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

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Thermal Hydrologic Environment and Thermal Seepage

Presented to:
Nuclear Waste Technical Review Board

Presented by:
Bo Bodvarsson
Lawrence Berkeley National Laboratory/BSC

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  - **Yvonne Tsang, Lawrence Berkeley National Laboratory**
- **Thermal Seepage**
  - **Jens Birkholzer, Lawrence Berkeley National Laboratory**
- **In-drift TH Conditions**
  - **Thomas Buscheck, Lawrence Livermore National Laboratory**
- **In-drift TH Conditions**
  - **Thomas Buscheck, Lawrence Livermore National Laboratory**
- **Ambient seepage**
  - **Stefan Finsterle, Lawrence Livermore National Laboratory**

Outline

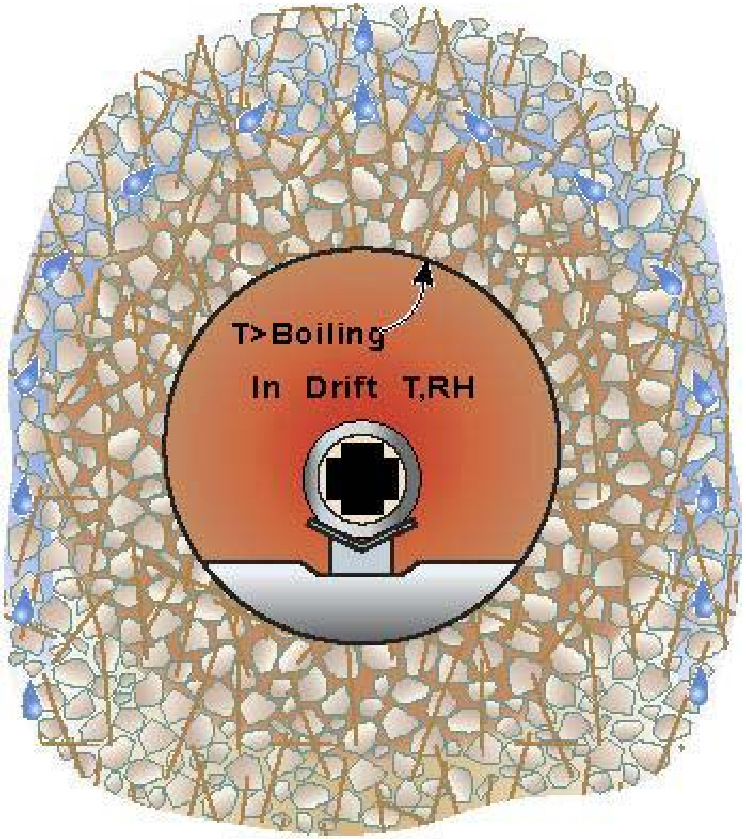
- Capillary Barrier
- Vaporization Barrier
- In-drift Thermal and Humidity Conditions
- Summary

Capillary Barrier And Vaporization Barrier Are Effective in Preventing Seepage

Little Seepage when $T < T_{Boiling}$

Capillary Barrier

No seepage when $T > T_{Boiling}$



Vaporization Barrier

NW04-007

Board's Concern over Effectiveness of The Capillary Barrier

Little Seepage when T< $T_{Boiling}$

> **"Capillarity is a well-recognized phenomenon in unsaturated rocks, but the DOE has not demonstrated that the conditions required for a capillary barrier to form are satisfied throughout the drifts. The DOE's view is based on insufficient data and modeling"**

Capillary Barrier

NW04-007

Extensive Seepage Testing and Modeling in Repository Units for Calibration and Validation

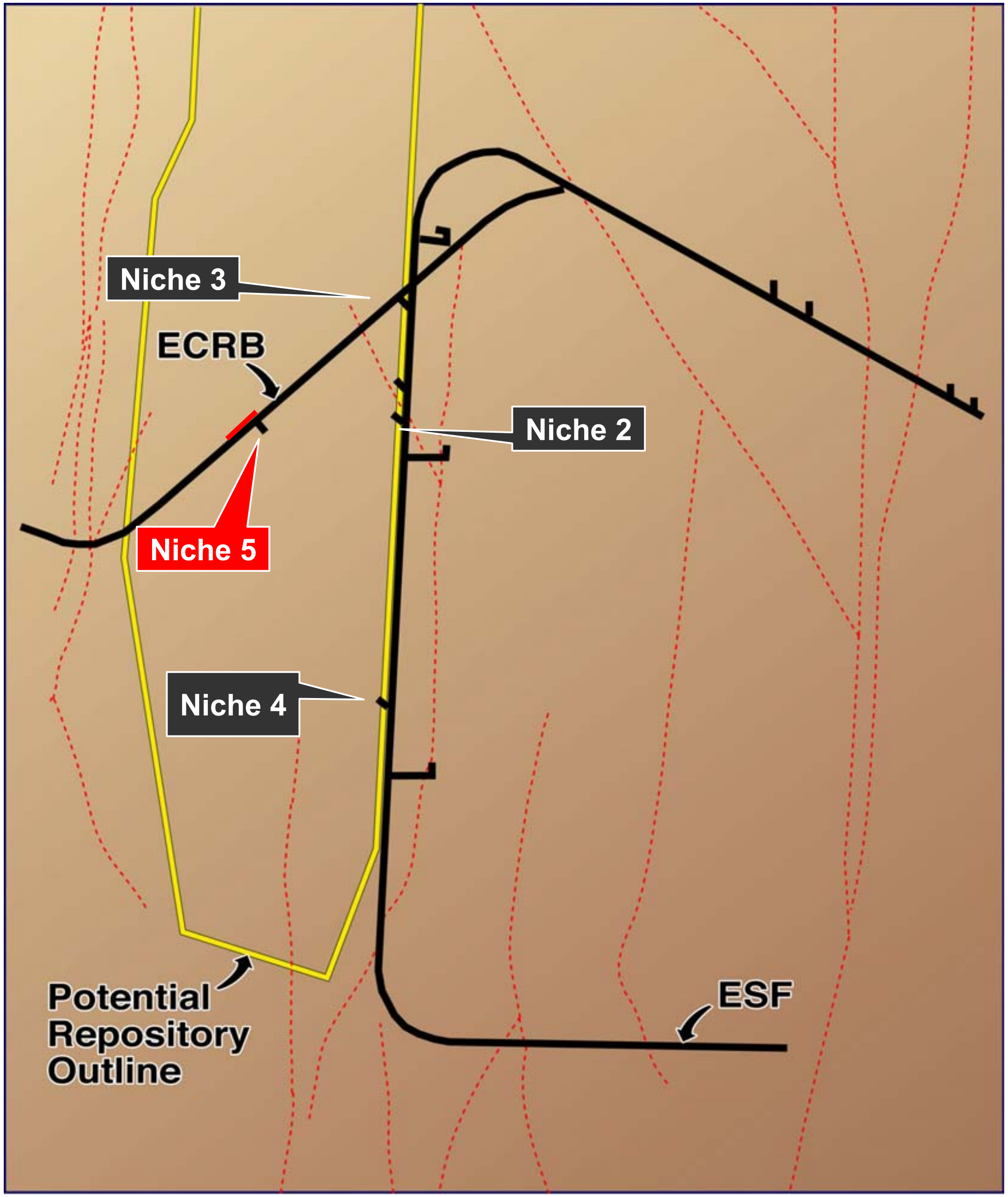
Niche 2: 40 short-term seepage threshold tests

Niche 3: 8 long-term tests

Niche 4: 11 long-term tests

Niche 5 (lower lithophysal): 10 long-term tests

Systematic Testing (lower lithophysal): in 4 boreholes and 10 zones along ECRB 18 large-scale tests



The Seepage Model is Soundly Based on Fundamental Principles, In-situ Testing, Process Modeling, Natural Analogues, and Abstraction Process

- **Based on Test Data**
  - **Liquid-release tests provide *seepage-relevant* data**
  - **Liquid-release tests provide data at the *scale of interest***
  - **Seepage-rate data *reflect most seepage-related processes***
  - **Heater test data corroborate coupled process modeling results**

- **Robust data-analysis/modeling approach**
  - ***Consistency* between data and calibration model**
  - ***Consistency* between calibration and prediction model**
  - **Traceable *uncertainty propagation analysis* (data ⇒ parameters ⇒ predictions)**

The following slides will present a summary of these tests and their relevance to the seepage characterization

Testing and Modeling

- **Data provide:**
  - Heterogeneity
  - Evaporation potential
  - Boundary conditions
  - Calibration data

- **Model predicts:**
  - Storage
  - Flow diversion
  - Evaporation
  - Seepage

- **Model captures:**
  - Drift geometry
  - Evaporation effects
  - Transient effects
  - Heterogeneity
  - Unsaturated flow
  - Capillary barrier effect

- **Effective, model-related parameter captures seepage-relevant mechanisms, including:**
  - Capillarity
  - Roughness effect
  - Film flow
  - Discretization effect

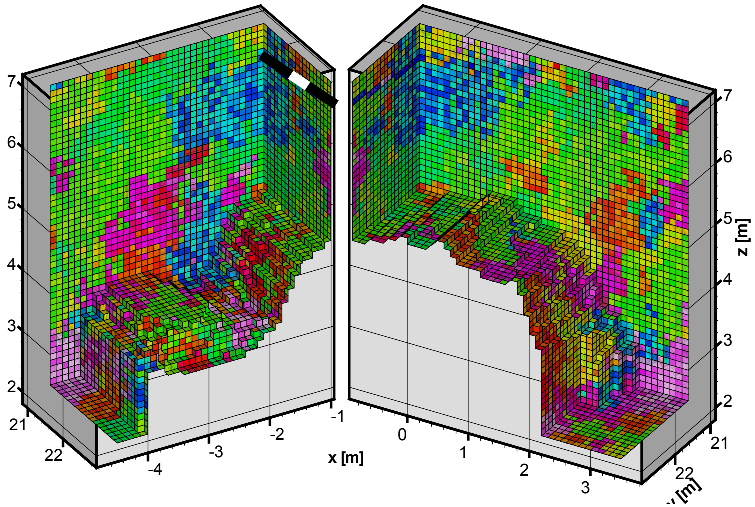
*Board's Concern over Validity of Capillary Diversion because

- Emplacement drifts do not have regular curvature or profile
- Surface roughness affects seepage
- No mass balance in seepage experiments
- No seepage tests in lower lithophysal unit
- Seepage threshold of 1,000 mm/year is too high
- Natural analogues indicate film flow and evaporation
- Active fracture model has not been fully validated
- Persistence of capillary-barrier conditions continuously along drift is in question

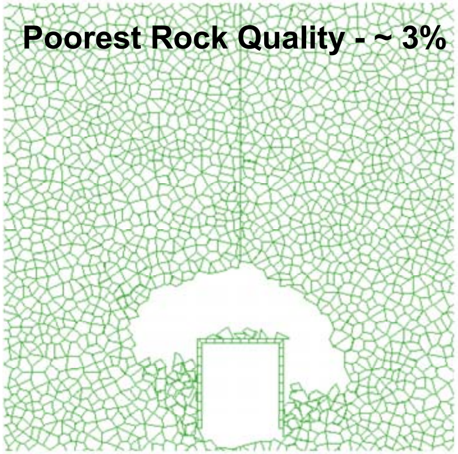
***U.S. Nuclear Waste Technical Review Board Letter and Report to Margaret Chu, Director, OCRWM (November 25, 2003)**

Seepage Model Accounts for Irregular Drift Shape and Drift Degradation

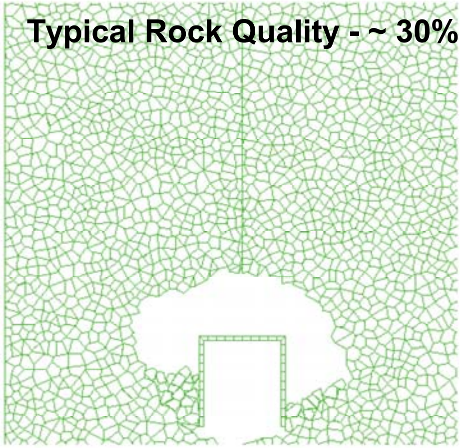
- Actual niche geometry is taken into account in calibration model
$\Rightarrow$ no bias in estimated parameters
- Effective parameters refer to a drift shape that is similar to that of the ECRB; drift radius is adjusted
- Changes to this overall drift shape due to drift degradation and their impacts on seepage have been evaluated
- Seepage into fully collapsed drifts has been evaluated



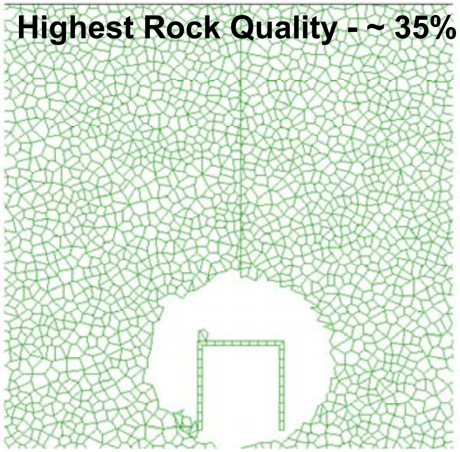
Results of Degradation Calculations – Lithophysal Rock



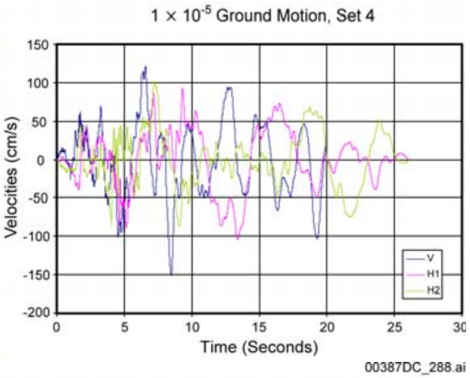
Poorest Rock Quality - ~ 3%



Typical Rock Quality - ~ 30%



Highest Rock Quality - ~ 35%

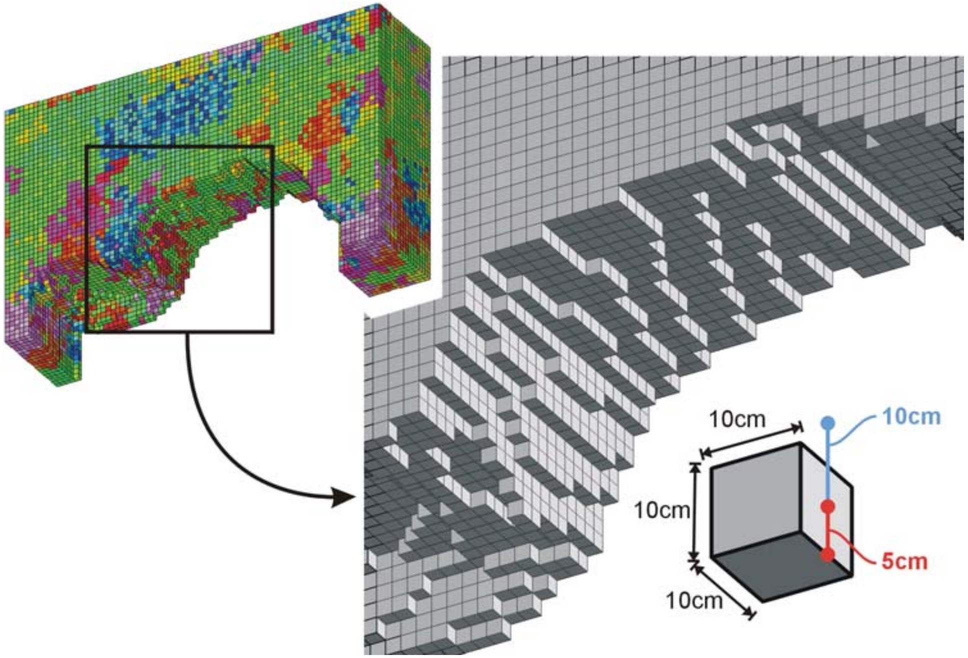


- **Range of rock mass quality categories used in analysis (function of lithophysal porosity)**
- **Minor damage from in-situ stress or thermal load even to 10,000 years**
- **Insignificant degradation for annual probabilities of 10^{-5} yr^{-1}**
- **Rock particles ~5-10 cm on a side**

Seismic degradation from 10^{-5} yr^{-1} time history with ~1.5 m/sec Peak Ground Velocity

Seepage Model Incorporates the Effect of Surface Roughness on Capillary Barrier

- Intermediate-scale surface roughness due to niche excavation and drift degradation is explicitly accounted for
- Spatial discretization addresses surface roughness with an amplitude of 5 cm (2 inches)
- Effect of lithophysal cavities and other small-scale roughness on seepage is accounted for through the use of an effective capillary-strength parameter
- This effective parameter is determined based on seepage-rate data from openings with rough surfaces
- A consistent conceptual model was used for calibration and prediction



Seepage Model Treatment of Mass Balance

$$Q_{release} = Q_{seepage} + Q_{evaporated} + Q_{storage} + Q_{diverted}$$

$Q_{release}$: measured

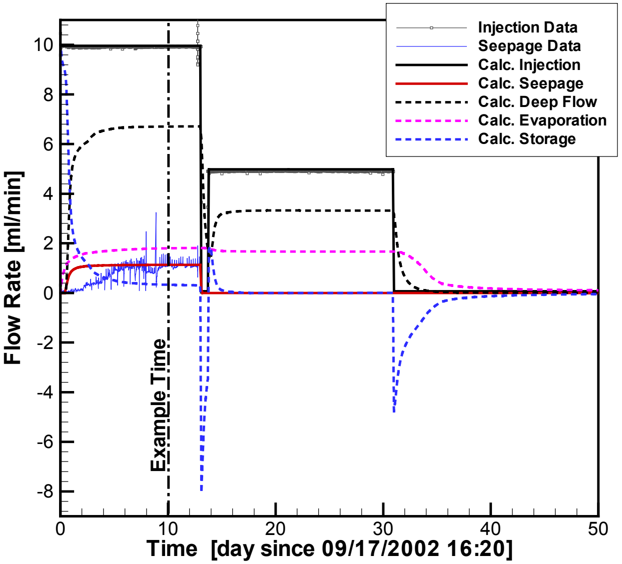
$Q_{seepage}$: measured

$Q_{evaporated}$: simulated based on measurements

$Q_{storage}$: negligible at near-steady state

$Q_{diverted}$: simulated

- **Tests were of sufficient duration to assure any potential seepage would have occurred**
- **Attempts to measure $Q_{diverted}$ in Niche 5 yielded only qualitative confirmation of flow diversion**
- **$Q_{diverted}$ is provided by calibrated simulation model**

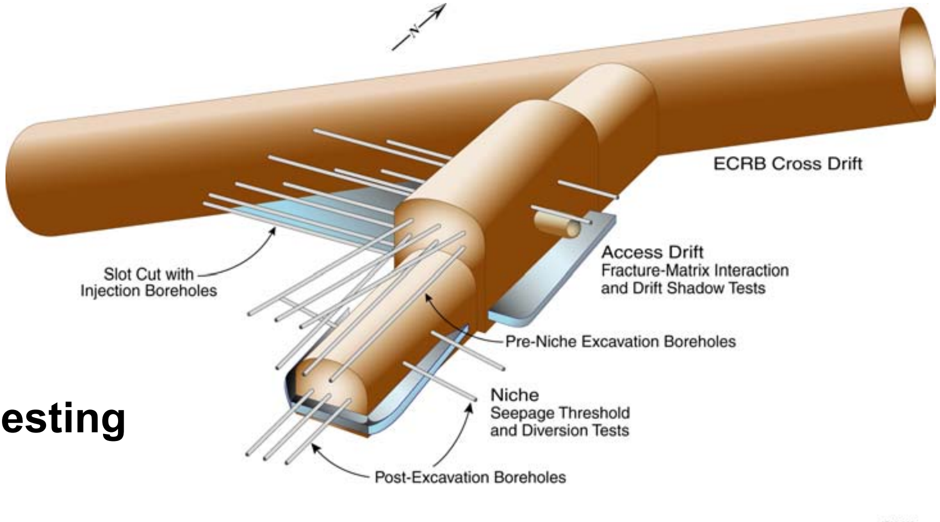


Seepage Experiments Have Been Conducted in the Lower Lithophysal Unit

- Long-term seepage tests were performed in both the middle nonlithophysal unit (Tptpmn) and the
- lower lithophysal unit (Tptpll):
  - Middle nonlithophysal (Tptpmn):
    - Niche 3 (1 borehole)
    - Niche 4 (3 boreholes)
  - Lower lithophysal (Tptpll):
    - Niche 5 (2 boreholes)
    - ECRB (4 boreholes, 10 zones)
- Additional tests were performed and used for model validation

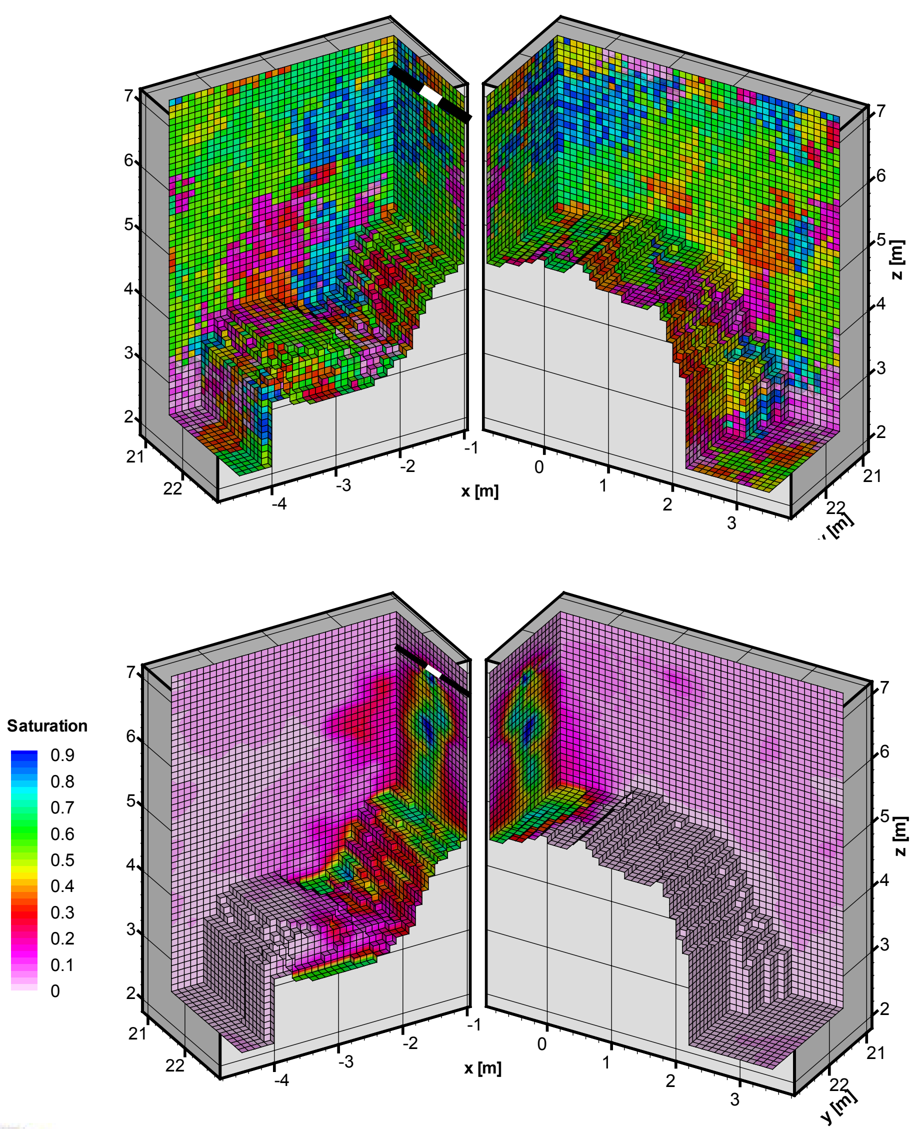
Lower Lithophysal Seepage Testing

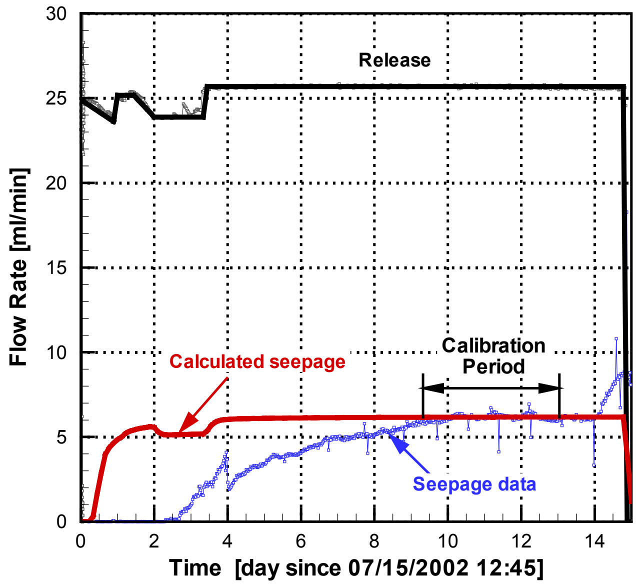
Systematic Testing

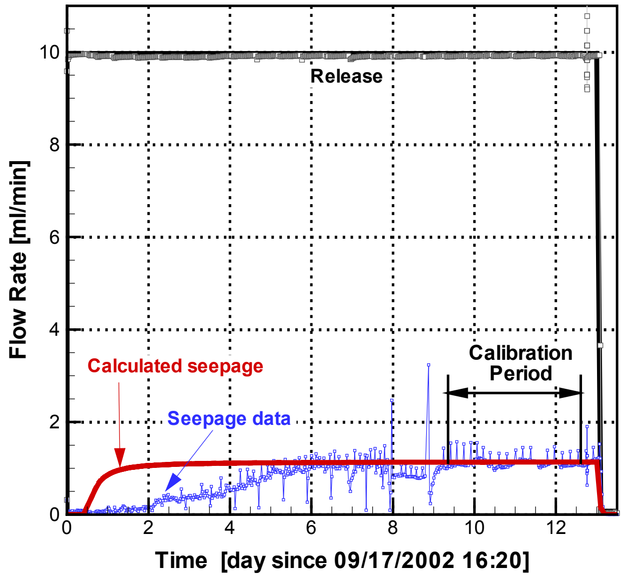


Niche 5 Batwing

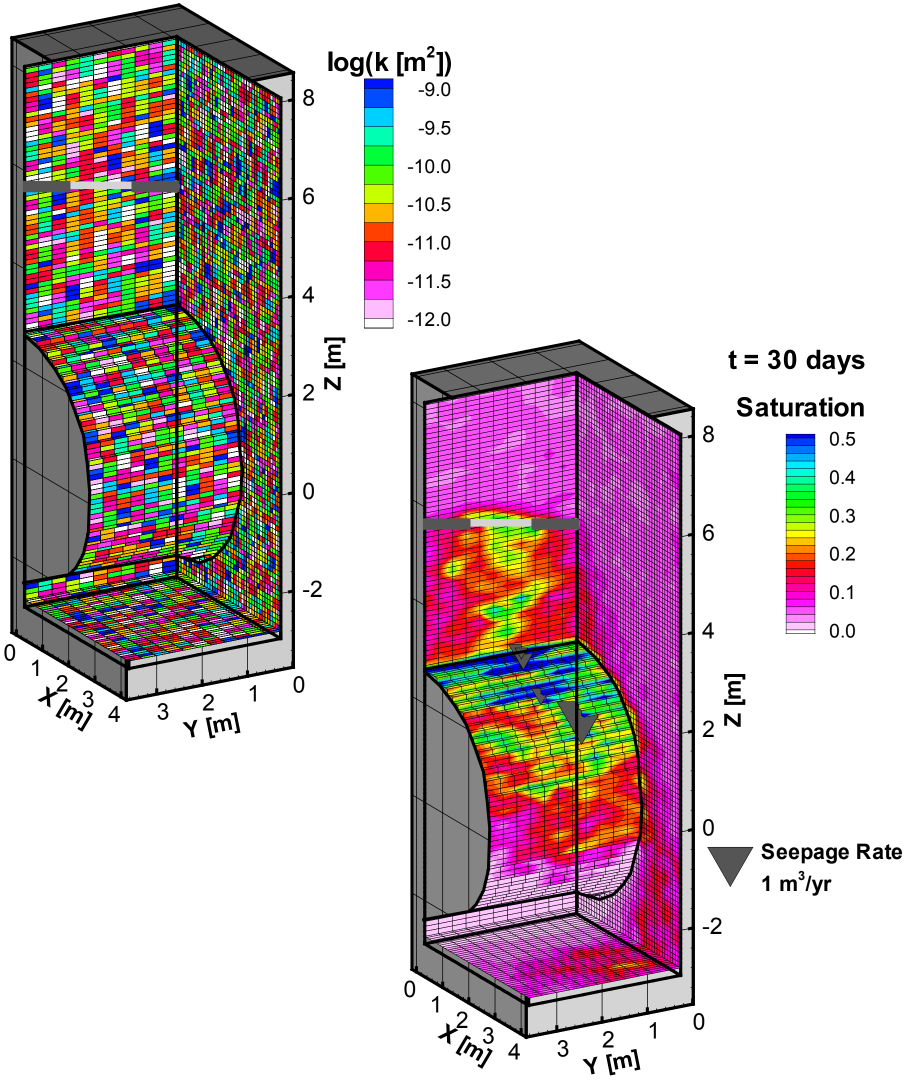
Seepage Testing in Niche 5, Tptpll

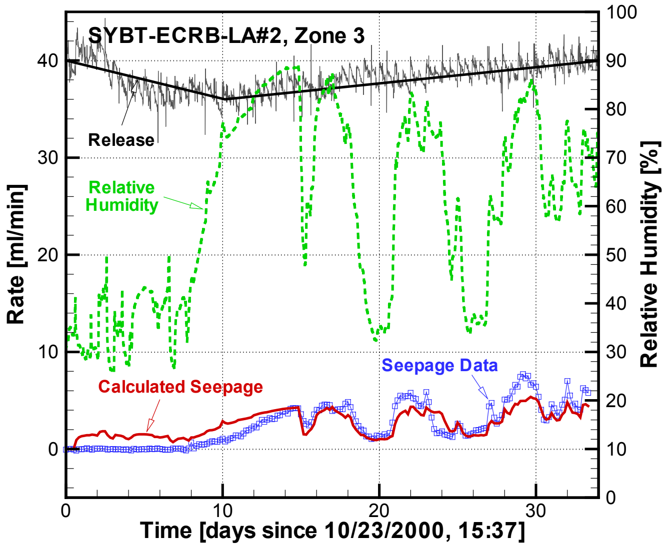


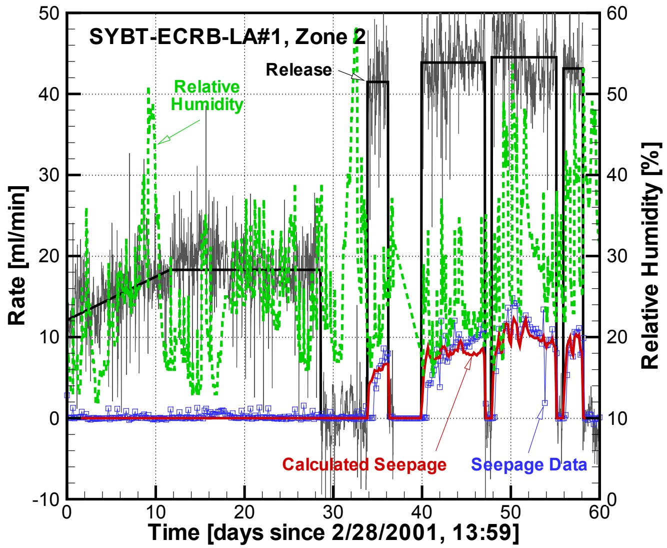




Systematic Seepage Testing in Tptpll





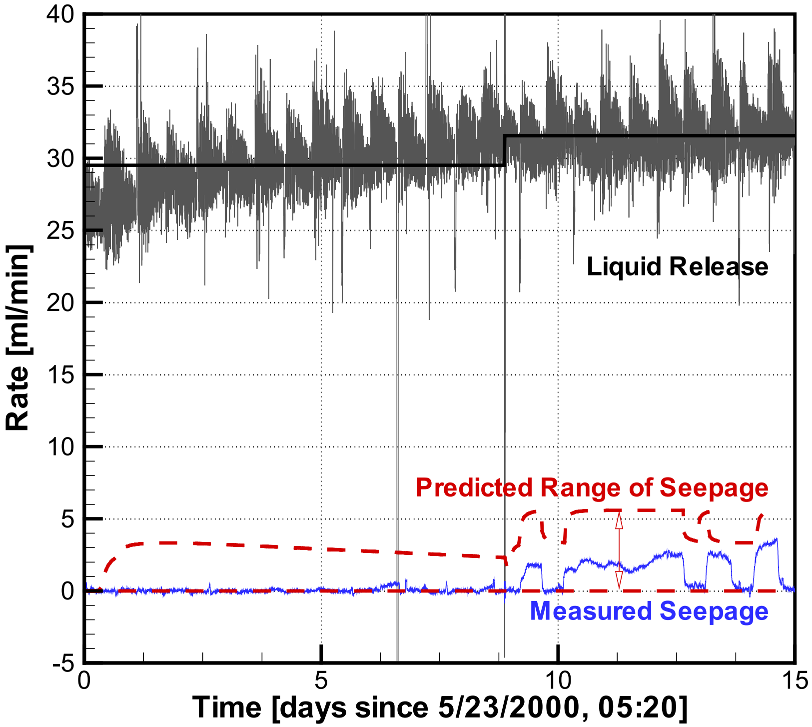


Validation

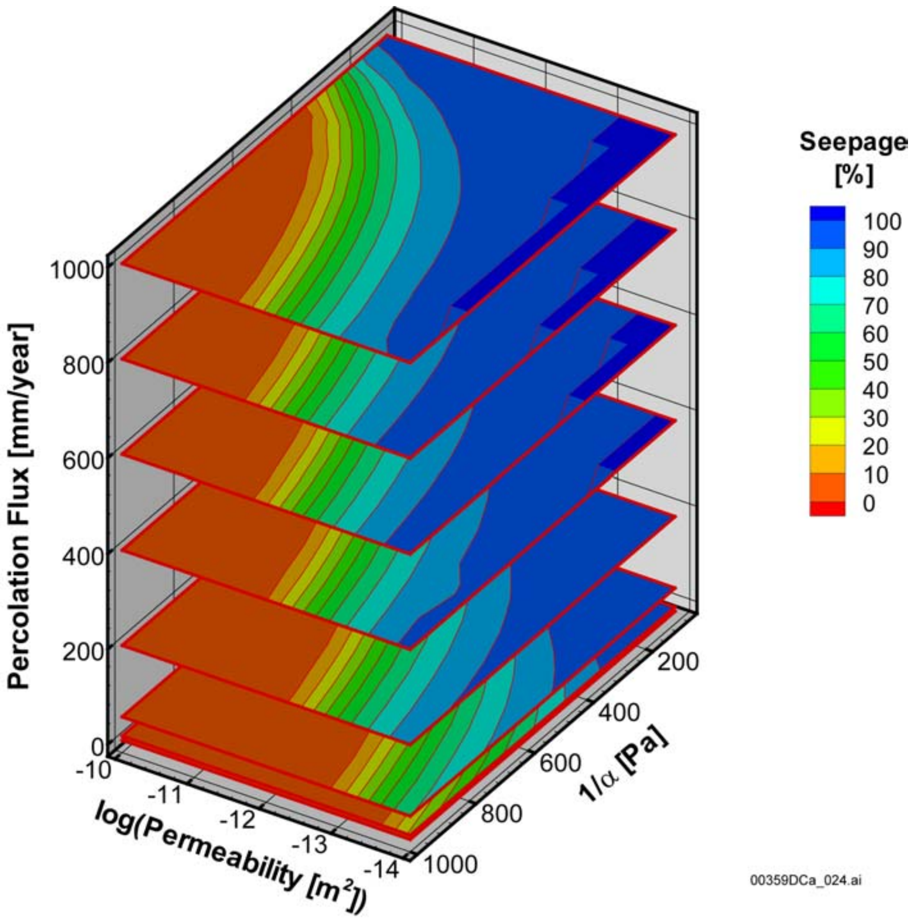
Model development, calibration and validation activities examined *relevant processes* on *appropriate scale*. The validated model is appropriate for its intended use

Validation activities:

- **Validation against seepage rate data from 22 long-term liquid-release test sequences using rigorous, quantitative acceptance criteria**
- **Various confidence-building activities during model development**
- **Publication of results in peer-reviewed journals**



TSPA Implements A Range of Seepage Threshold Values



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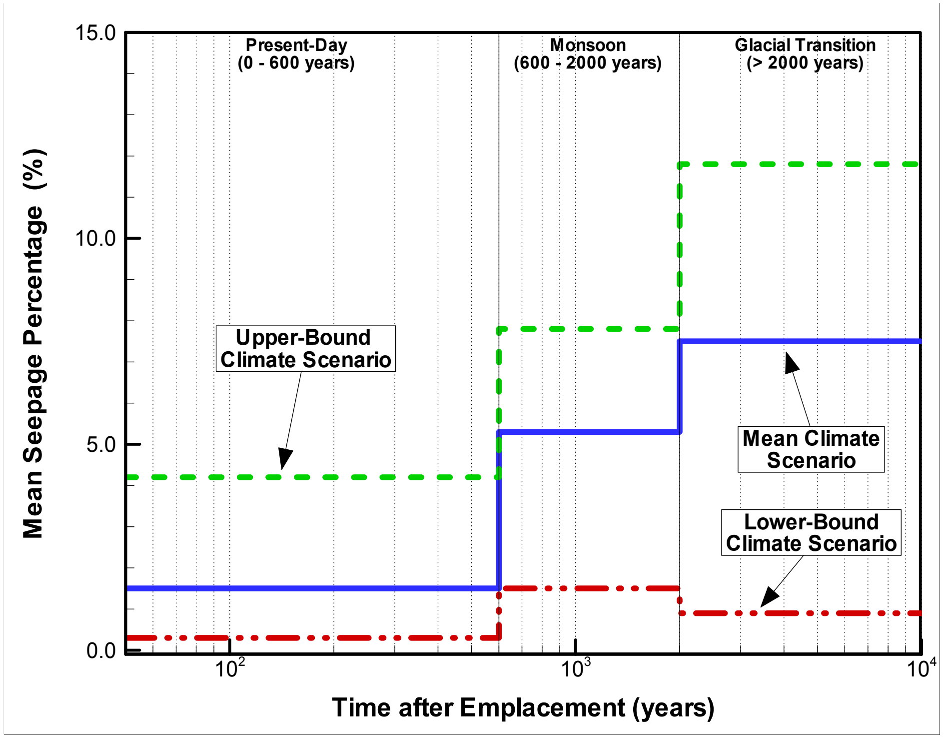
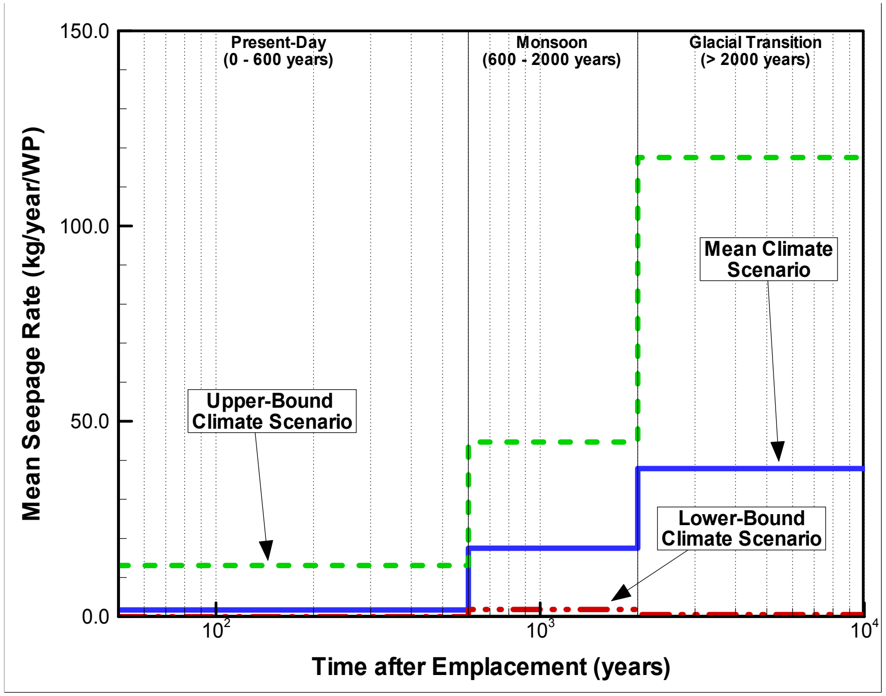
- The seepage threshold is calculated as a function of permeability and capillary strength
- The DOE seepage model does not predict a universal seepage threshold of 1000 mm/yr
- A high seepage threshold of 1000 mm/yr will be sampled in TSPA only with a very low probability

Mean Seepage Percentage (in % of percolation flux)

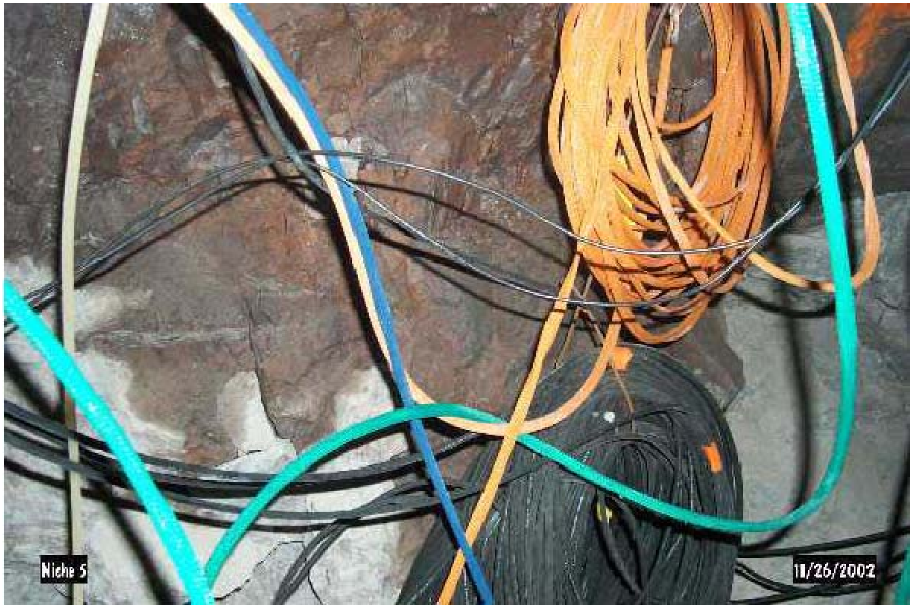


Mean Seepage Rate as a Function of Time (in kg/year/waste package)



Evidence of Film Flow and Evaporation in Natural Analogue Openings

- **Seepage predictions are based on a site-specific, calibrated, and validated process model**
- **The effects of evaporation and film flow observed at natural analogue sites are included in the seepage model**
- **Natural analogues are only used to corroborate conceptual model**



Testing of Active Fracture Model

- Seepage model does not rely on the active fracture model
  - Seepage predictions are based on a site-specific, calibrated model validated against seepage tests
- Active fracture model is important for transport
- Uncertainty in parameters describing the active fracture model has been included in the unsaturated zone transport model

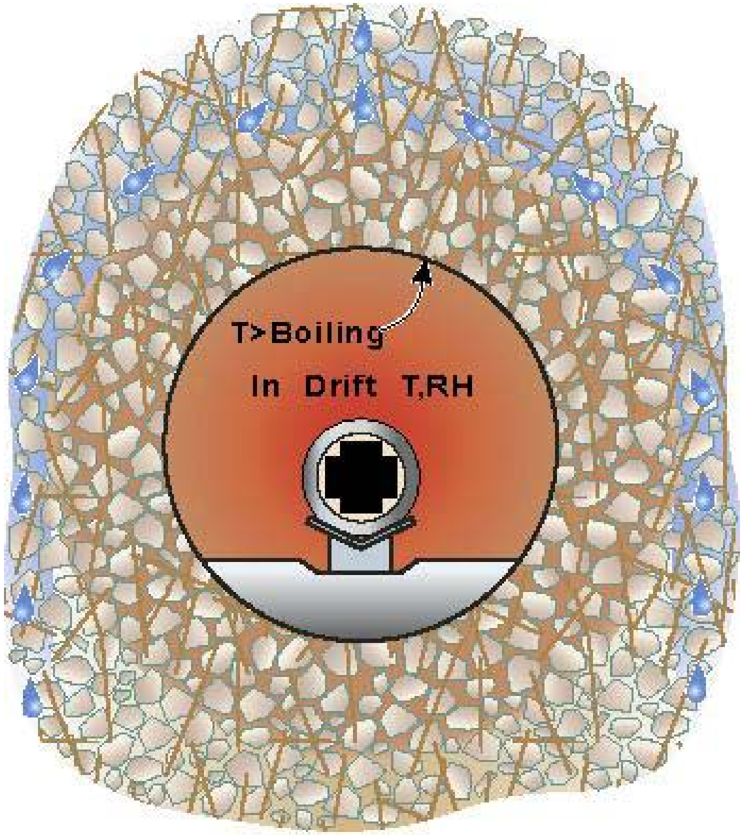
Persistence of Capillary Diversion along All Sections of The Repository Drifts

- **Capillary barrier effect is result of fundamental physical behavior of fractured porous media**
  - Capillary barrier effect has been observed and tested at various locations in ESF and ECRB, in the Tptpmn and Tptpll
  - No seepage has ever been observed behind the closed bulkheads in ECRB
- **Uncertainty and spatial variability of quantitative measure of capillary diversion are accounted for by the distributions of seepage-relevant parameters used in TSPA**

Board's Concern over Effectiveness of Vaporization Barrier

"DOE has not demonstrated that the conditions required for a pervasive vaporization barrier to form will occur everywhere. **The DOE's view is based on an insufficient analysis**. Future testing under *in situ* conditions in Yucca Mountain may improve technical defensibility of any claim about the effectiveness, or lack of effectiveness, of a vaporization barrier"

No seepage when $T > T_{Boiling}$



Vaporization Barrier

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Thermal Seepage Model Based on

Ambient Seepage Testing and Associated Modeling

Niche 2

Niche 3

Niche 4

Niche 5

Systematic testing along ECRB

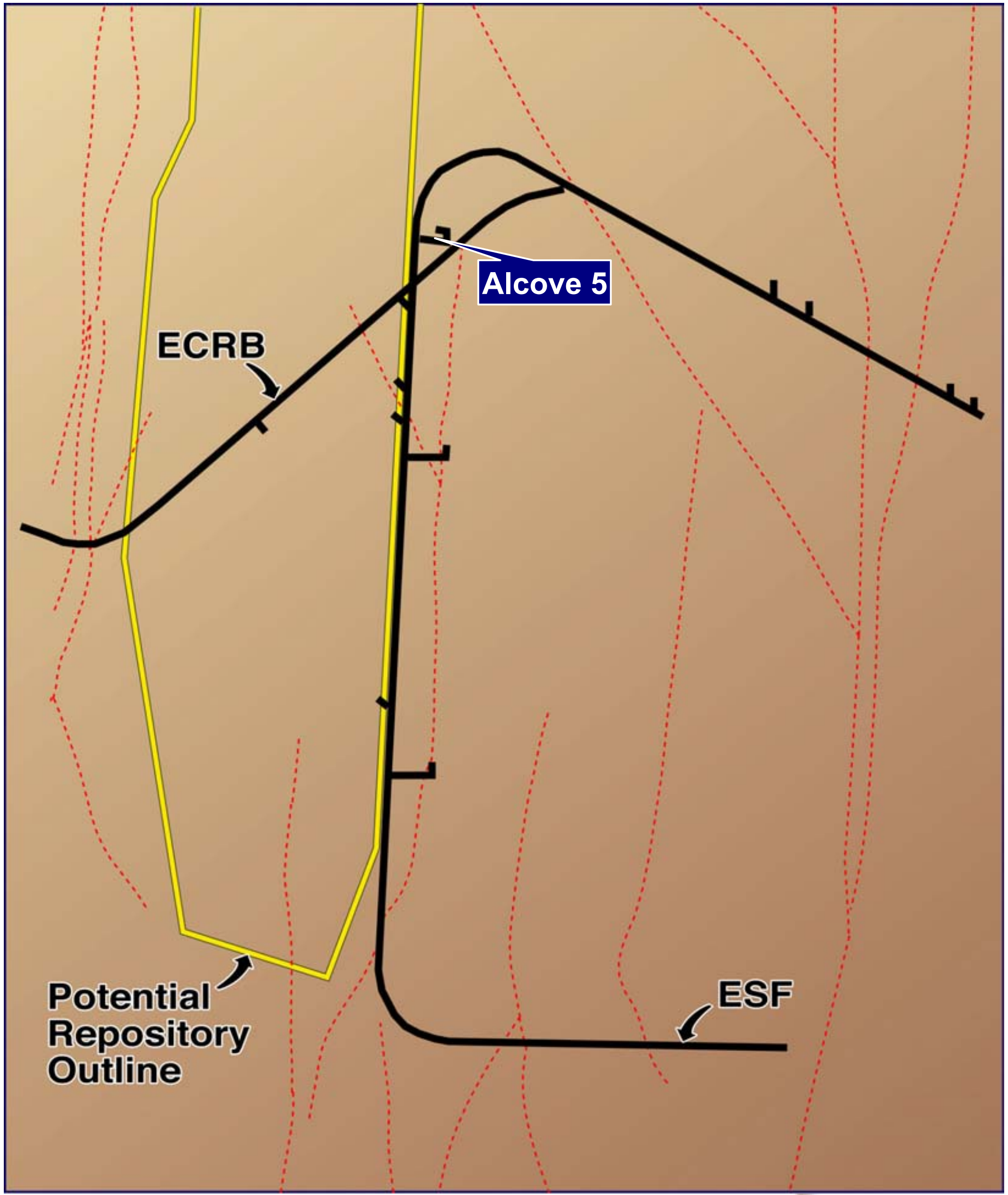
Couple Process Testing and Associated Modeling

Single Heater Test

Large Block Test

Drift Scale Test

Extensive Sensitivity Study for Thermal Seepage

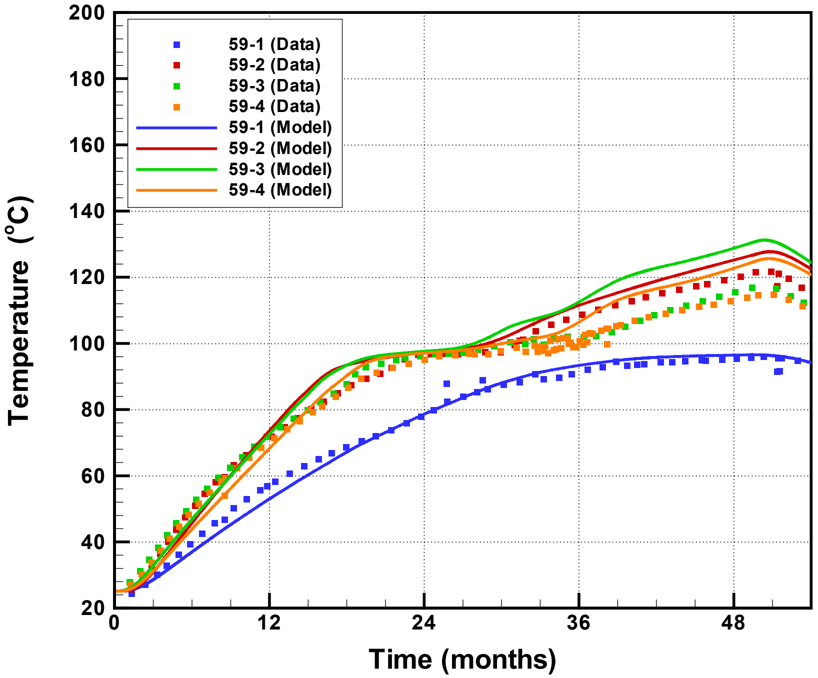


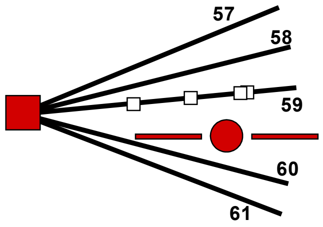
Thermal Seepage Model Is Appropriate

- Conceptual model has been validated against seepage test data and thermal test data
- "Leaky" bulkhead is properly incorporated in models
- Model findings for thermal seepage are consistent over a wide range of seepage-relevant parameters and conditions
- Geothermal analogue adds confidence to DOE model
- Conceptual model applied to NRC thermal seepage laboratory experiment
- Conceptual model is supported by results from alternative conceptualization for thermal seepage
  - To address finger flow penetrating "above boiling" zone
- Abstraction method for thermal seepage for TSPA is well supported
  - Seepage threshold temperature of 100°C at drift wall
  - Instantaneous rewetting at threshold temperature
  - No vaporization barrier for collapsed drifts

The Drift Scale Test (DST)

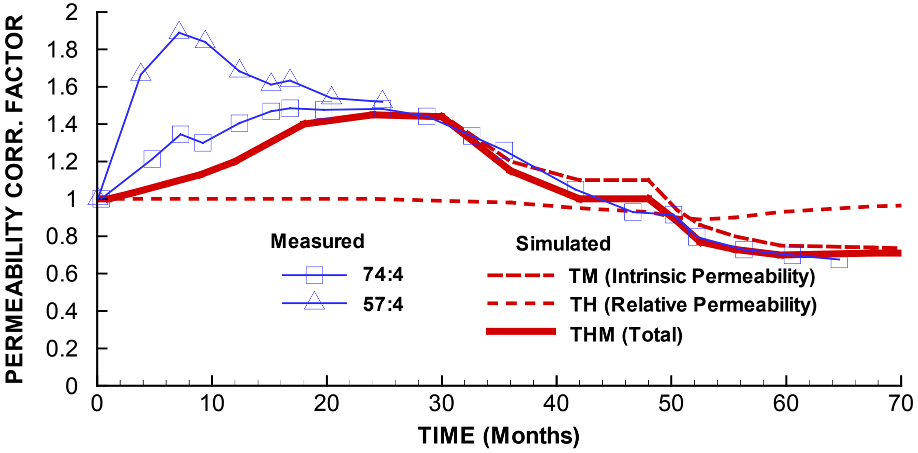
- Has provided a rich and high-quality data set for process identification and model testing
  - Favorable comparison between measurements and model predictions gives confidence in our understanding of THMC coupled processes in unsaturated fractured welded tuff
- Lends credibility to the thermal seepage model which
  - Incorporates all THMC processes validated against DST data
  - Employs respective thermal and hydrological properties for middle nonlithophysal and lower lithophysal repository units
  - Prescribe specific repository geometry, thermal load and boundary conditions





Vaporization Barrier at Yucca Mountain Is Based on Physics and In-situ Testing

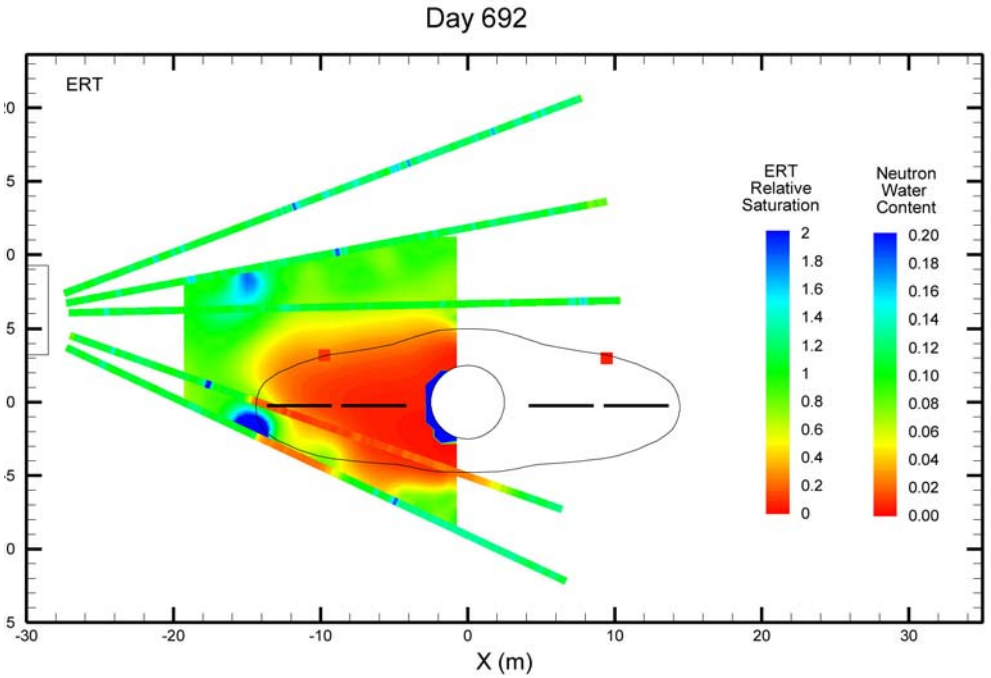
- Vaporization barrier is a physical process
  - It is based on the fact that water can only exist as vapor at above boiling temperatures
- Role of vaporization barrier is to prevent liquid water from reaching the drift during thermal period (when there is a zone of above-boiling temperature around the drift)
- Thermal hydrological process that give rise to the vaporization barrier is validated against the DST data
  - Temperature, Mean error in ~1,700 sensors of a few degrees °C
  - Drying and wetting zones in matrix and fractures corroborated by geophysical and air permeability measurements



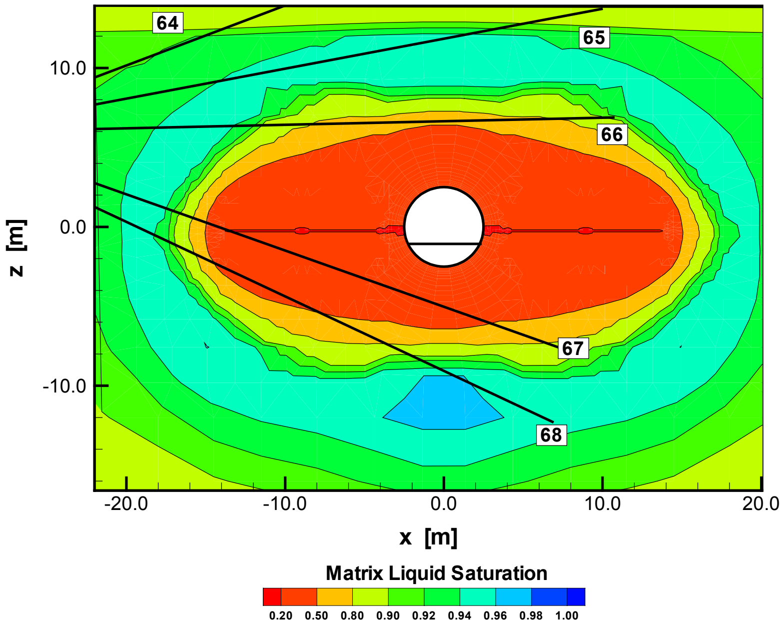
Time Evolution of Moisture Distribution in Rock Matrix

- **Periodic geophysical surveys to track moisture changes**
- **Locations of drying and wetting as function of time in general correlate well with simulated liquid saturation in rock matrix**

Electric Resistance Tomography, Neutron Log

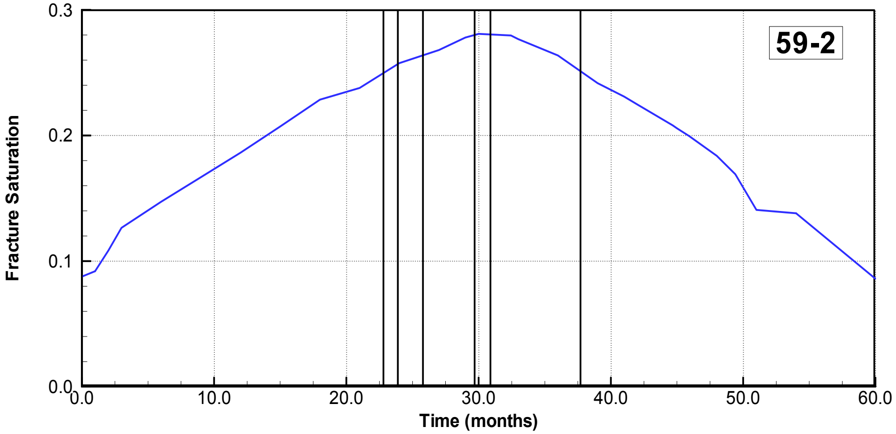


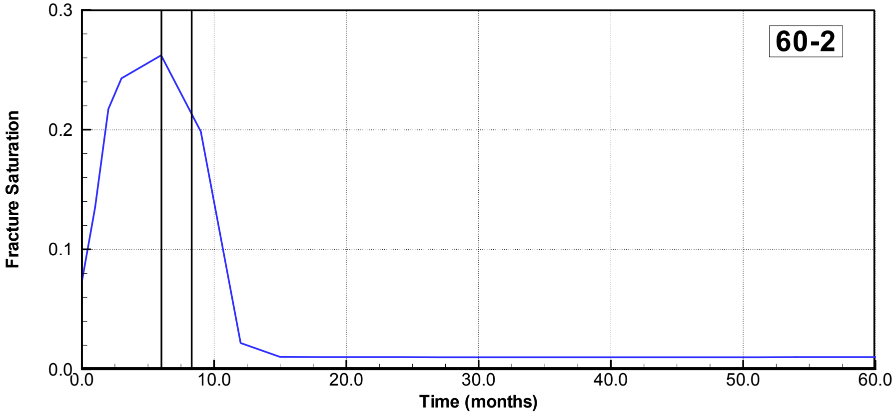
Simulated Saturation



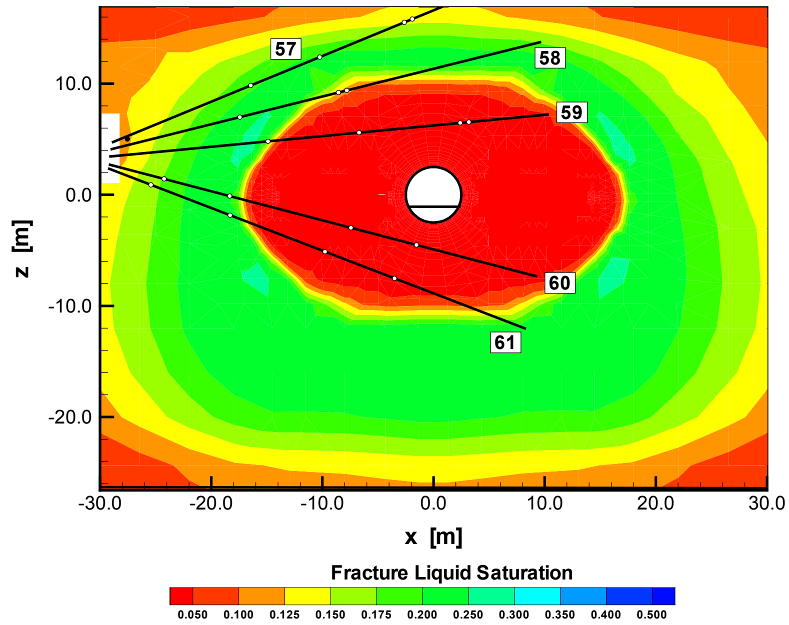
DST Provides Valuable Insight for Thermal Seepage

- **The Drift Scale Test was intended for improved understanding of coupled processes**
  - Validated T and RH models
  - No direct validation for thermal seepage
- **The data in the DST gives insight to thermal seepage issues**
  - DST is in the third year of cooling, the drift wall temperatures have now come down below boiling
  - No evidence of seepage water has ever been observed in the Heated Drift from periodic camera runs
- **While we have an adequate basis for licensing, we agree that laboratory tests that specifically address thermal seepage can improve confidence**

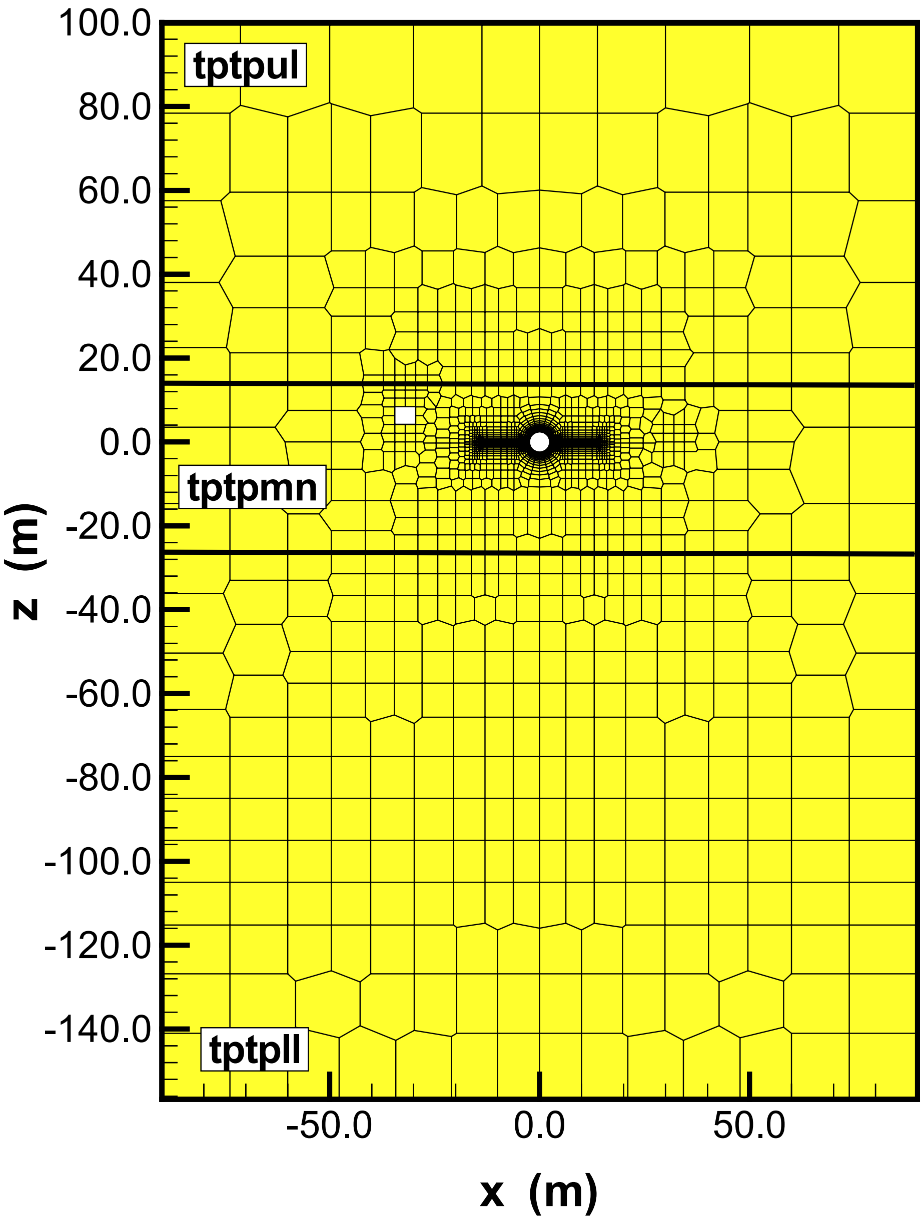




The DST Centers in Middle Nonlithophysal Unit, Spans Upper and Lower Lithophysal Units

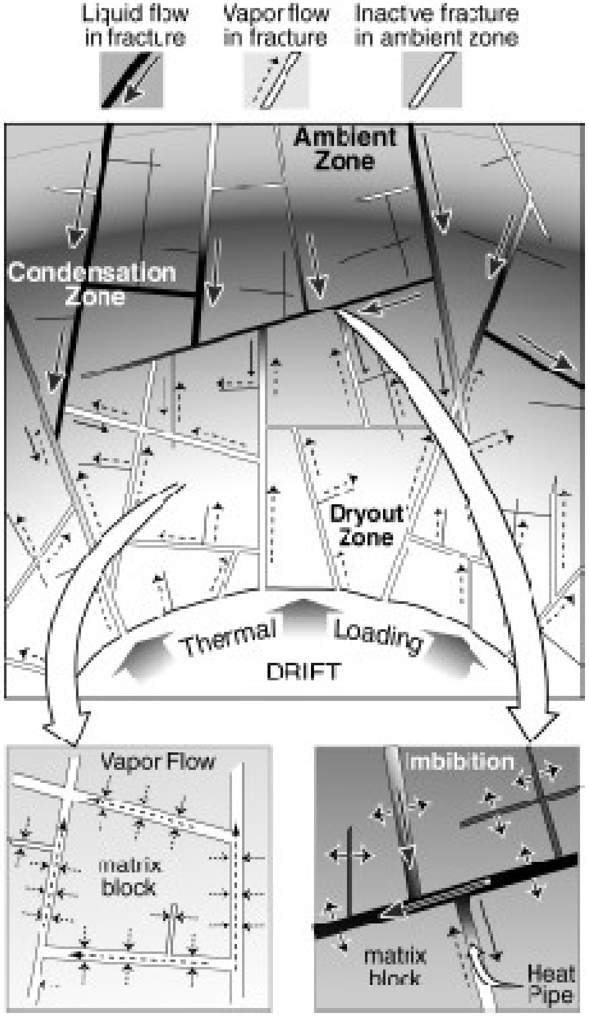


Fracture Saturation 1 week into cooling



DST Results Relevant to Lithophysal Units

- **Thermal response dominated by heat conduction**
  - **Most important thermal properties are thermal conductivity and heat capacity**
  - **Thermal properties in the lower lithophysal unit are from laboratory measurements and in-situ testing**
- **THMC processes captured in the Drift Scale Test are applicable to the lower lithophysal**
  - **Thermal and hydrological properties for respective middle nonlithophysal and lower lithophysal units are employed**
- **Effects of lithophysal cavities are generally captured by the thermal conductivity and heat capacity values**
  - **Possible effects of lithophysal cavities that have not been explicitly considered**
    - Heterogeneity affecting transport
    - THC mineral precipitation

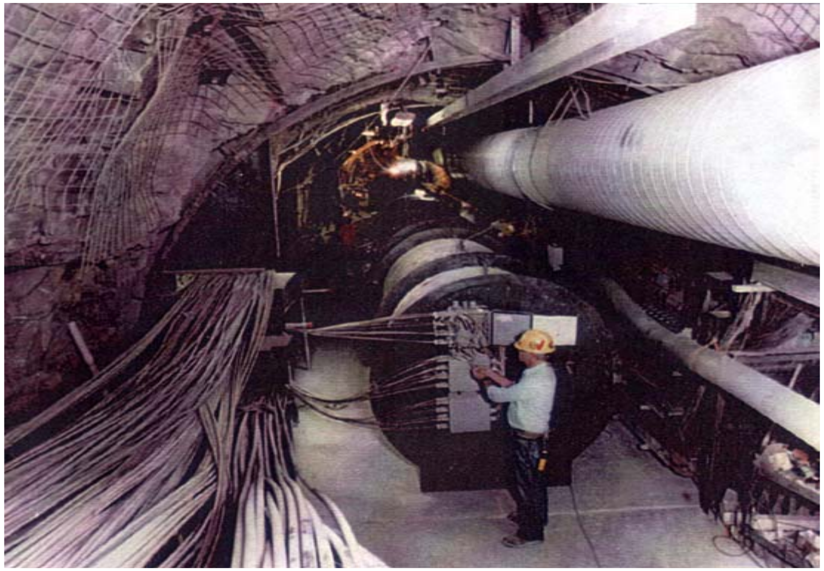


Impact of "Leaky" Bulkhead on Vaporization Barrier

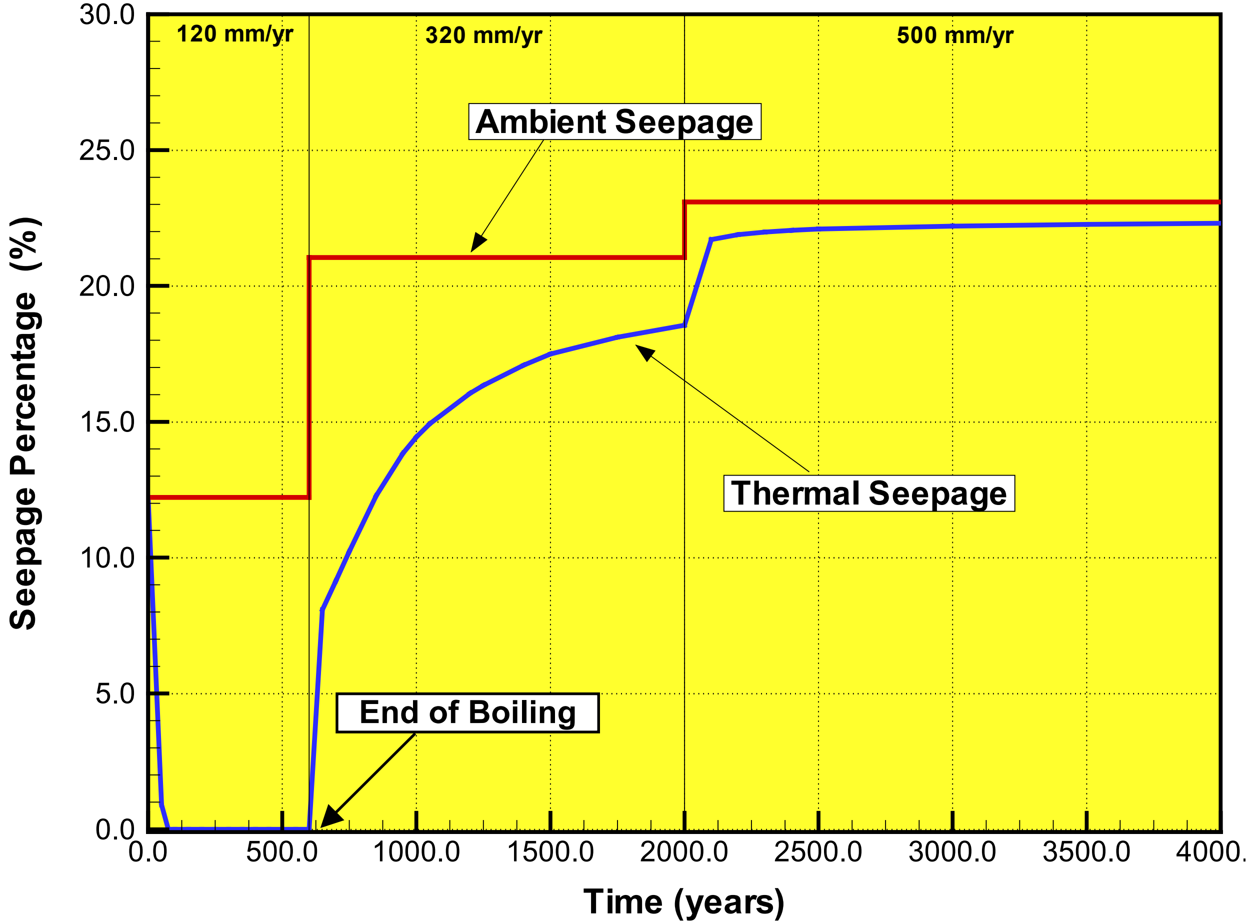
- Modeling to evaluate the uncertainties in heat and mass loss through the open bulkhead and their impact on the outcome of DST (Mukhopadhyay and Tsang, J. Contaminant Hydrology 2003) shows
  - Less than 13% of the input heat energy in the DST went into vaporizing water
  - For a hypothetical closed system where NO vapor is allowed to escape through the bulkhead, the average fracture saturation would have been about 0.2 higher than that in the DST with open boundaries
- Air permeability data that track time and spatial evolution of drying in the fractures confirm model predictions for the DST with open boundaries allowing mass and heat loss through the bulkhead
  - Drift Scale Test Model "correctly" incorporates leaky bulkhead

Thermal Seepage Model Validation

- Seepage processes of the model are consistent with and validated against ambient seepage models
- TH processes of the model are consistent with and validated against the Drift Scale Test Model



Thermal Seepage Model Results

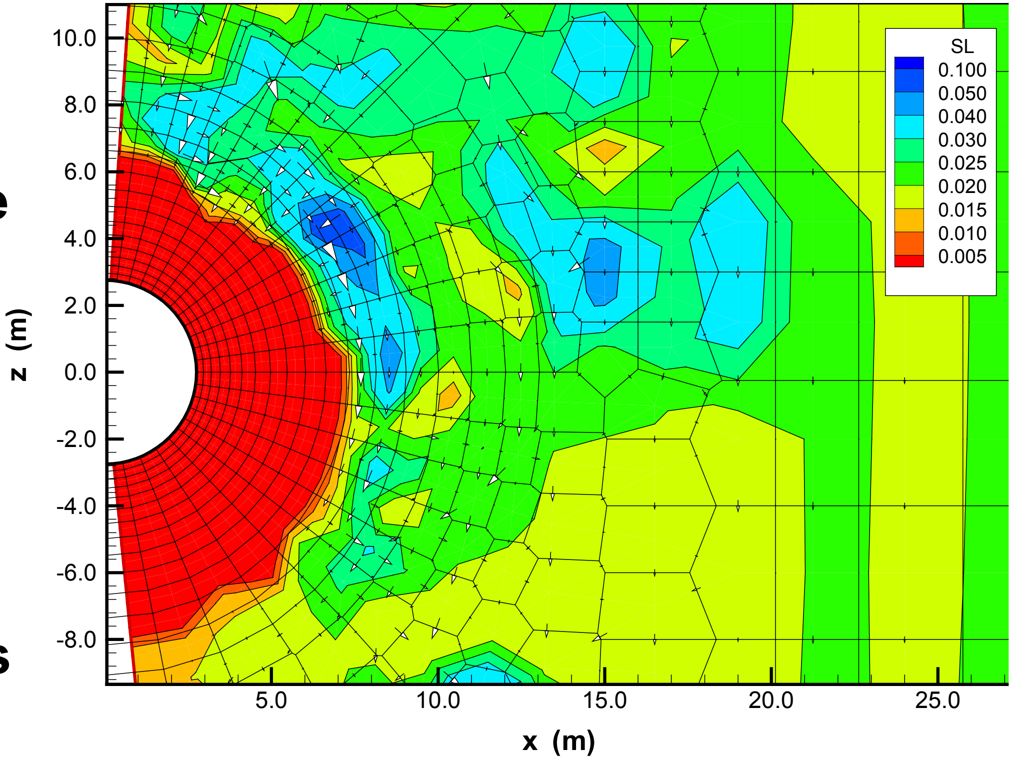


- Predict the combined capability of capillary and vaporization barrier for various relevant parameter cases
- No seepage during boiling period
- Thermal seepage smaller than ambient seepage at all times
- Provide basis for thermal seepage abstraction methodology

Thermal Seepage Model Results

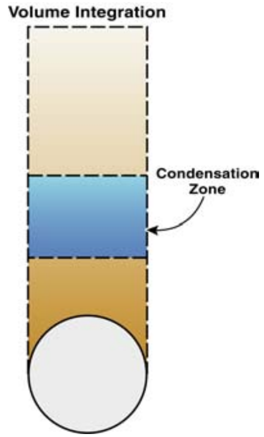
(continued)

- Condensate water above drift is mostly diverted sideways
- Fracture saturations in condensation zone increase by a few percent only
- Condensate cannot penetrate far into superheated rock zone
- Downward flux of condensate toward the drift is strongest when heating is most intense (coincides with the period of strongest vaporization barrier)

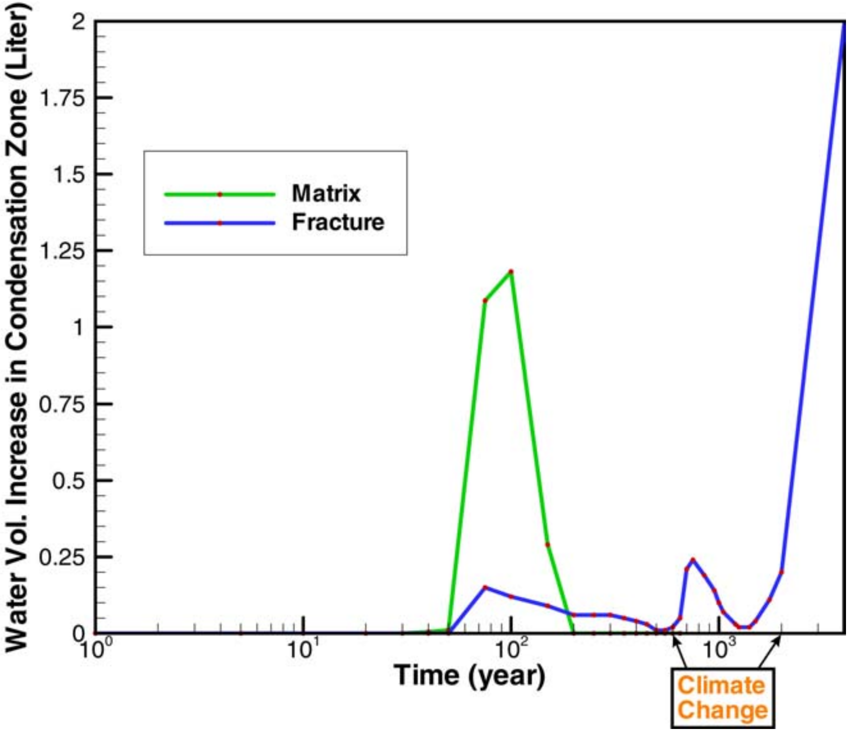


T = 500 years

Water Volume Increase from Ambient in Condensation Zone



- **Amount of water in fracture and matrix increase only slightly in the condensation zone above drifts**
- **The average fracture saturation in the condensation zone increases from 3% to only 6%**
- **High fracture permeability makes water shedding around the drift very efficient**

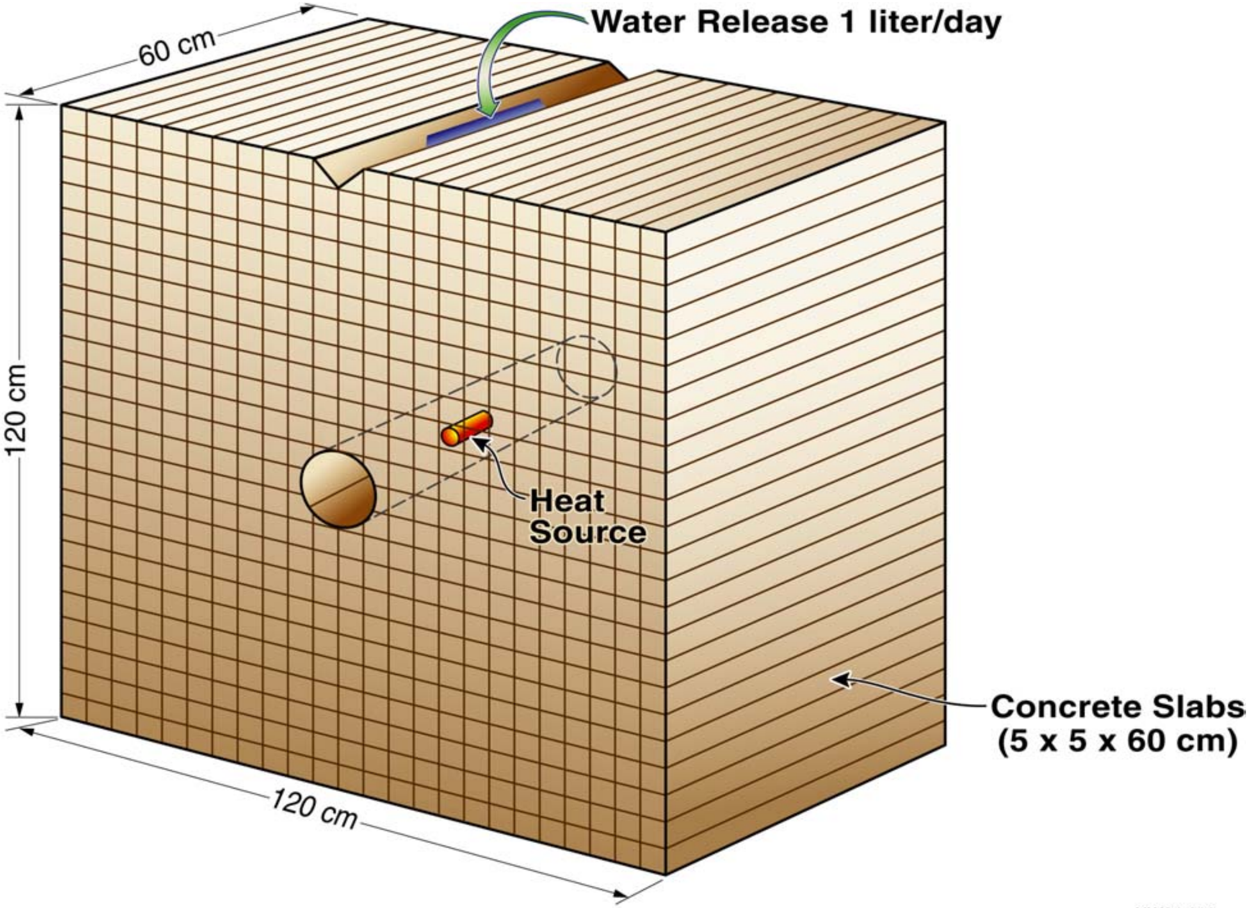


Geothermal Analog Adds Confidence to DOE's Thermal Seepage Model

- Numerical tool (TOUGH2) and coupled processes models similar to the thermal seepage model have been successfully applied to geothermal reservoir characterization for the last two decades
- Processes in geothermal reservoir
  - Injection of cold water into vapor dominated geothermal reservoir (stronger driving force than percolation flux in the repository at Yucca Mountain)
  - Penetration depth of injected water into the vapor zone is a function of reservoir heat reservoir and injection rate

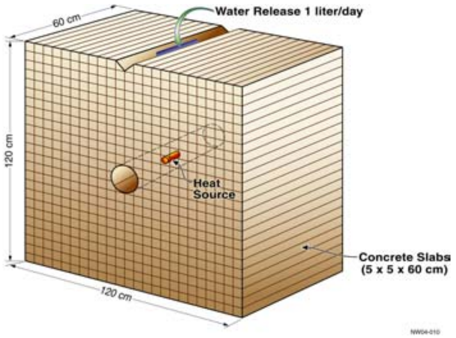
TH Coupled Process Model Applied to NRC Laboratory Experiment on Thermal Seepage

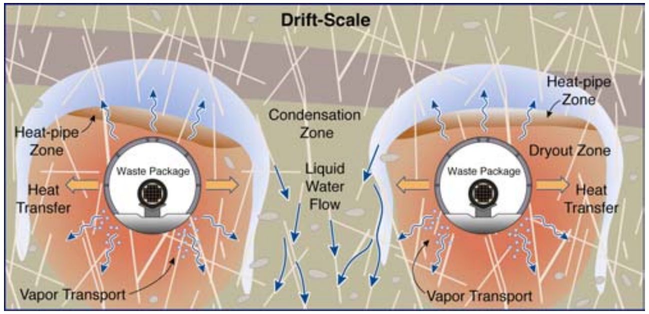
- **Heater placed in a 0.15 m diameter drift**
- **Heat input (142 W) from 0 to 130 days**
- **Water release (1 liter/day) from 5 to 140 days**
- **Though not visually observed and not seen in temperature signals, seepage may have occurred during the test, as evidenced by precipitates in the drift**



NW04-010

Comparison of CNWRA Laboratory Test and Yucca Mountain Conditions



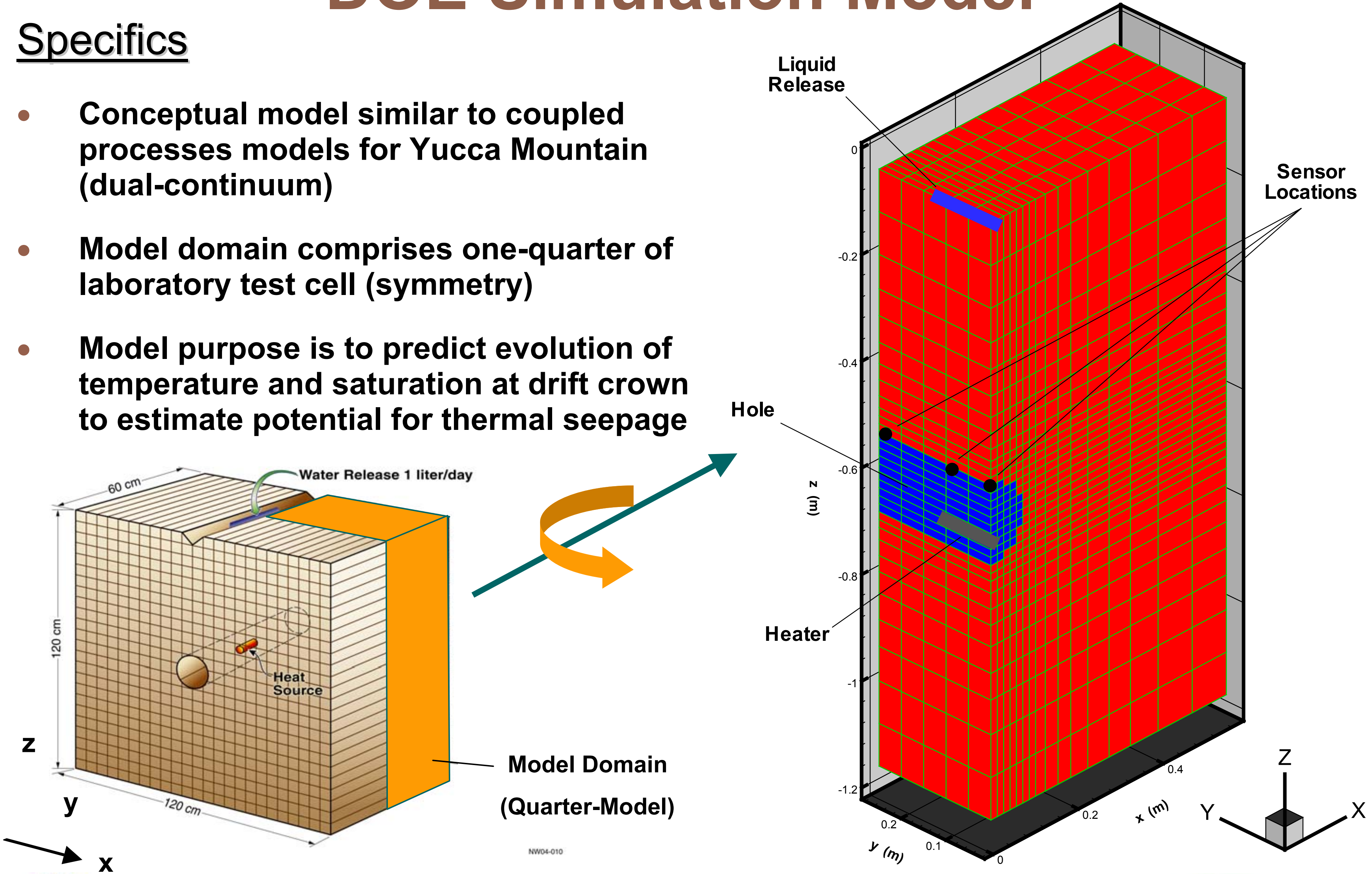


Physical Characteristic	CNWRA Experiment	Yucca Mountain
Matrix	Concrete Slabs	Tuff
Fractures	Continuous, regular	Discontinous, irregular
Opening Diameter	0.15 m	5.5 m
Open. Diam./Fract. Spacing	3	50 to 100
Percol. Flux per Open. Area	11 liter/day/m^2	0.14 to 0.28 liter/day/m^2
Heat Input per Length	About 0.71 kW/m	About 1.45 kW/m
Maximum Crown Temp.	About 170°C	About 140°C

DOE Simulation Model

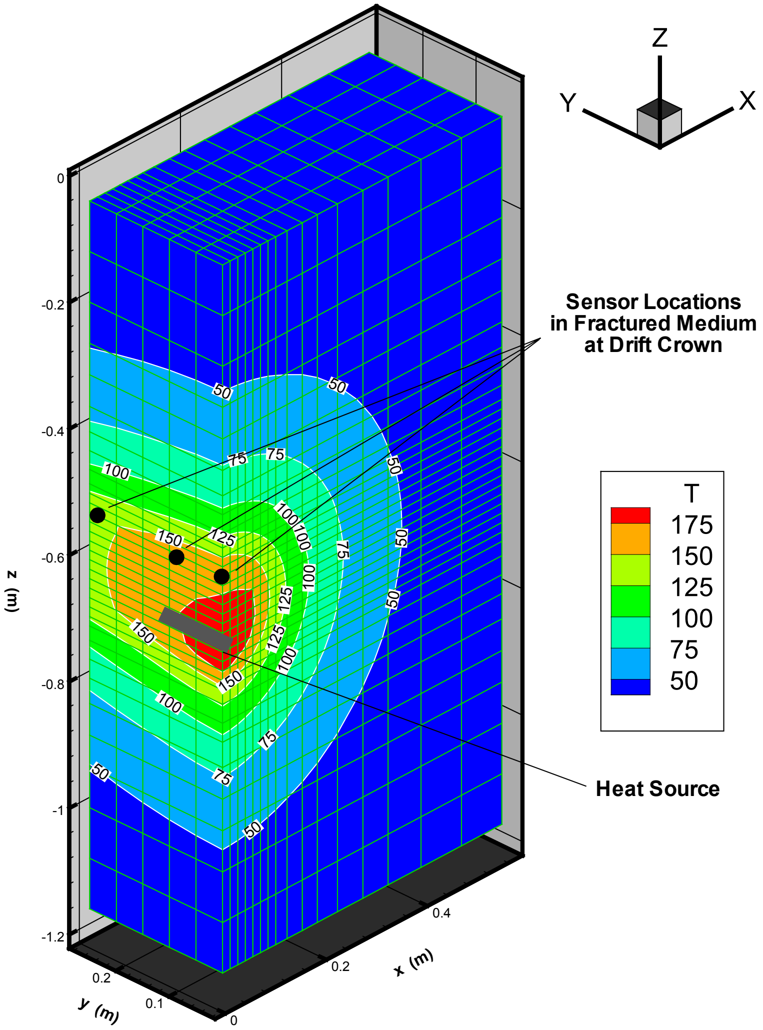
Specifics

- **Conceptual model similar to coupled processes models for Yucca Mountain (dual-continuum)**
- **Model domain comprises one-quarter of laboratory test cell (symmetry)**
- **Model purpose is to predict evolution of temperature and saturation at drift crown to estimate potential for thermal seepage**

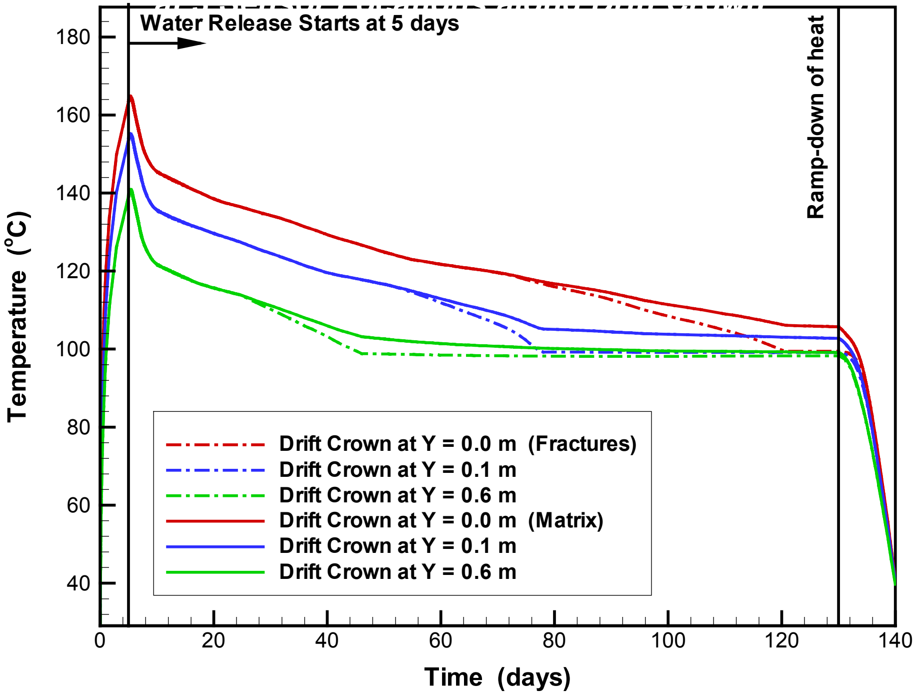


Model Results

Temperature Field
at 5 days (just before water release)

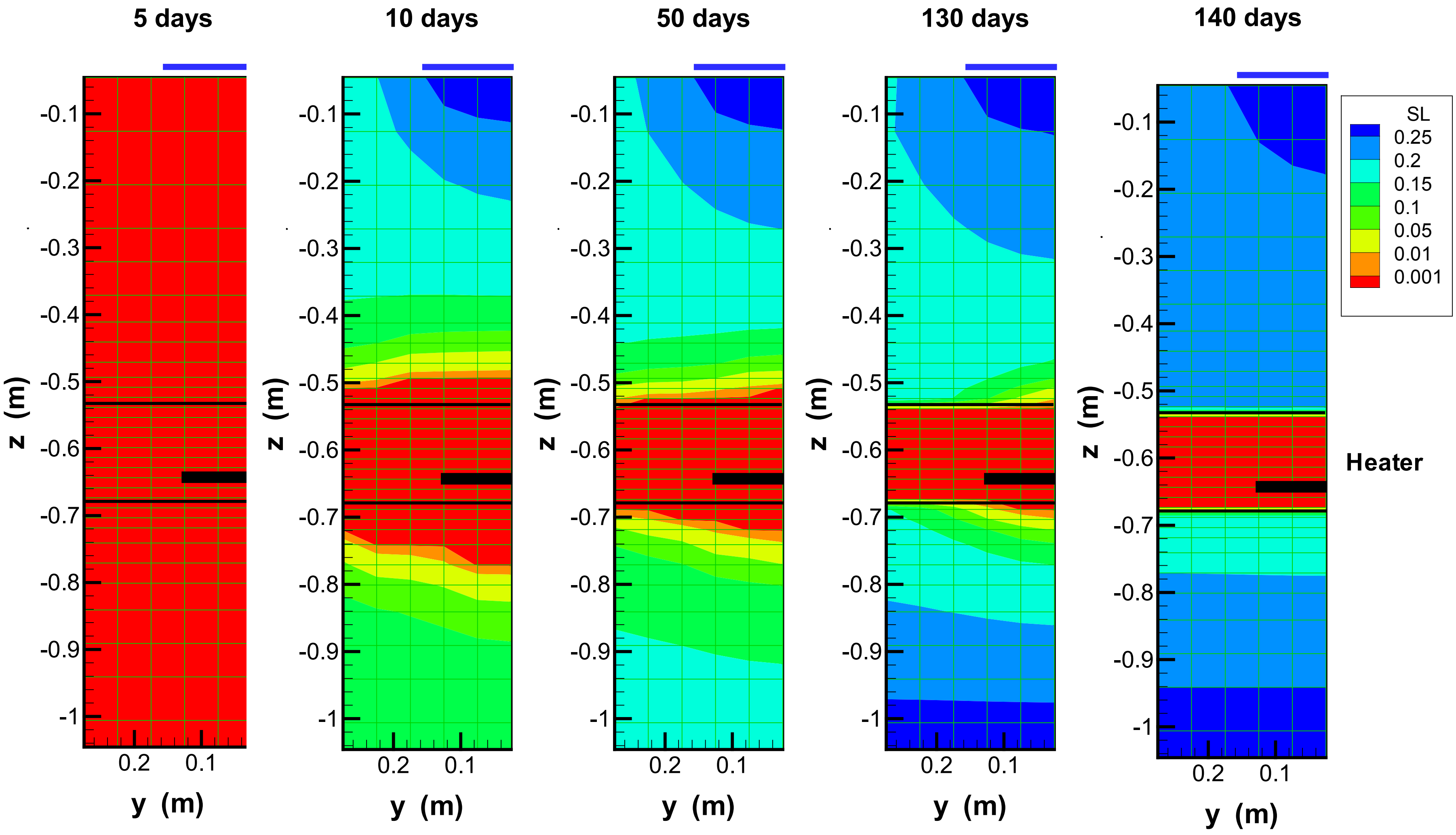


- **Test cell cools rapidly after 5 days when water is released at one liter per day**
- **Fracture temperature at drift crown decreases to the boiling point**
- **Another strong temperature drop at 130 days when heat input is ramped down**



Model Results

Fracture Saturation in a Vertical Cross Section Along Drift



DOE Conceptual Model Indicates No Vaporization Barrier for CNWRA Experiment

- **CNWRA Experimental setup was very favorable for seepage to occur**
  - **High-conductivity fracture connecting water source with drift crown**
  - **2D fracture network limits flow diversion around drift**
  - **Very small boiling zone in matrix (a few cm above drift crown)**
  - **Fractures at borehole crown resaturate soon after water release and remain wet till the end of the experiment**
  - **Final phase of experiment with ramp-down of heat input and continuing injection leads to sub-boiling temperatures, with (1) higher chances for seepage, and (2) possibility of in-drift condensation**
- **Based on the seepage abstraction method, TSPA would allow for thermal seepage for the CNWRA test conditions**

Episodic Fingering Flow and Vaporization Barrier

- Heterogeneity and episodic fingering flow are factors that may allow moving water to break through a zone of above boiling temperature before it has time to completely vaporize
  - Effects of heterogeneity and episodic flow are accounted for in an alternative model for thermal seepage
  - The alternate model to investigate the ability of episodic fingering flow to penetrate vaporization barrier (Birkholzer 2003, Water Resources Research) supports thermal seepage model conclusions
    - The WRR 2003 paper is a more realistic representation of the physical processes described in Phillips, 1996
(reference quoted in Board's November 2003 letter)

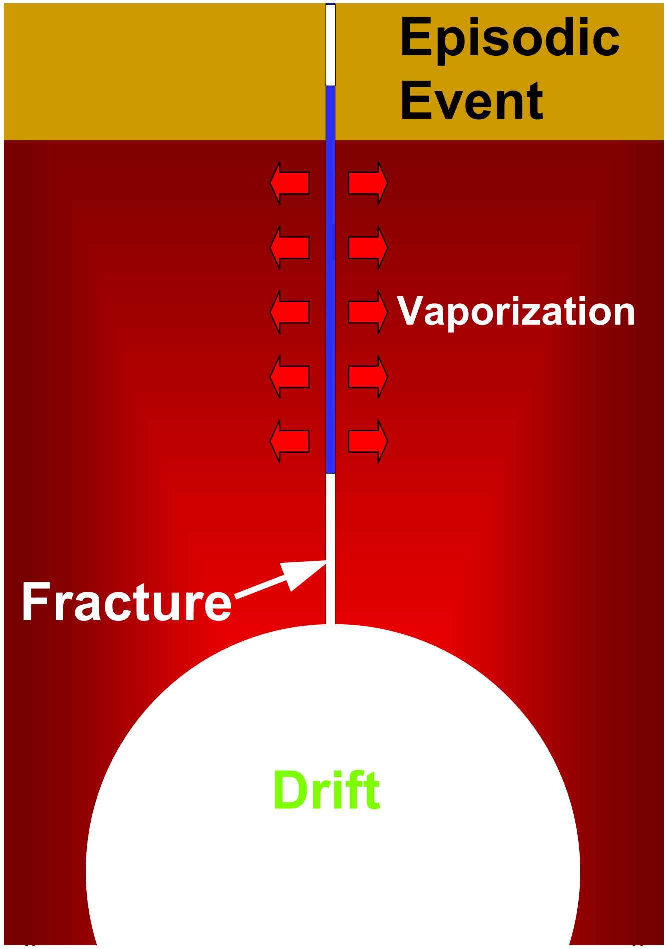
Alternative Conceptual Model: Finger Flow

Conservative Assumptions

- Episodic fingers are generated in the zone of elevated saturation above repository
- Vertical continuous fracture connects condensation zone with drift crown
- Entire amount of reflux predicted with Thermal Seepage Model drains down in episodic fingers

Solution

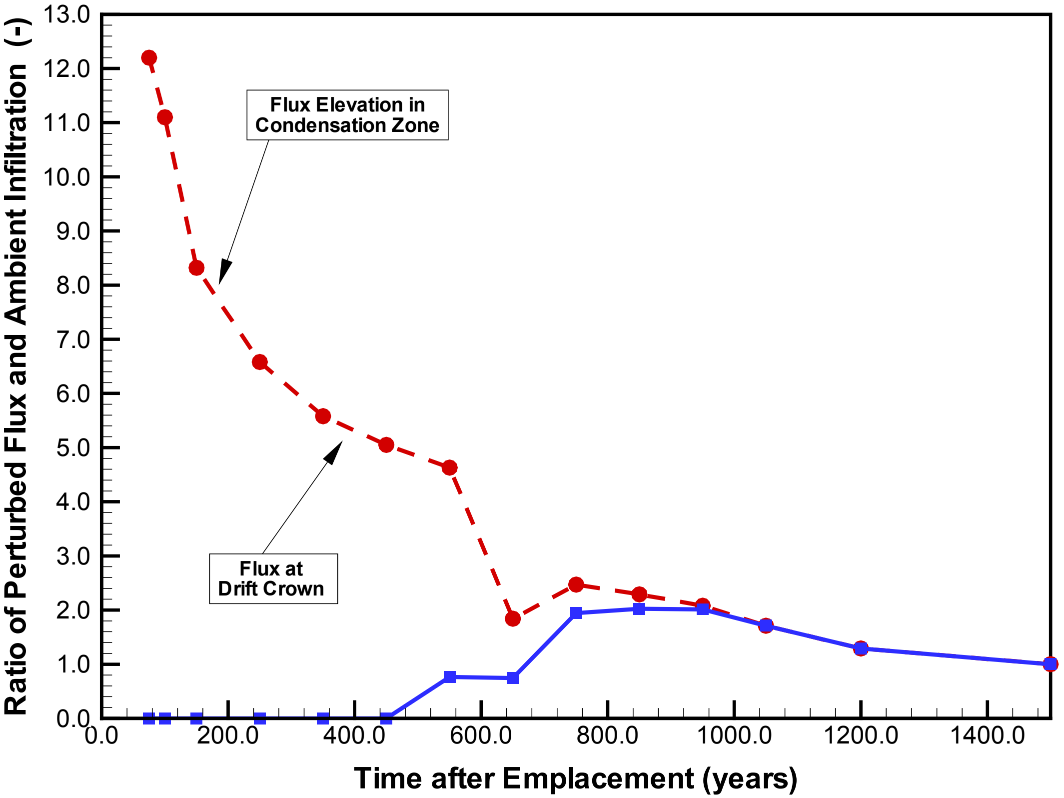
- Semi-analytical solution (Birkholzer, 2003) based on Phillips (1996)
- Solution calculates penetration depth of episodic flow event into hot rock
- Calculates amount of flow arriving at given location



Alternative Conceptual Model: Finger Flow

ACM Results

- Penetration of episodic fingers into superheated rock zone depends on maximum temperature and extent of “hot” rock zone
- Episodic fingers vaporize before arriving at the drift crown for “hot” strongly perturbed TH conditions
- Episodic fingers may reach drift crown only at late times, when temperature is back to just above boiling (and strong thermal perturbation has ceased)
- Net result of reflux from episodic fingering is equal to ambient percolation flux (will not lead to seepage because of capillary barrier)

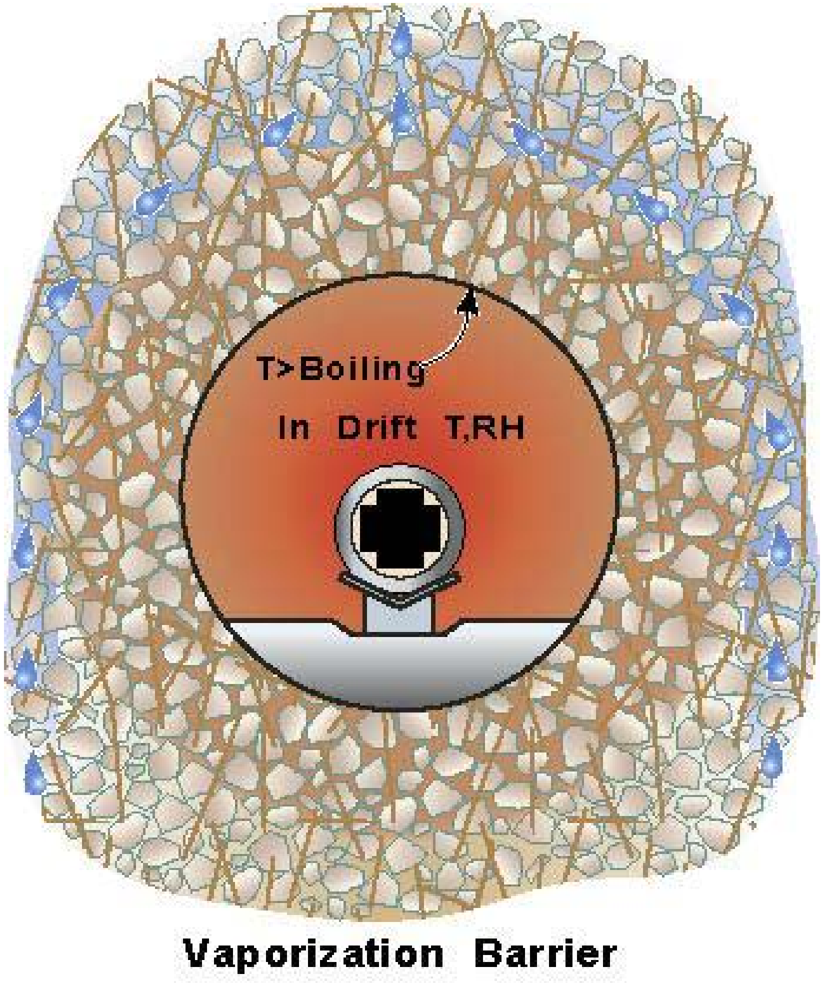


Conclusions for TSPA

- ACM supports the overall findings of the Thermal Seepage Model
- TSPA threshold temperature for no-seepage condition was set to 100^{o}C)

Board's Concern on DOE's Views on Drift Conditions during the Thermal Pulse

The Board questions DOE's views that "Temperature (*and relative humidity*) is adequately or conservatively modeled". The Board's evaluation is that "In general, the Board believes that there are significant parametric and conceptual uncertainties associated with the DOE's representation of repository tunnel environments during the period after the repository is closed."

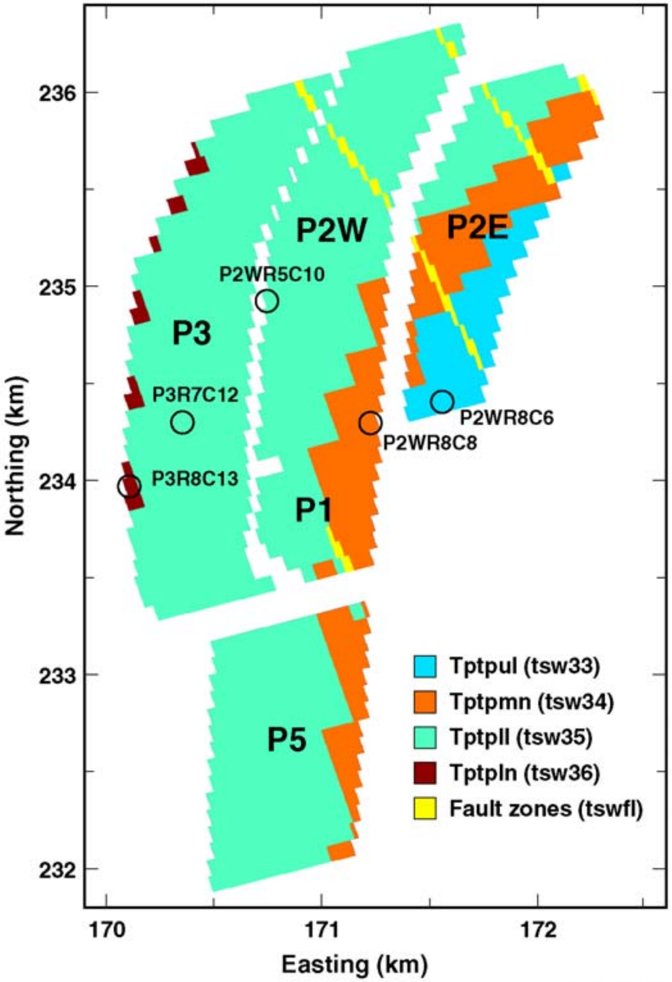


Vaporization Barrier

NW04-007

In-Drift TH Conditions Simulations Account for Range of Key Conceptual Model Elements and Uncertain Parameters

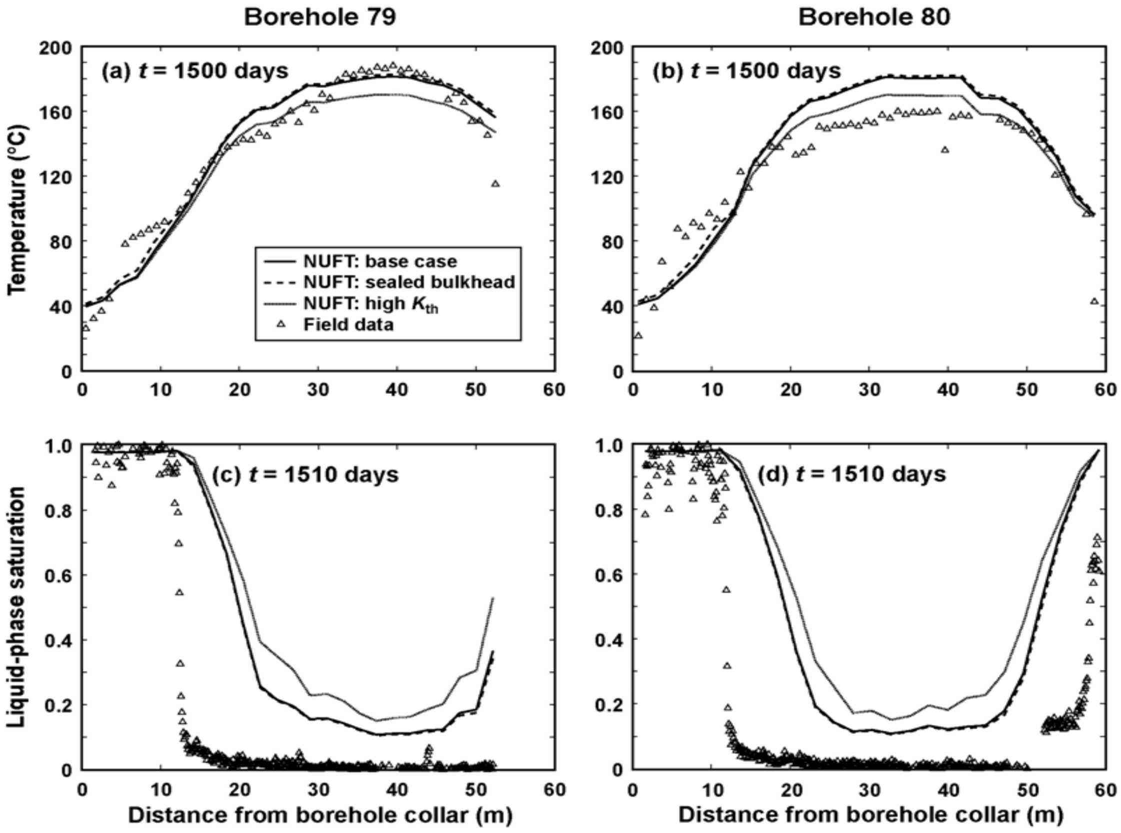
- **Multiscale TH model simulations of the in-drift TH conditions accounts for the four primary host rock repository units**
- **The five representative locations selected account for the effects of repository edge cooling**
- **For each location selected, temperature (T) and relative humidity (RH) conditions are simulated for different waste package (WP) types**



hostRockImage

Multiscale Thermohydrologic Model (MSTHM) Validation

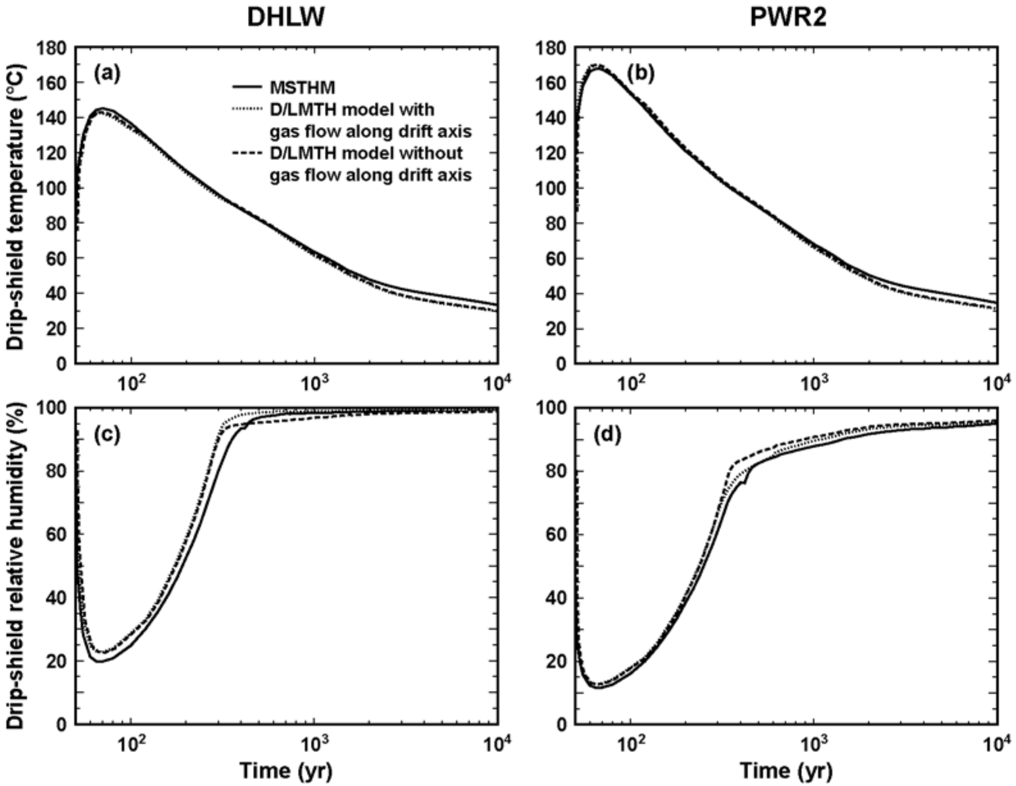
- **TH behavior predicted by the MSTHM are consistent with and validated against observed TH behavior in the Drift Scale Test**



ss-T-S-79-80_1500d

Multiscale Thermohydrologic Model (MSTHM) Validation

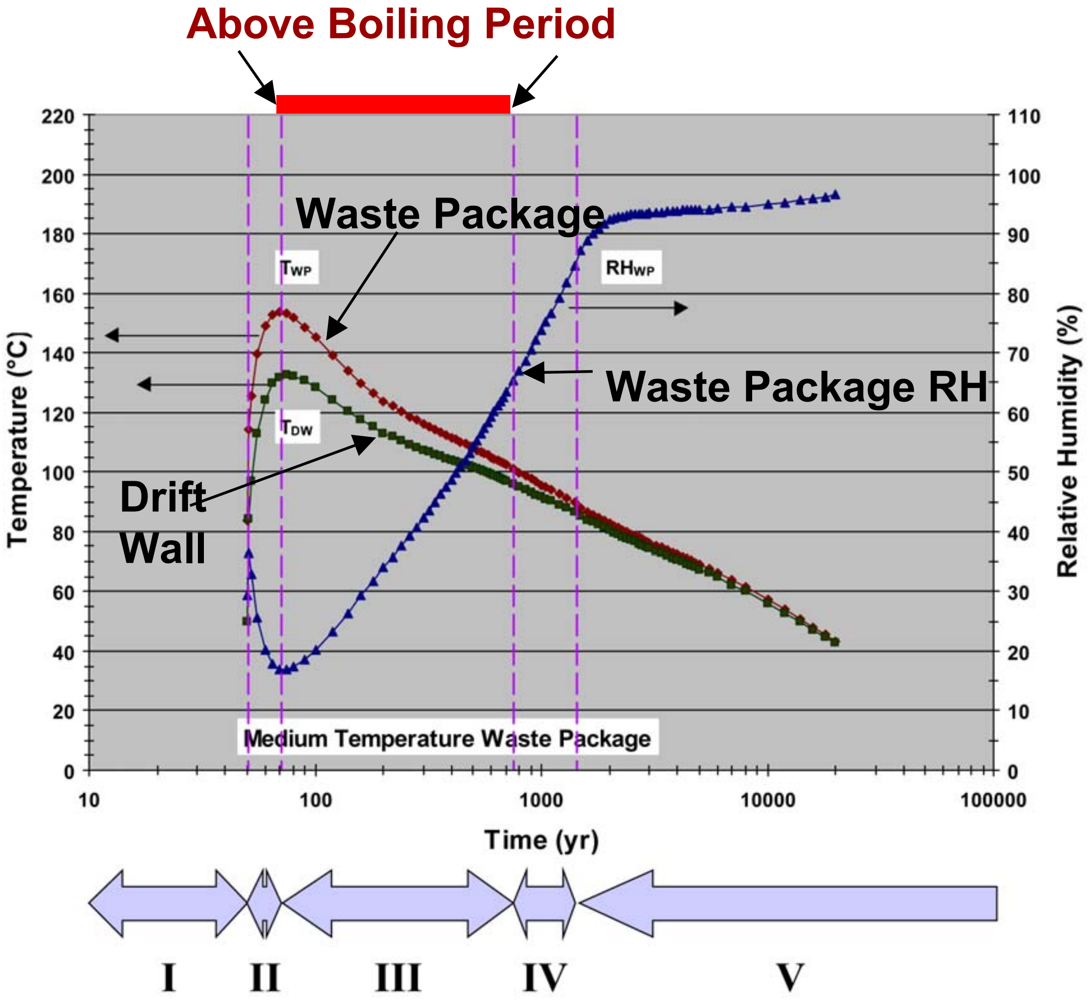
- **The MSTHM is validated against a monolithic discrete/line-heat-source, mountain-scale TH (D/LMTH) model**



T-RHdw-ds_pwr1-2-dhlw-bwr_c

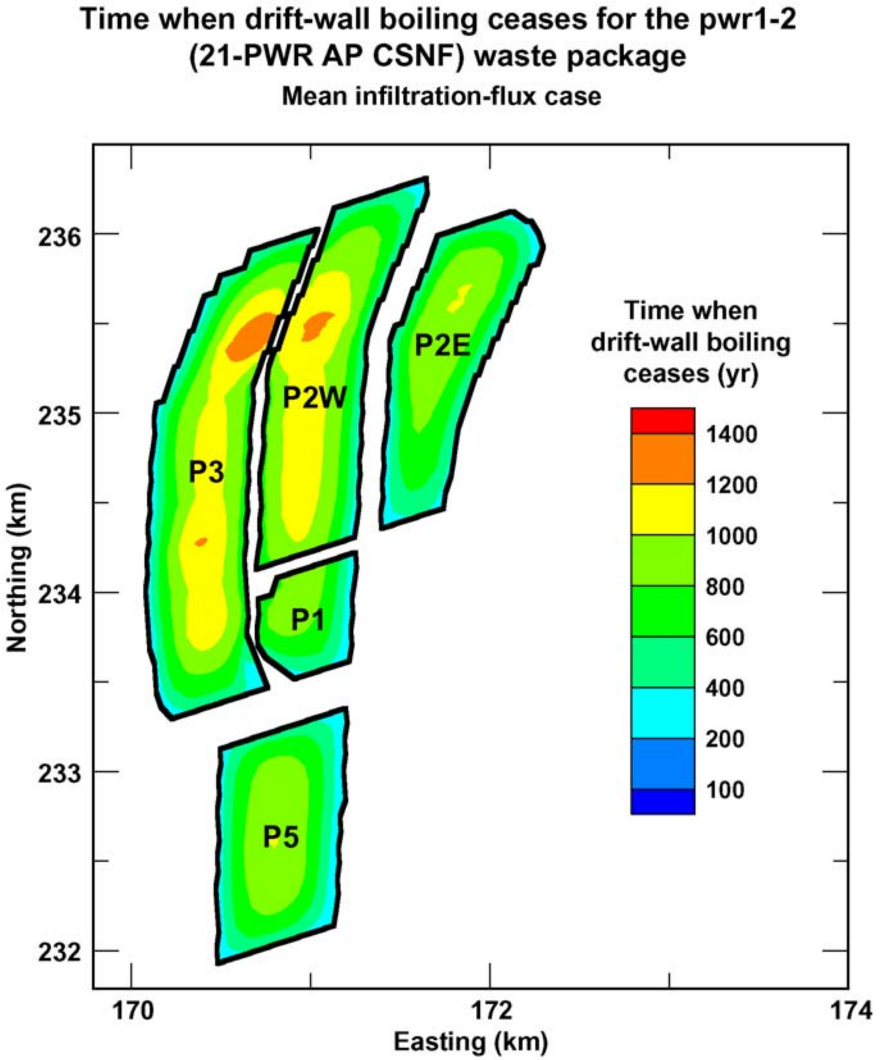
Range of WP Temperature and RH

- The range of T and RH for the different waste package types are based on five combinations of infiltration flux and thermal conductivity values:
  1. lower infiltration, low k_{th}
  2. lower infiltration, mean k_{th}
  3. mean infiltration, mean k_{th}
  4. upper infiltration, mean k_{th}
  5. upper infiltration, high k_{th}



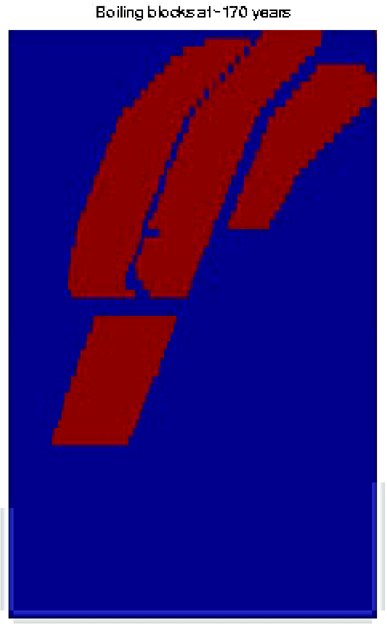
Typical Contour Map of the Time When Boiling at the Drift Wall Ceases

- **Note the repository edge effect on temperature**
- **Similar calculations carried out for**
  - **Different WP types (pwr1-2 is hottest in the sequence)**
  - **Different infiltration flux**
  - **Range of thermal conductivity values**



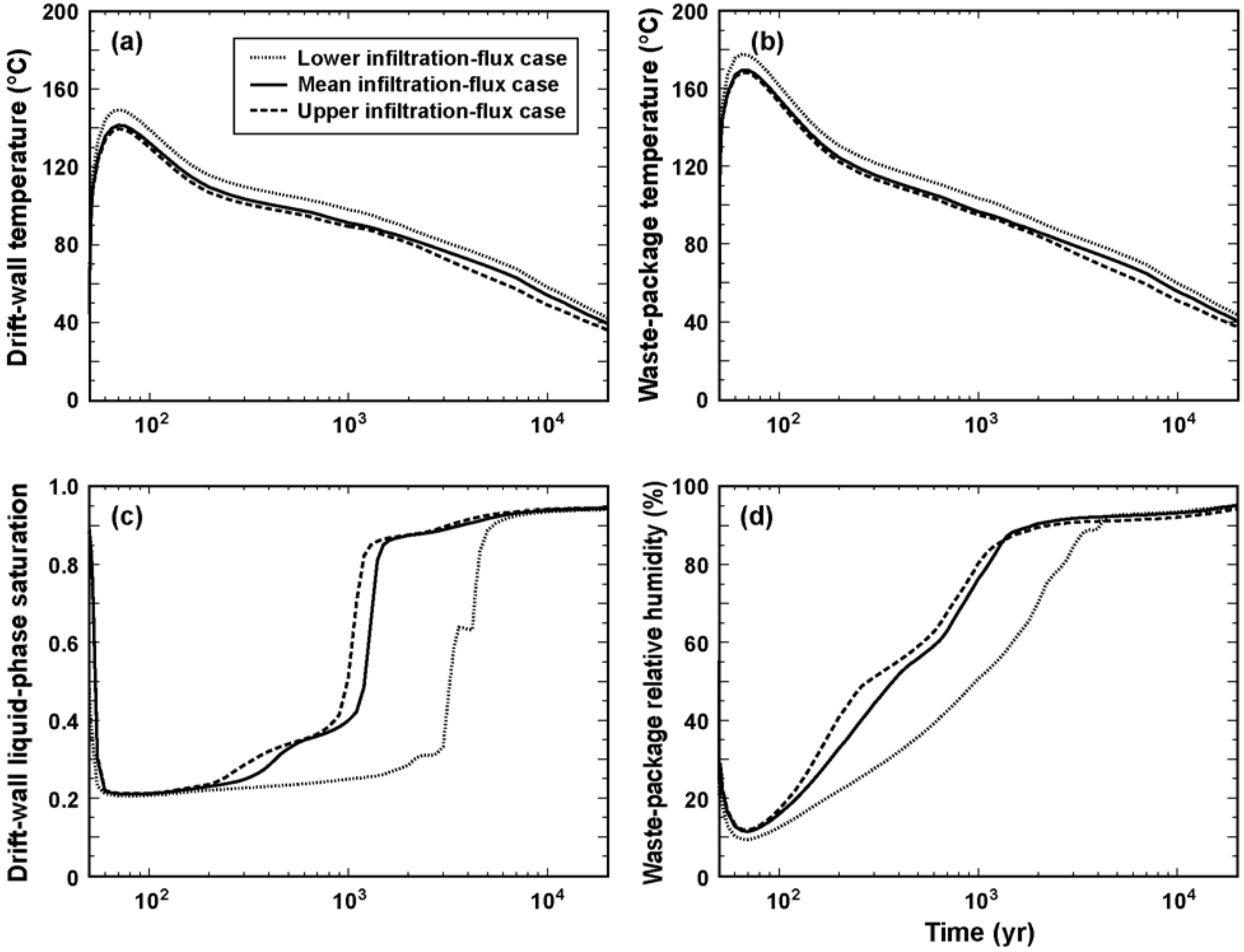
Tdw_boil_dura_pwr1-2

Time Evolution of Repository Blocks with Boiling Temperature at Drift-Wall



Typical Plots of Drift-Wall T, Waste Package T, Drift-Wall Liquid Saturation and Waste Package RH

For pwr1-2 WP at repository center in Tptpll

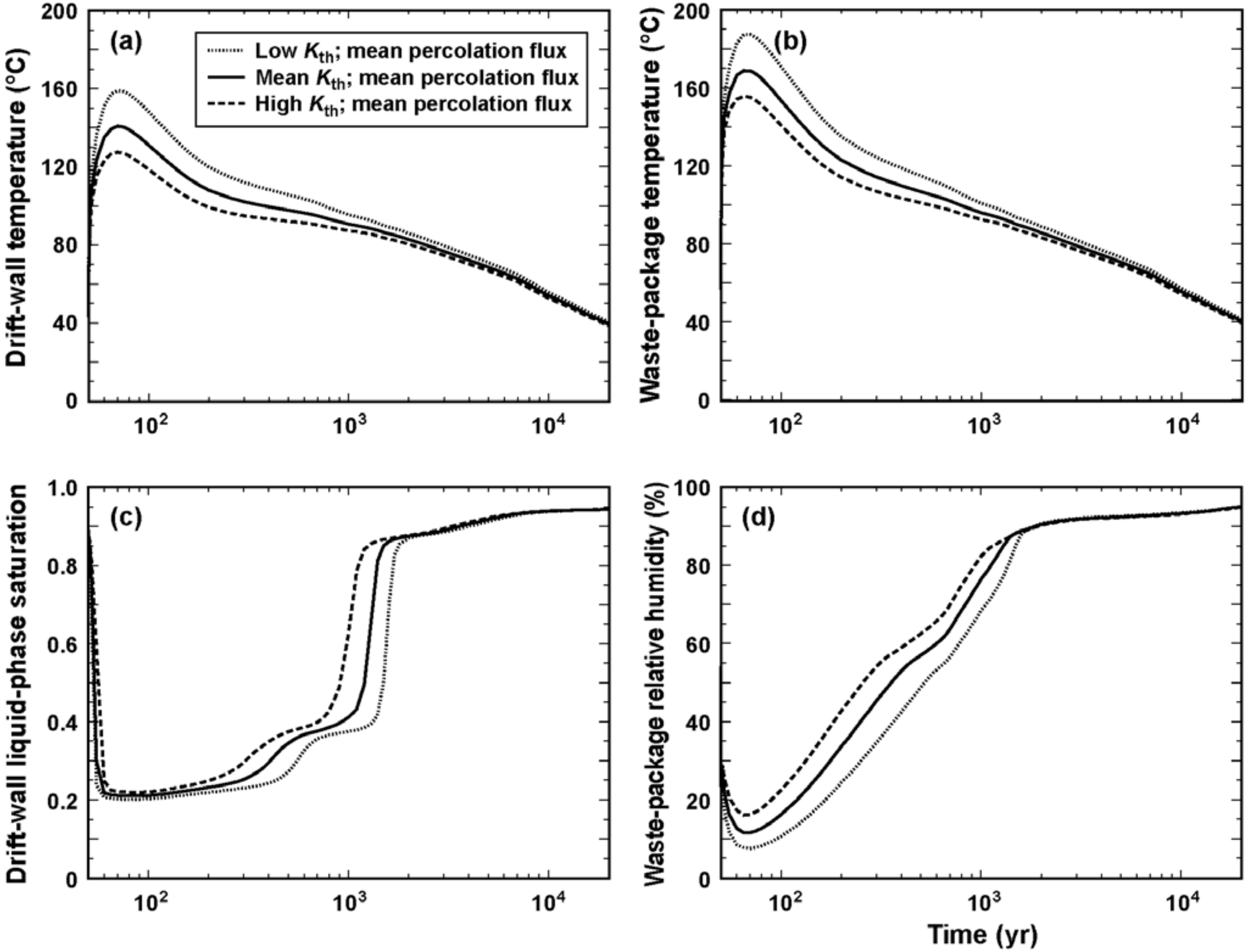


P2WR5C10-li_mi_ui_1

Thermal Conductivity Values and Predicted In-drift Temperatures

- **There is an abundance of project thermal conductivity measurements (laboratory core data and in-situ field measurements)**
  - **DOE TH modeling uses a range of thermal conductivity values:**
    - **The mean of all measure values, and plus and minus one standard deviation of the measured values**
  - **The "recent laboratory work" cited by the Board has value that fall within the range of values employed in DOE modeled studies**
- **Thermal conductivity is only one of the key parameters for in-drift TH conditions, DOE models also account for other key parameters such as infiltration flux, waste package types and location of drift**

Typical In-drift TH Conditions Plots for Low, Mean, and High Thermal Conductivity



P2WR5C10-mi-1kth_1

Summary

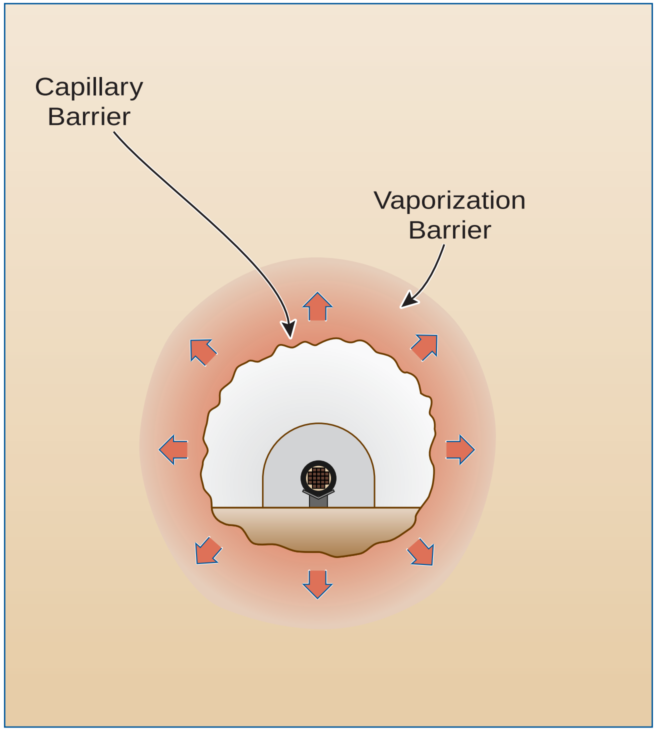
- Case for effectiveness of capillary barrier and vaporization barrier in the repository environment is soundly based on
  - All relevant processes
  - In-situ field testing
  - Extensive sensitivity studies
- Seepage into drifts during sub-boiling time periods is conservatively represented in TSPA
- All evidences support no seepage when the drift-wall temperature exceeds boiling temperature for water at the prevailing air pressure (approximately 96°C)
- Temperature and relative humidity variability within emplacement drifts are realistically represented in TSPA with thorough uncertainty treatment
- Thermal testing results can be applied to all repository units with appropriate modifications in thermal properties

Backup Slides

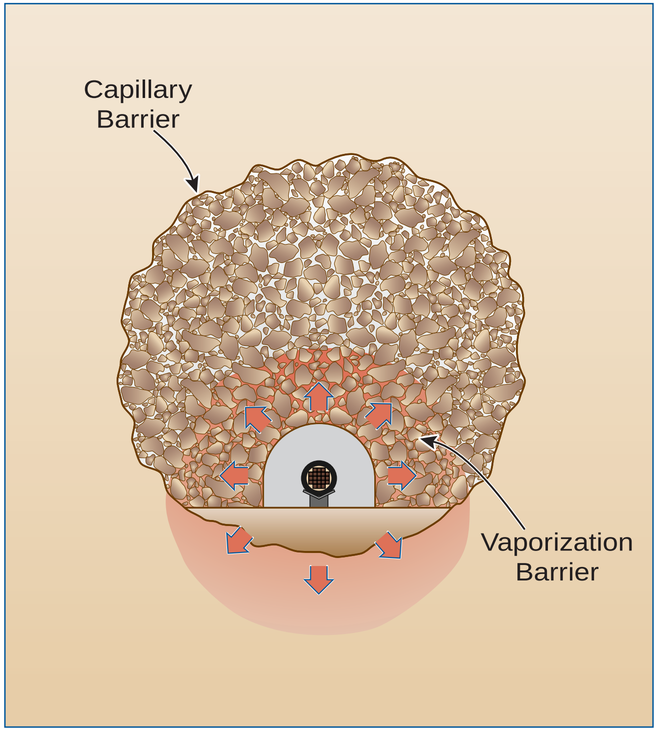
Capillary Barrier and Vaporization Barrier Remain Effective Even with Drift Collapse

- TH conditions were analyzed for collapsed drift conditions
- Collapse was assumed to occur soon after emplacement, while heat input is still high

Non-degraded Open Drift



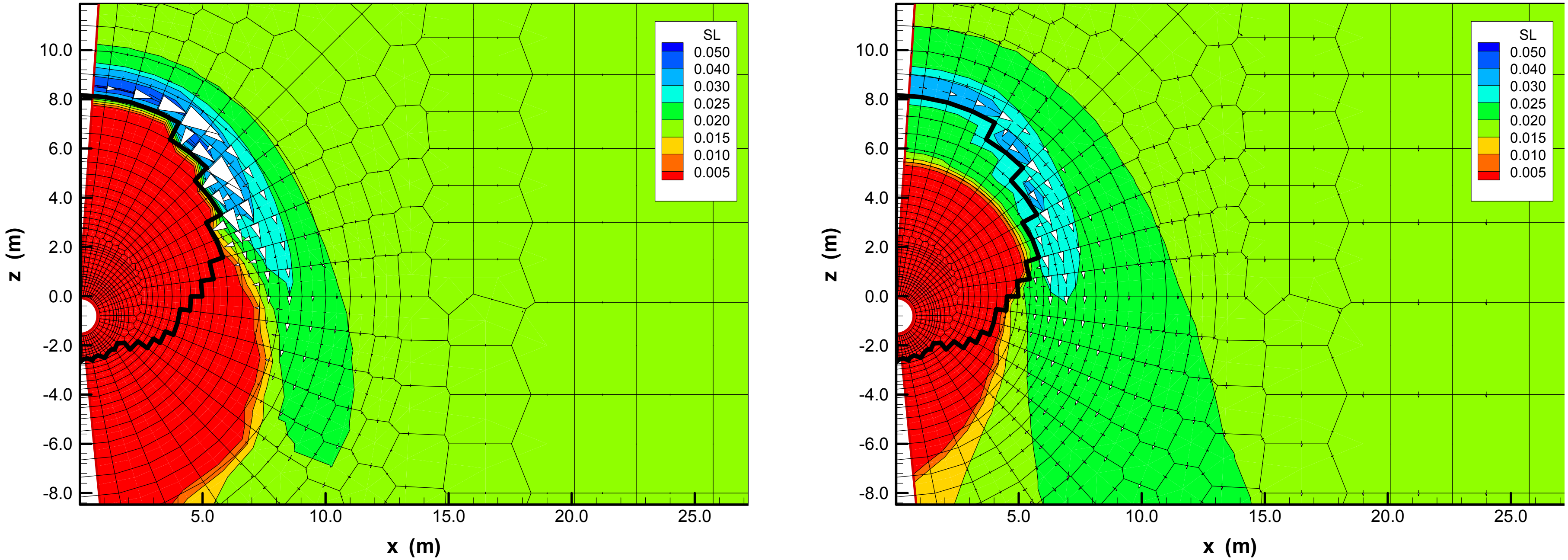
Collapsed Drift



TT03-009

Thermal Seepage Model Results for Collapsed Drifts

- Waste package temperature is significantly higher
- Capillary barrier diverts most percolation water above rubble zone
- Water present in rubble material is vaporized and driven away

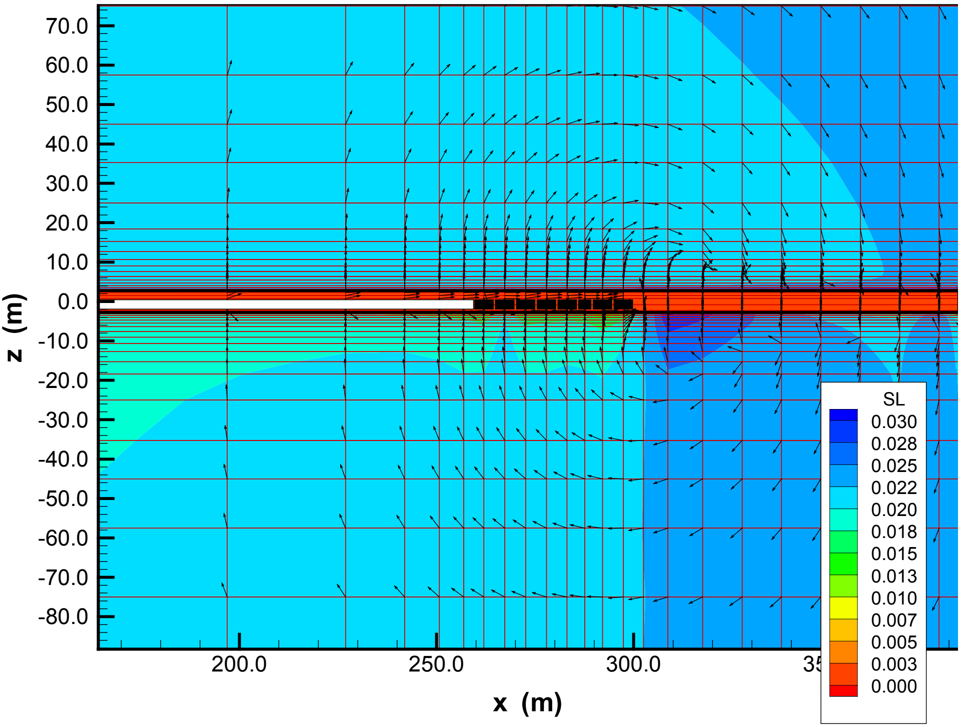


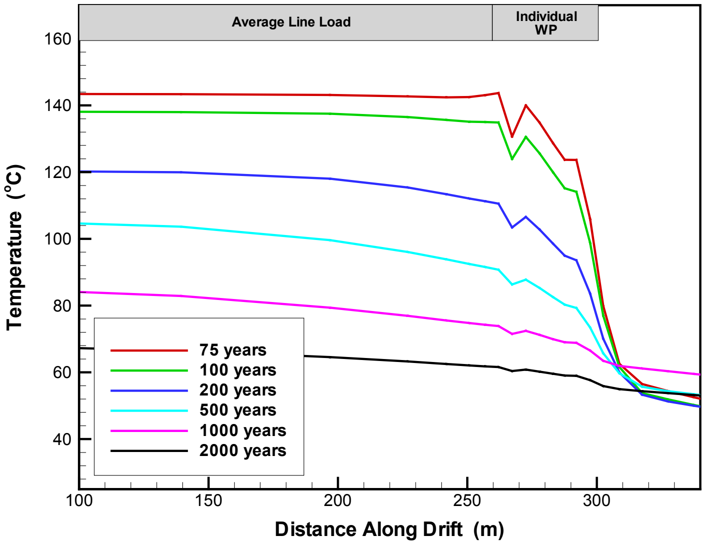
Vaporization barrier is NOT accounted for in TSPA (uncertainties regarding properties of rubble material)

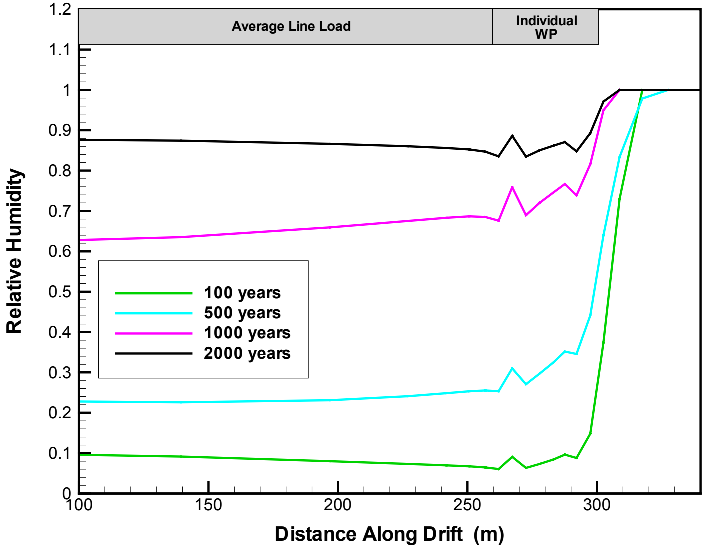
Effects of In-drift Natural Ventilation and Air Circulation on T and RH Conditions

- Results from MSTHM simulations of open drift boundary (natural ventilation) and close boundary show insignificant in-drift temperature differences
- 3D Coupled process model that account for air circulation (by means of an large effective dispersion) indicate that the major impact is on the cool drift ends
  - Condensation on the drift ends
  - Little pressure build-up within the drift

3D Model for Rock and In-drift Conditions







Histogram of Non-Zero Seepage Rates (in kg/year/waste package)