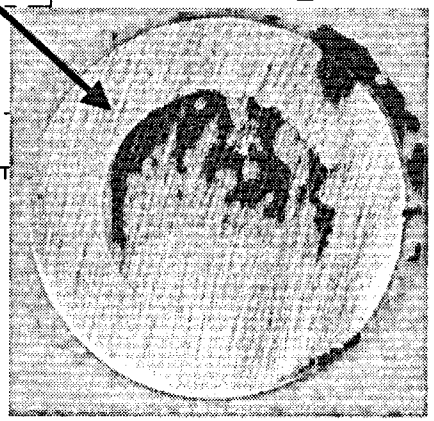
9M $CaCl_2$ + 0.9M $Ca(NO_3)_2$



100X

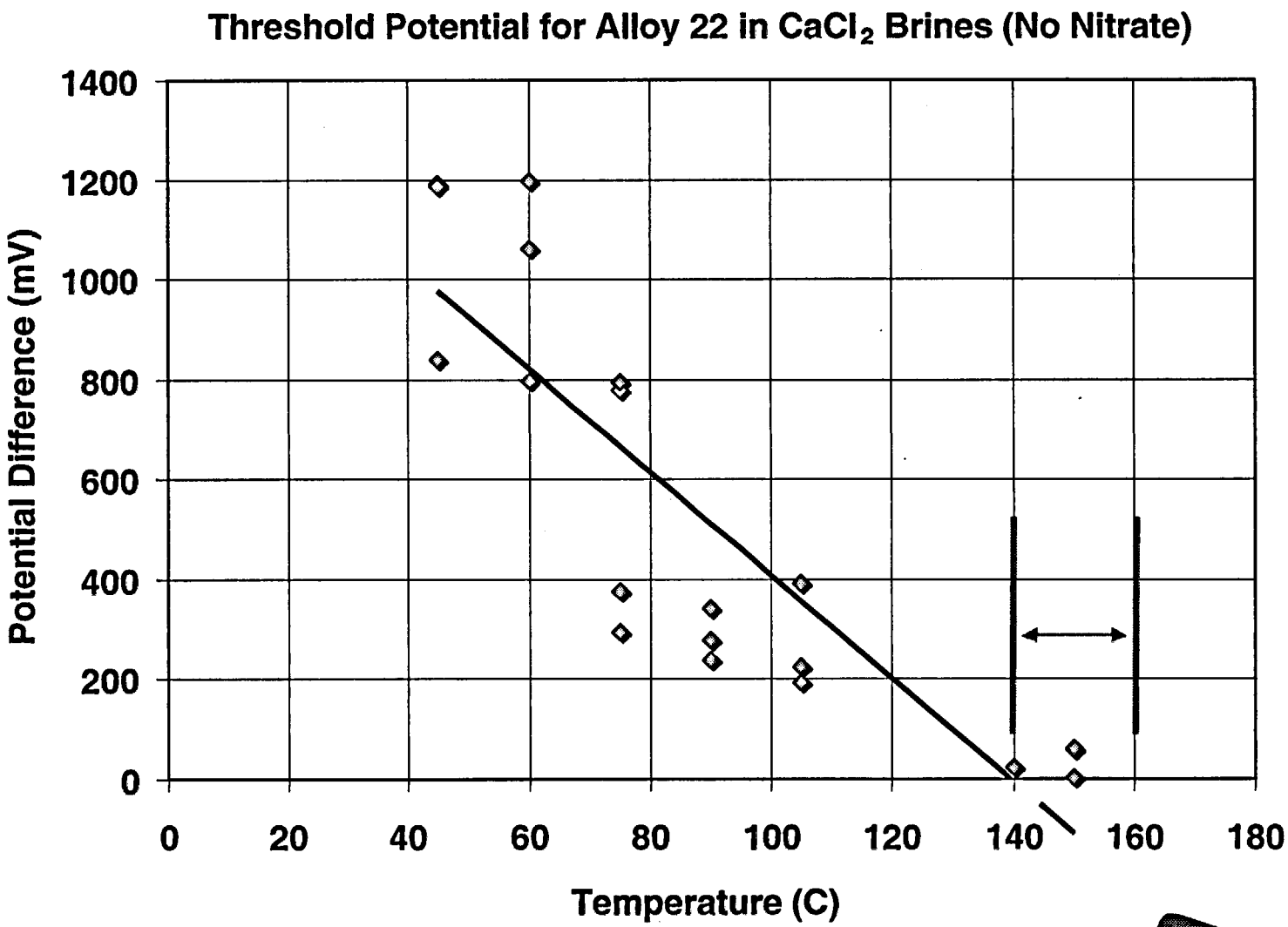


9M $CaCl_2$



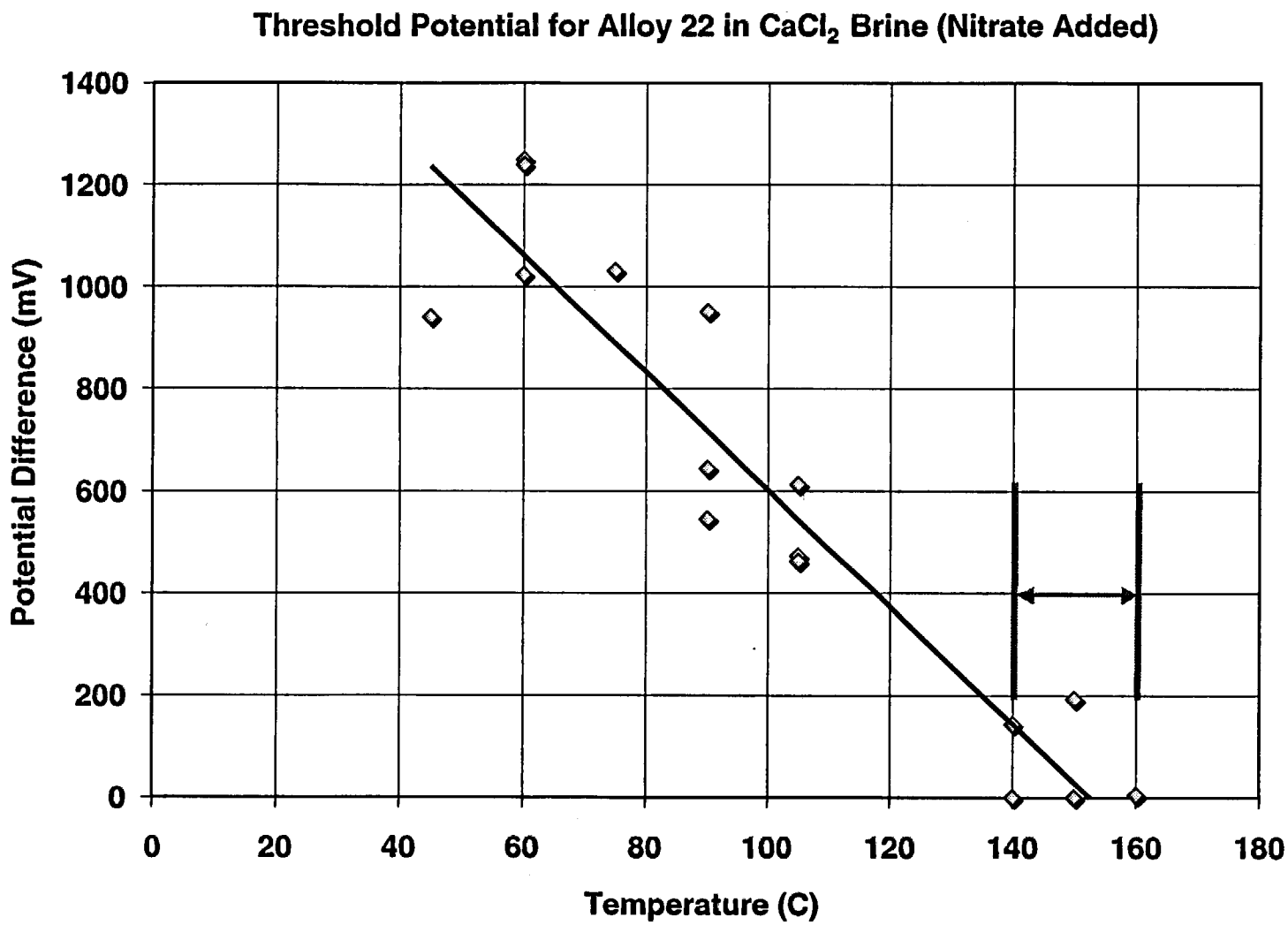
Disc Samples

CP of Alloy 22 in $CaCl_2$ Brines (No Nitrate)



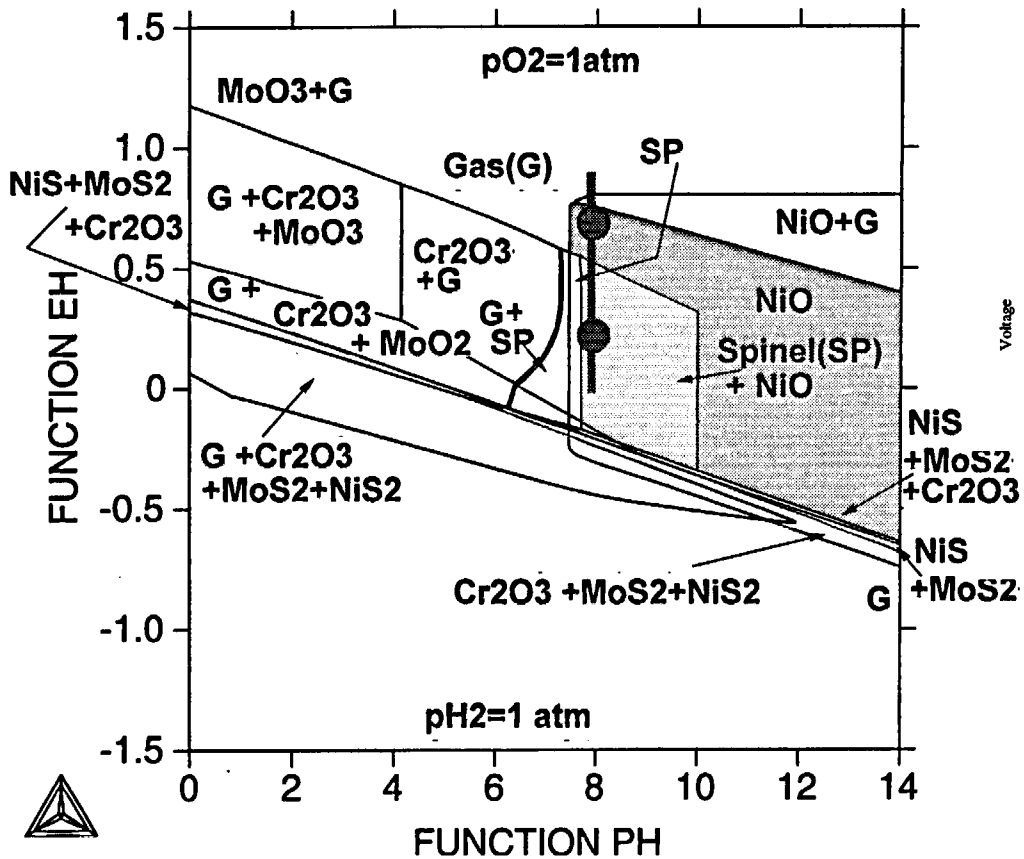
CP of Alloy 22 in $CaCl_2$ Brines (No Nitrate)

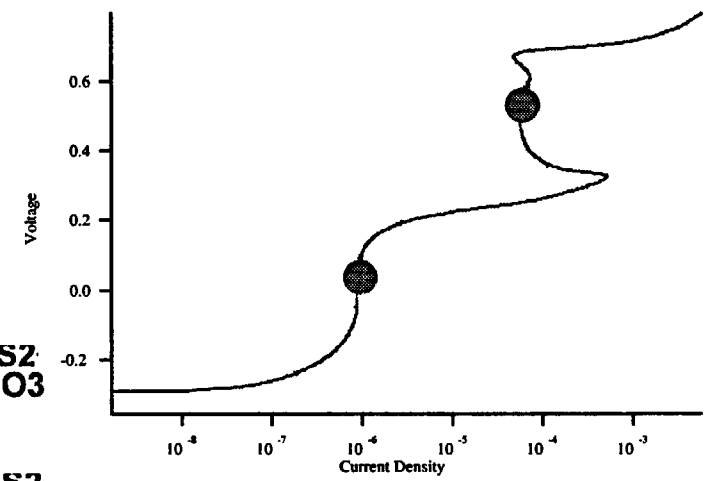
(Continued)



Environment-Surface Interactions

Pourbaix Diagrams Predict Stable Equilibrium Oxide Phases





(Ni, Cr, Mo Alloy SCW, 25°C)
Calculations by Larry Kauffman

Pourbaix diagrams are being used to help establish the chemical stability of Alloy 22 in relevant environments.

Heat Transfer Through Scale

- Mineral scale on WP may inhibit rate of heat transfer
  - Elevated temperatures under deposits
  - Thermogalvanic corrosion
- Modeling has been conducted to determine the extent that scale build-up can effect temperature variation
- Comparison of Heat Fluxes (Nominal)
  - Waste packages (heat transferred to air): 0.3 to 0.4 kW/m^2
  - Steam generators (heat transfer to water): 0.14 to 0.22 MW/m^2
  - These two cases are very different

Reference: W.D. Fletcher and D.D. Malinowski, Operating Experience with Westinghouse Steam Generators, Nuclear Technology 28, 356-373 (1976)

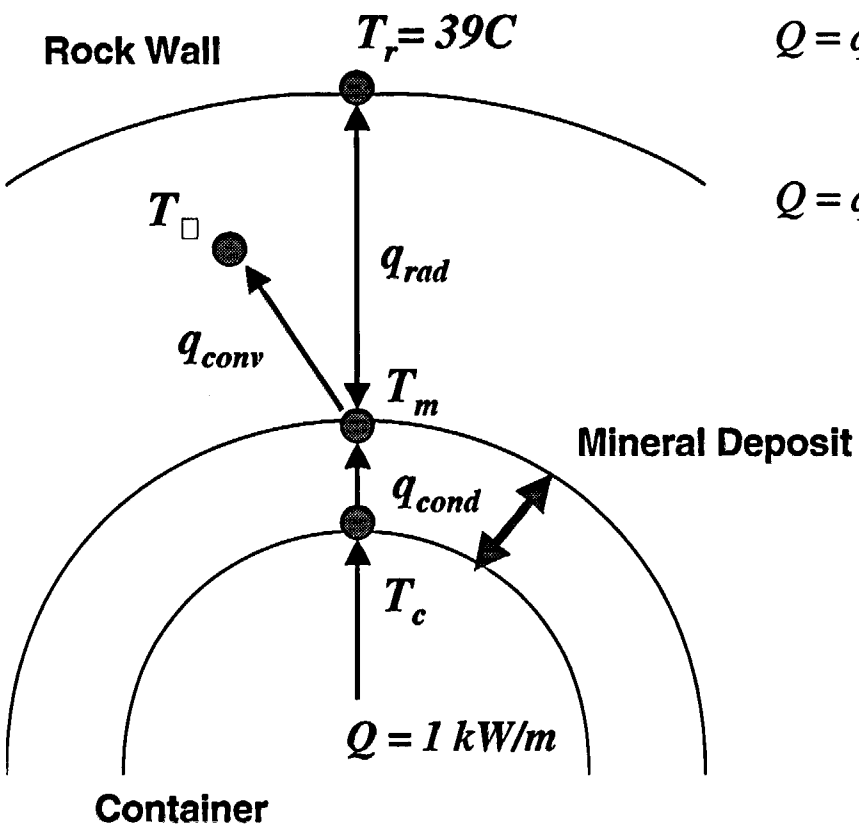
Heat Transfer Through Scale

(Continued)

The container wall temperature can be readily calculated by solving the following heat-transfer equations simultaneously ...

$$Q = q_{conv} + q_{rad} = h\,2\pi\, r_m\, L\left(T_m - T_\infty\right) + \frac{\sigma\, 2\pi\, r_m L\left(T_m^4 - T_r^4\right)}{\frac{1}{\varepsilon_m} + \frac{1-\varepsilon_r}{\varepsilon_r}\left(\frac{r_m}{r_r}\right)}$$

$$Q = q_{cond} = \frac{2\pi\, k_m L}{\ln\left(\frac{r_m}{r_c}\right)}\left(T_c - T_m\right)$$



Deposit Thickness (cm)	T_c [C]	T_m [C]
0	63.6	63.6
1	66.8	63.4
2	70.0	63.1
3	73.1	62.9
4	76.2	62.6

Note: the results are for a uniform mineral deposit covering the entire surface. The temperature rise will be much less for spot deposits.

Heat Transfer Through Scale

(Continued)

- **Boundary Conditions for Heat Transfer Equations**
  - Temperature at the drift wall (rock) = 39°C ($T_r = 39°C$)
  - Average linear power of waste package = 1 kW/m ($Q = 1.0\ kW/m$)
  - Temperature of air in the drift is set to average ($T_8 = (T_m + T_r)/2$)
- **Characteristic Dimensions**
  - The container length is assumed to be 1 m ($L = 1\ m$)
  - The container radius is assumed to be 0.835 m ($r_c = 0.835\ m$)
  - The drift (rock) radius is assumed to be 2.75 m ($r_r = 2.75\ m$)
- **Important Characteristics & Properties**
  - Heat transfer coefficient for free convection ($h = 1.83\ W/m^2\text{-}K$)
  - Waste package surface emissivity 0f 0.87 ($e_c = 0.87$)
  - Rock surface emissivity of 0.90 ($e_r = 0.90$)
  - Calcium carbonate mineral deposit with a 55% porosity
    - The thermal conductivity of 0.55 W/m-K ($k_m = 0.55\ W/m\text{-}K$)
    - Emmissivity of 0.90 ($e_m = 0.90$)

Summary

- Categories of Water Possibly Contacting Waste Package
  - Deliquescence Brines from Dust-Water Interaction (Expected)
  - Seepage Brines from Fracture Flow (Expected)
  - Calcium Chloride Brines from Pore Water (Unlikely)
  - Acid Gas Evolved from Calcium Chloride Brines (Unlikely)
- Deliquescence Brines from Dust-Water Interaction (Expected)
  - Low-to-Neutral pH ($6 < pH < 9$)
  - No Localized Corrosion of Alloy 22 at 150°C (Deliquescence)
  - The localized attack of Alloy 825 was stifled after limited attack
- Seepage Brines from Fracture Flow (Expected)
  - High pH from Grout Interactions ($9 < pH < 12.5$)
  - No Crevice Corrosion of Alloy 22 at 110°C (Boiling)

Summary
(Continued)

- $CaCl_2$ brines are unstable in open systems at high temperature, and are believed to be unrealistic
- Acidic solutions from $CaCl_2$ brines can not be maintained at elevated temperature under continuous-flow (open-system) conditions
  - The volatilization of acid gas during the evaporative concentration of brines causes the pH of the residue to increase
  - Volatilized acid gas will be distributed (diluted) in drift air
- Electrochemical testing in extremely concentrated artificial $CaCl_2$ solutions indicates that no localized attack of Alloy 22 should occur at temperatures below about 140 to 160°C

Backup

Acknowledgements

- Chemical Engineering & Electrochemistry
  - Joseph Farmer – Ph.D. Chemical Engineering, UC Berkeley
  - Greg Gdowski – Ph.D. Chemical Engineering, Stanford
- Geochemistry
  - Tom Wolery – Ph.D. Geological Sciences, Northwestern
  - Susan Carroll – Ph.D. Geological Sciences, Northwestern
- Materials Science, Metallurgy & Corrosion
  - R. Daniel McCright – Ph.D. Metallurgy, Ohio State
  - Tammy Summers – Ph.D. Materials Science, UC Berkeley
  - Raul Rebak – Ph.D. Metallurgy, Ohio State
  - Gabriel Ilevbare – Ph.D. Materials Science, Cambridge
  - Tiangan Lian – Ph.D. Materials Science, University of Nevada

Acknowledgements
(Continued)

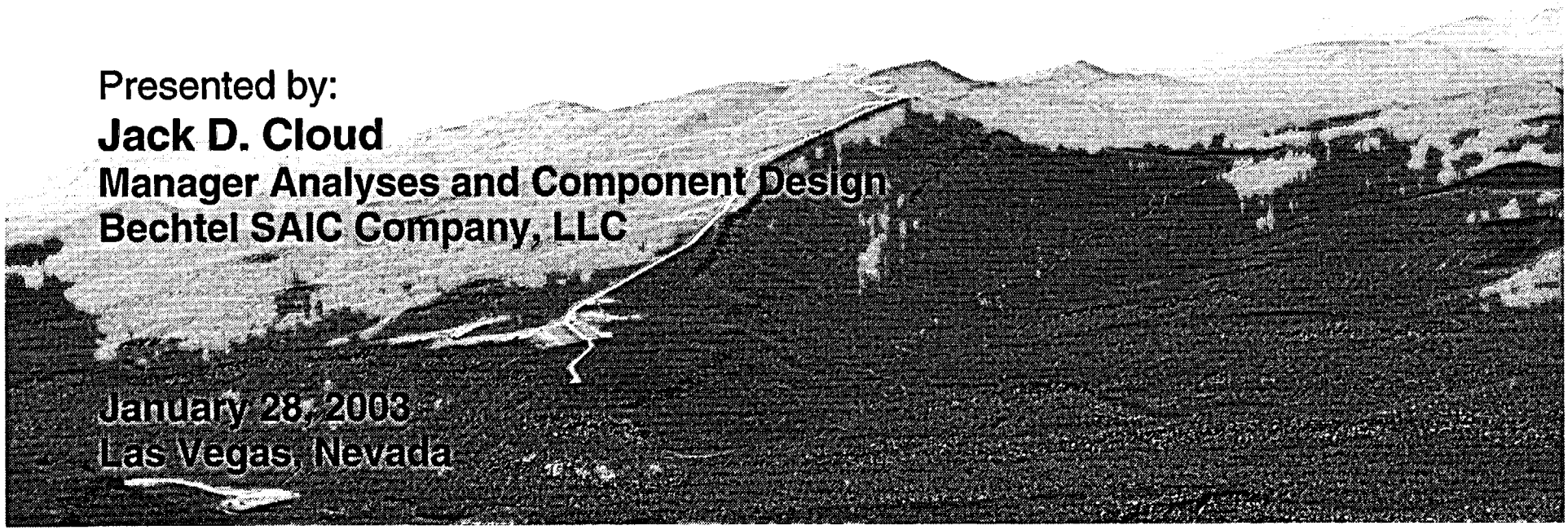
- **Microbiology**
  - Joanne Horn – Ph.D. Microbiology, UC Berkeley
- **Surface Science**
  - Christine Orme – Ph.D. Physics, University of Michigan
  - Peter Bedrosian – Ph.D. Physics, Harvard
- **Management & Support Staff**
  - Tom Doering – BSC Manager, Engineered Barrier System
  - Pasu Pasupathi – BSC Manager, Engineered Barrier System
  - Martha Kohler – LLNL Program Manager
  - Curtis Clower – LLNL Deputy Program Manager
  - John Estill – LLNL Manager, Corrosion Laboratory
  - Ken Evans – LLNL Corrosion Technician
  - Phil Hailey – LLNL Corrosion Technician
  - Kirk Staggs – LLNL Corrosion Technician

U.S. Department of Energy
Office of Civilian Radioactive Waste Management

YUCCA MOUNTAIN PROJECT

Waste Package Manufacturing and Closure Welds

Presented to:
Nuclear Waste Technical Review Board



Presented by:
Jack D. Cloud
Manager Analyses and Component Design
Bechtel SAIC Company, LLC

January 28, 2003
Las Vegas, Nevada

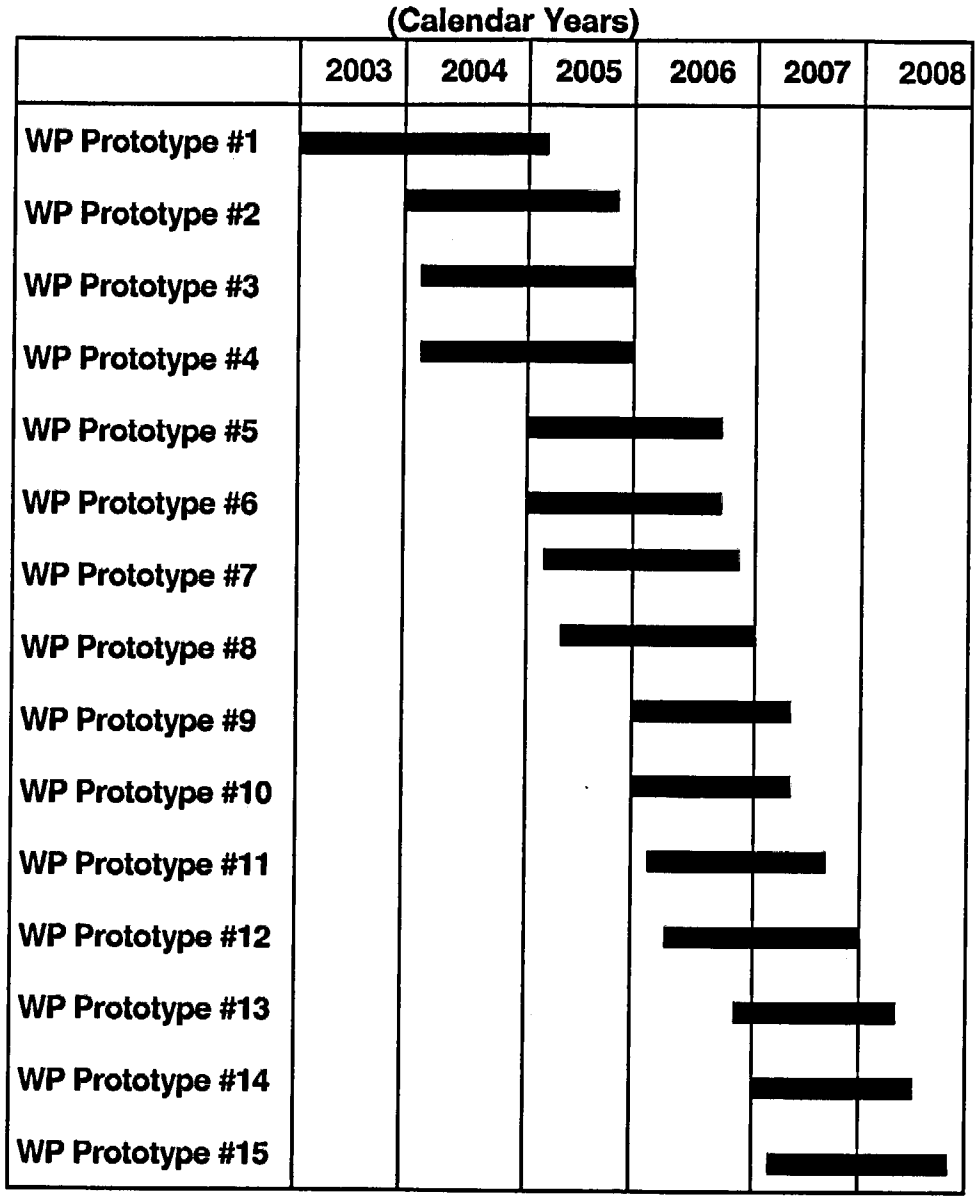
Waste Package Prototype Procurement

- Determine population of qualified fabricators
- Constructed to exact requirements of actual production models
- Demonstration of fabrication process
- Integral part of design process
- First prototype coincident with License Application submittal

Waste Package Prototype Procurement
(Continued)

- 15 prototypes
- Uses of prototypes
- American Society of Mechanical Engineers (ASME) Code
  - Inner vessel
  - Corrosion barrier
  - Internals
  - ASME code position paper

Waste Package Prototype Schedule

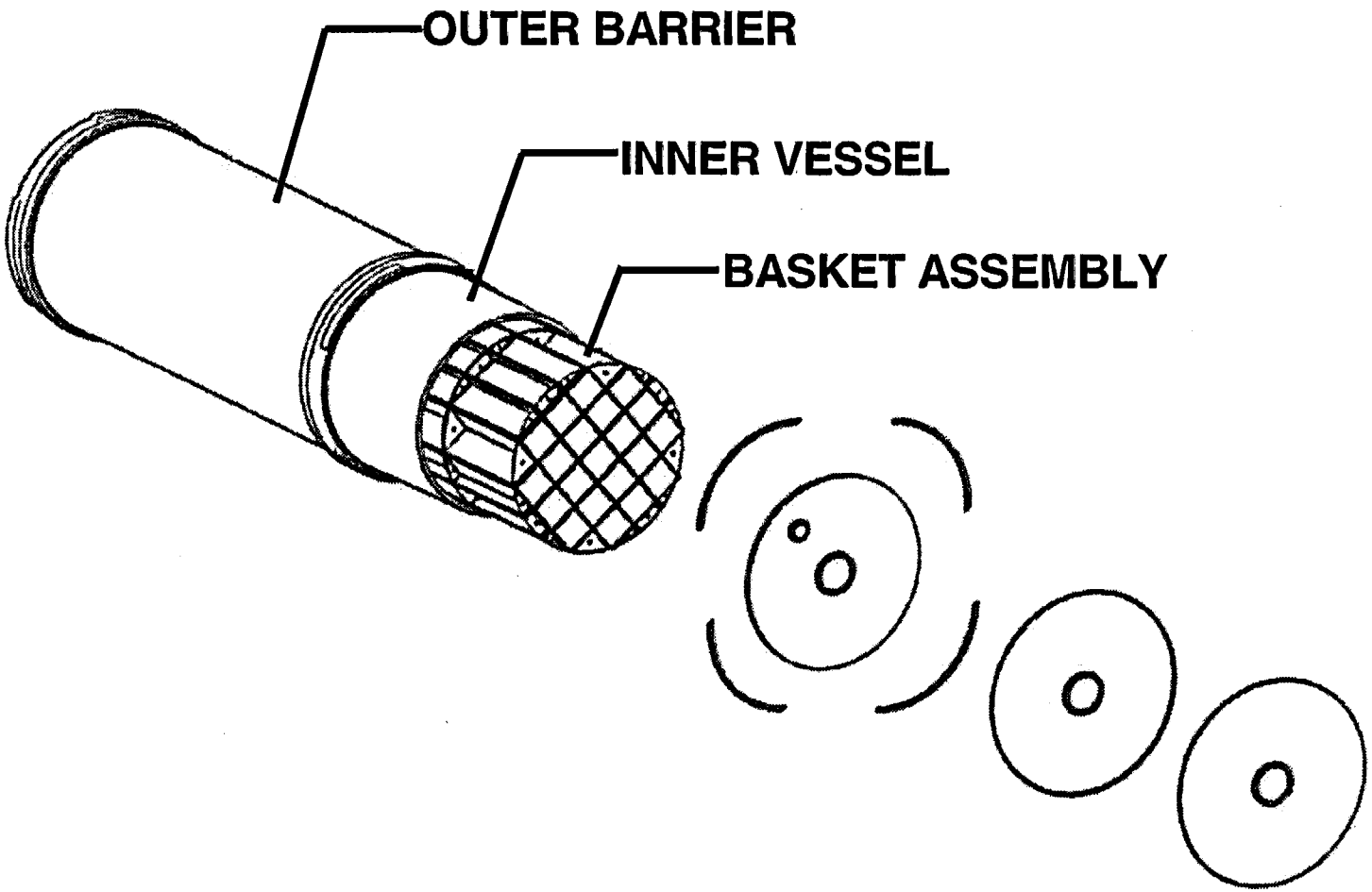


Status of First Prototype Procurement

- Fabrication specification and drawings
- ASME design specification
- Pre-qualification document
- Request for Proposal (RFP)
- Schedule

• Pre-qualification	-- Feb 2003
• RFP	-- Mar 2003
• Bid Date	-- 3rd QTR 2003
• Award	-- 4th QTR 2003
• Deliver	-- 4th QTR 2004 - 1st QTR 2005 (Calendar years)

Typical Waste Package



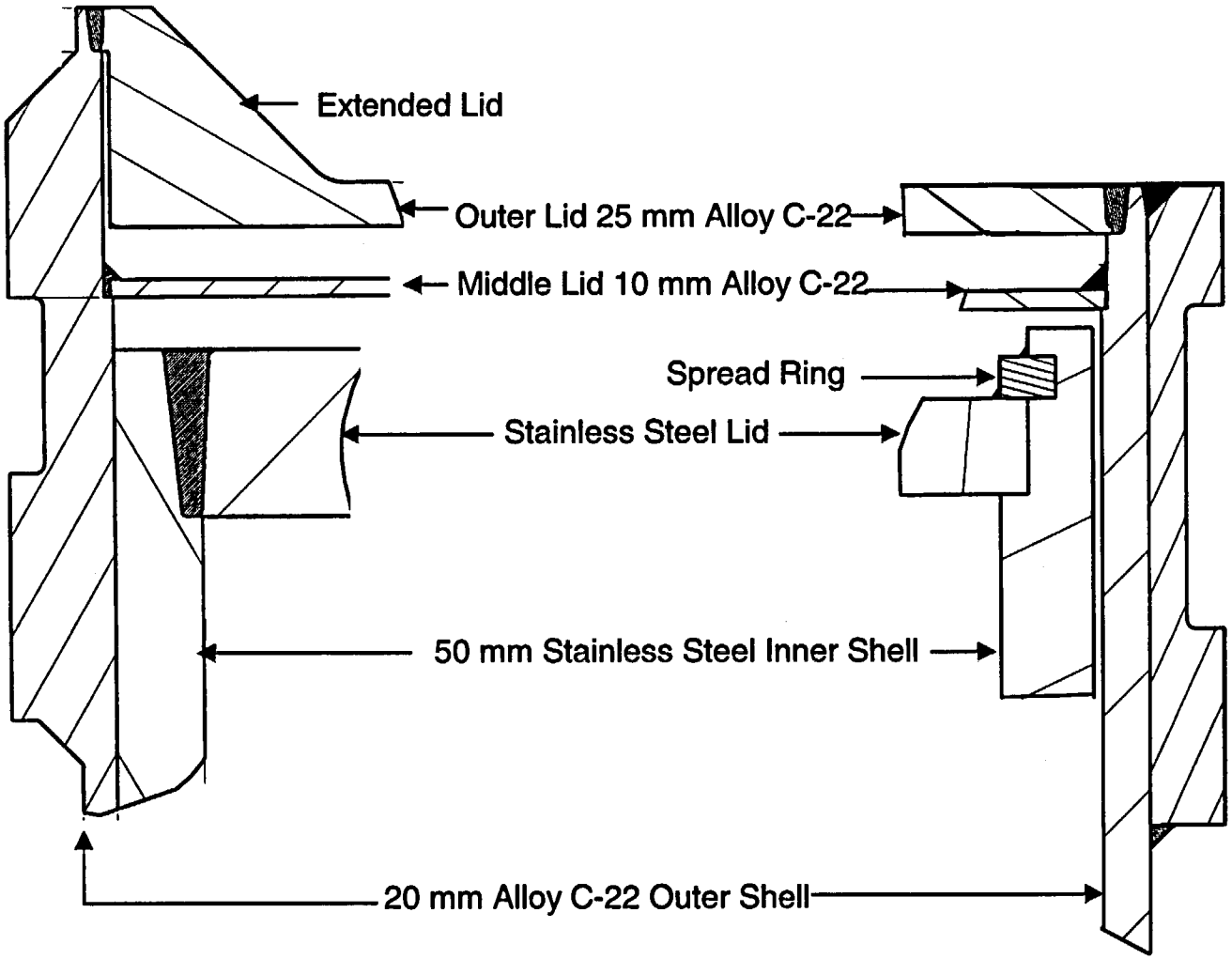
Weld Process Verification

- Recognize that there are various welding processes
- Weld selection process
  - Waste Package Closure Development Report
- Consultant position and conclusion
  - Dr. Carl Lundin - University of Tennessee
  - Confirmed Cold Wire - Gas Tungsten Arc Weld (CW-GTAW) welding process

Closure Welds at Yucca Mountain Project

- Six-month value engineering study resulted in design modifications
- Recent design modifications
- Process equipment development and design strategy
- Contracting strategy
- Prototype strategy and schedule
- Prototypes are integral part of design

Waste Package Final Closure



Site Recommendation Design **Proposed Design**

Benefits of Design Modifications

- Time in weld cell reduced by > 50%
- Eliminated thermal stress mitigation
- Less complicated fabrication and closure
- Reduced risk (licensing, operations, performance uncertainties)
- Cost savings
- Recommended by DOE Project Operations Review Board

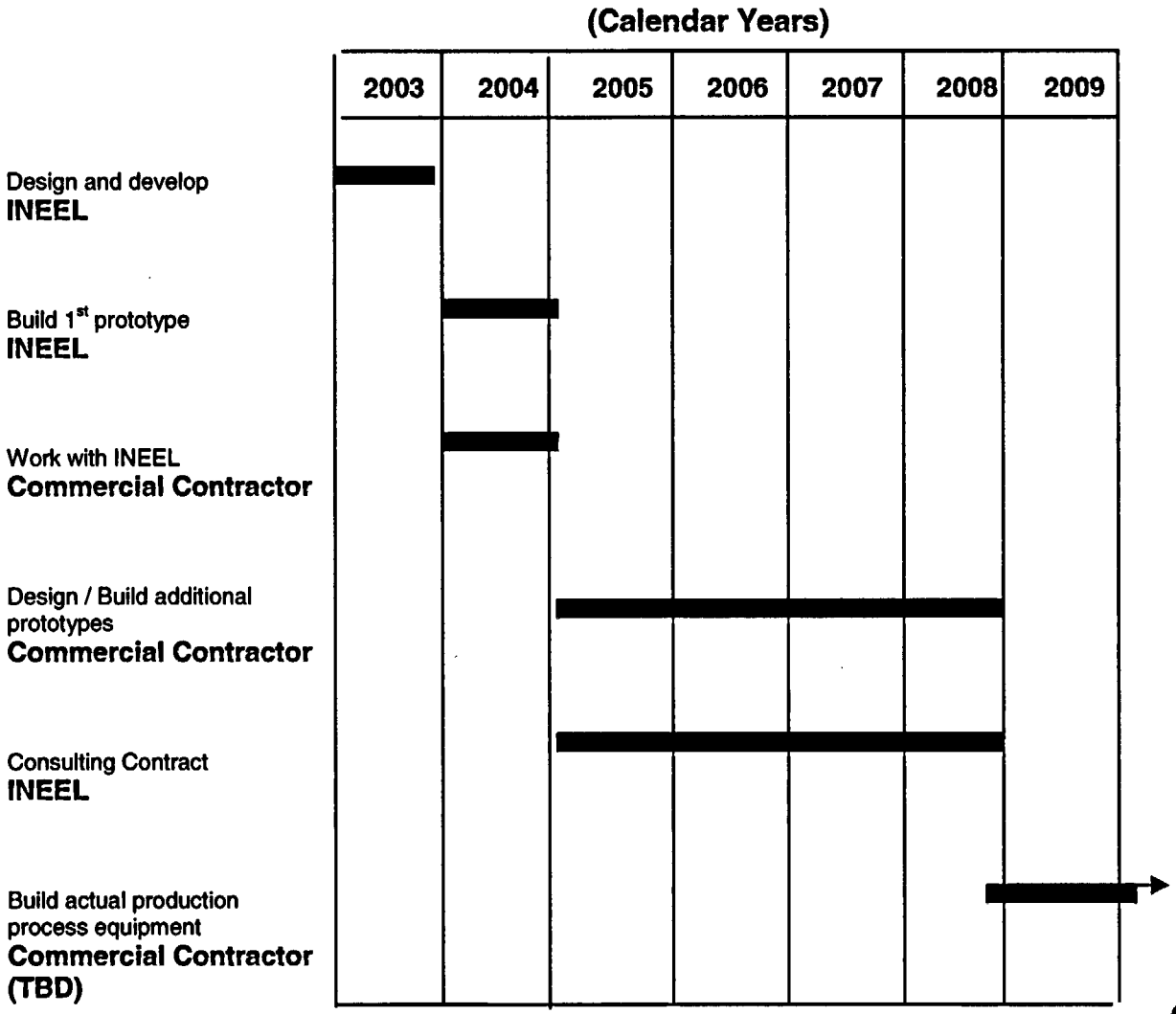
Weld Process Equipment Contracting Strategy

- Idaho National Engineering and Environmental Laboratory (INEEL)
- Commercial Contractor - Integrated with INEEL
- BSC Hire Specific Expertise
- Commercial Contractor
  - Future Generation Prototypes
  - Production Models - TBD
- Integral part of the Design Process
- 5 Prototype Systems

Weld Process Equipment Contracting Strategy
(Continued)

- Use of prototypes - installed in Training Facility
  - Establish proof of concept and operations
  - Perform closure operations on waste package prototypes
  - Provide for operator training
  - Establish procedures and processes for Operations Readiness Review (ORR) and operations
  - Potentially used to perform ORR
  - Potentially used in operational facilities

Weld Cell Process Equipment Development Schedule



Influence of Paleosols on Fluid Flow and Transport: Perspective on Alluvial Complexity and Hydrogeology

Presentation to Nuclear Waste Technical Review Board, Jan. 28, 2003, Las Vegas, NV

Graham E. Fogg
Department of Land, Air and Water Resources
and Department of Geology
Hydrologic Sciences Graduate Group
University of California, Davis
http://lawr.ucdavis.edu/faculty/fogg

Research Supported by

NSF, CA Water Resources Center, Monterey County Water Resources Agency, USGS, EPA Center for Ecological Health Research, UC Agricultural Exp. Station

Collaborators/Contributors

Gary S. Weissmann*
Yong Zhang
Karen Burow*

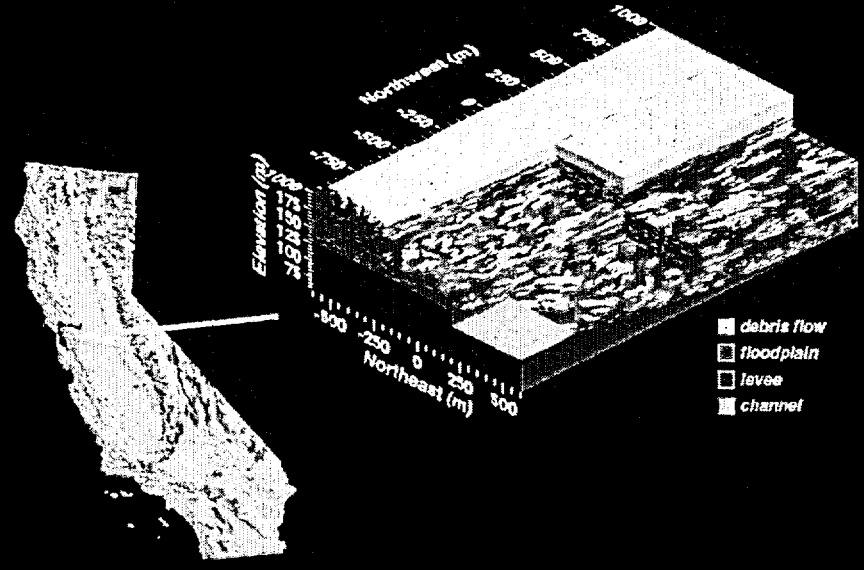
Eric M. LaBolle*
Steve Carle*
Lisa Maserjian*

Dennis Rolston
Ken Versosub

Jeff Mount

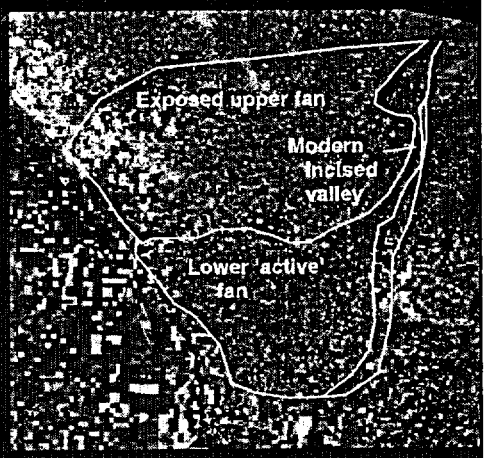
* *Thesis/Dissertation work*

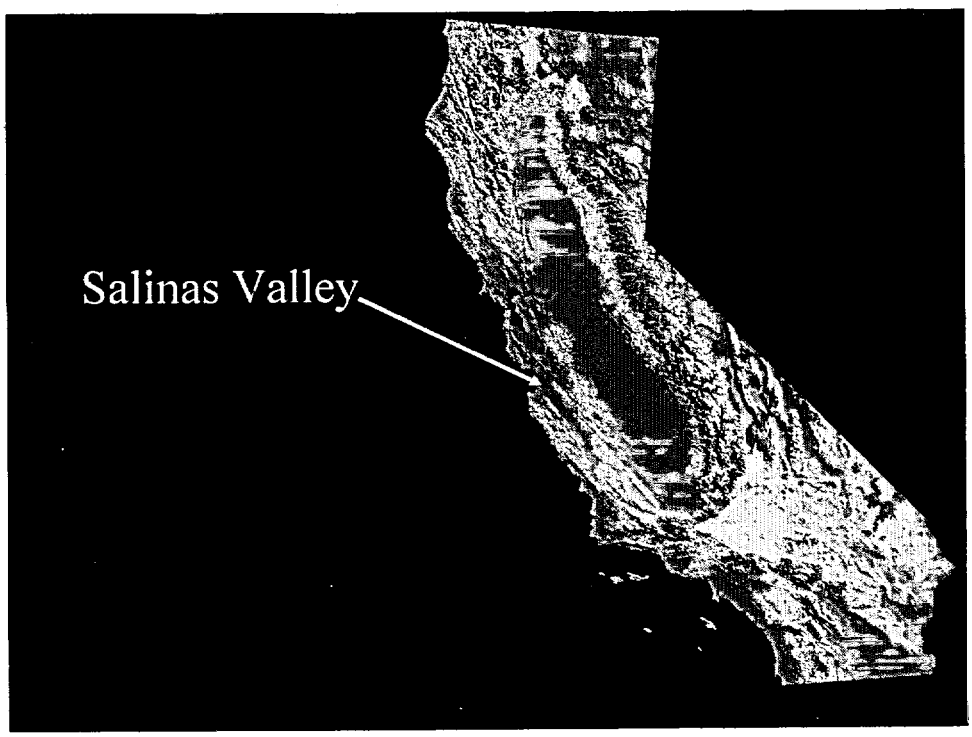
LLNL STUDY AREA

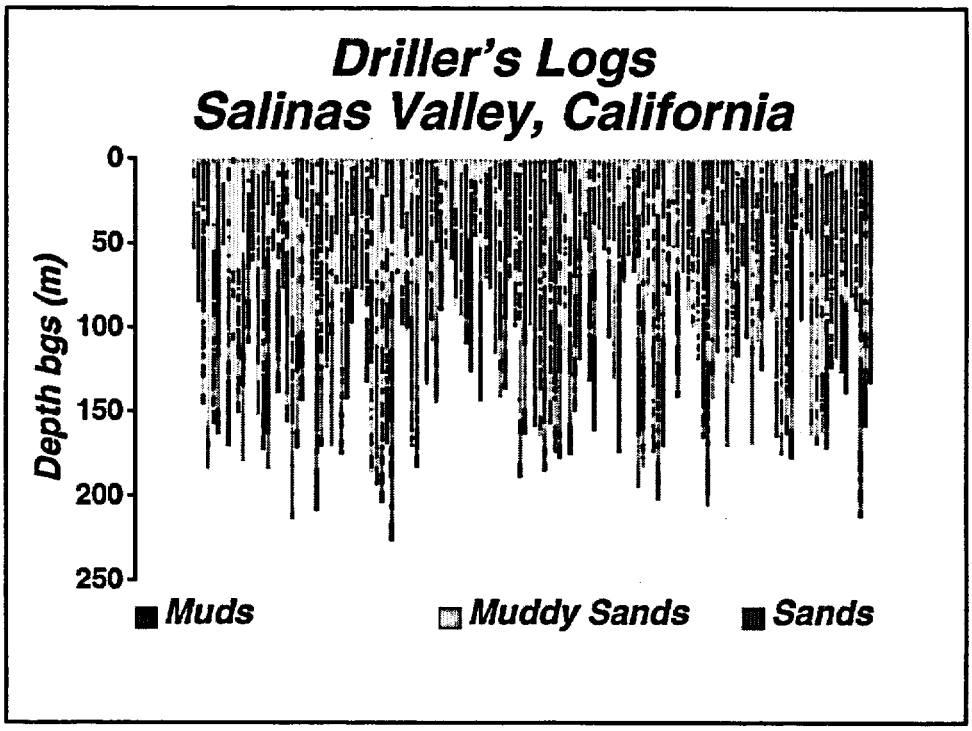


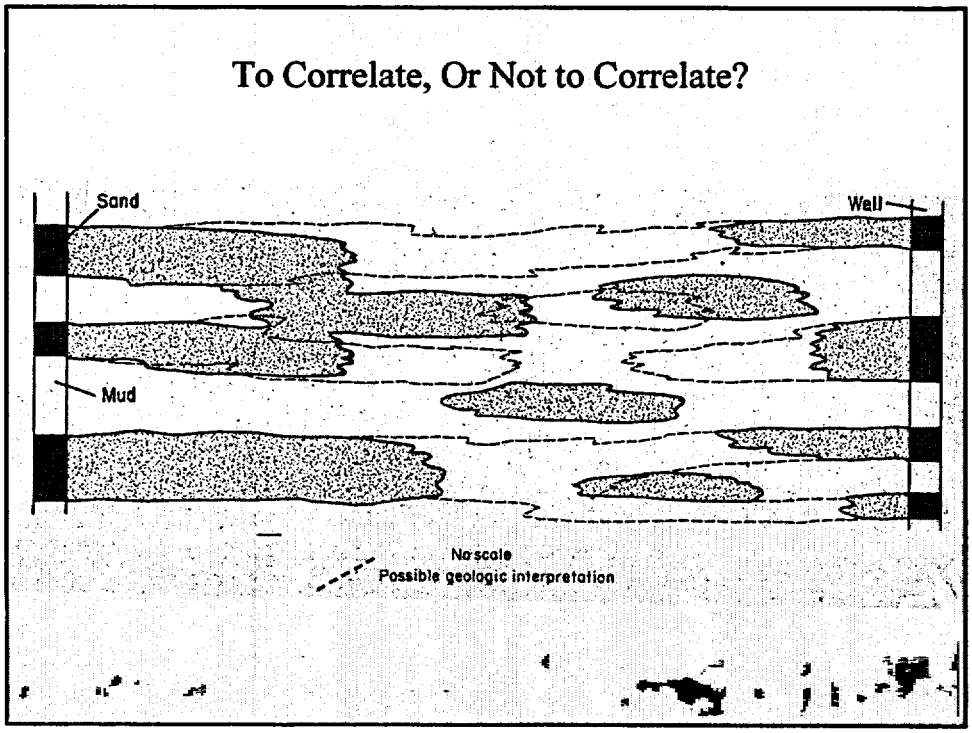
Kings River Fan Aquifer System

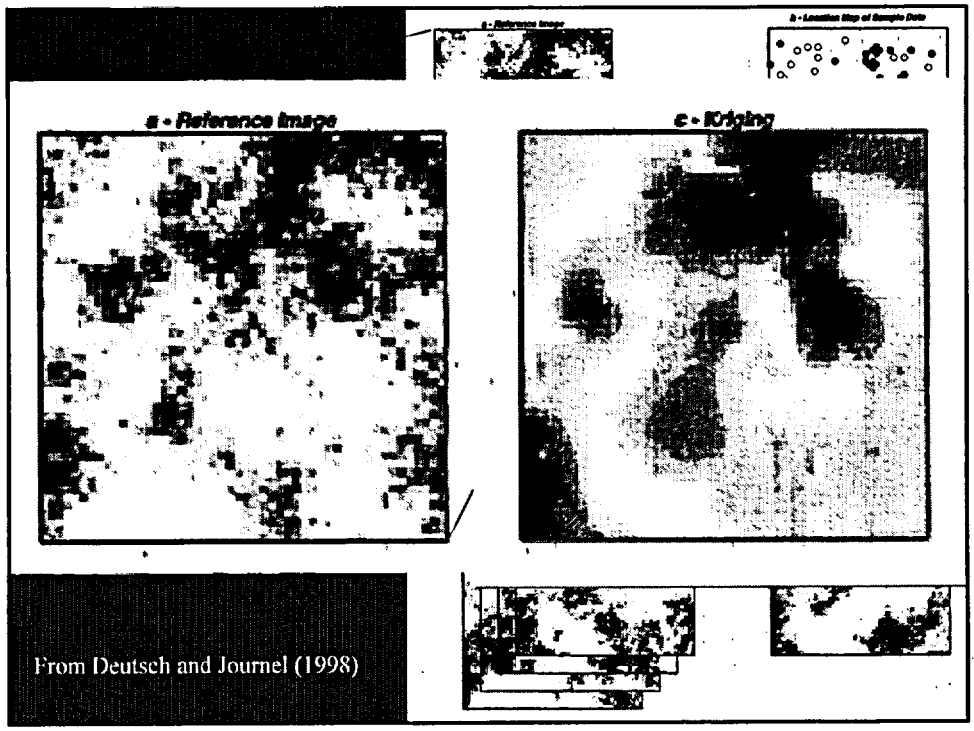
- Stream-dominated alluvial fan system (fluvial depositional system);
- Located southeast of Fresno, California;
- Study area located in medial fan area.






Driller's Logs
Salinas Valley, California
Depth bgs (m)
0
50
100
150
200
250
Muds
Muddy Sands
Sands


To Correlate, Or Not to Correlate?
Sand
Well
Mud
No scale
Possible geologic interpretation



From Deutsch and Journel (1998)

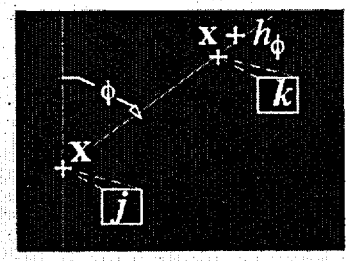
Transition Probability Definitions

From Probability Theory:

$$t_{jk}(h_\phi) = \Pr\{\, k \text{ occurs at } x + h_\phi \mid j \text{ occurs at } x \,\}$$

w.r.t. Indicator Variables:

$$t_{jk}(h_\phi) = \frac{E\{I_j(x) I_k(x + h_\phi)\}}{E\{I_j(x)\}}$$



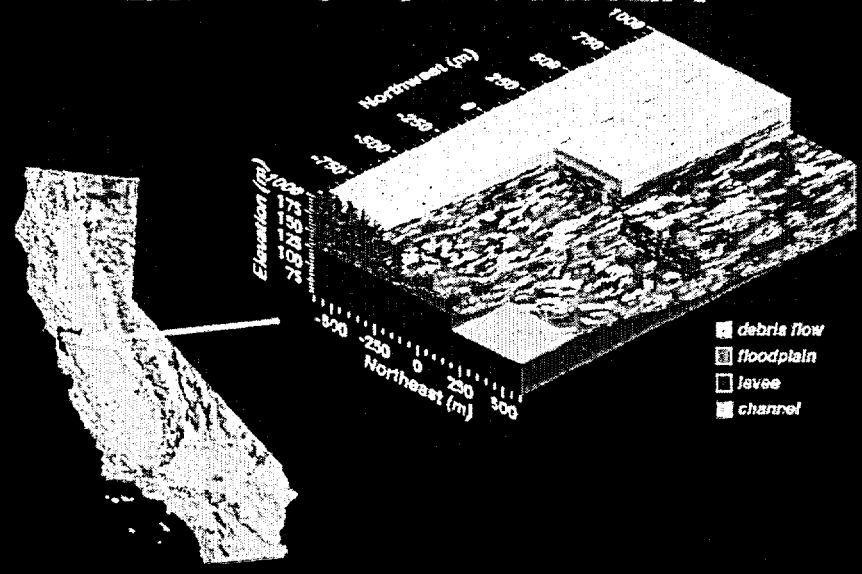
Transition Probability Matrix

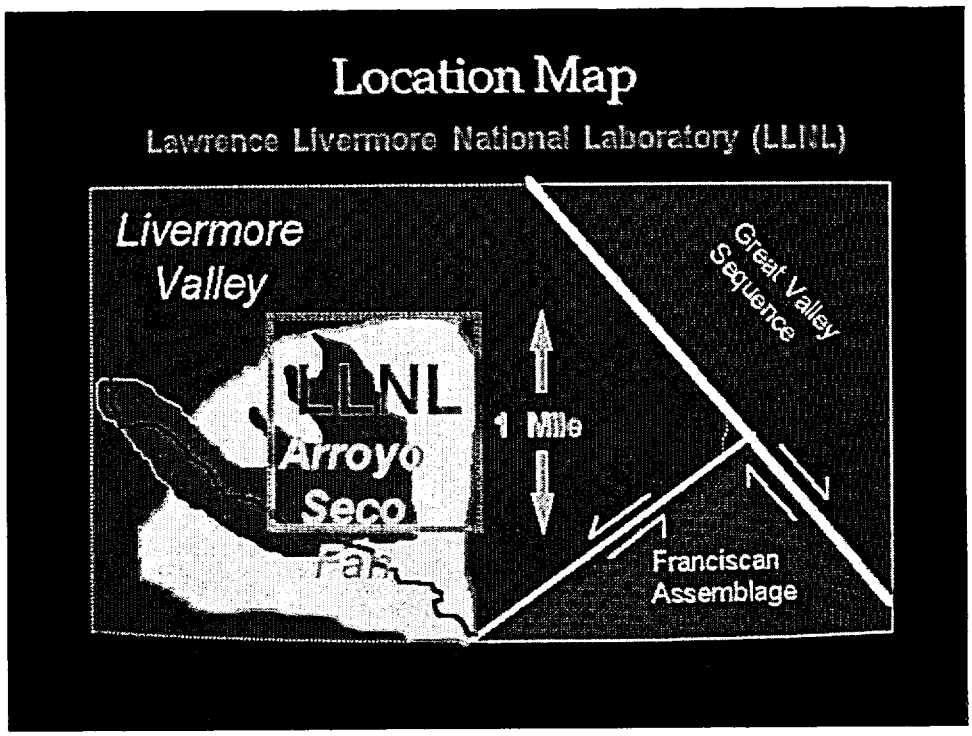
Facies ⟹ 1 ..... K

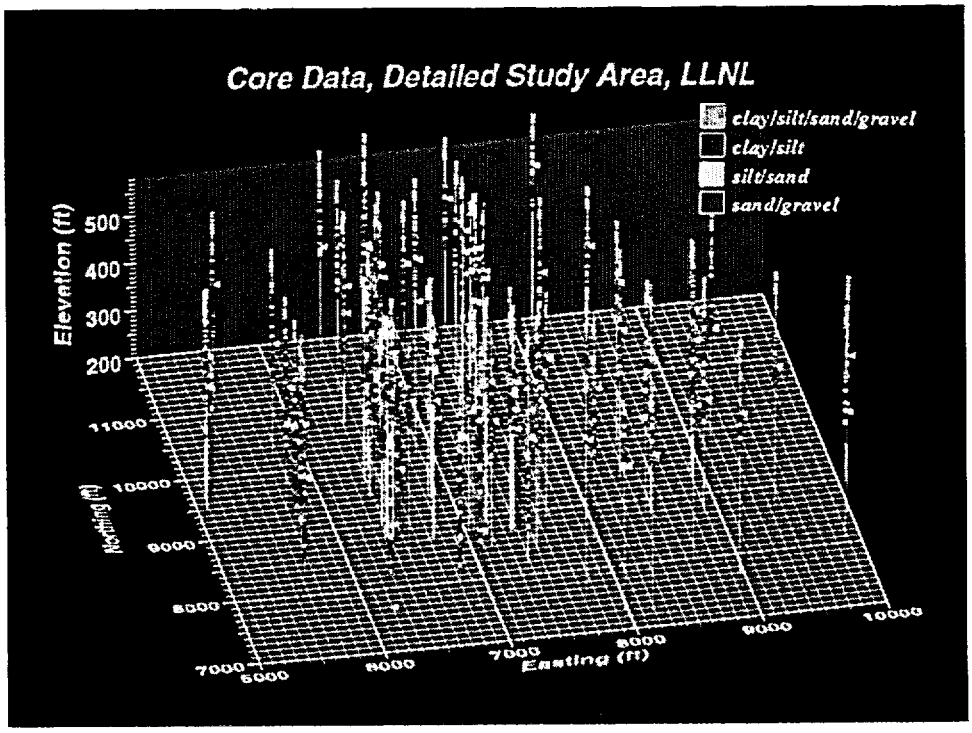
$$\mathbf{T}(h_\phi) = \begin{bmatrix} t_{11}(h_\phi) & \mathrm{L} & t_{1K}(h_\phi) \\ \mathrm{M} & \mathrm{O} & \mathrm{M} \\ t_{K1}(h_\phi) & \mathrm{L} & t_{KK}(h_\phi) \end{bmatrix}$$

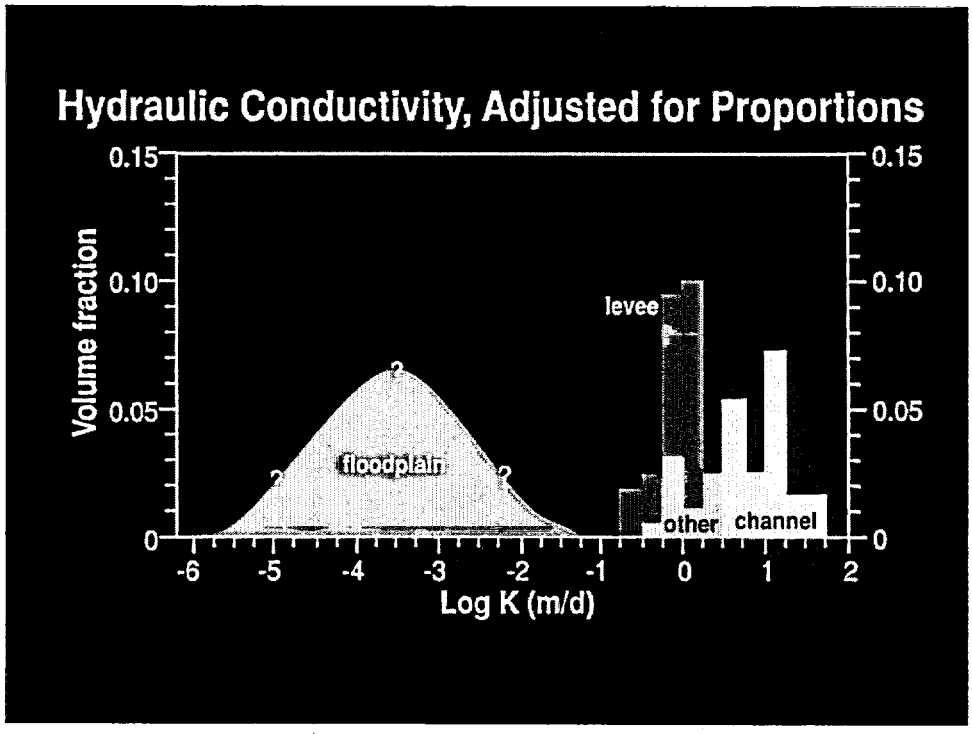
1 ⋮ K

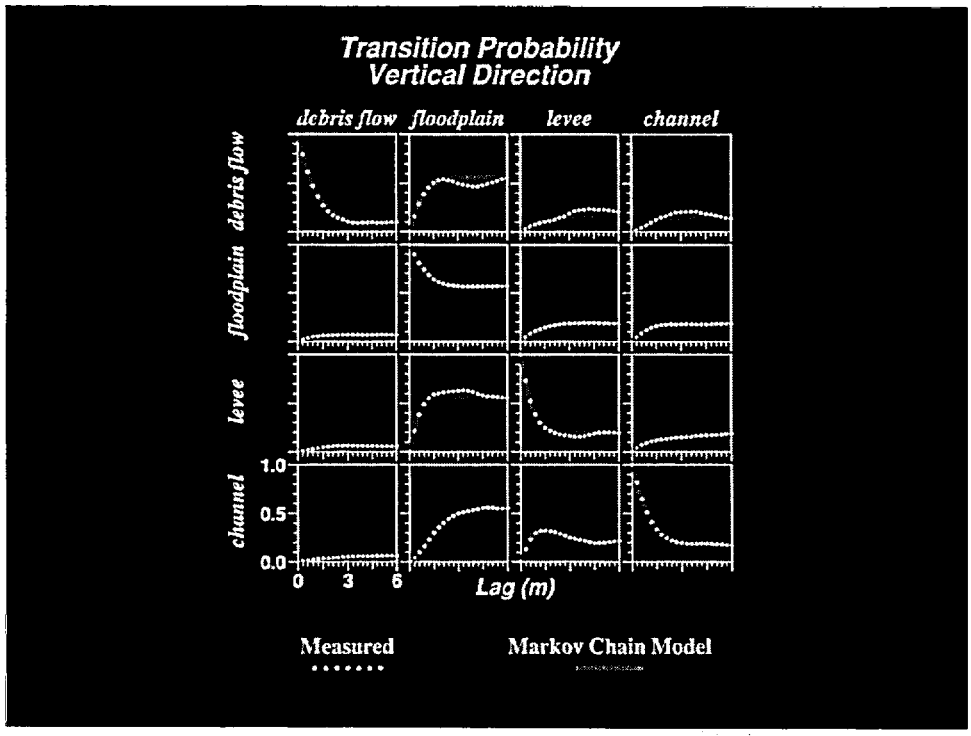
LLNL STUDY AREA

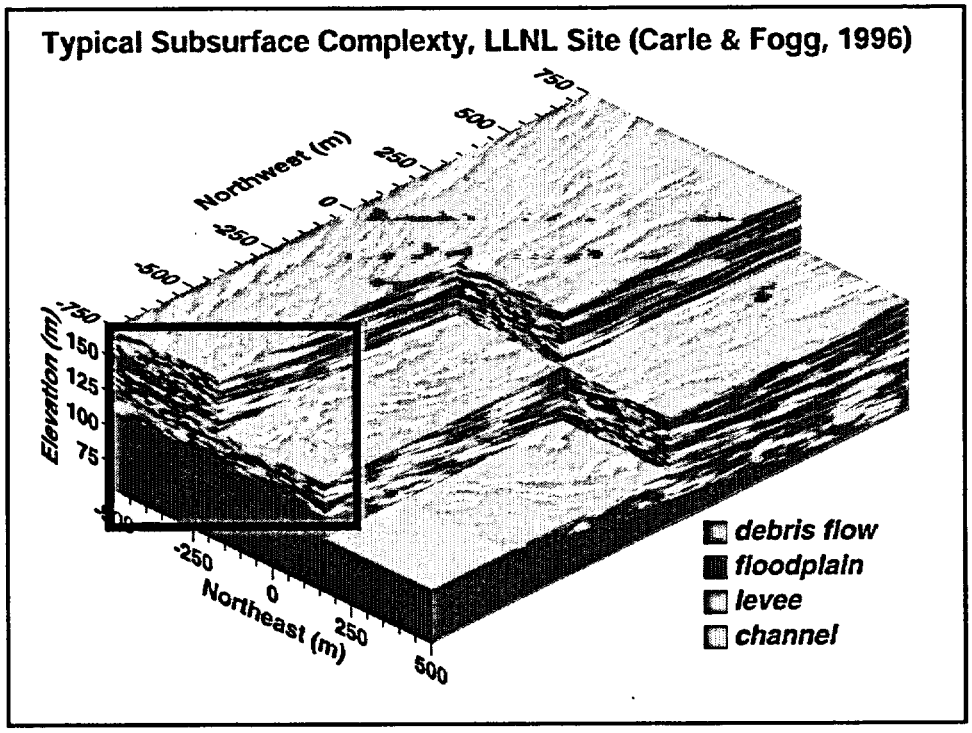


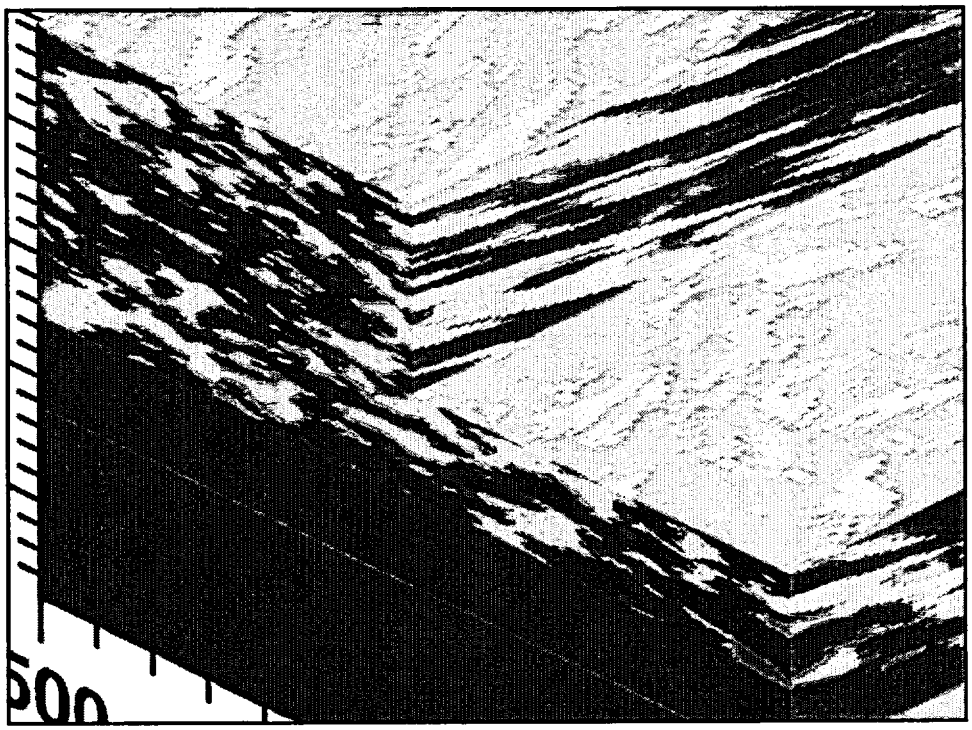

Location Map
Lawrence Livermore National Laboratory (LLNL)
Livermore Valley
LLNL
Arroyo Seco
Fan
1 Mile
Great Valley Sequence
Franciscan Assemblage

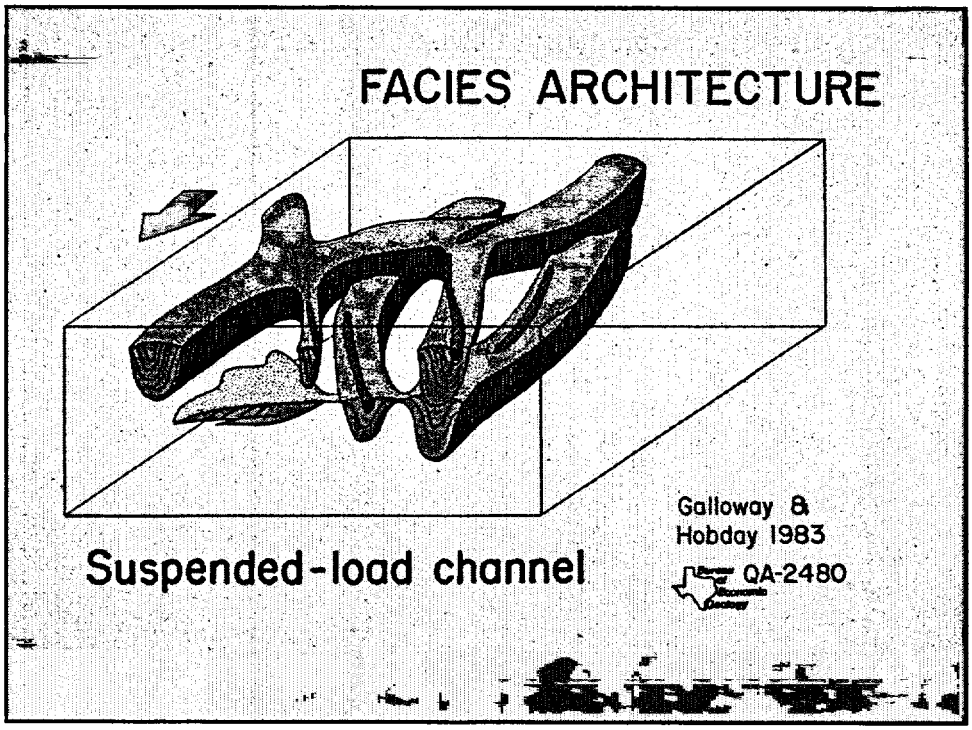

Core Data, Detailed Study Area, LLNL
clay/silt/sand/gravel
clay/silt
silt/sand
sand/gravel
Elevation (ft)
500
400
300
200
Northing (ft)
11000
10000
9000
8000
7000
Easting (ft)
5000
6000
7000
8000
9000
10000


Hydraulic Conductivity, Adjusted for Proportions
Volume fraction
0.15
0.10
0.05
0
levee
floodplain
other
channel
-6
-5
-4
-3
-2
-1
0
1
2
Log K (m/d)


Transition Probability
Vertical Direction
debris flow
floodplain
levee
channel
1.0
0.5
0.0
0
3
6
Lag (m)
Measured
Markov Chain Model

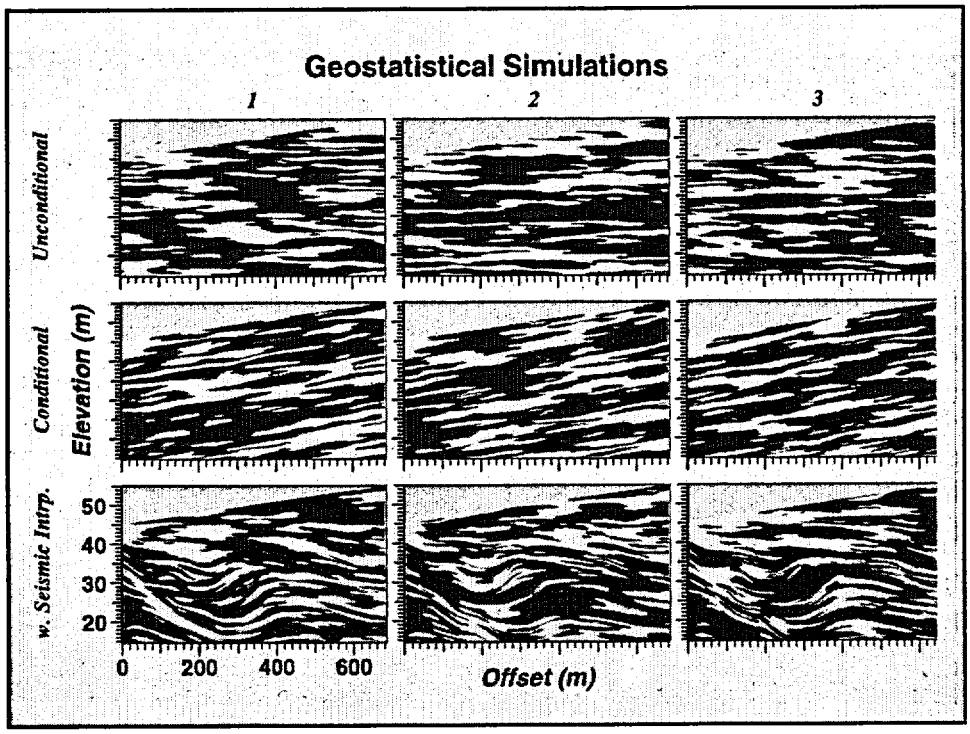

Typical Subsurface Complexty, LLNL Site (Carle & Fogg, 1996)
Northwest (m)
-500
-250
0
250
500
750
Elevation (m)
150
125
100
75
-250
0
250
500
Northeast (m)
debris flow
floodplain
levee
channel

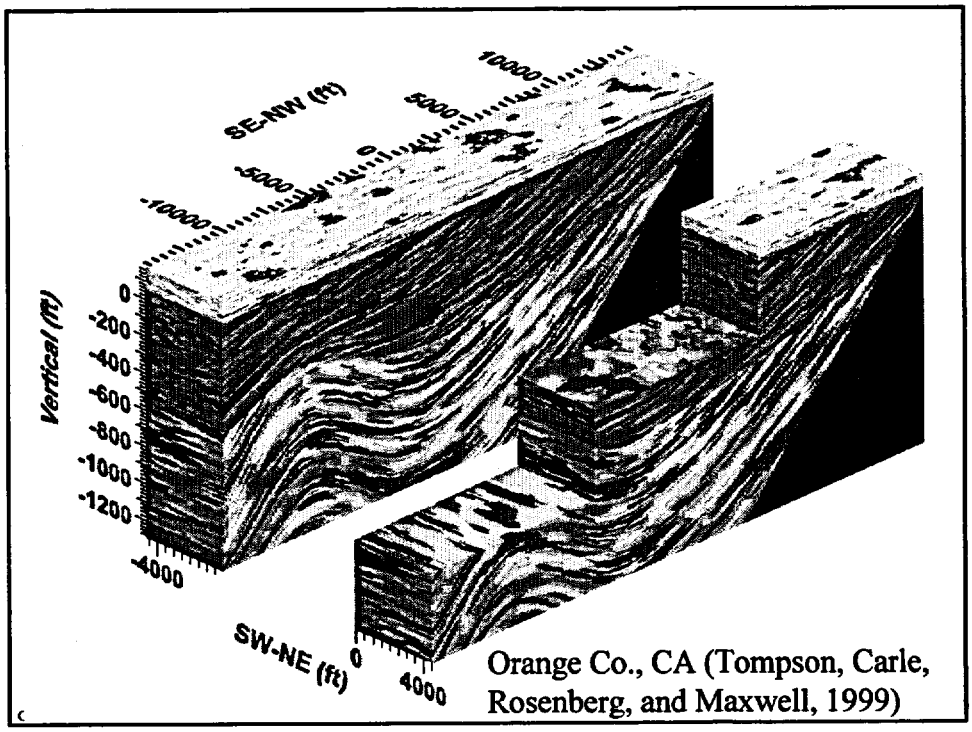




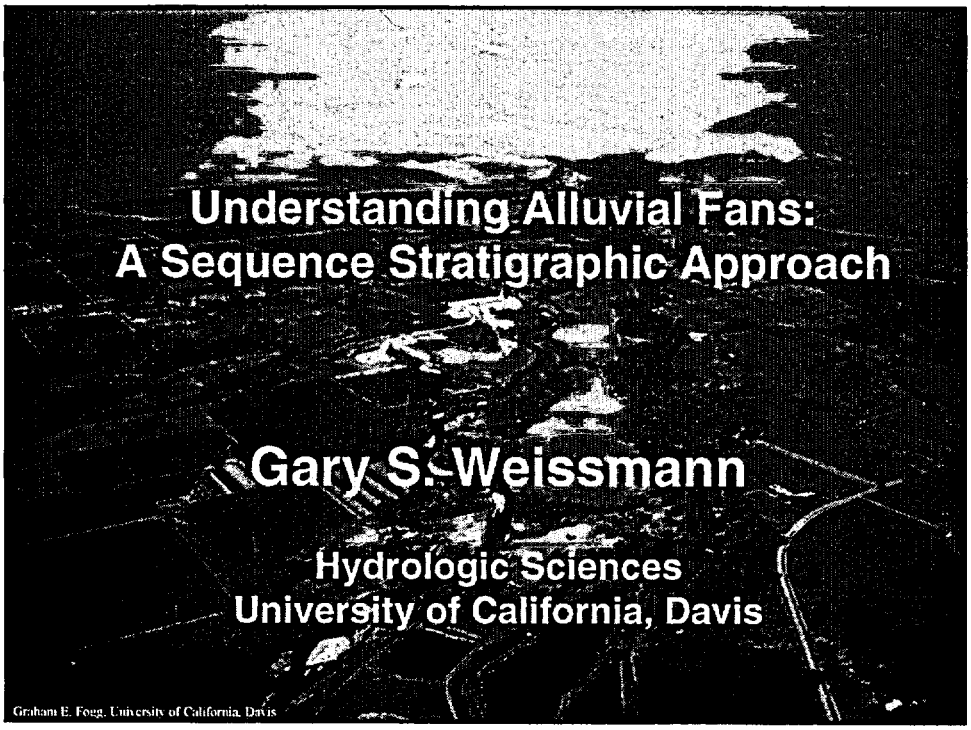
Consequences of Heterogeneity

Movie of LLNL results.....



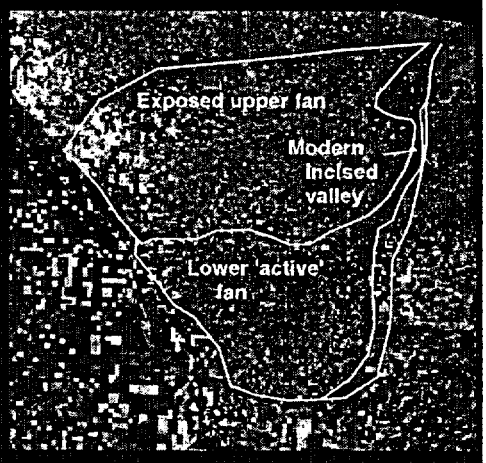


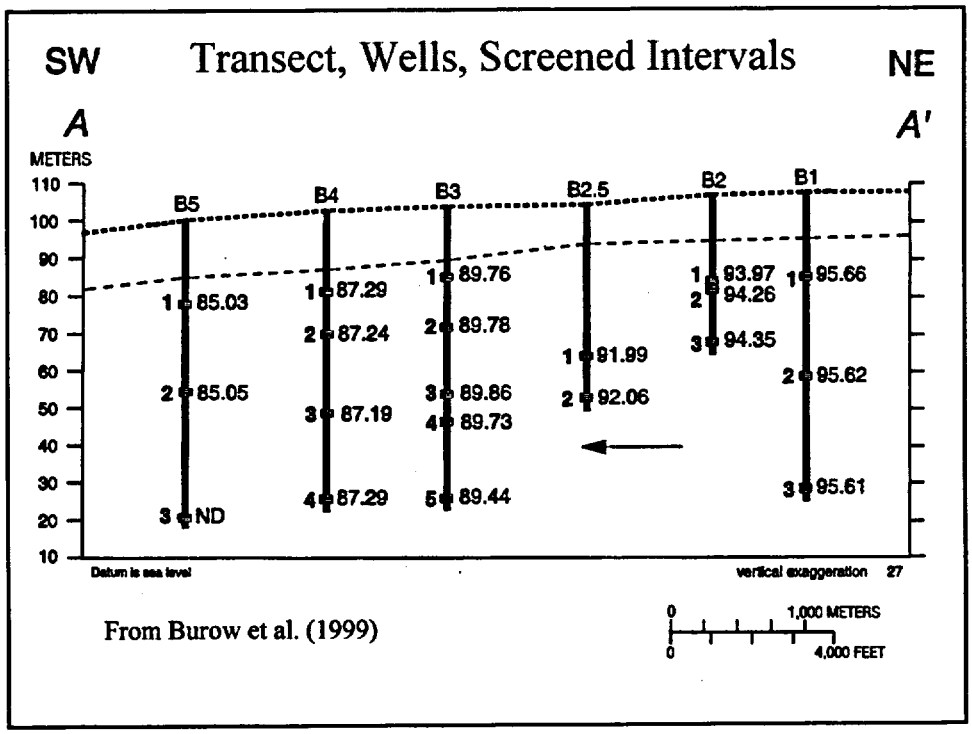
Orange Co., CA (Tompson, Carle, Rosenberg, and Maxwell, 1999)



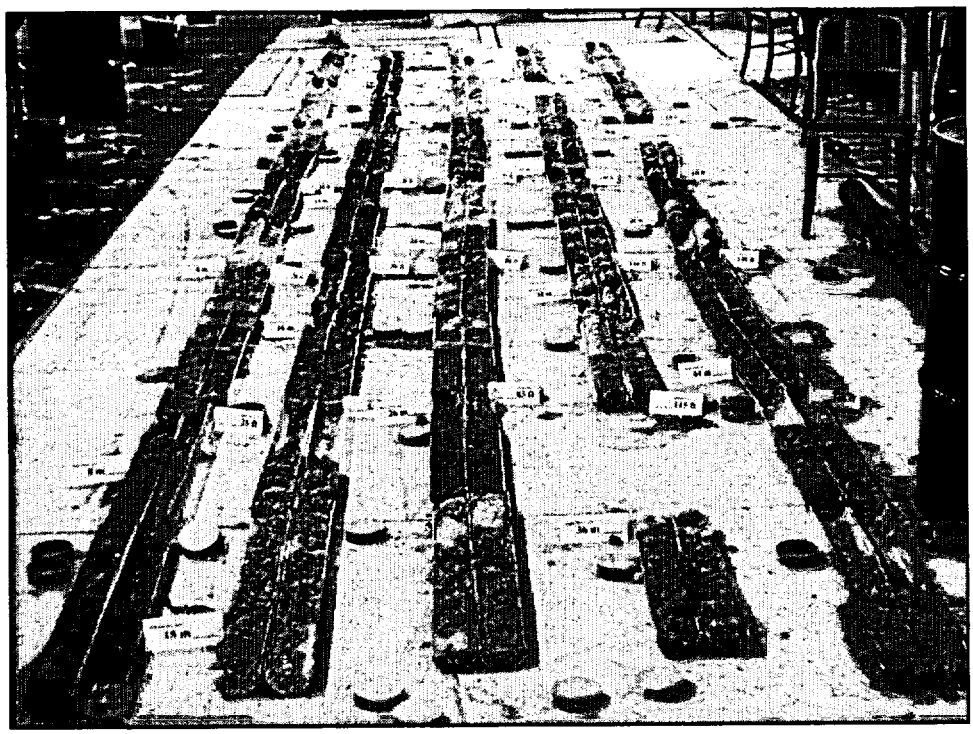
Kings River Fan Aquifer System

- Stream-dominated alluvial fan system (fluvial depositional system);
- Located southeast of Fresno, California;
- Study area located in medial fan area.

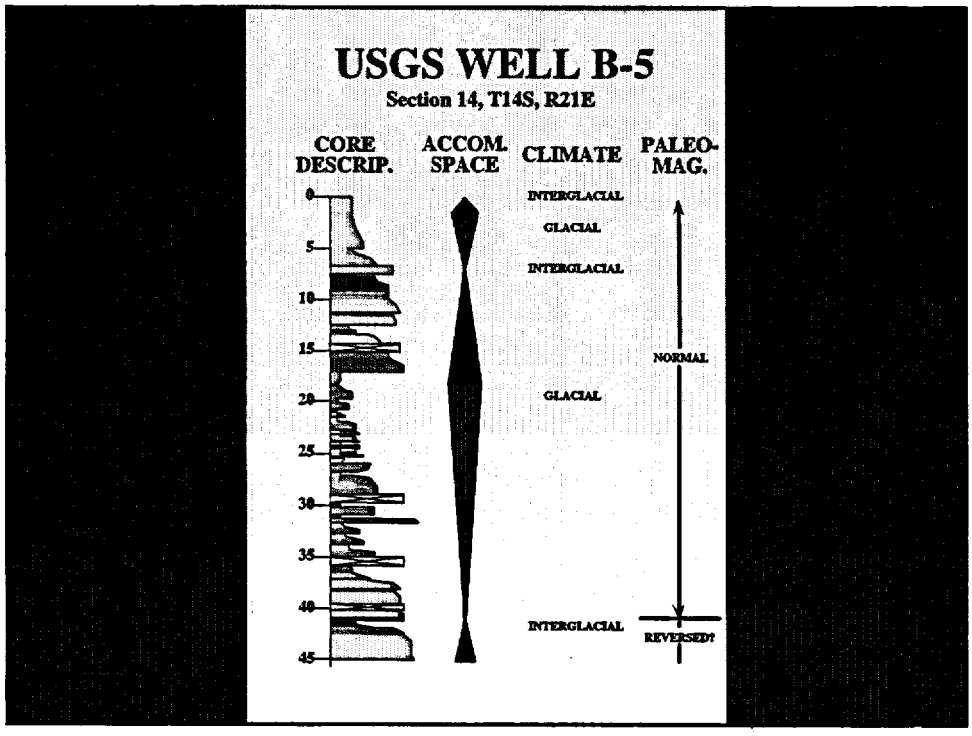


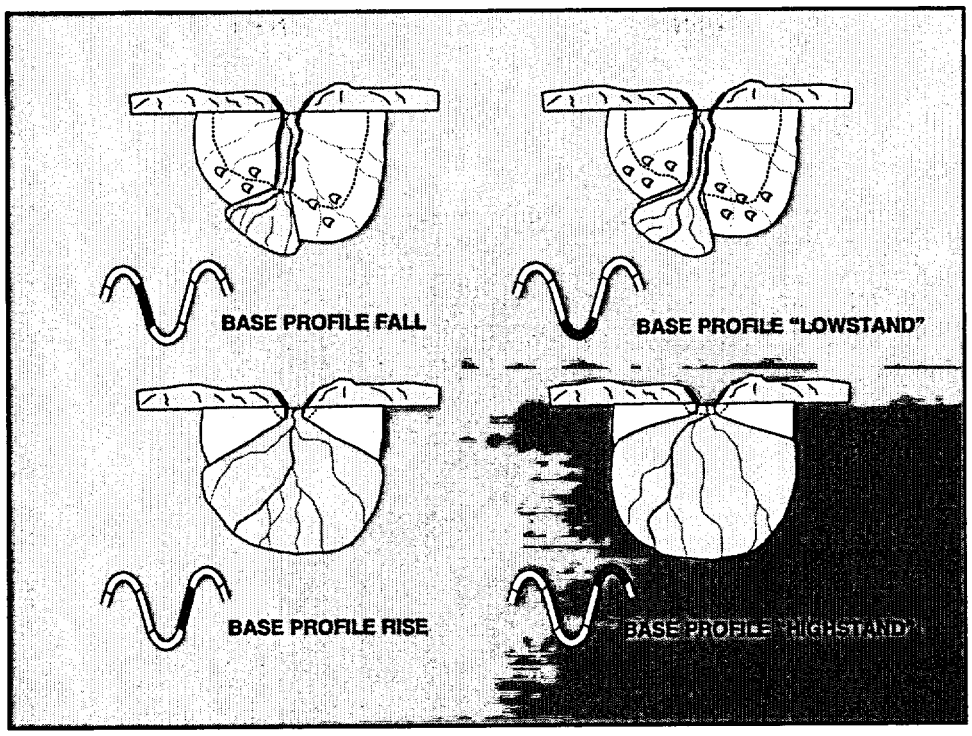


From Burow et al. (1999)

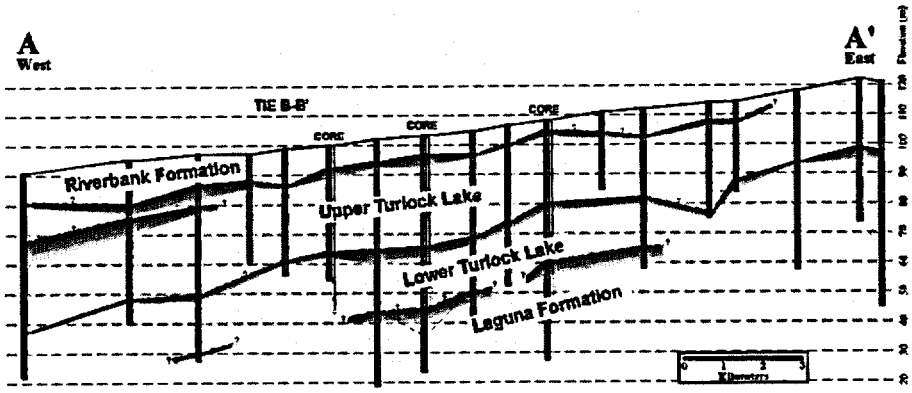


15 cm
85 ft


USGS WELL B-5
Section 14, T14S, R21E
CORE DESCRIP.
ACCOM. SPACE
CLIMATE
PALEO-MAG.
0
5
10
15
20
25
30
35
40
45
INTERGLACIAL
GLACIAL
INTERGLACIAL
GLACIAL
INTERGLACIAL
NORMAL
REVERSED?

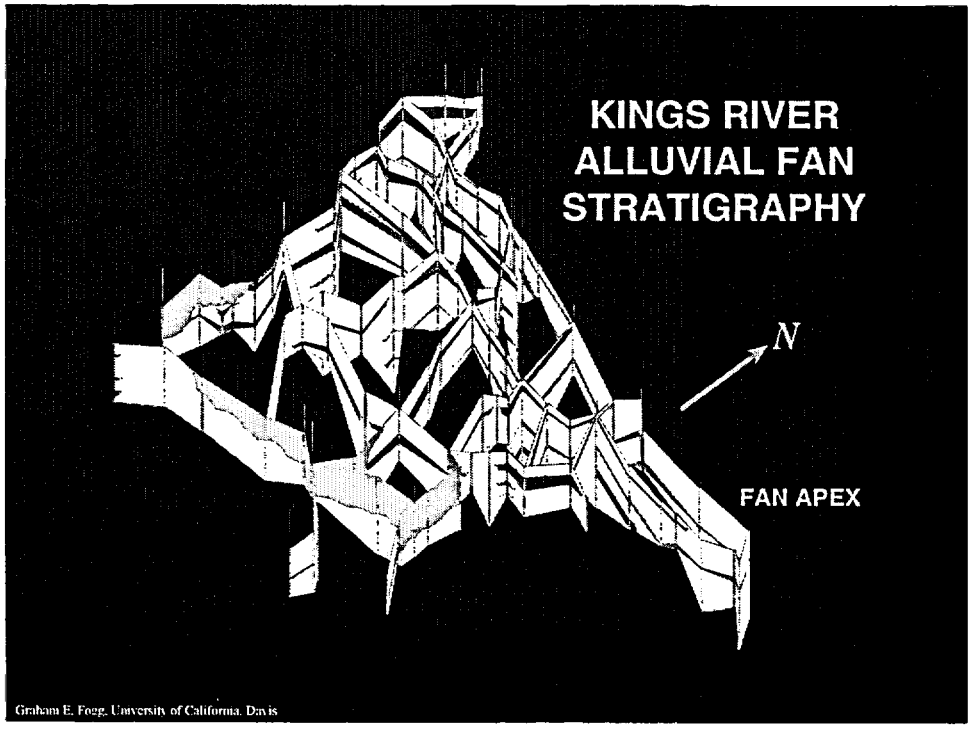


Sequence Stratigraphic Organization; Paleosol Aquitards

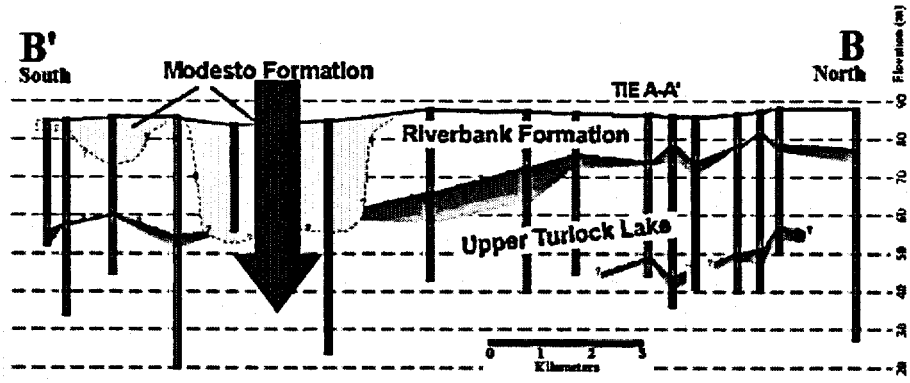


Weissmann & Fogg, 1999

Graham E. Fogg, University of California, Davis

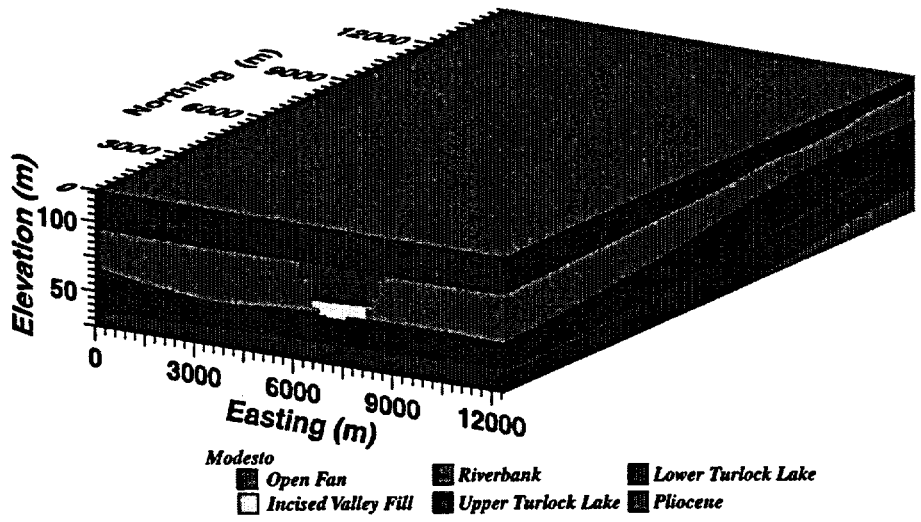


Where Paleosols Channeled Out, Vertical Flow Enhanced

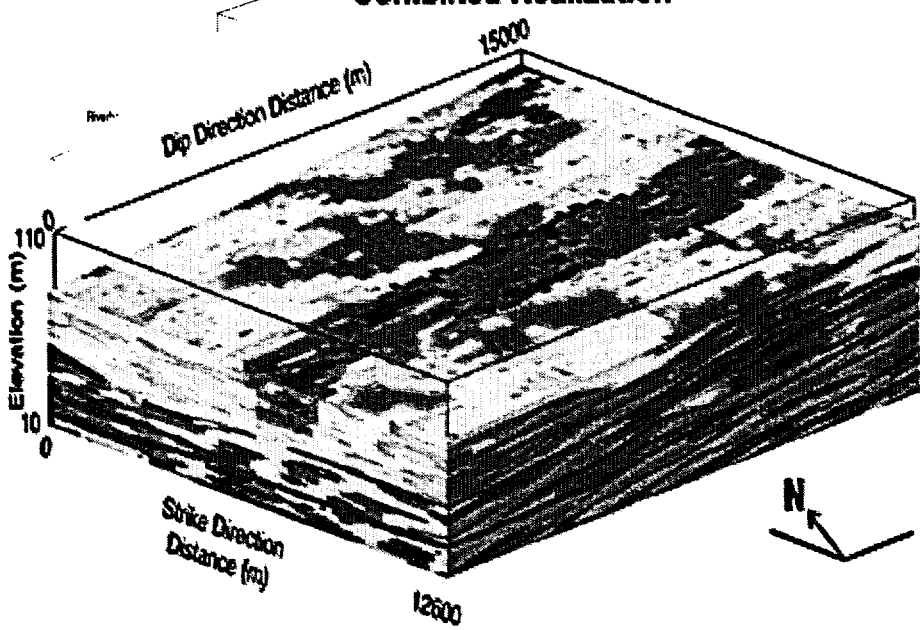


Graham E. Fogg, University of California, Davis

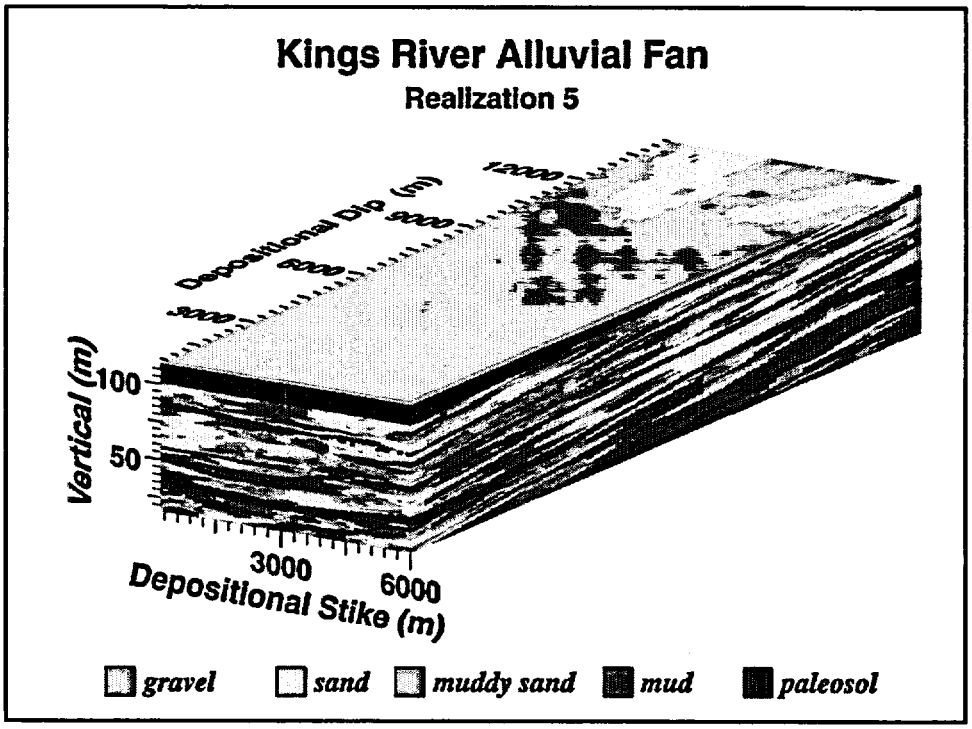
Sequence Stratigraphic Units for Non-Stationary Conditional Simulation

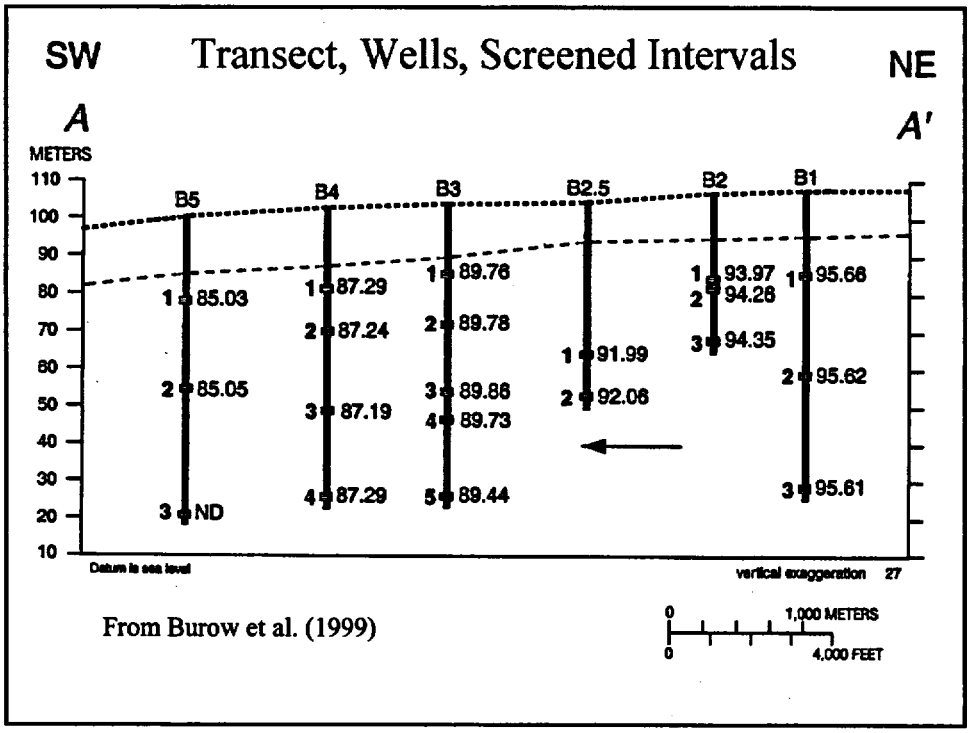


Combined Realization



Graham E. Fogg, University of California, Davis



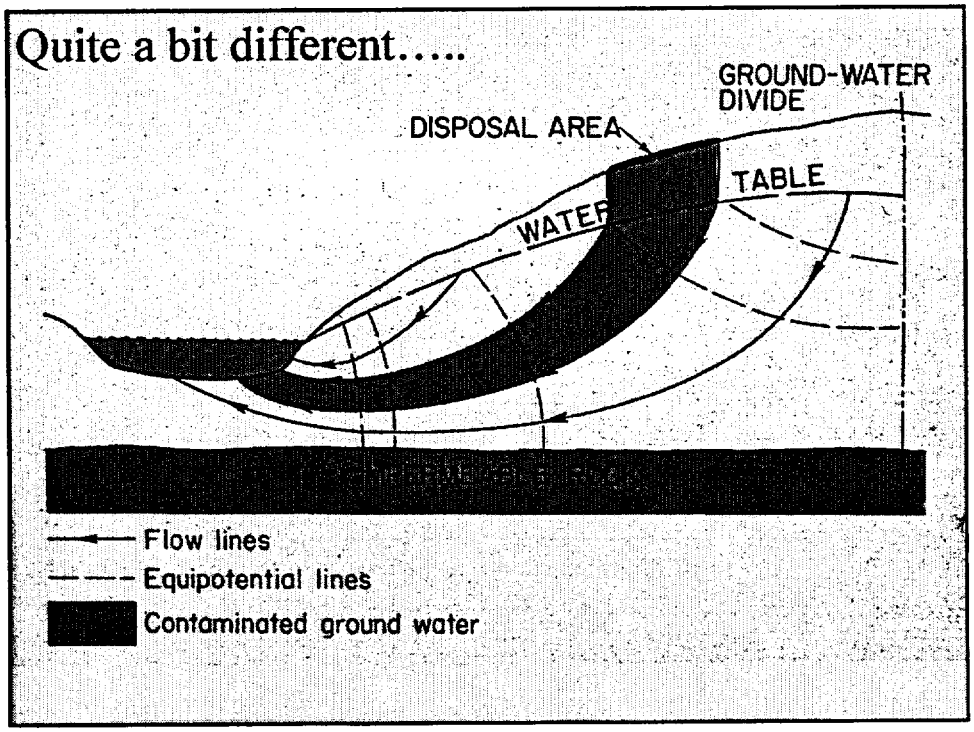


From Burow et al. (1999)

Groundwater Age:

Elapsed time since a water "particle" entered the saturated zone.

Quite a bit different.....

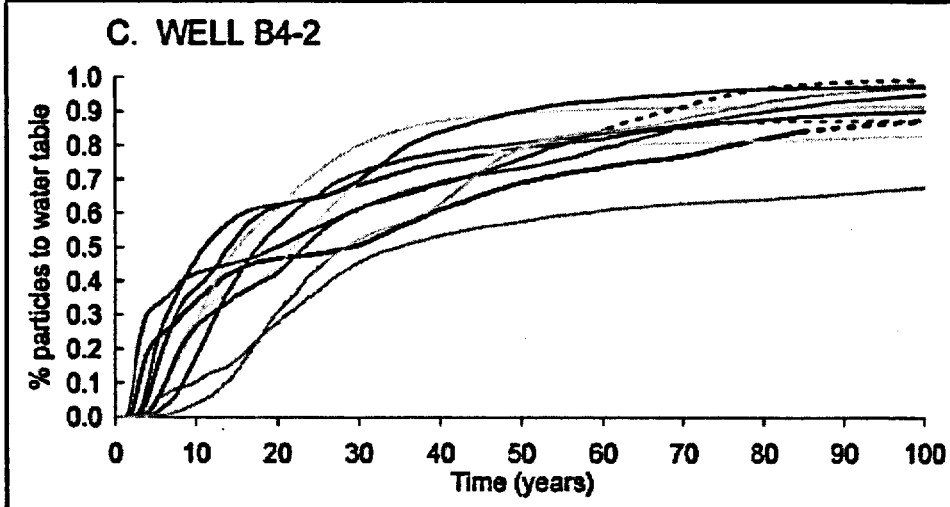


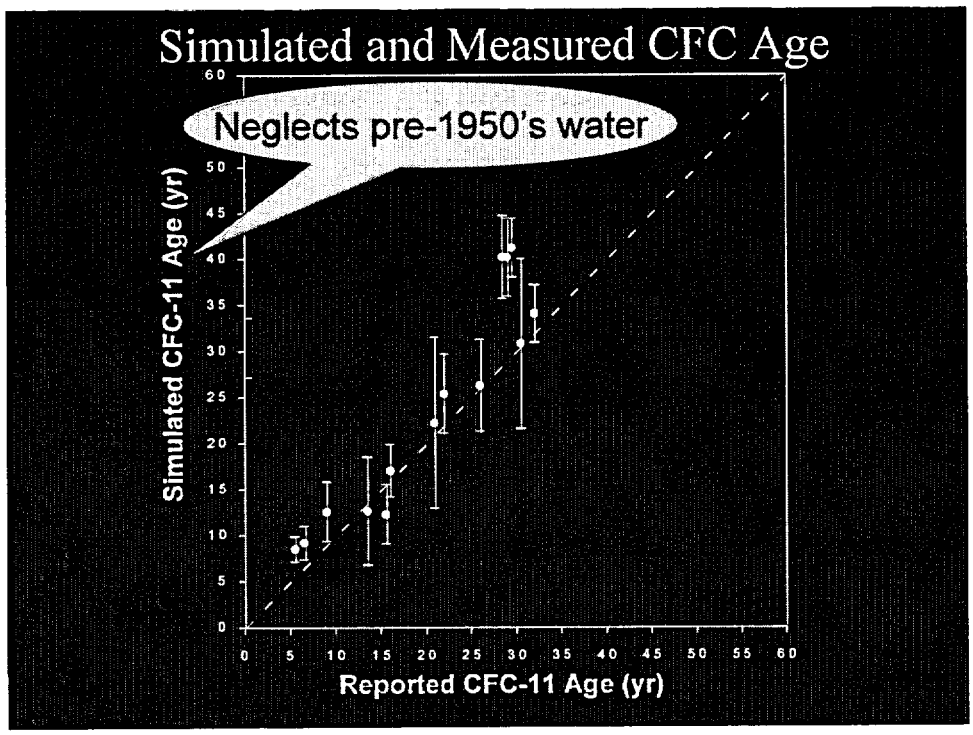
Backward Tracking Results: Heterogeneous

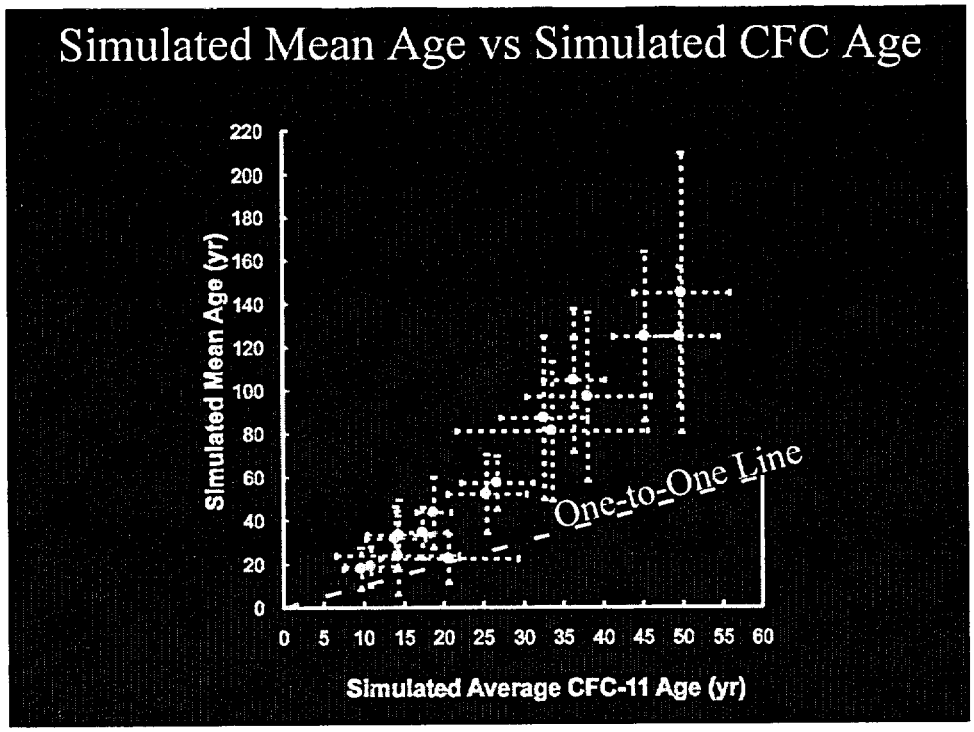
QuickTime™ and a GIF decompressor are needed to see this picture.

Graham E. Fogg, University of California, Davis

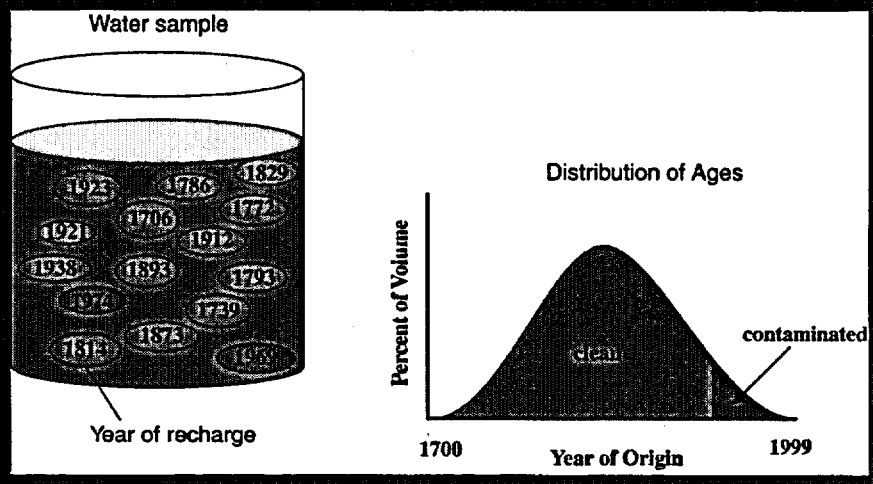
Groundwater age distributions for well B4-2 (screen depth: 35.1 m)



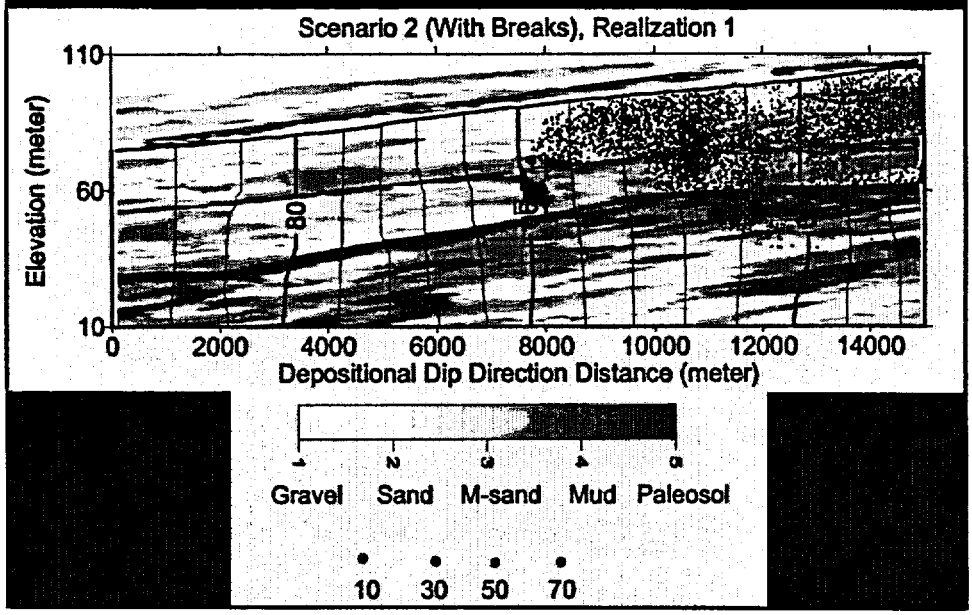

Simulated and Measured CFC Age
Neglects pre-1950's water
Simulated CFC-11 Age (yr)
Reported CFC-11 Age (yr)
0
5
10
15
20
25
30
35
40
45
50
55
60


Simulated Mean Age vs Simulated CFC Age
One-to-One Line
Simulated Mean Age (yr)
Simulated Average CFC-11 Age (yr)
0
20
40
60
80
100
120
140
160
180
200
220
5
10
15
25
30
35
45
50
55

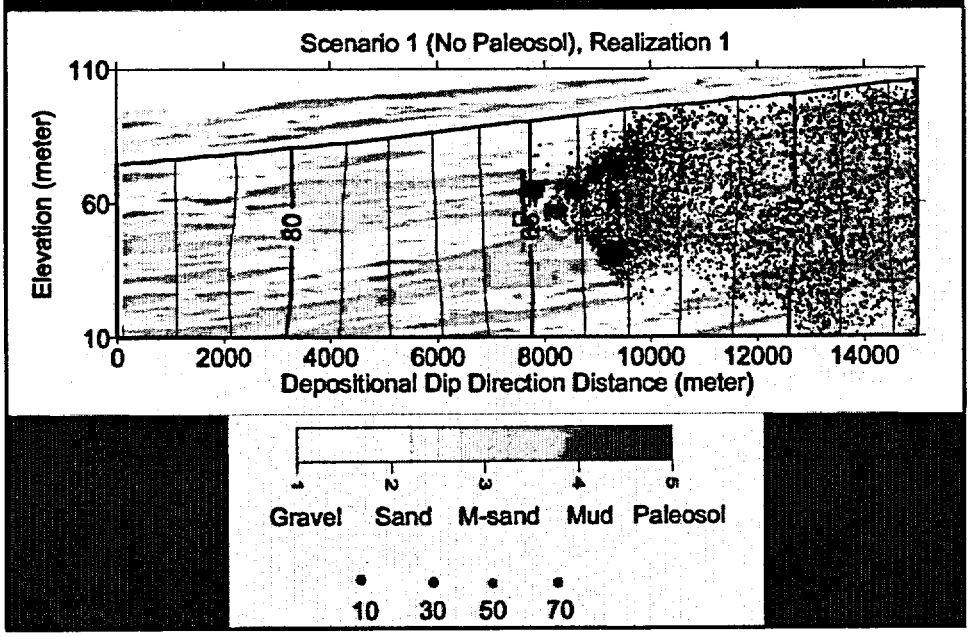
Essence of an Age Distribution



Backward Tracking Results: Heterogeneous, Paleosols



Backward Tracking Results: Heterogeneous, No Paleosols



Summary

- Hydrofacies (geologic) approach provides added perspective on hydrogeologic processes.
- Transition probability, Markov chain method (TProGS) generates heterogeneous models (realizations) that honor the data AND geologic fundamentals.
- TP-MC approach allows relatively easy incorporation of geologic information.
- Sequence-stratigraphic approach enhances characterization of the Kings River alluvial fan.
- Paleosols can be mapped regionally in KRF and are aquitards.

Summary continued

- Typical alluvial heterogeneity leads to significant dispersion of groundwater ages within water samples, even when samples are collected from short-screen wells.
- Significant age dispersion confounds interpretation of estimated or inferred groundwater ages.
- Conventional, nearly-homogeneous models of groundwater flow and transport can be grossly misleading when used to forecast groundwater travel times.

U.S. Department of Energy
Office of Civilian Radioactive Waste Management

YUCCA MOUNTAIN PROJECT

Barrier Capability Analyses

Presented to:
Nuclear Waste Technical Review Board

Presented by:
Peter Swift, Manager
Performance Assessment Strategy and Scope
Sandia National Laboratories
Bechtel SAIC Company, LLC

January 28, 2003
Las Vegas, Nevada

Overview

- Barrier Importance, Barrier Capability, and Part 63
- Brief summary of available analysis techniques
- Analyses currently being considered to support the License Application (LA)
  - Representative examples based on past work
  - All examples for nominal performance scenario
  - All examples are draft
    - All quantitative results will be updated for LA
  - Examples are shown as mean results for simplicity in illustration; full discussion in the LA will address uncertainty

Regulatory Basis

- "*Important to waste isolation*, with respect to design of the engineered barrier system and characterization of natural barriers, means those engineered and natural barriers whose function is to provide a reasonable expectation that high-level waste can be disposed of without exceeding the requirements of §63.113(b) and (c)" (10 CFR 63.2)
- "*Barrier* means any material, structure, or feature that, for a period of time to be determined by NRC, prevents or substantially reduces the rate of movement of water or radionuclides from the Yucca Mountain repository... or... the release rate of radionuclides from the waste..." (10 CFR 63.2)

Regulatory Basis
(Continued)

- "Describe the capability of barriers, identified as important to waste isolation, to isolate waste, taking into account uncertainties in characterizing and modeling the behavior of the barriers" (10 CFR 63.115(b))
- "Provide the technical basis for the description of the capability of barriers ... based on and consistent with the technical basis for the performance assessments used to demonstrate compliance with §63.113(b) and (c)" (10 CFR 63.115(c))

Summary of Barrier Analysis Approaches

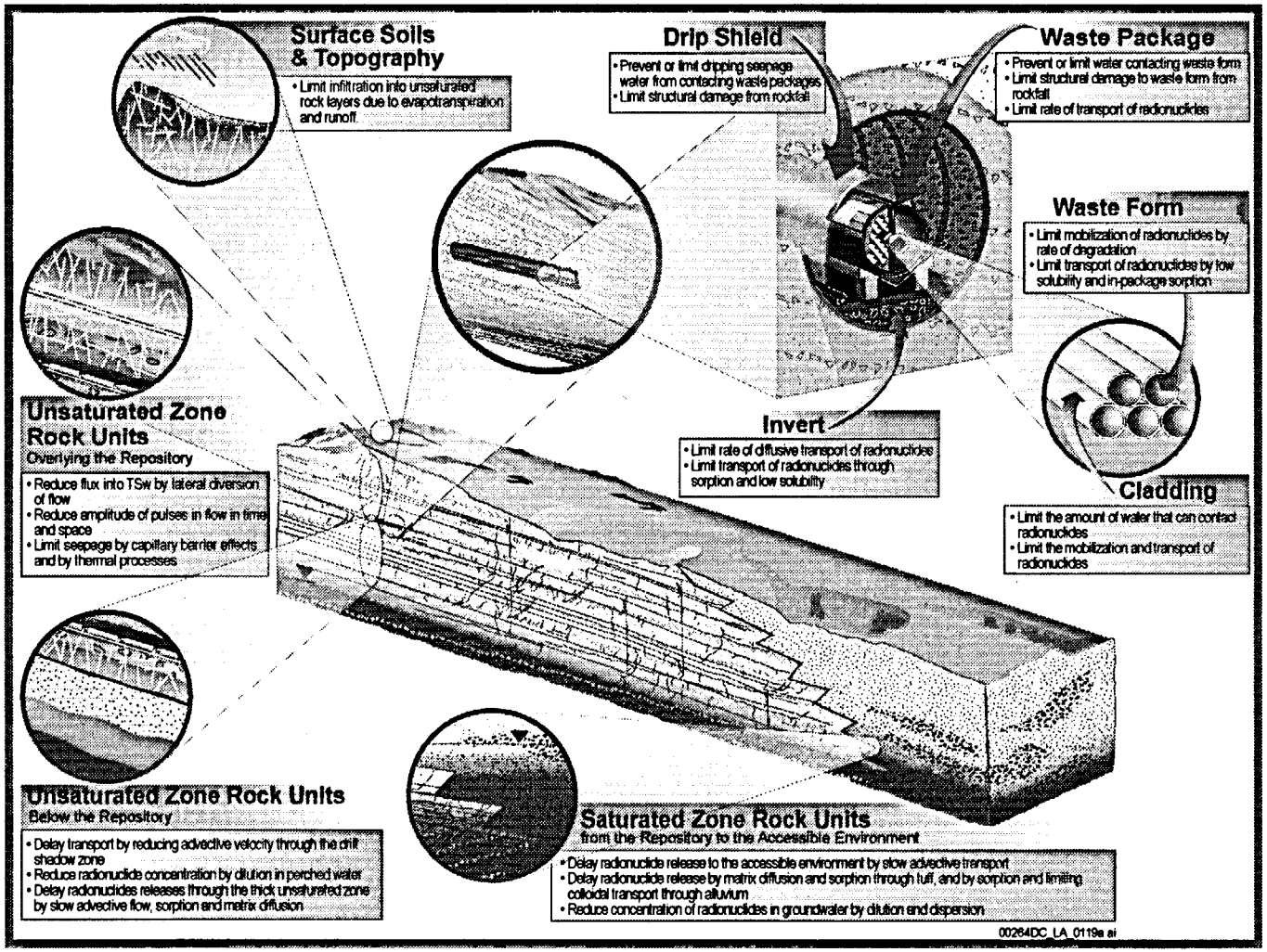
- System-level regression analysis
  - Provides insights into main contributors to uncertainty in total system performance
  - Emphasis on total system limits insights at component level
- One-on analyses
  - Good display of relative contributions of barriers
    - Strongly dependent on order
    - Not physically realistic (e.g., waste will not be emplaced without engineered barriers)
- One-off and neutralization analyses
  - Show individual barrier contribution independent of order, but
    - Redundant capabilities are difficult to characterize
    - Not physically realistic (i.e., all barriers are expected to contribute)

Summary of Barrier Analysis Approaches

(Continued)

- Intermediate results from full Total System Performance Assessment (TSPA)
  - Show individual barrier contribution in context of full system, but
    - Redundant capabilities are difficult to characterize
    - Different types of results (e.g., water flux, radionuclide flux) for different barriers: total dose is not the primary metric
- Proposed Approach for LA
  - Intermediate metrics using component analysis, full-system analysis, and one-off/one-on techniques as appropriate
    - Capability in terms of limiting water or radionuclide movement
    - Provide insight on individual components
    - Will address 10 CFR 63.115 requirements

Nine Barriers Proposed for Consideration in the License Application

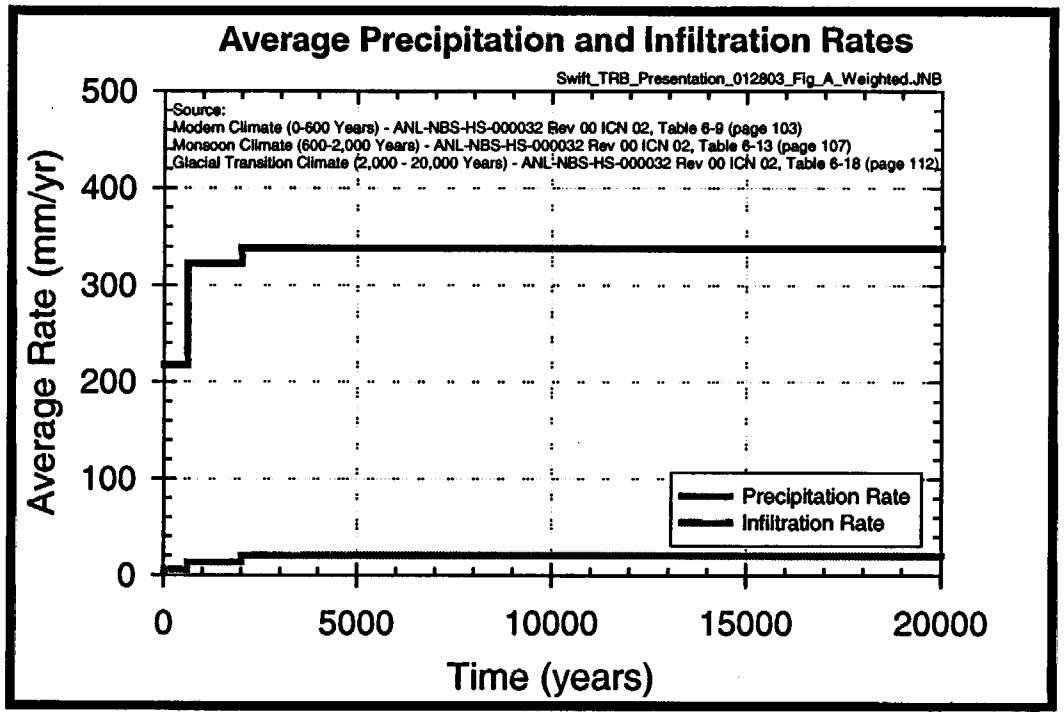


- Surface soils and topography
- Unsaturated Zone (UZ) above (seepage, drift effects)
- Drip shield
- Waste Package
- Cladding
- Waste Form
- Invert
- UZ below (transport)
- Saturated Zone (SZ)

YUCCA MOUNTAIN PROJECT

Surficial Soils and Topography Example Barrier Capability Description

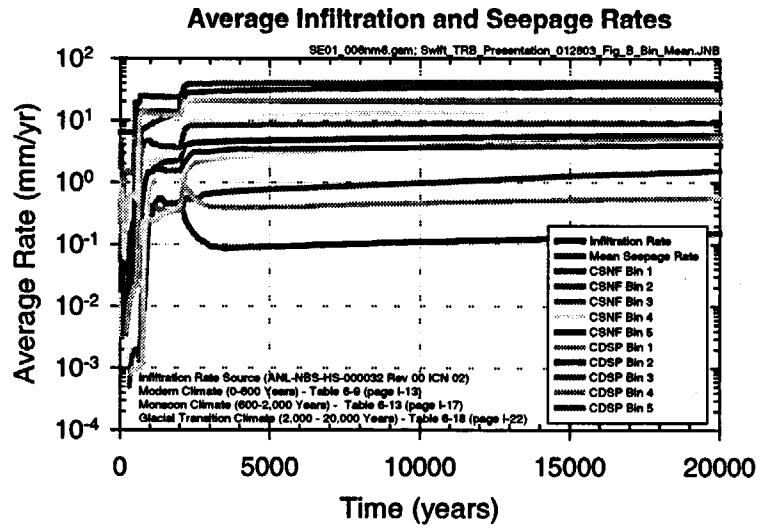
- **Capability: reduce the rate of movement of water**
- **Draft comparison of precipitation and infiltration**
  - Precipitation and infiltration are shown as spatial averages for 38.7 km² domain
  - Curves are weighted averages for low, medium, and high infiltration conditions corresponding to uncertainty in climate states
  - Steps in time history correspond to climate changes
- **Surficial soils and topography reduce spatially-averaged water movement at 10,000 years approximately 16x**

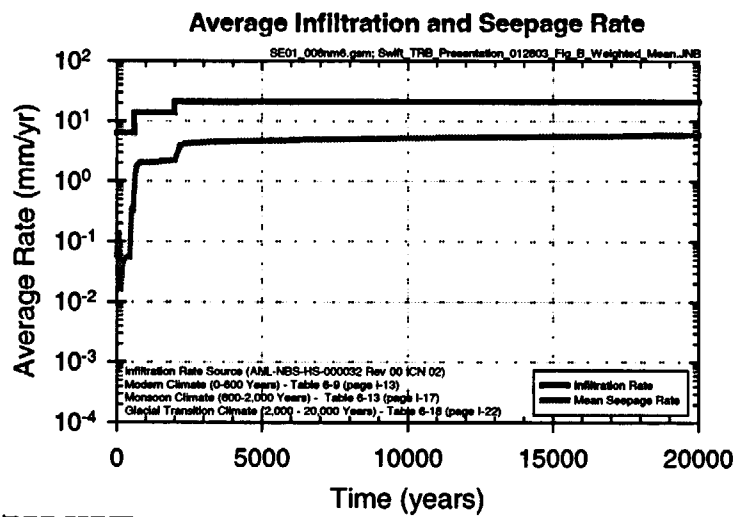


Draft precipitation and infiltration based on spatially-averaged results from ANL-NBS-HS-000032, Rev. 00 ICN 02 [FEIS/SSPA Infiltration Model AMR) for three infiltration maps, weighted by the relative frequency of occurrence of these maps in TSPA-FEIS

Unsaturated Zone above the Repository Example Barrier Capability Description

- Capability: reduce the rate of movement of water
- Draft comparison of mean seepage flux for seeping environments to average infiltration flux
  - Mean seepage shown for 10 waste package bins (upper plot) and for overall mean weighted by bin frequency in 300 realizations (lower plot)
  - Infiltration shown as spatial average for 38.7 km ^{2} model domain (see previous slide)
- UZ flow and drift effects reduce total water flux onto drip shields at 10,000 years ~ 4x relative to infiltration



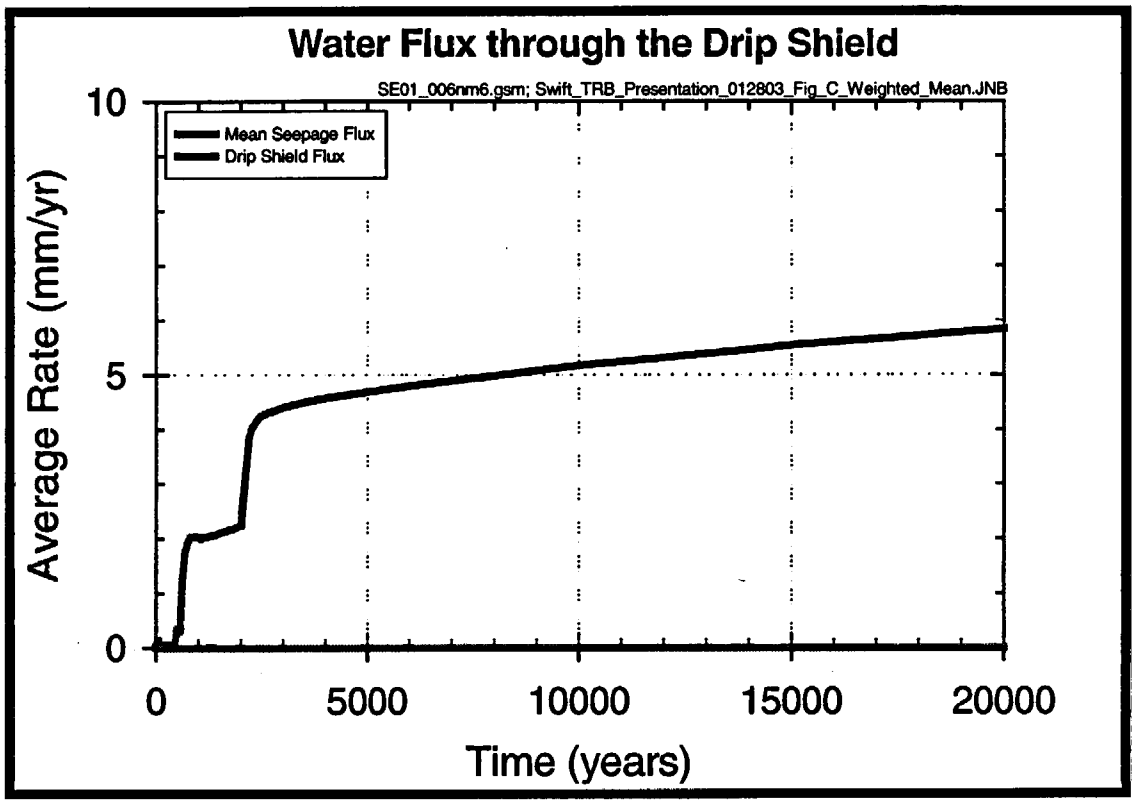


Draft seepage results show mean performance from 300 realizations. Source: calculations performed for SL986M3 Rev. 00, figure 6-5 (TSPA-FEIS).

YUCCA MOUNTAIN PROJECT

Drip Shield
Example Barrier Capability Description

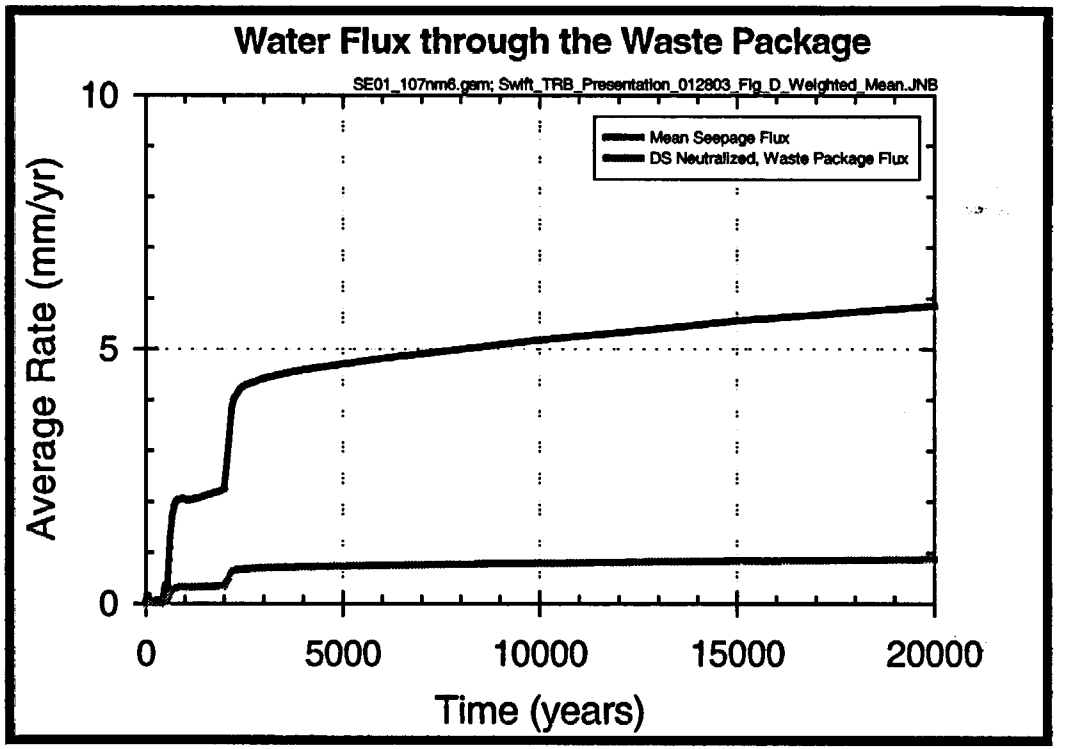
- Capability: reduce the rate of movement of water
- Draft comparison of spatially-averaged mean seepage flux to mean water flux reaching waste package
- Drip shields reduce water flux at 10,000 years to zero (no drip shield failures during first 20,000 years)



Draft results show mean performance from 300 realizations. Note linear scale rather than logarithmic scale shown for same information on figure 9. Source: calculations performed for SL986M3 Rev. 00, figure 6-5 (TSPA-FEIS).

Waste Package
Example Barrier Capability Description

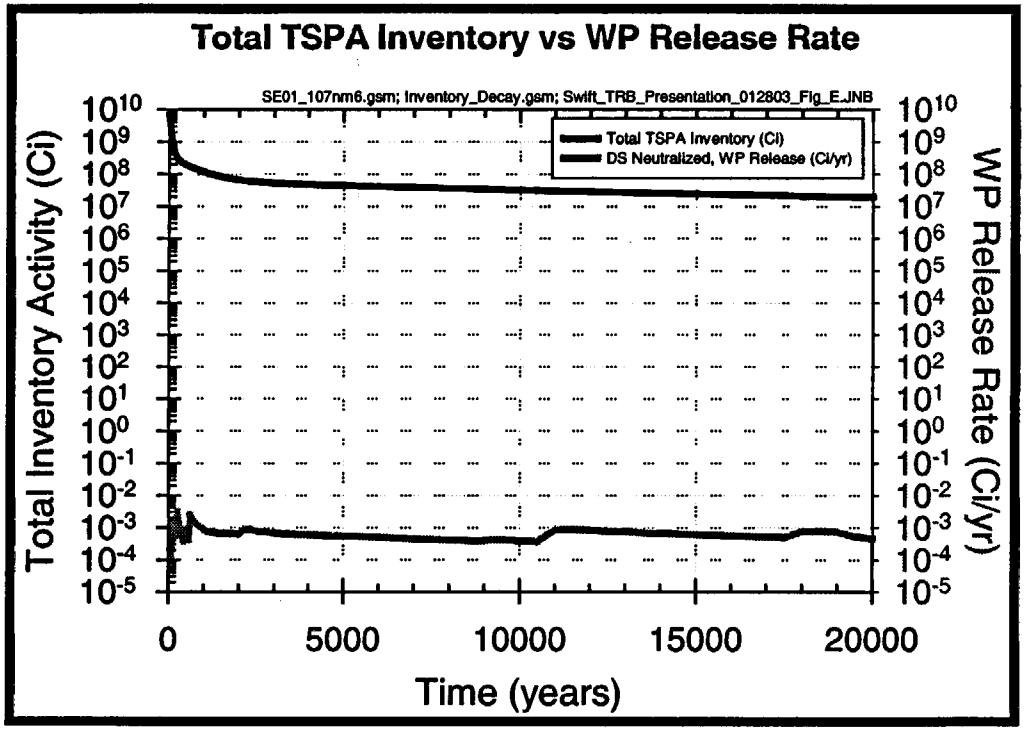
- Capability: reduce the rate of movement of water
- Draft comparison of spatially-averaged mean seepage flux to mean water flux through waste packages with early failures and without a drip shield
- Waste packages alone (independent of drip shields) can reduce water flux to less than 1 mm/yr for packages with early failures and to zero for all other packages



Draft results show mean performance from 300 realizations. Source: draft mean seepage calculations prepared for figure 9 of this presentation, scaled by area fraction of early package failure opening.

Waste Package
Example Barrier Capability Description
(Continued)

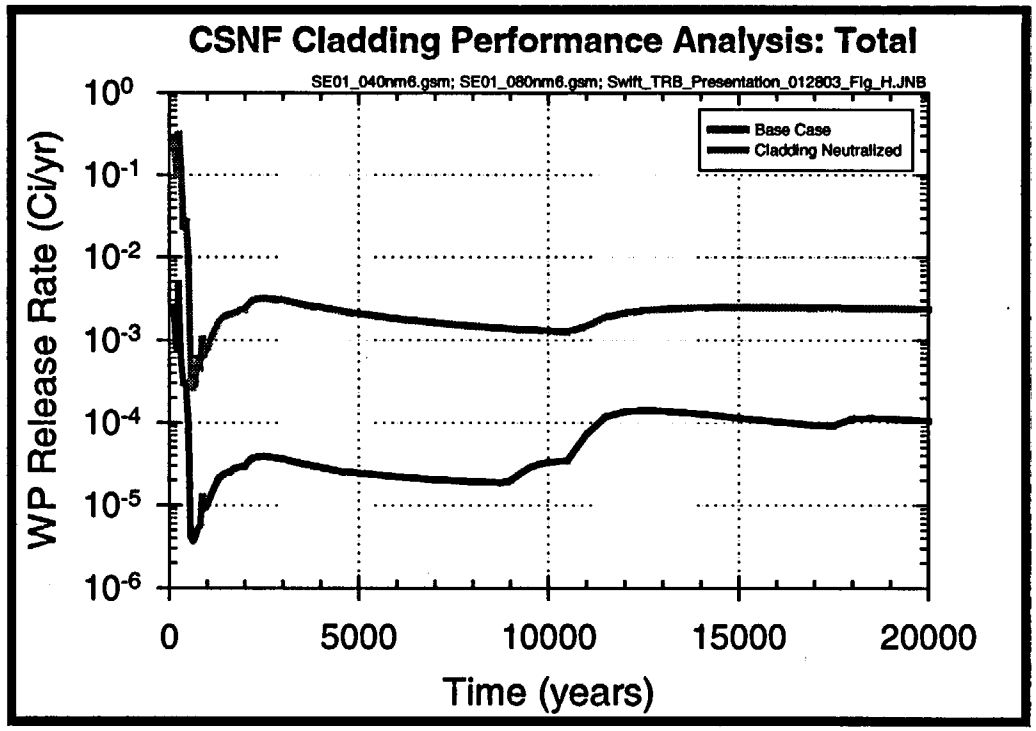
- Capability: reduce the rate of radionuclide movement
- Draft comparison of total activity leaving waste package to total activity in TSPA inventory shows capability of barrier to limit radionuclide movement
  - Drip shield removed
  - Releases result from one early waste package failure in each realization
- Waste packages alone limit annual releases to less than one ten-billionth of the total inventory



Draft results show mean performance from 300 realizations. Source: calculations performed for TDR-WIS-PA-000009, rev. 01, ICN 01, figure 10.

Cladding
Example Barrier Capability Description

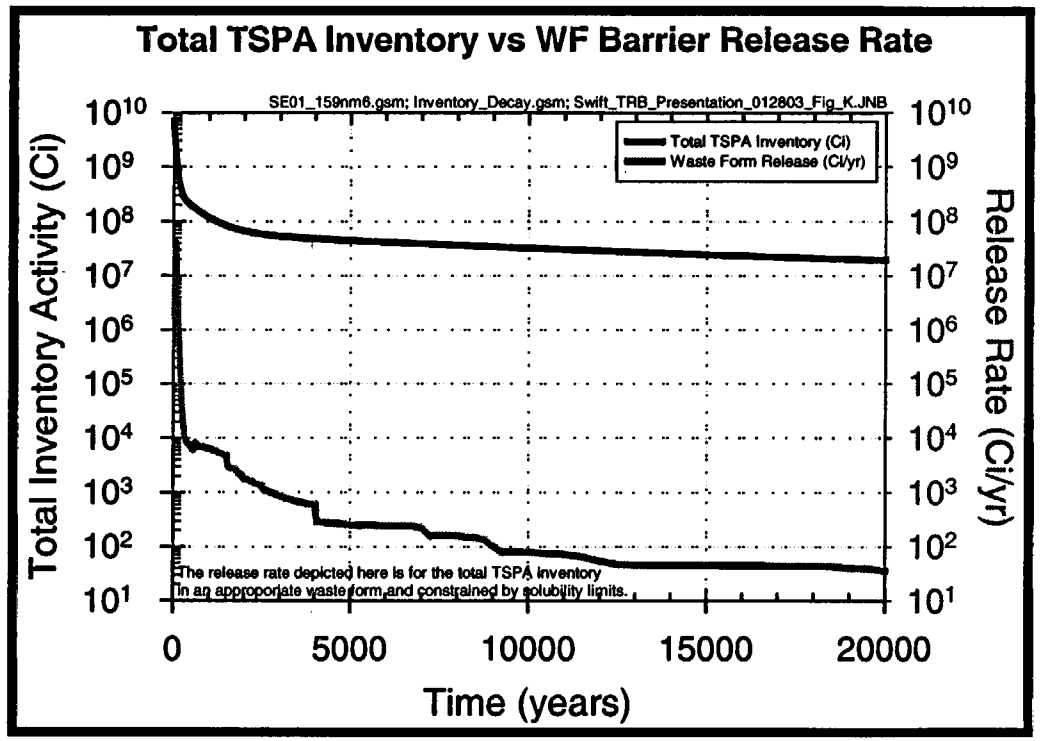
- Capability: reduce the rate of radionuclide movement
- Draft comparison of total activity leaving waste package with and without cladding present on commercial spent nuclear fuel (CSNF)
  - Other barriers (e.g., drip shield and waste package) perform as expected
- Cladding has the potential to reduce total activity flux leaving the CSNF waste packages at 10,000 years ~40x



Draft results show mean performance from 201 realizations, which represent the CSNF fraction early waste package failures in the the total of 300 realizations. Source: calculations performed for TDR-WIS-PA-000009, rev. 01, ICN 01, figure 19.

Waste Form Degradation and Dissolution Example Barrier Capability Description

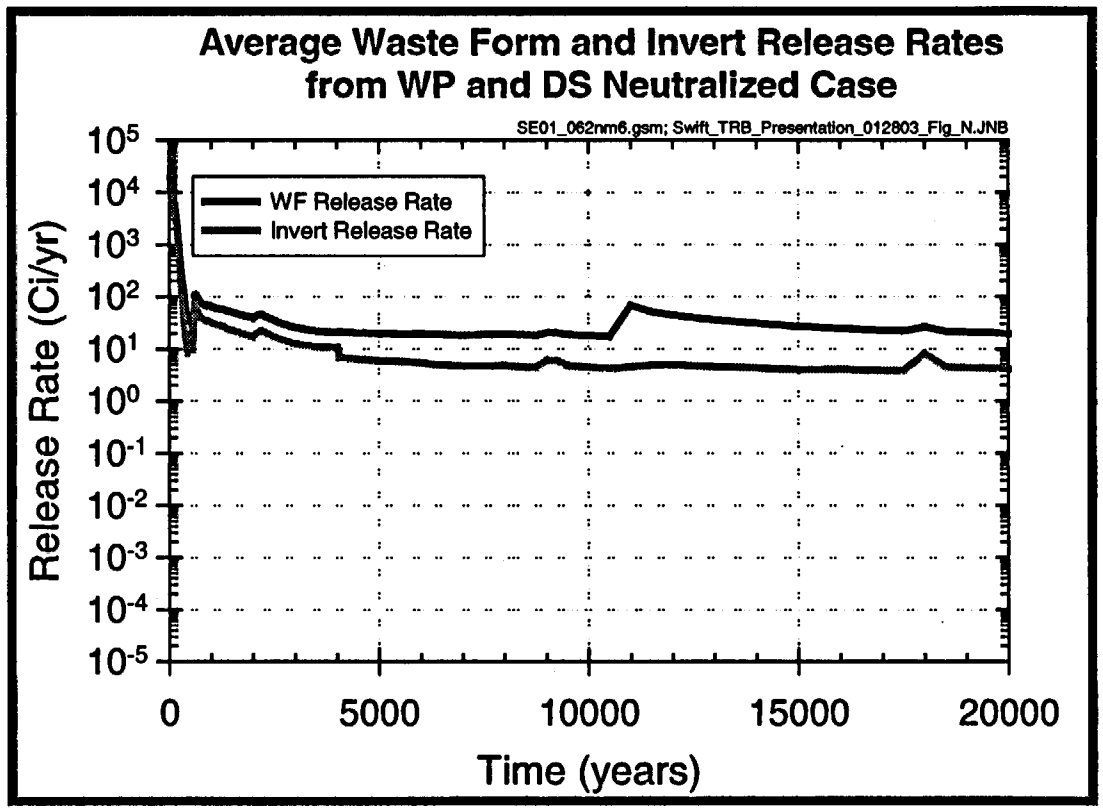
- Capability: reduce the rate of radionuclide release from waste
- Draft comparison of total activity in TSPA inventory and total activity mobilized from waste form exposed to precipitation flux
  - Drip shield, Waste Package, and Cladding removed
- At 10,000 years, waste form alone has the potential to reduce annual radionuclide mobilization to approx. 1/400,000 of total inventory



Draft results show mean performance from 300 realizations.
Source: calculations performed for TDR-WIS-PA-000011, rev. 00, ICN 01, figure 7-3 (one-on analysis case 3).

Invert
Example Barrier Capability Description

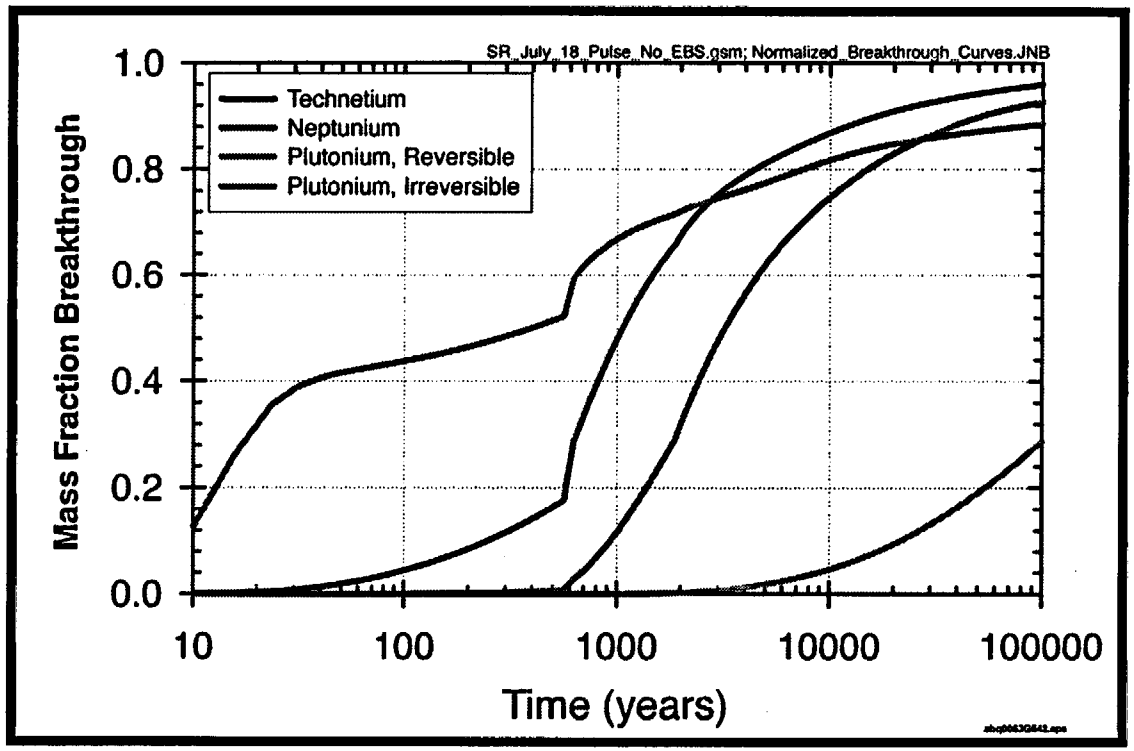
- Capability: reduce the rate of radionuclide movement
- Draft comparison of total activity entering and exiting the invert
  - Waste package and drip shield removed
- At 10,000 years, invert has the potential to reduce total activity in groundwater approximately 4x



Draft results show mean performance from 300 realizations. Source: unpublished calculations performed for TDR-WIS-PA-000009, rev. 01, ICN 01.

Unsaturated Zone Below the Repository Example Barrier Capability Description

- **Capability: reduce the rate of radionuclide movement**
- **Draft breakthrough curves for Tc, Np, Pu**
  - Breakthrough based on unit release into UZ at time zero, effectively removes all engineered barriers
  - No radioactive decay
- **Median UZ transport times for mean breakthroughs vary for different species**
  - Tc-99: ~ 1000 yr
  - Np-237: ~ 3000 yr
  - Pu (dissolved and reversible colloids): > 100,00 yr
  - Irreversible Pu colloids: ~ 300 yr

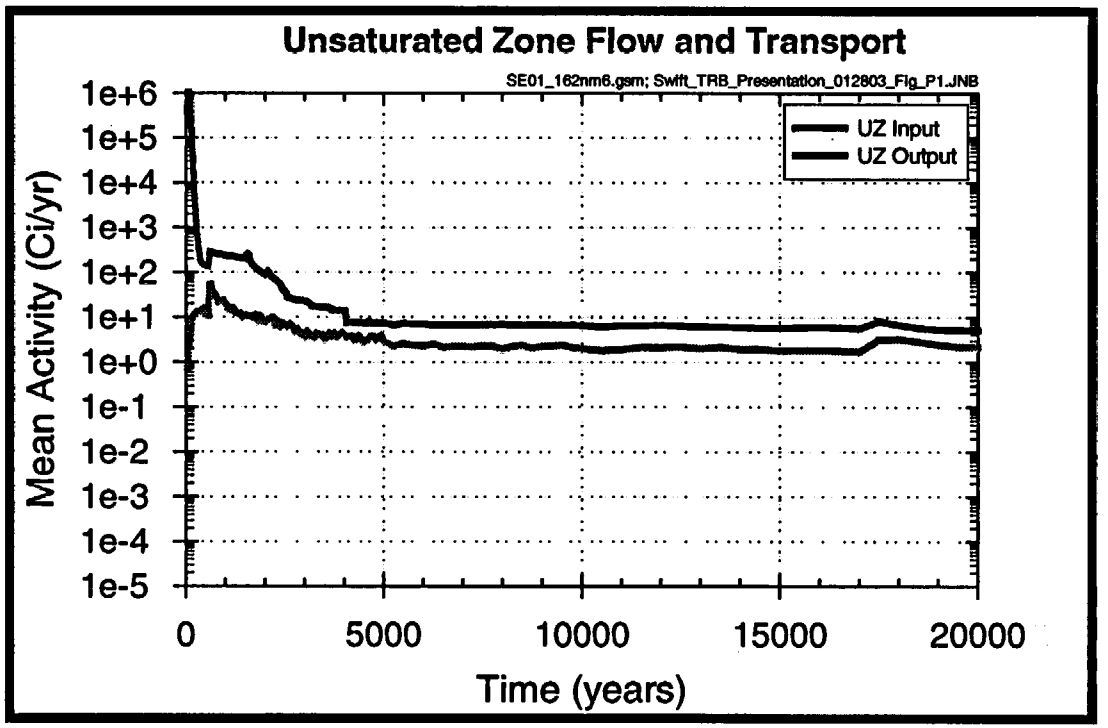


TSPA-SR Rev. 00, ICN 01, figure 3.7-12

Unsaturated Zone below the Repository Example Barrier Capability Description

(Continued)

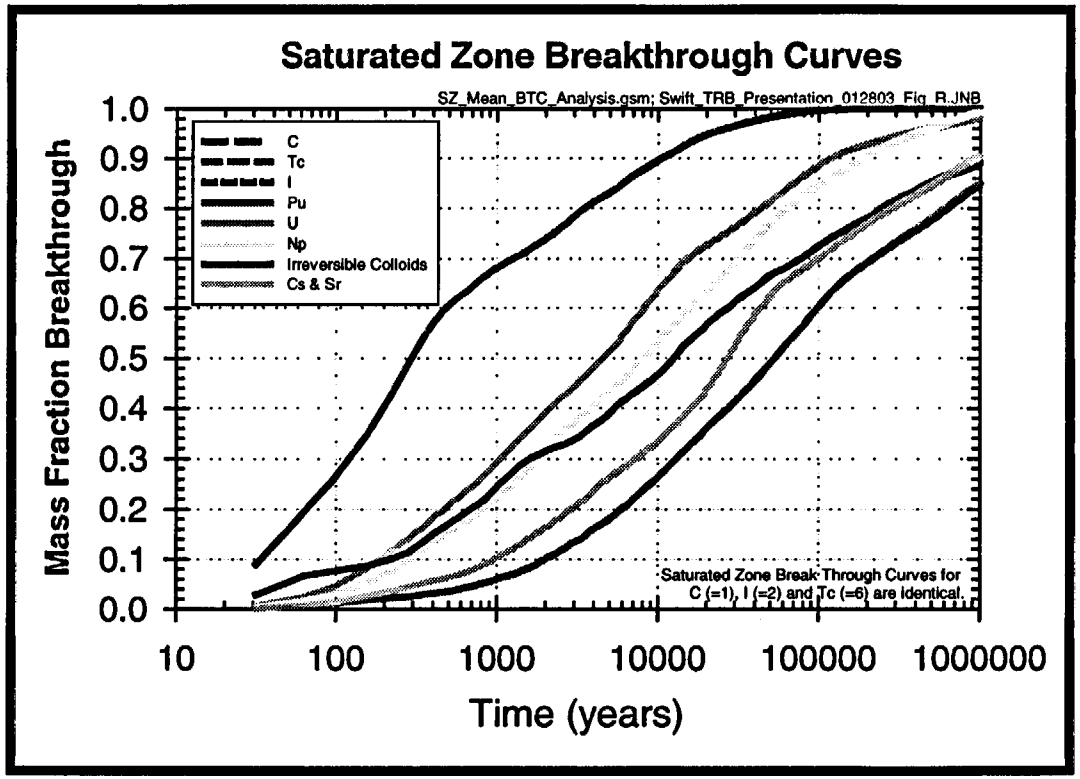
- Capability: reduce the rate of radionuclide movement
- Draft comparison of total activity entering and exiting the unsaturated zone
  - Results shown with seepage effects, drip shield, waste package, and invert removed
- Potential activity reduction at 1000 years is > 10x, due to strong retardation of Am-241, Cs-137, Sr-90



Draft results show mean performance from 300 realizations.
Source: calculations performed for TDR-WIS-PA-000011, rev. 00, ICN 01, figure 7-6 (one-on analysis case 6).

Saturated Zone
Example Barrier Capability Description

- **Capability: reduce the rate of radionuclide movement**
- **Draft mean breakthrough curves for SZ**
  - Breakthrough based on unit release into SZ at time zero, effectively removes all engineered barriers
  - Present climate, scaled for wetter conditions
  - No radioactive decay
- **Median SZ transport times for mean breakthroughs vary for different species**
  - Tc-99: ~ 300 yr
  - Np-237: ~ 8,000 yr
  - Pu (dissolved and reversible colloids): ~ 53,000 yr
  - Cs-137, Sr-90: ~ 27,000 yr
  - Irreversible colloid species ~ 12,500 yr

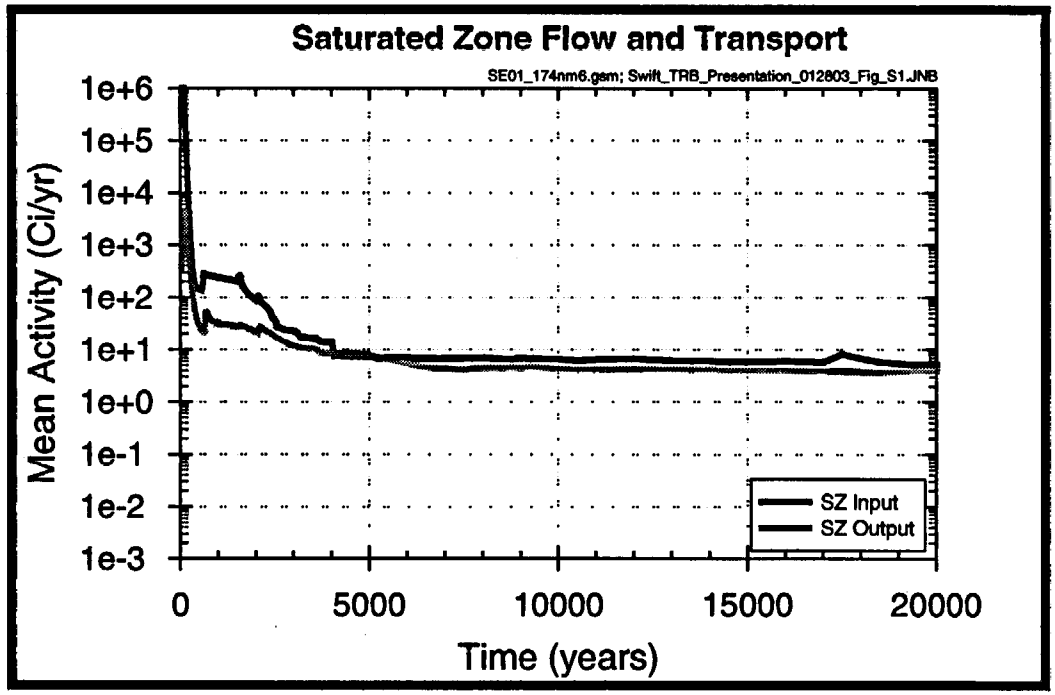


Draft results show mean performance from 100 realizations. Source: calculations performed for this presentation using models developed for SL986M3 Rev. 00, figure 6-5 (TSPA-FEIS).

YUCCA MOUNTAIN PROJECT

Saturated Zone
Example Barrier Capability Description
(Continued)

- Capability: reduce the rate of radionuclide movement
- Draft comparison of activity entering and exiting the SZ
  - Results shown with the unsaturated zone removed
  - For comparison with UZ results on page 17, seepage effects, drip shield, waste package, and invert also removed
- Potential activity reduction at 1000 years ~ 7x, due to strong retardation of Am-241, Cs-137, Sr-90



Draft results show mean performance from 300 realizations.
Source: calculations performed for TDR-WIS-PA-000011, rev. 00, ICN 01, figure 7-13 (one-on analysis case 13).

Summary of Draft Barrier Capabilities

Barrier	Limits Water Movement	Limits Radionuclide Release or Movement
Surficial Soils and Topography	Reduces spatially averaged mean annual precipitation ~ 16x at 10,000 years	-
Unsaturated Zone above the Repository (including seepage and drift effects)	Large spatial variability in water flux onto drip shield, spatial average reduced ~ 4x from average infiltration at 10,000 years	-
Drip shield	Reduces water flux onto waste packages throughout 10,000 years to zero	-
Waste Package	Independent of drip shield, can reduce water flux at 10,000 years more than 10x for early failure packages, to zero for other packages.	Reduces annual radioactivity release at 10,000 years to less than $1/10^{10}$ of total inventory

Summary of Draft Barrier Capabilities

(Continued)

Barrier	Limits Water Movement	Limits Radionuclide Release or Movement
Cladding	Independent of drip shield or waste package, prevents water from reaching CSNF until failure	Potential at 10,000 years to reduce CSNF radioactivity release rate ~40x
Waste Form	-	Independent of all other barriers, potential to reduce annual radionuclide release at 10,000 years to ~ 1/400,000 of total inventory
Invert	-	Independent of drip shield and waste package, potential to reduce radioactivity flux at 10,000 years ~4x

Summary of Draft Barrier Capabilities

(Continued)

Barrier	Limits Water Movement	Limits Radionuclide Release or Movement
Unsaturated zone below the repository	-	Transport times vary for different species; median breakthrough times range from ~300 years (colloidal species) to > 100,000 years (dissolved Pu). Potential to reduce radioactivity flux at 1000 years > 10x
Saturated zone	-	Transport times vary for different species: median breakthrough times range from ~300 yr (Tc-99) to ~ 50,000 years (dissolved Pu). Independent of UZ, potential to reduce radionuclide flux at 1000 years ~7x

Conclusions

- Draft work to date confirms that each of the nine barriers has a capability to reduce movement of water or radionuclides
- Capabilities can be quantified using subsystem model and TSPA results
- Capability description analyses provide valuable insights into TSPA