ATTACHMENT 4

PRESENTER'S SLIDES

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

Radionuclide Transport

Presented to:
DOE/NRC Technical Exchange on the Radionuclide Transport Key Technical Issue

Presented by:
Eric Smistad
Yucca Mountain Site Characterization Office
Department of Energy

December 5-7, 2000
Lawrence Berkeley National Laboratory
Berkeley, CA

YUCCA MOUNTAIN PROJECT

Radionuclide Transport

- Subissue 1: Radionuclide Transport through Porous Rock
- Subissue 2: Radionuclide Transport through Alluvium
- Subissue 3: Radionuclide Transport through Fractured Rock
- Subissue 4: Nuclear Criticality in the Far Field
- Status of Subissues 1, 2, and 3 will be discussed at this technical exchange
- Subissue 4 was addressed at the October 2000 Criticality Technical Exchange

Subissue 1: Radionuclide Transport through Porous Rock

Acceptance Criterion	NRC IRSR Status	DOE Proposed Status
1a …DOE has determined whether radionuclide attenuation processes are important to performance…	Closed	Closed
1b For the estimation of radionuclide transport through porous rock, sorption coefficient (K_d) values have been determined as appropriate …	Closed	Closed
2a For the valid application of constant K_d approach, DOE has demonstrated that the portion of the flow path to which the transport equation applies acts as a single continuum porous medium …	Open	Closed
2b For the valid application of constant K_d approach, DOE has determined appropriate values for the parameters in the transport equation…	Open	Closed-pending
2c For the valid application of constant K_d approach, DOE has demonstrated that the three implicit assumptions are valid…	Open	Closed-pending

Subissue 1: Radionuclide Transport through Porous Rock (Continued)

Acceptance Criterion	NRC IRSR Status	DOE Proposed Status
3a, 3b, 3c deal with use of process models for determining radionuclide transport parameters through porous rock…	Open	Closed
4 …If used, expert elicitations were conducted and documented in accordance with the guidance in NUREG-1563 …	Open	Closed-Pending
5 Data and models have been collected developed, and documented under acceptable QA procedures …	Open	Not addressed at this technical exchange

Subissue 2: Radionuclide Transport through Alluvium

Acceptance Criterion	NRC IRSR Status	DOE Proposed Status
1a …DOE has determined whether radionuclide attenuation processes are important to performance…	Closed	Closed
1b For the estimation of radionuclide transport through porous rock {sic: Alluvium}, sorption coefficient (K_d) values have been determined as appropriate …	Open	Closed
2a For the valid application of constant K_d approach, DOE has demonstrated that the portion of the flow path to which the transport equation applies acts as a single continuum porous medium …	Open	Closed-pending
2b For the valid application of constant K_d approach, DOE has determined appropriate values for the parameters in the transport equation…	Open	Closed-pending

Subissue 2: Radionuclide Transport through Alluvium (Continued)

Acceptance Criterion	NRC IRSR Status	DOE Proposed Status
2c For the valid application of constant K_d approach, DOE has demonstrated that the three implicit assumptions are valid…	Open	Closed-Pending
3a, 3b, 3c deal with use of process models for determining radionuclide transport parameters through porous rock {sic: Alluvium} …	Open	Closed
4 …If used, expert elicitations were conducted and documented in accordance with the guidance in NUREG-1563 …	Open	Closed-Pending
5 Data and models have been collected developed, and documented under acceptable QA procedures …	Open	Not addressed at this technical exchange

Subissue 3: Radionuclide Transport through Fractured Rock

Acceptance Criterion	NRC IRSR Status	DOE Proposed Status
1a …DOE has determined whether radionuclide attenuation processes are important to performance…	Closed	Closed
1b For the estimation of radionuclide transport through fractured rock, sorption coefficient (K_d) values have been determined as appropriate …	Open	Closed
1c For the estimation of radionuclide transport through fractured rock, length of flow path have been justified	Open	Closed
2a If credit is taken for radionuclide attenuation in fractured rock, then capability to predict breakthrough curves has been demonstrated …	Open	Closed-pending
2b If credit is taken for radionuclide attenuation in fractured rock, then use of tracers used in field tests as appropriate homologues for radionuclides has been demonstrated …	Closed	Closed

Subissue 3: Radionuclide Transport through Fractured Rock (Continued)

Acceptance Criterion	NRC IRSR Status	DOE Proposed Status
2c For the estimation of radionuclide transport through fractured rock, length of flow path has been justified…	Open	Closed
3 …If used, expert elicitations were conducted and documented in accordance with the guidance in NUREG-1563 …	Open	Closed
4 Data and models have been collected developed, and documented under acceptable QA procedures …	Open	Not addressed at this technical exchange

Radionuclide Transport Summary

	Status	
	IRSR Rev 02	**DOE Proposed**
• **Subissue 1:** Transport through porous rock	Open	Closed-Pending
• **Subissue 2:** Transport through alluvium	Open	Closed-Pending
• **Subissue 3:** Transport through fractured rock	Open	Closed-Pending

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

Impact of Radionuclide Transport in the Unsaturated Zone on Total System Performance Assessment

Presented to:
DOE/NRC Technical Exchange on the Radionuclide Transport Key Technical Issue

Presented by:
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December 5-7, 2000
Lawrence Berkeley National Laboratory
Berkeley, CA

YUCCA MOUNTAIN PROJECT

Outline

- Presentation Objectives
- Implementation of Unsaturated Zone Radionuclide Transport in Total System Performance Assessment for the Site Recommendation (TSPA-SR)
- Unsaturated Zone Transport Conceptual Model
- Mathematical Implementation Using Particle Tracking
- Parameter Uncertainty Distributions
- Representative Total System Performance Assessment Unsaturated Zone Model Results
- Conclusions

Presentation Objectives

- Explain implementation of radionuclide transport simulations in the unsaturated zone for use in Total System Performance Assessment for the Site Recommendation
- Describe treatment of uncertainty in radionuclide transport in the unsaturated zone for Total System Performance Assessment for the Site Recommendation
- Provide sensitivity analyses from Total System Performance Assessment for the Site Recommendation to assist in the subsequent discussion and resolution of acceptance criteria for radionuclide transport in the unsaturated zone

Implementation of Unsaturated Zone Radionuclide Transport in TSPA-SR

- Full decay-chain capability
- Quasi-steady state flow assumption - flow fields imported directly from unsaturated zone flow process model
- Climate change - change in flow field and water table elevation
- Particle release locations and mass per particle are determined dynamically from engineered barrier system radionuclide mobilization and transport calculations
- Particles are released into the fracture continuum
- Radionuclide mass versus time at various locations at the water table is computed and input to the saturated zone model

Role of Unsaturated Zone Transport in Total System Performance Assessment

Unsaturated Zone Radionuclide Transport

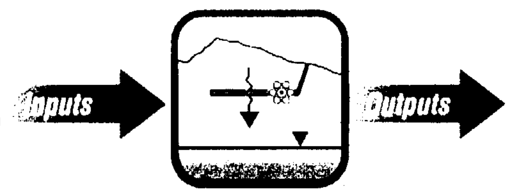
- *Three-dimensional particle-tracking model*
- *Steady-state water flow between climate changes*
- *Dual-continuum transport model*
- *Active fracture model*
- *Reversible and irreversible colloids*

Unsaturated Zone Flow
- Mountain-scale unsaturated zone flow field

Waste Package and Drip Shield Degradation
- Number of failed waste packages

Waste Form Degradation
- Colloid size distribution for irreversible colloids

Engineered Barrier System Transport
- Radionuclide mass flux at EBS boundary



Saturated Zone Flow and Transport
- Radionuclide mass flux at water table

- Laboratory sorption experiments
- Laboratory diffusion experiments
- Hydrochemical data
- Core data
- Mineralogic description
- Literature data
- Colloid measurements

Model Confidence Foundation

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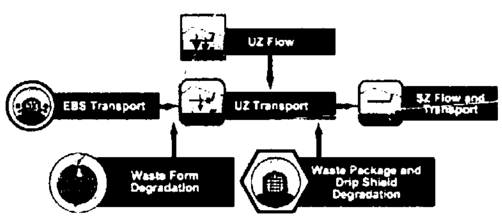
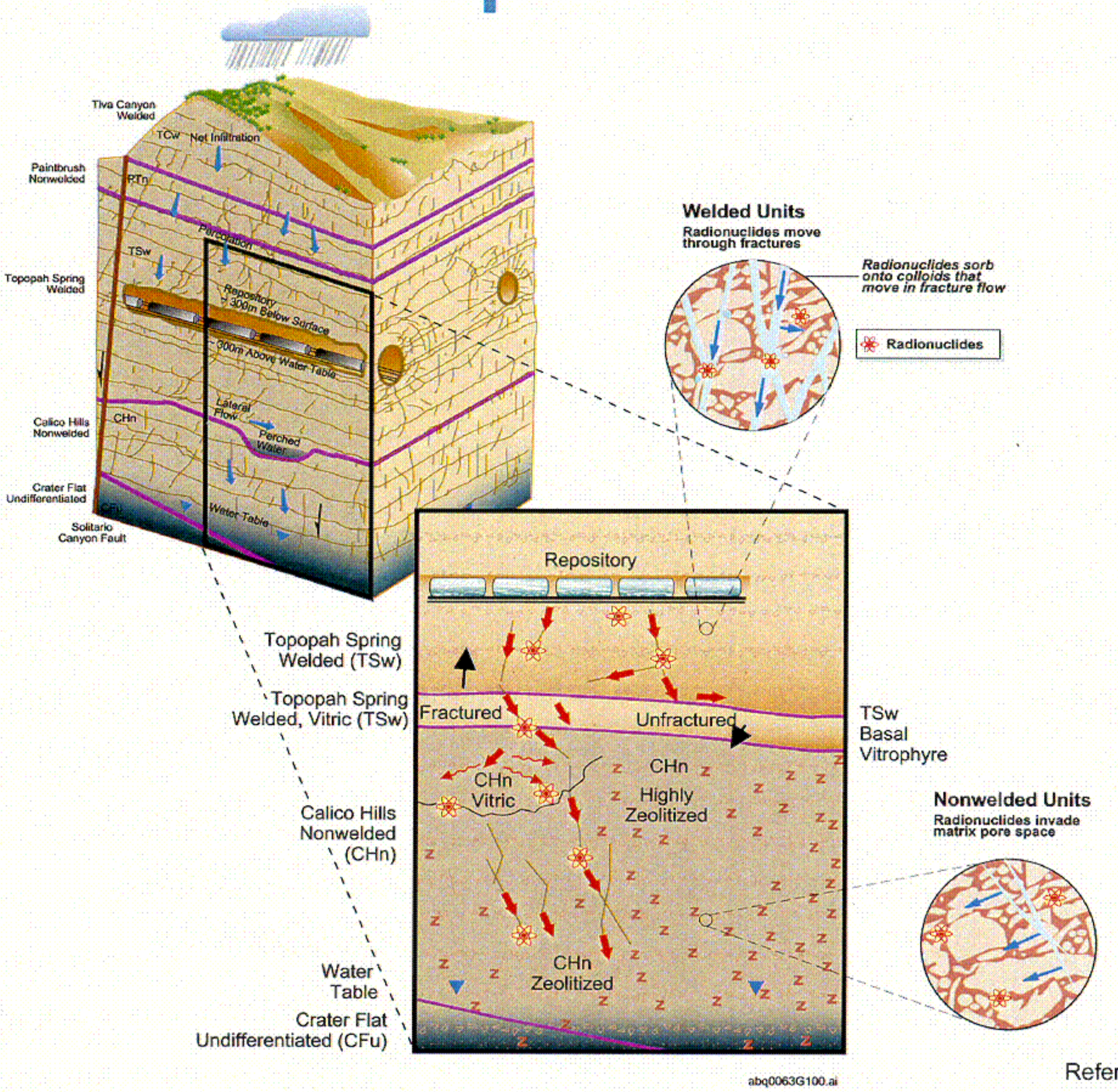


Unsaturated Zone Transport Conceptual Model



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Reference: TDR-NBS-HS-000002

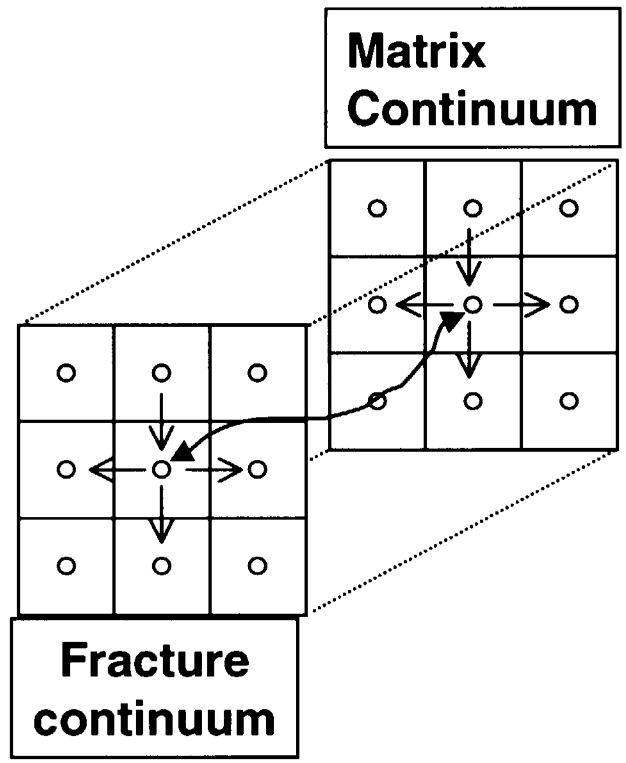
Mathematical Implementation Using Particle Tracking

The Residence-Time/Transfer Function Particle Tracking Technique

A cell-based particle tracking technique consisting of two steps:

- Keep the particle at the cell for a prescribed time, and
- Decide which adjacent cell the particle travels to next

Dual Permeability Model

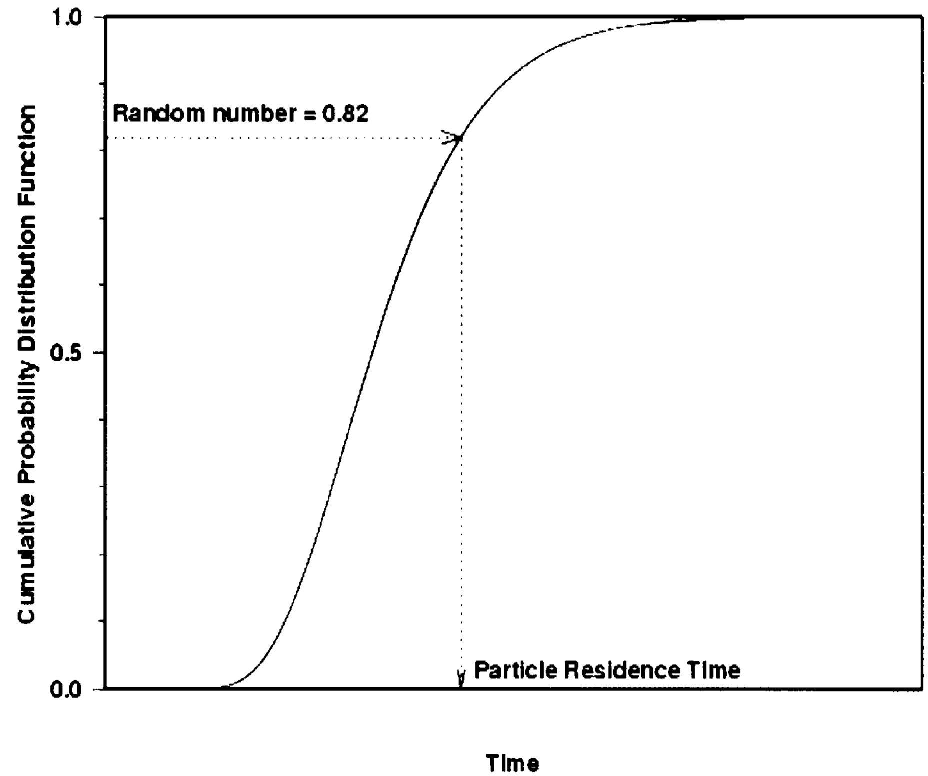


Mathematical Implementation Using Particle Tracking Sorption and Matrix Diffusion

Transfer Function Approach

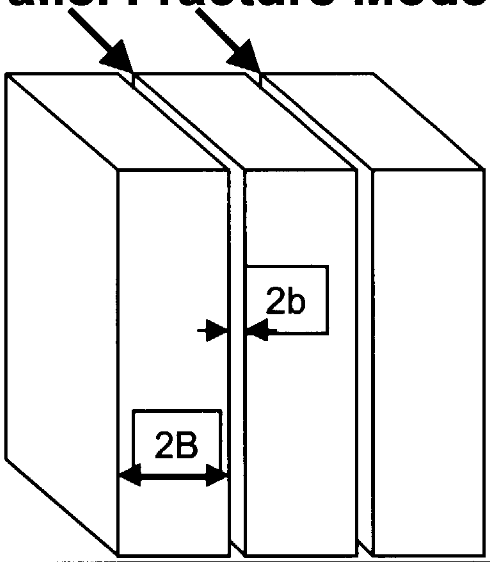
- Transfer function corresponds to a distribution of residence times that reproduces an analytical solution
- Travel time through each cell is computed based on the transport properties in that cell
- Similar approach is used in the saturated zone

Determination of Particle Travel Time



Mathematical Implementation Using Particle Tracking Matrix Diffusion Model

Parallel Fracture Model



Parameters:
- b (1/2 fracture aperture)
- t (elapsed time)
- z (distance traveled)
- v (velocity)
- θ (volumetric water content)
- B (1/2 fracture spacing)
- D' (diffusion coefficient)
- R (fracture retardation factor)
- R' (matrix retardation factor)

Dimensionless Groups

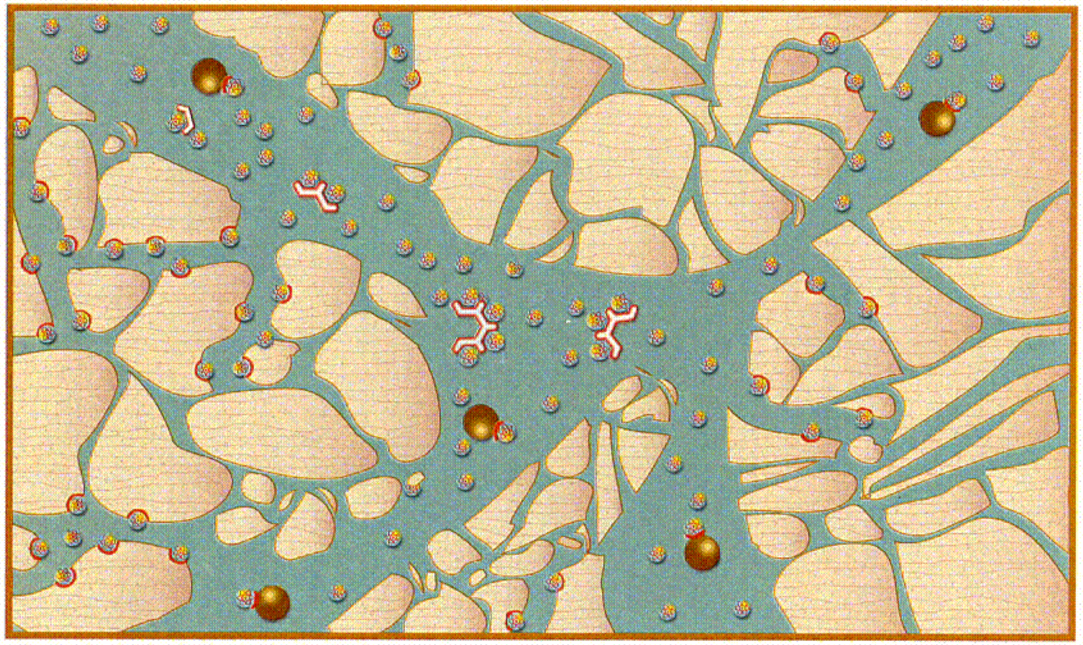
$$T_1^0 = \frac{t}{\tau_0} - R$$, where $$\tau_0 = \frac{z}{v}$$

$$\omega_1 = \frac{\theta(R'D'\tau_0)^{1/2}}{b}$$

$$\sigma_1 = (\frac{R'}{D'\tau_0})^{1/2}(B-b)$$

Reference: Sudicky and Frind (1982)

Mathematical Implementation Using Particle Tracking - Colloid Transport Model



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Radionuclide

Sorbed Radionuclide

Reversible Sorption Type Colloid shown with radionuclide temporarily attached

Reversible Sorption Type Colloid shown without radionuclide attached

Irreversible Sorption Type Colloid shown with radionuclide permanently attached

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Mathematical Implementation Using Particle Tracking Colloid Transport Model Assumptions

- **Reversible Sorption Type Colloid**
  - Colloid partitioning coefficient (K_c) describes the relative amount of radionuclide on colloids versus that in the aqueous phase
  - Only aqueous phase radionuclides can sorb or diffuse into the rock matrix
- **Irreversible Sorption Type Colloid**
  - Advective transport without diffusion or sorption
  - Size exclusion model to prevent transport from fractures into some matrix units
  - Filtration model for colloids at interfaces of matrix units
  - Source term obtained from waste form degradation process model

Unsaturated Zone Parameter Uncertainty

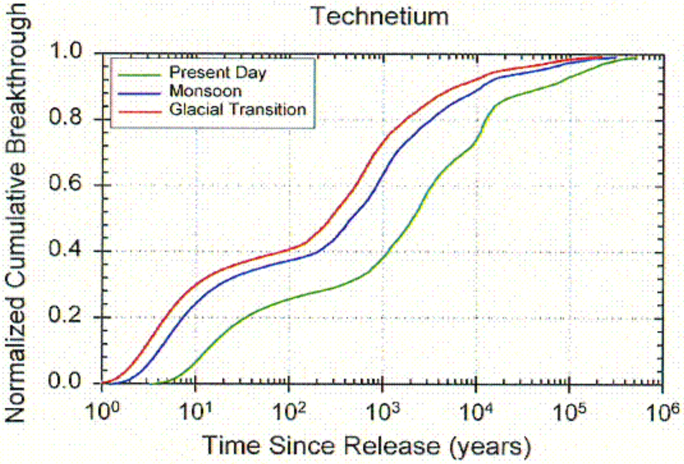
- **The unsaturated zone transport model incorporates probabilistically defined parameters and constant value parameters**
- **The parameter uncertainty distributions propagate the quantified uncertainty and variability throughout the unsaturated zone component**
- **Transport parameter uncertainty distributions include the following:**
  - matrix diffusion parameters
  - sorption parameters
  - colloid-related parameters
  - fracture aperture

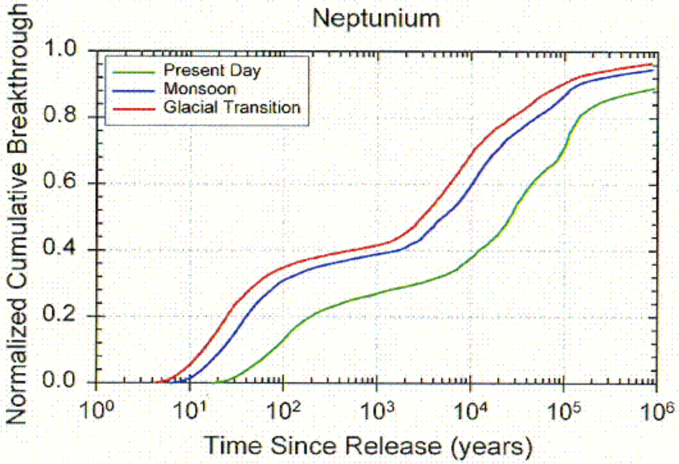
Unsaturated Zone Model Uncertainty

- **Three-Dimensional Flow Model**
  - Model samples from three distinct infiltration scenarios
  - Three climate states for each scenario capture temporal variability
- **Radionuclide source (uncertainty captured in other process models)**

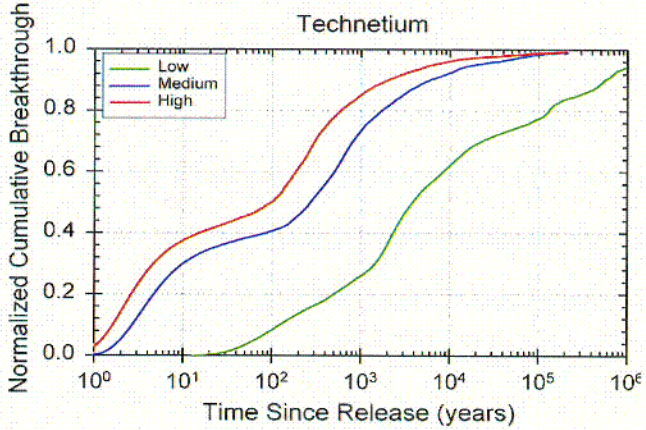
Representative Total System Performance Assessment Unsaturated Zone Model Results

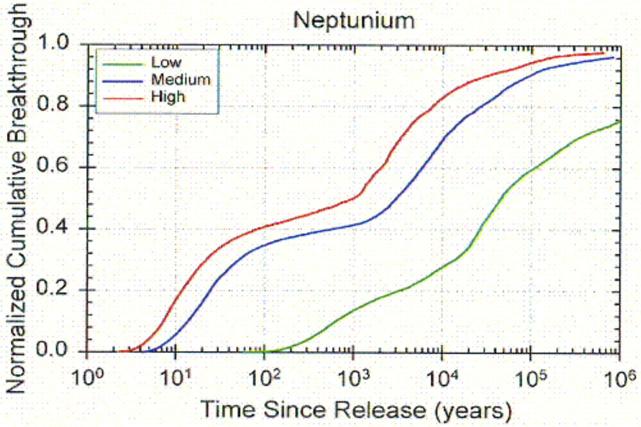
Three Climate States





Three Infiltration Scenarios

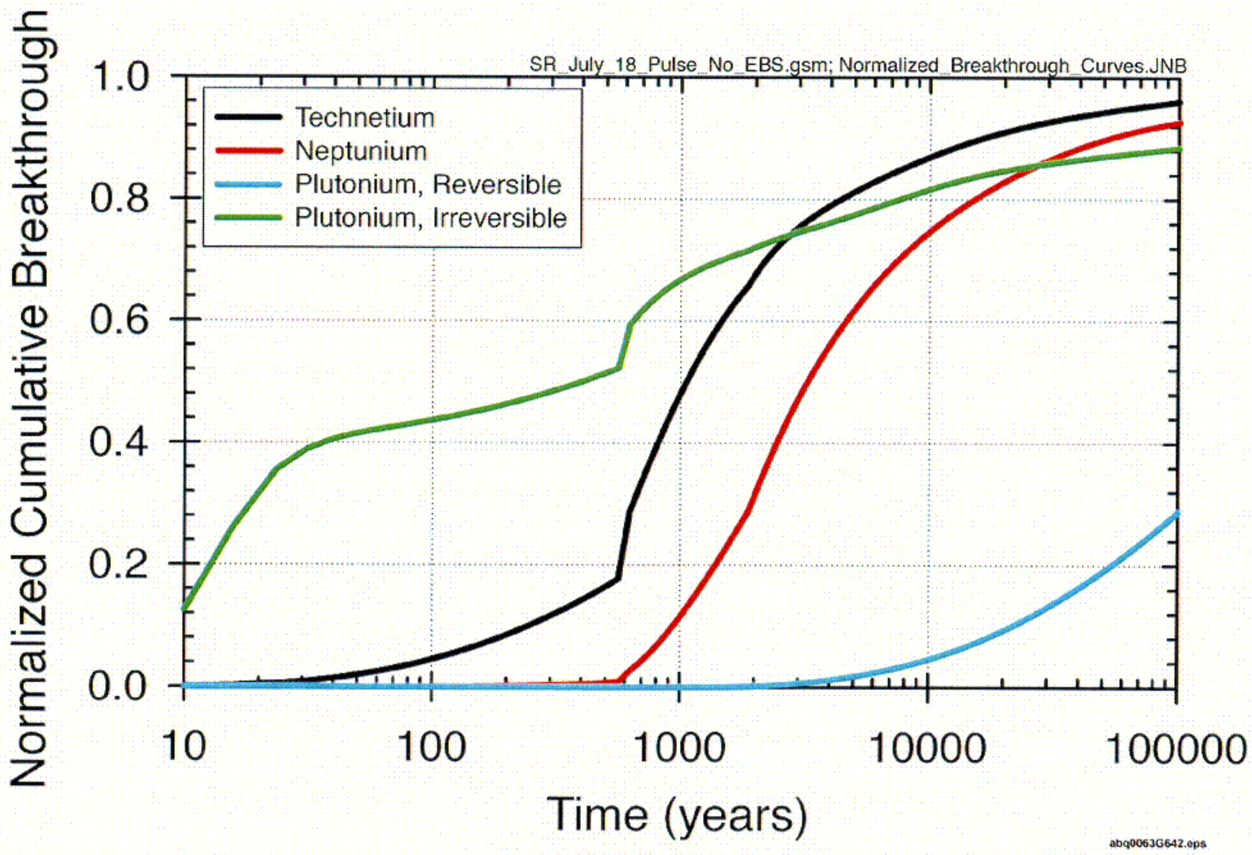




Note that breakthrough curves do not include decay and represent transport only in the unsaturated zone

Mean Unsaturated Zone Breakthrough Curves

100 Realizations



Note that breakthrough curves do not include decay and represent transport only in the unsaturated zone

Reference: MDL-WIS-PA-000002

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Unsaturated Zone Transport Model

- **References**
  - *Unsaturated Zone Flow and Transport Model Process Model Report* (TDR-NBS-HS-000002)
  - *Total System Performance Assessment (TSPA) Model for Site Recommendation* (MDL-WIS-PA-000002 REV 00)
  - Analysis and Model Report *Particle Tracking Model and Abstraction of Transport Processes* (ANL-NBS-HS-000026)
  - Analysis and Model Report *Uncertainty Distributions for Stochastic Parameters* (ANL-NBS-MD-000011)
  - Sudicky and Frind, 1982. Contaminant Transport in Fractured Porous Media: Analytical Solutions for a System of Parallel Fractures: Water Resources Research 18, 1634-1642

Conclusions

- **Radionuclide transport in the unsaturated zone for Total System Performance Assessment for the Site Recommendation is simulated considering the relevant processes of advection, matrix diffusion, sorption, dispersion, and colloid-facilitated transport**
- **Uncertainty in key transport parameters relevant to all of these radionuclide transport processes is incorporated in the stochastic realizations of the unsaturated zone flow and transport model**
- **Propagated quantified uncertainty in the behavior of radionuclide transport in the unsaturated zone is carried forward to the Total System Performance Assessment for the Site Recommendation analyses from the abstraction modeling of unsaturated zone flow and transport**

BACKUP SLIDES

Parameter Uncertainty Distributions
Sorption K_d Distributions

Parameter Description	Distribution
K_d for Am and Th in devitrified tuff (ml/g)	Uniform; min = 100, max = 2,000
K_d for Am and Th in vitric tuff (ml/g)	Beta; mean = 400, COV = 0.2, min = 100, max = 1,000
K_d for Am and Th in zeolitic tuff (ml/g)	Uniform; min = 100, max =1,000
K_d for Pu in devitrified tuff (ml/g)	Uniform; min = 5, max = 70
K_d for Pu in vitric and zeolitic tuff (ml/g)	Beta; mean = 100, COV = 0.25, min = 30, max = 200
K_d for Np in devitrified tuff (ml/g)	Beta; mean = 0.3, COV = 0.3, min = 0, max = 1
K_d for Np in vitric tuff (ml/g)	Beta; mean =0.3, COV = 1, min = 0, max = 1
K_d for Np in zeolitic tuff (ml/g)	Beta; mean = 0.5, COV = 0.25, min = 0, max = 3
K_d for U in devitrified tuff (ml/g)	Beta; mean = 0.5, COV = 0.3, min = 0, max = 2
K_d for U in vitric tuff (ml/g)	Beta; mean = 0.5, COV = 0.3, min = 0, max = 1
K_d for U in zeolitic tuff (ml/g)	Beta; mean = 4, COV = 1, min = 0, max = 10
K_d for Pa in all units (ml/g)	Uniform; min = 0, max = 100
K_d for I, Tc, and C in all units (ml/g)	Not sampled; 0

Source: TDR-NBS-HS-000002, Table 3.11-1

NOTE: COV=coefficient of variation = standard deviation divided by mean; Am=americium; Th=thorium; Pu=plutonium; Np=neptunium; U=uranium; Pa=protactinium; I=iodine; Tc=technetium; C=carbon

Parameter Uncertainty Distributions Unsaturated Zone Transport Parameters

Parameter Description	Distribution
Diffusion Coefficient for Am, Pu, Np, U, Pa, Th (m^2/s)	Beta; mean = 1.6×10^{-10}, SD = 0.5×10^{-10}, min = 0, max = 10^{-9} (TDR-NBS-HS-000002, Table 3.11-2; MDL-WIS-PA-000002, Table 83)
Diffusion Coefficient for I, Tc, C (m^2/s)	Beta; mean = 3.2×10^{-11}, SD = 10^{-11}, min = 0, max = 10^{-9} (TDR-NBS-HS-000002, Table 3.11-2; MDL-WIS-PA-000002, Table 83)
Dispersivity for both fractures and matrix (m)	Not sampled; 20 (MDL-WIS-PA-000002, Table 79)
Fracture aperture (mm)	Log-normal; geometric mean is different for each hydrogeologic unit, varying from 1.5 to 4.6 outside of fault zones and from 6.8 to 8.4 in fault zones (ANL-NBS-HS-000026, Table 3[a]); geometric SD = 1.9 (ANL-NBS-HS-000026, Section 6.2.1).
Fracture spacing (m)	Not sampled; different for each hydrogeologic unit, varying from 0.23 to 25 outside of fault zones and from 0.59 to 7.7 in fault zones (ANL-NBS-HS-000026, Table 3)
Colloid partitioning factor (K_c)	Log-normal; geometric mean = 3×10^{-3}, geometric SD = 10 (ANL-NBS-MD-000011, Table 15); only used for reversible colloids
Colloid retardation factor (R_c)	Not sampled; 1
Colloid size distribution (nm)	Not sampled; distribution of sizes from 1 to 450, median size approximately 75 (MDL-WIS-PA-000002, Table 93); only used for irreversible colloids
Fraction of colloids that can enter one matrix unit from another	Not sampled; function of colloid size and hydrogeologic unit (ANL-NBS-HS-000026, Table 6); only used for irreversible colloids
Fraction of colloids that can enter the matrix from fractures	Not sampled; different for each hydrogeologic unit, varying from 4% to 79% (ANL-NBS-HS-000026, Table 5); only used for irreversible colloids

NOTE: SD=standard deviation (geometric SD is 10 raised to the power equal to the standard deviation of the logs); Am=americium; Th=thorium; Pu=plutonium; Np=neptunium; U=uranium; Pa=protactinium; I=iodine; Tc=technetium; C=carbon

[a]The values listed as fracture apertures in this reference are actually half-apertures.

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

Impact of Radionuclide Transport in the Saturated Zone on Total System Performance Assessment

Presented to:

DOE/NRC Technical Exchange on the Radionuclide Transport Key Technical Issue

Presented by:

John H. Gauthier
Stephanie P. Kuzio
Civilian Radioactive Waste Management System Management and Operating Contractor

December 5-7, 2000
Lawerence Berkeley National Laboratory
Berkeley, CA

YUCCA MOUNTAIN PROJECT

Outline

- Presentation Objectives
- Implementation of Saturated Zone Radionuclide Transport in Total System Performance Assessment for the Site Recommendation
- Parameter Uncertainty
- Transport Parameter Sensitivity
- Conclusions

Presentation Objectives

- Explain implementation of radionuclide transport simulations in the saturated zone for use in Total System Performance Assessment for the Site Recommendation
- Describe treatment of uncertainty in radionuclide transport in the saturated zone for Total System Performance Assessment for the Site Recommendation, Rev. 0
- Provide sub-system and system-level sensitivity analyses from Total System Performance Assessment for the Site Recommendation, Rev. 0, to assist in the subsequent discussion and resolution of subissues for radionuclide transport in the saturated zone

Implementation of Saturated Zone Radionuclide Transport in Performance Assessment - General Approach

- Saturated zone site-scale flow and transport model is used to simulate radionuclide mass transport to 20 km distance from a point mass source (four source regions below the repository)
- Convolution integral method is used to couple the radionuclide source term from the unsaturated zone with the saturated zone transport in the Total System Performance Assessment for the Site Recommendation calculations

Implementation of Saturated Zone Radionuclide Transport in Performance Assessment - General Approach (Continued)

- Radionuclide concentration in groundwater source to the biosphere is calculated by dividing radionuclide mass crossing the 20 km "fence" by the average annual groundwater usage of the hypothetical farming community
- Climate change is incorporated by scaling radionuclide mass breakthrough curves in proportion to saturated zone flux changes
- Abstracted one-dimensional transport model is used for some radioactive decay chains

Simulation of Radionuclide Transport

- Particle tracking with the FEHM code is used to simulate radionuclide mass migration in the saturated zone
- Matrix diffusion of dissolved radionuclides is implemented in fractured volcanic units
- All volcanic units along the flow path from the repository are treated as fractured media
- Linear sorption model is used in the matrix of the volcanic units (as a component of the matrix diffusion model)

Simulation of Radionuclide Transport
(Continued)

- No sorption on fracture surfaces is simulated in the fractured volcanic units
- The valley-fill (alluvium) units are simulated as a porous medium using the effective porosity approach for the purpose of radionuclide transport simulations
- Linear sorption model is used for relevant radionuclides in the alluvium units
- Colloid-facilitated transport of radionuclides is simulated to occur by two modes (reversible attachment to colloids and irreversible attachment)

Simulation of Radionuclide Transport
(Continued)

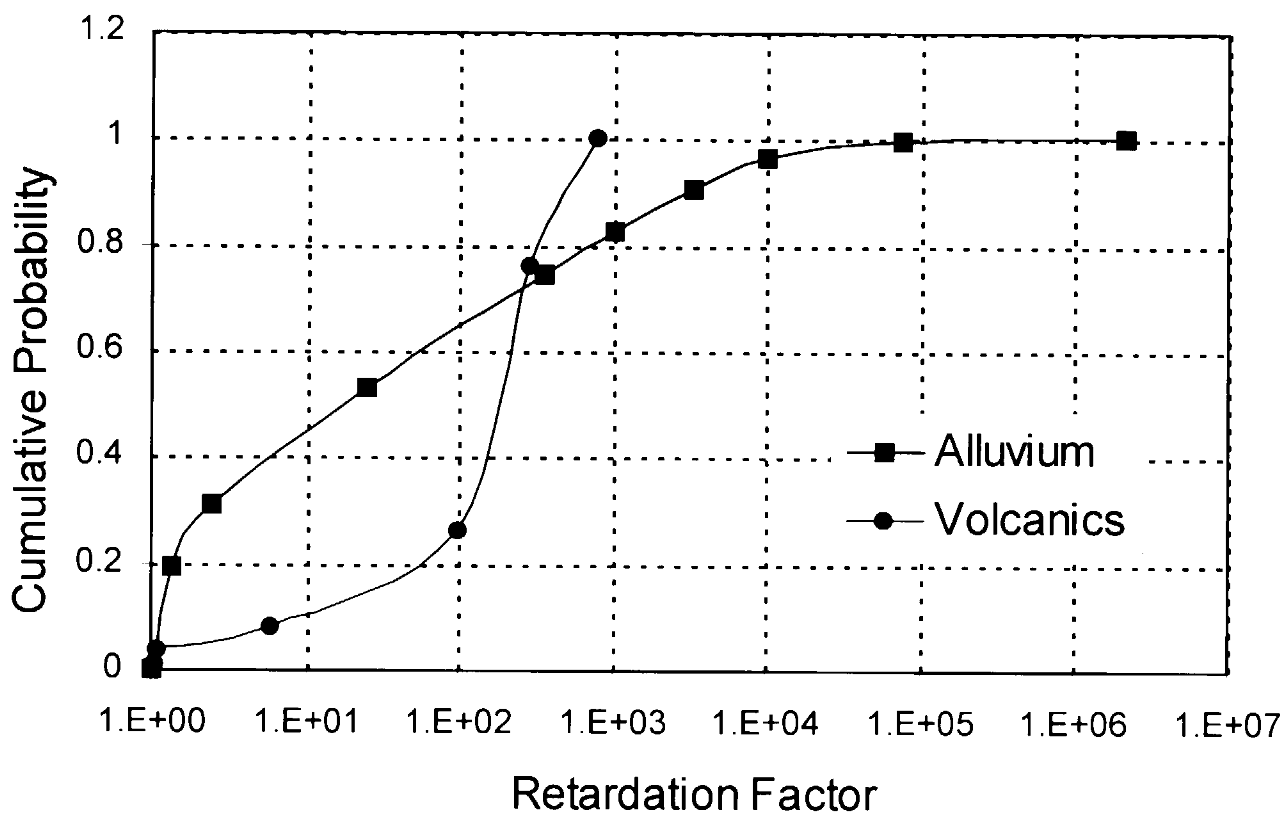
- Radionuclides reversibly attached to colloids are modeled to be in equilibrium with the aqueous phase and with aquifer material
- Colloids are not subject to matrix diffusion in fractured units in the model
- Colloids with irreversibly attached radionuclides experience retardation in fractured units and alluvium due to filtration
- Am, Pu, Th, Pa, Cs, and Sr are simulated to be transported as reversibly attached to colloids
- Am and Pu are simulated to be as irreversibly attached to colloids

Implementation of Reversible Colloid (K_c) Model for the Saturated Zone

- The model accounts for radionuclides sorbed onto colloids, aqueous radionuclides, and radionuclides sorbed onto the volcanic matrix and alluvial material
- Basic implementation strategy is to increase mobility of radionuclides associated with colloids by keeping them in mobile water
- In the volcanics, the model is implemented by adjusting the diffusion coefficient to reduce matrix diffusion
- In the alluvium, the model is implemented by adjusting the radionuclide K_d to reduce sorption onto the alluvial material

Implementation of Irreversible Colloid Model for the Saturated Zone

Radionuclides irreversibly attached to colloids are restricted to the mobile water, but subjected to a retardation factor (a sampled parameter)



Reference: ANL-NBS-MD-000011 Rev 00

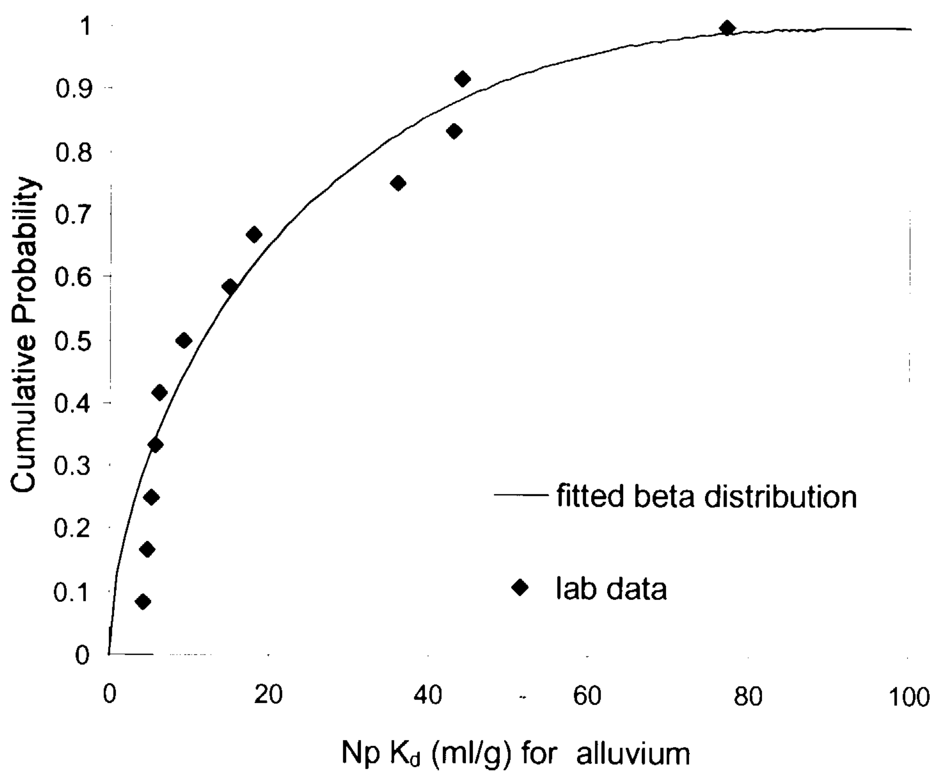
Colloids: Conservative Assumptions

- **Reversible-colloid model**
  - K_c defined by Am K_d on waste form colloids
  - no filtration
  - colloid concentration based on low ionic strength
  - used lowest range of radionuclide K_ds on the substrate
- **Irreversible-colloid model**
  - no diffusion of colloids into the matrix
  - no loss of mass because of filtration

Saturated Zone Parameter Uncertainty

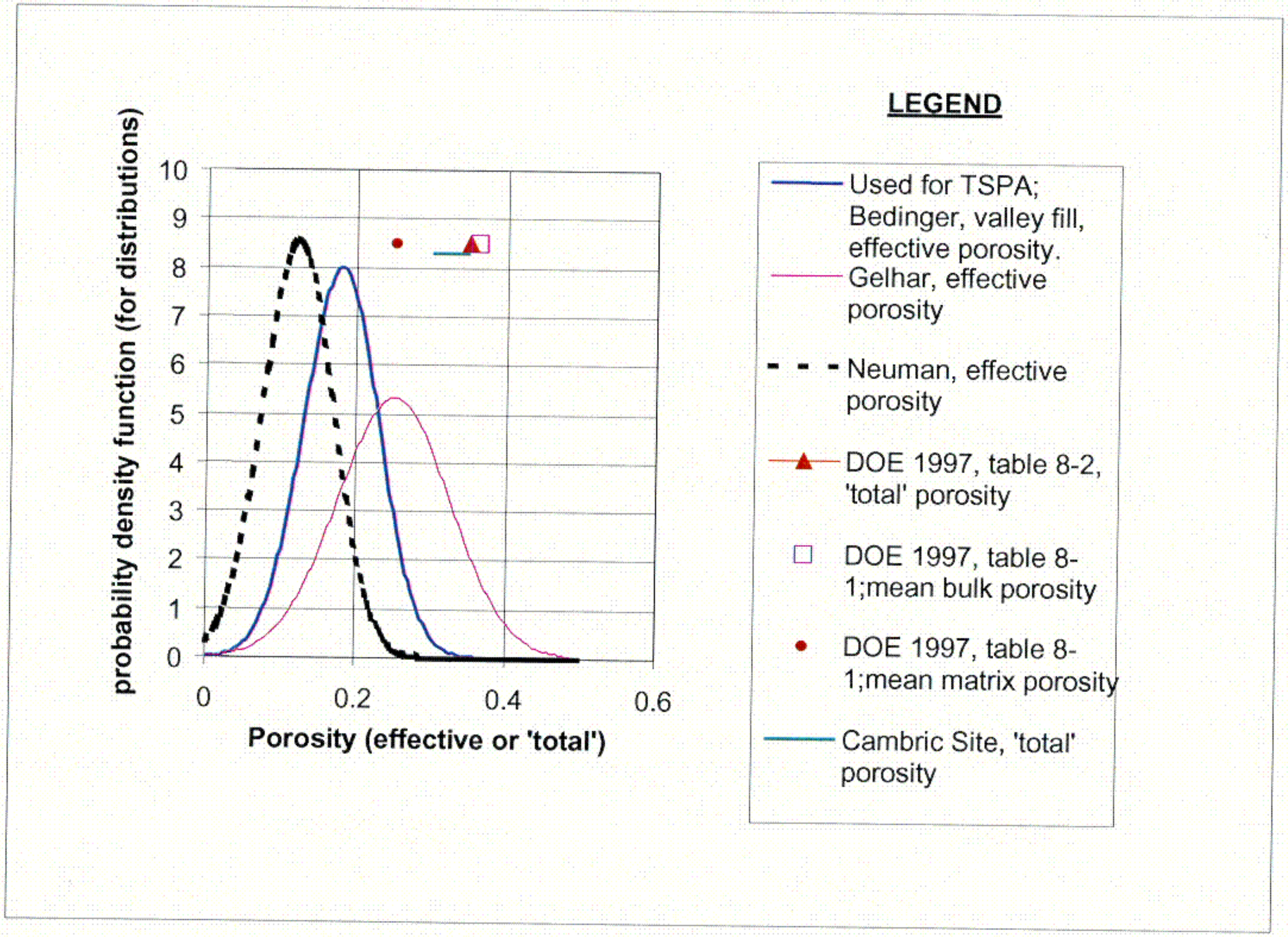
- **The saturated zone site-scale model incorporates probabilistically defined parameters and constant value parameters.**
- **The parameter uncertainty distributions propagate the quantified uncertainty and variability throughout the saturated zone component of Total System Performance Assessment**
- **Quantified parameter uncertainty distributions include the following:**
  - Matrix diffusion parameters
  - Sorption parameters
  - Colloid-related parameters
  - Alluvium boundaries

Uncertainty Distribution: Sorption Coefficient for Np in Alluvium



Reference: ANL-NBS-MD-000011

Uncertainty Distribution: Effective Porosity in Alluvium



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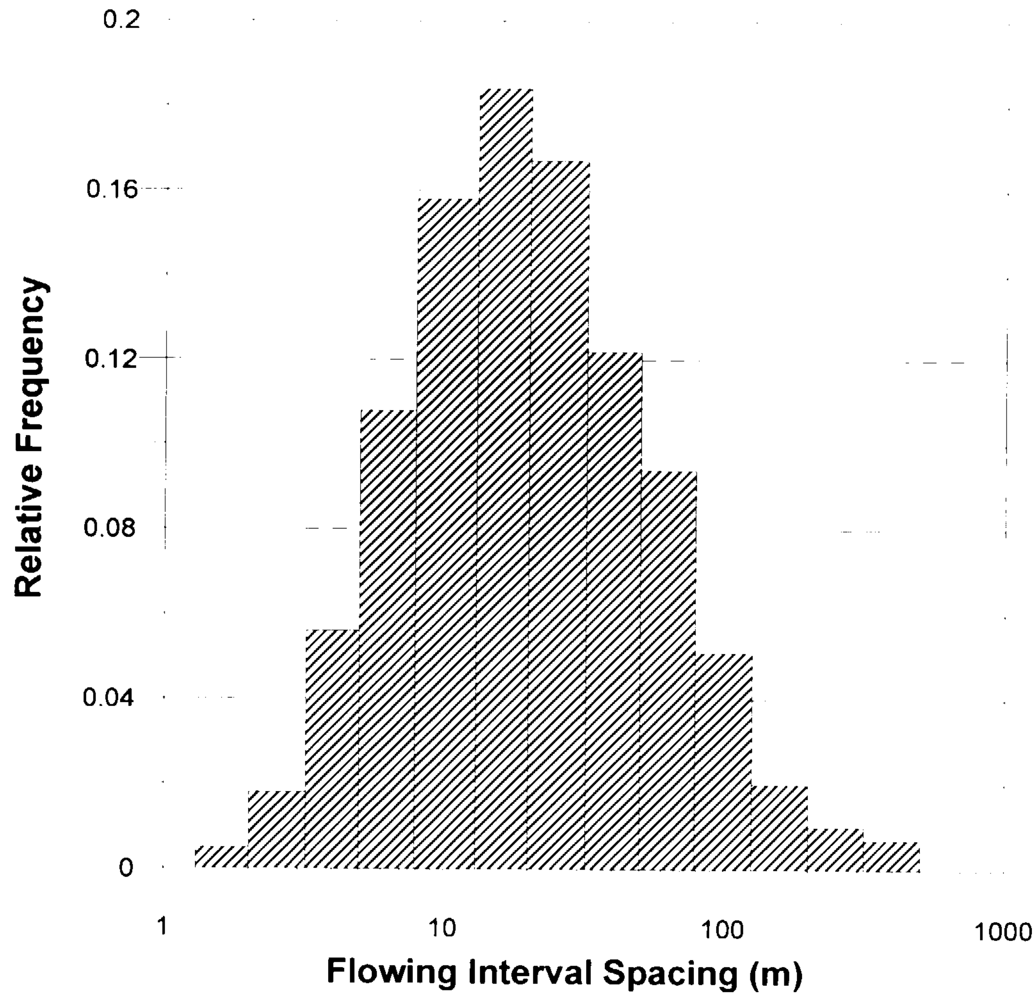
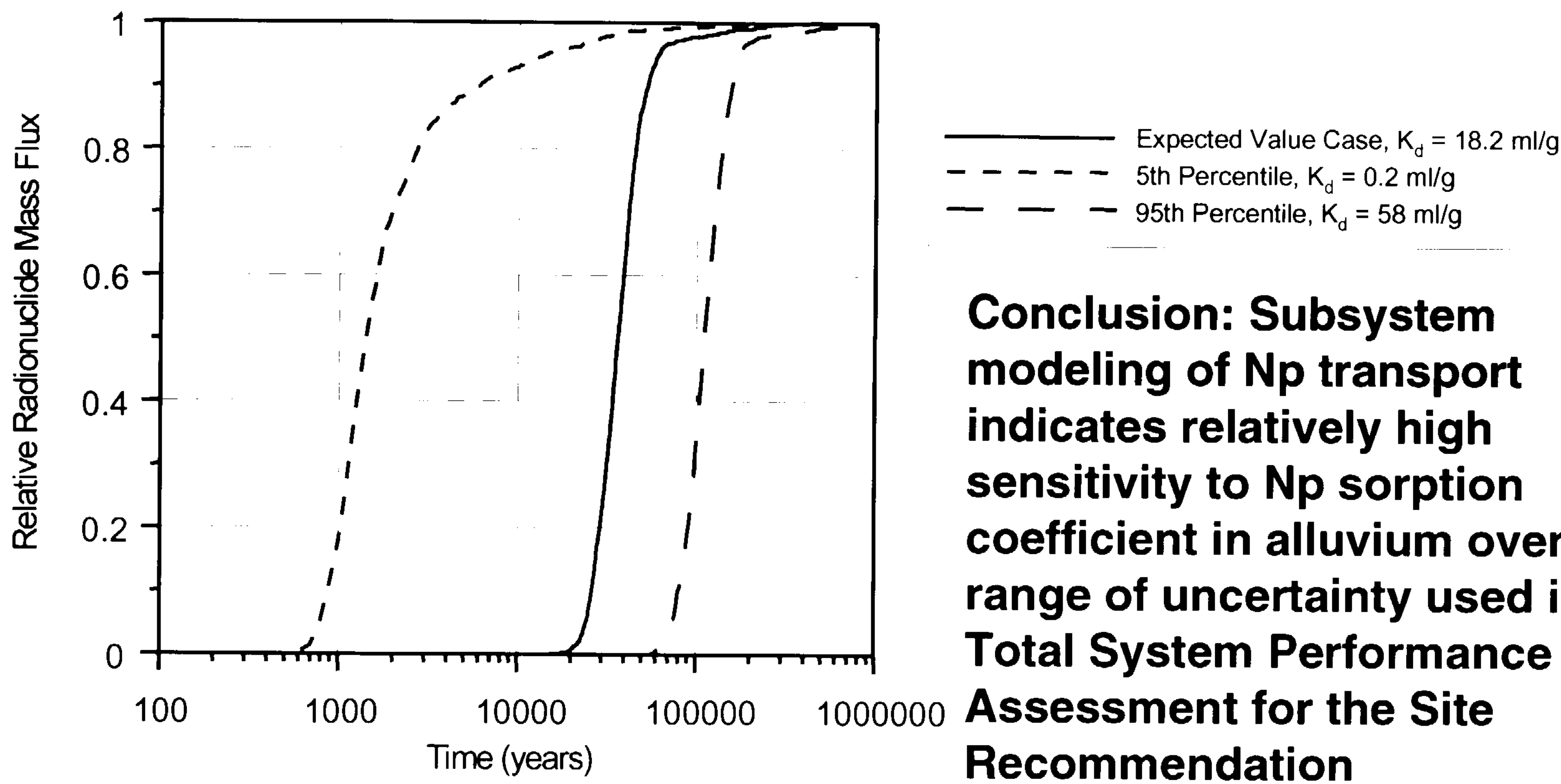
Uncertainty Distribution: Flowing Interval Spacing in Fractured Tuff (F_{smc})



Reference: ANL-NBS-MD-000003

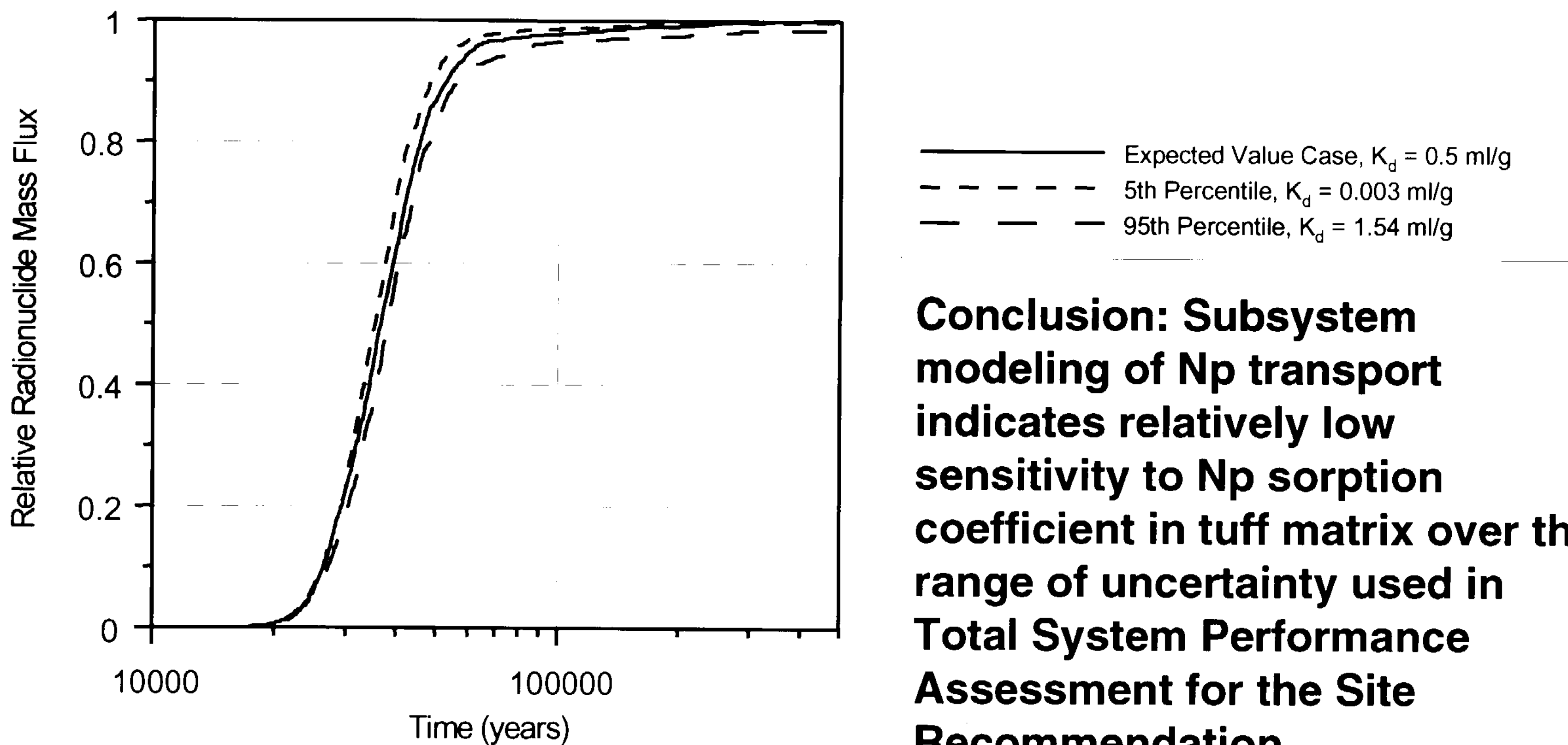
Transport Parameter Sensitivity to Sorption Coefficient for Np in Alluvium
(using TSPA-SR Rev 00 model)



Conclusion: Subsystem modeling of Np transport indicates relatively high sensitivity to Np sorption coefficient in alluvium over the range of uncertainty used in Total System Performance Assessment for the Site Recommendation

Breakthrough at 20 km, expected values for all other parameters

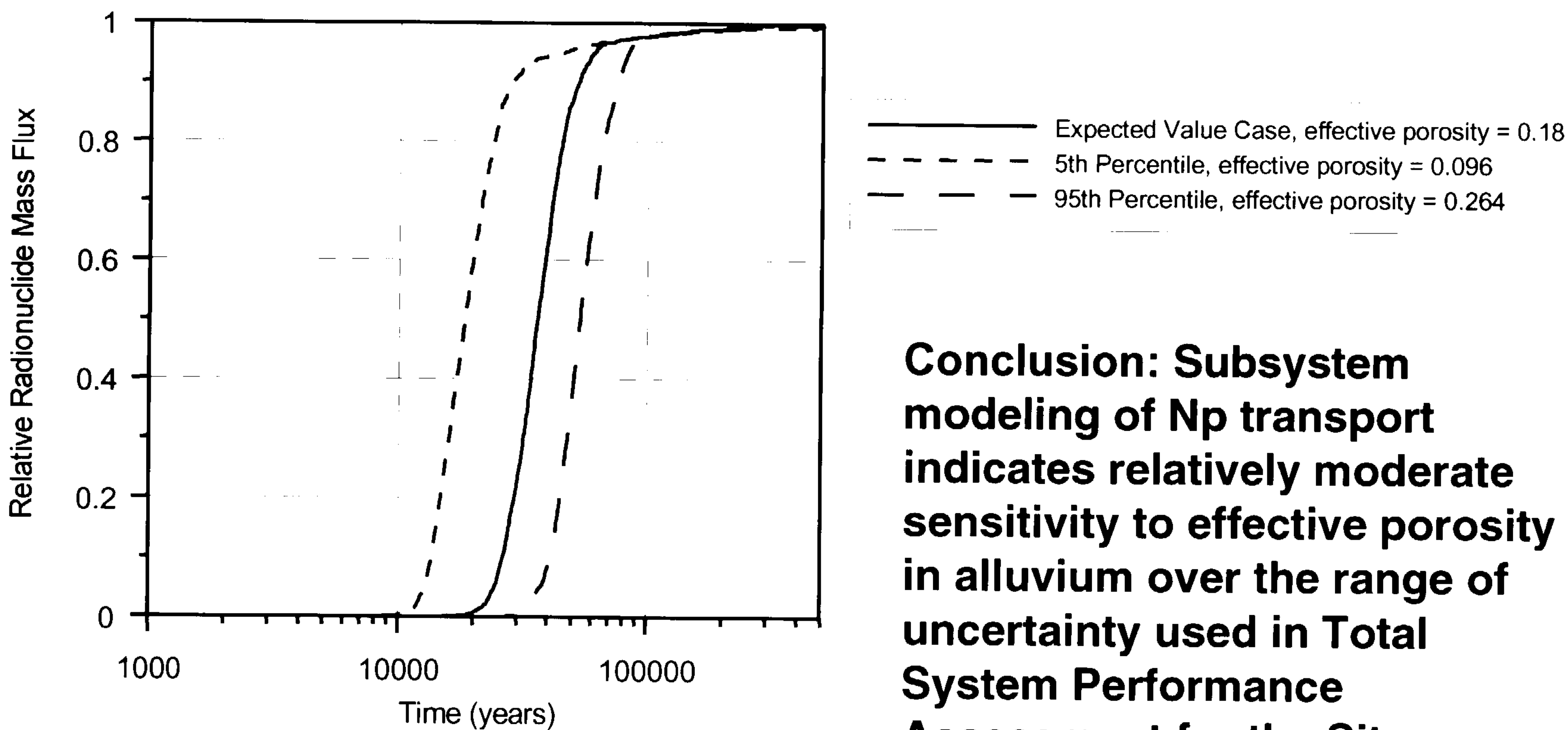
Transport Parameter Sensitivity to Sorption Coefficient for Np in Tuff Matrix (using TSPA-SR Rev 00 model)



Conclusion: Subsystem modeling of Np transport indicates relatively low sensitivity to Np sorption coefficient in tuff matrix over the range of uncertainty used in Total System Performance Assessment for the Site Recommendation

Breakthrough at 20 km, expected values for all other parameters

Sensitivity to Effective Porosity in Alluvium for Np Transport
(using TSPA-SR Rev 00 model)

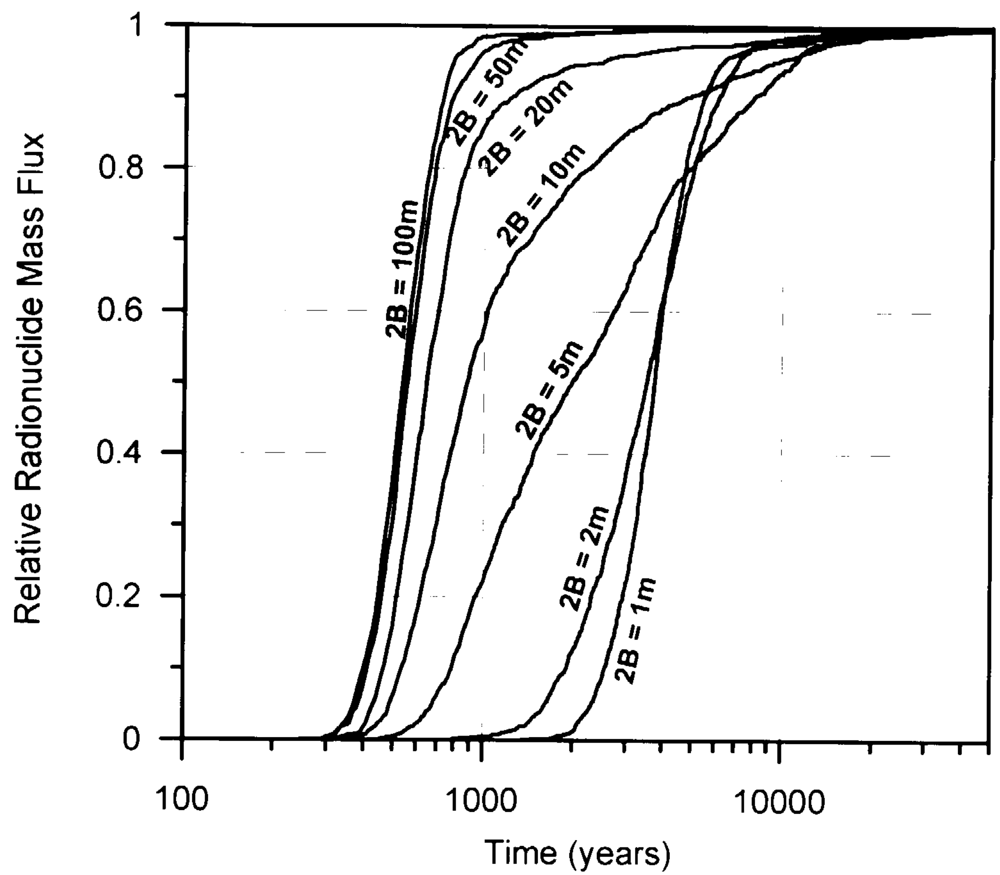


Conclusion: Subsystem modeling of Np transport indicates relatively moderate sensitivity to effective porosity in alluvium over the range of uncertainty used in Total System Performance Assessment for the Site Recommendation

Breakthrough at 20 km, expected values for all other parameters

Sensitivity to Flowing Interval Spacing in Fractured Tuff (Nonsorbing Radionuclide)

(using TSPA-SR Rev 00 model)



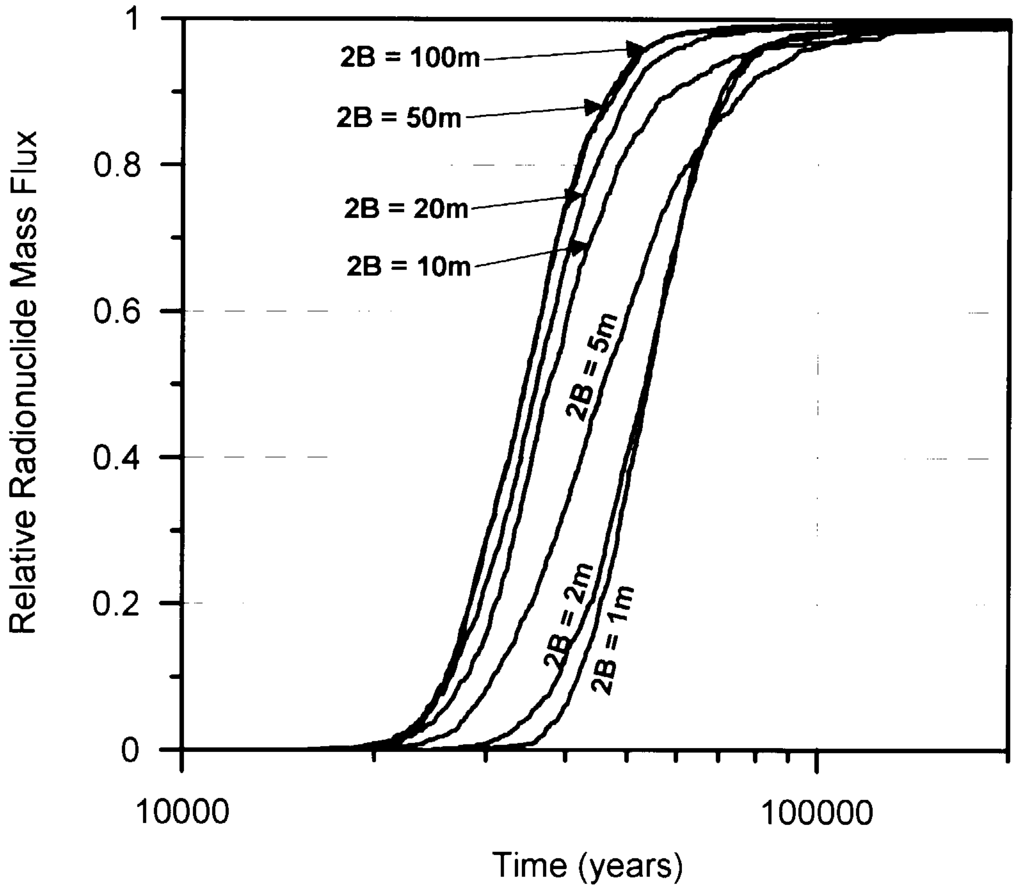
Conclusion: Subsystem modeling of non-sorbing radionuclide transport indicates relatively significant sensitivity to flowing interval spacing over the range of uncertainty used in Total System Performance Assessment for the Site Recommendation

The expected value of flowing interval spacing (21 m) results in radionuclide breakthrough near the conservative limit of behavior

Breakthrough at 20 km, no sorption, expected values for all other parameters

Flowing Interval Spacing expected value 2B = 21 m

Sensitivity to Flowing Interval Spacing in Fractured Tuff for Np Transport



Conclusion: Subsystem modeling of Np transport indicates relatively moderate sensitivity to flowing interval spacing over the range of uncertainty used in Total System Performance Assessment for the Site Recommendation

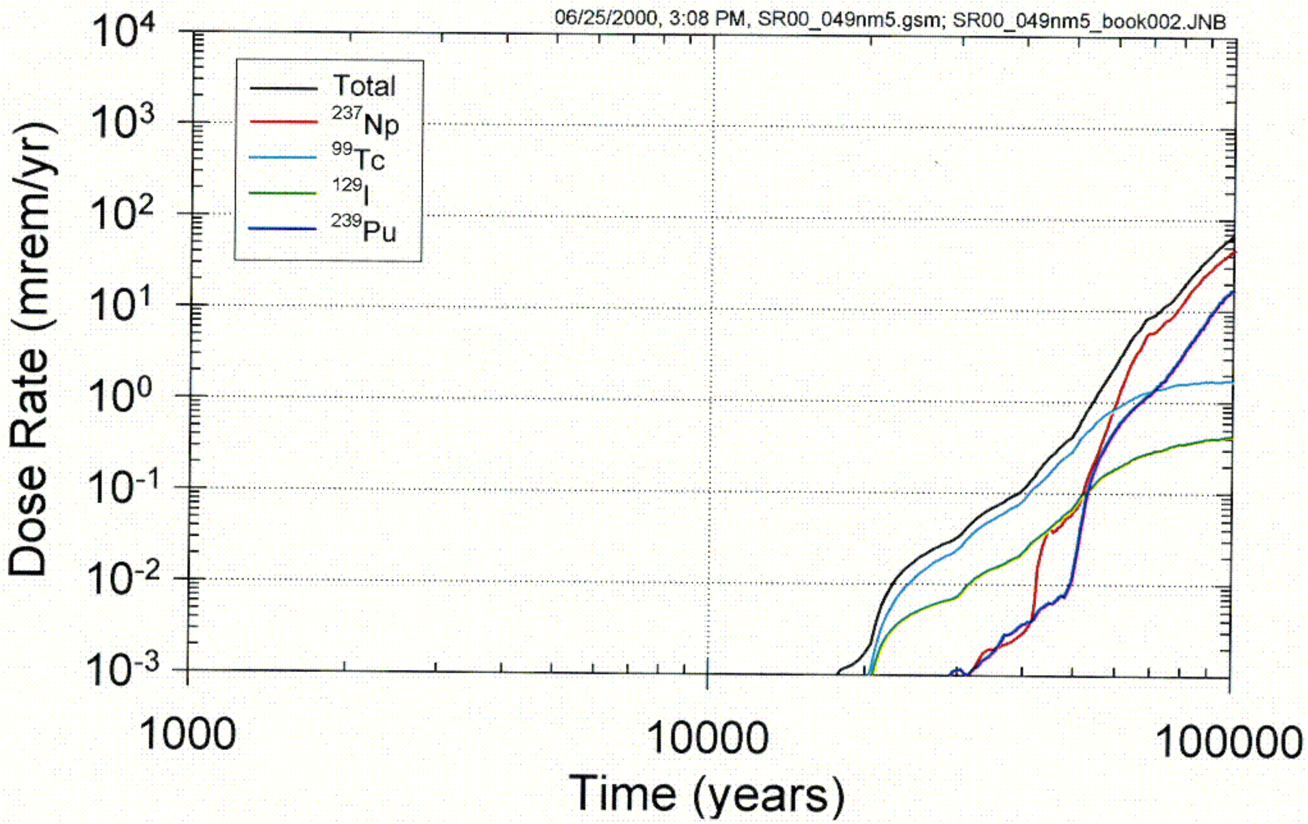
The expected value of flowing interval spacing (21 m) results in radionuclide breakthrough near the conservative limit of behavior

Breakthrough at 20 km, expected value for all other parameters

Flowing Interval Spacing expected value 2B = 21 m

Relative Impacts of Different Radionuclides

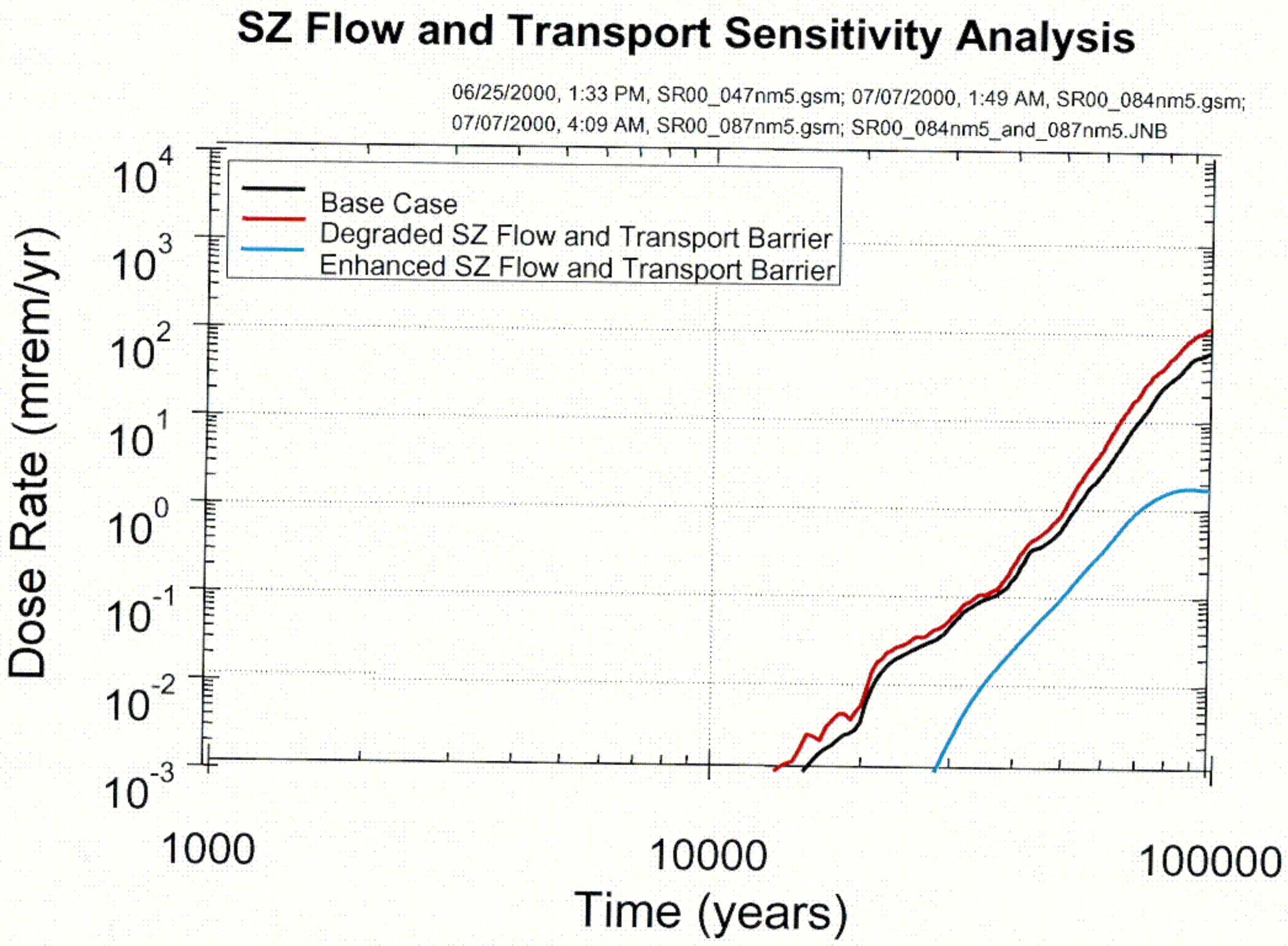
(Total System Performance Assessment Results)



C-6

Reference: ***Total System Performance Assessment-Site Recommendation*** **Rev 00**

Consideration of Uncertainties
(Total System Performance Assessment Results)



C-7

Reference: *Total System Performance Assessment-Site Recommendation* Rev 00

Saturated Zone Radionuclide Transport

- **References**
  - Analysis and Model Report *Uncertainty Distributions for Stochastic Parameters* (ANL-NBS-MD-000011)
  - Analysis and Model Report *Input and Results of the Base Case Saturated Zone Flow and Transport Model for TSPA* (ANL-NBS-HS-000030)
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 01)
  - *Total System Performance Assessment (TSPA) Model for Site Recommendation* (MDL-WIS-PA-000002 REV 00)
  - Analysis and Model Report *Probability Distribution for Flowing Interval Spacing* (ANL-NBS-MD-000003)

Conclusions

- Radionuclide transport in the saturated zone for Total System Performance Assessment for the Site Recommendation is simulated considering the relevant processes of advection, matrix diffusion, sorption, dispersion, and colloid-facilitated transport
- Uncertainty in key transport parameters relevant to all of these radionuclide transport processes is incorporated in the stochastic realizations of the saturated zone flow and transport model

Conclusions
(Continued)

- Propagated quantified uncertainty in the behavior of radionuclide transport in the saturated zone is carried forward to the Total System Performance Assessment for the Site Recommendation analyses from the abstraction modeling of saturated zone flow and transport

Backup Slides

Implementation of Reversible Colloid Model for the Saturated Zone

- **In the volcanics...**

$$D_e^{adjusted} = \frac{D_e}{(1 + K_c)^2}$$

- **In the alluvium...**

$$K_d^{new} = \frac{K_d^{orig}}{1 + K_c}$$

$D_e^{adjusted}$ is the adjusted effective diffusion coefficient

D_e is the effective diffusion coefficient

K_c is the colloid/aqueous partitioning coefficient

K_d^{orig} is the original sorption coefficient for a radionuclide

K_d^{new} is the new sorption coefficient for a radionuclide

Reference: ANL-NBS-HS-000030 Rev 00

Saturated Zone Parameter Uncertainty

Description	Distribution Type	Distribution Statistics for TSPA-SR REV 00
Groundwater specific discharge	Uniform	[0.0 1.0]
Northern and Western Boundary of Alluvium	Uniform	[0.0 1.0]
Effective porosity alluvium	Truncated normal	Mean: 0.18, SD: 0.051
Flowing interval spacing (m)	Log-normal	Mean: $E[\log_{10}(F_{smc})]$: 1.29 m and $S.D.[\log_{10}(F_{smc})]$: 0.43
Flowing interval porosity	Log-Uniform	Log_{10} [-5.0, -1.0]
Diffusion Coefficient (m^2/s)	Log-Uniform	Log_{10} [-13.0, -10]
K_d [Np] (ml/g) Volcanic Units	Beta (exp)	Mean: 0.5; SD: 0.5; [0.0, 2.0]
K_d [Np] (ml/g) Alluvium	Beta	Mean: 18.2; SD: 18.8; [0, 100]
K_d [I] (ml/g) Alluvium	Uniform	[0.32, 0.63]
K_d [U] (ml/g) Volcanic Units	Uniform	[0.0, 4.0]
K_d [U] (ml/g) Alluvium	Uniform	[0.0, 8.0]
K_d [Tc] (ml/g) Alluvium	Uniform	[0.27, 0.62]
K_ds Actinides (Am, Pu, Pa, Th) matrix/alluvium, Kc model	Uniform	[0,100]
K_ds Fission Products (Cs and Sr) matrix/alluvium, Kc model	Uniform	[0,50]
Longitudinal Dispersivity (m)	Truncated Log-normal	$E[\log_{10}(\alpha)]$: 2.0; $S.D.[\log_{10}(\alpha)]$: 0.75
Colloid Retardation Volcanic Units (irreversible colloids)	Piece-wise CDF	[1.06, 800]
Colloid Retardation Alluvium (irreversible colloids)	CDF	Log_{10} [0.0011, 6.32]
K_c for reversible colloids	Log-normal	Geometric mean: 3×10^{-3}, Geometric SD: 10.0

Legend: S.D. = standard deviation
K_d = sorption coefficient
α = dispersivity
F_{smc} = flowing interval spacing

CDF = cumulative distribution function
K_c = partitioning coefficient for radionuclides on colloids
E = expected value

Note: Uncertainty distributions for the K_ds in the alluvium for T_c and I will be zero for Total System Performance Assessment for the Site Recommendation REV 00 ICN 01

Reference: ANL-NBS-MD-000011

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

Radionuclide Transport Key Technical Issue, Subissue 1, Radionuclide Transport in Porous Rock

Presented to:
DOE-NRC Technical Exchange on the Radionuclide Transport Key Technical Issue

Presented by:
Jim Houseworth, Ph.D
Arend Meijer, Ph.D
Civilian Radioactive Waste Management System Management and Operating Contractor

December 5-7, 2000
Lawrence Berkeley National Laboratory
Berkeley, CA

YUCCA MOUNTAIN PROJECT

Outline

- **Presentation Objectives**
- **Current Subissue Status**
- **For items identified in the Radionuclide Transport Issue Resolution Status Report, Rev. 02, this presentation will:**
  - Summarize technical basis for item resolution
  - Identify basis documents (References)
  - Summarize technical adequacy of basis
- **Conclusions**

Note: Additional details are provided in the "delta" analysis

Presentation Objectives

- **Describe the basis for resolving Subissue 1, Radionuclide Transport in Porous Rock, of the Radionuclide Transport Issue Resolution Status Report, Rev. 02**
  - Acceptance Criterion 1a: "Processes important to performance are included in TSPA". The processes identified in this criterion are included or conservatively neglected in the Total System Performance Assessment. DOE considers this criterion closed
  - Acceptance Criterion 1b: "Demonstrate K_d of zero is conservative" Zero K_d is conservatively assigned to C, Tc, and I. DOE considers this criterion closed
  - Acceptance Criterion 2a: "Demonstrate single-continuum" DOE considers this criterion closed. Completion of Busted Butte testing considered confirmatory
  - Acceptance Criterion 2b: "Demonstrate evaluation of R_f" DOE considers this criterion closed-pending evaluation of need for additional testing

Presentation Objectives
(Continued)

- Acceptance Criterion 2c: "Demonstrate assumptions for K_d approach are valid". DOE considers this criterion closed-pending evaluation of need for additional testing
- Acceptance Criterion 3a: "Process model approach" Method not used. DOE considers this criterion closed
- Acceptance Criterion 3b: "Process model approach" Method not used. DOE considers this criterion closed
- Acceptance Criterion 3c: "Process model approach" Method not used. DOE considers this criterion closed
- Acceptance Criterion 4: "Expert judgement/elicitation" Expert judgement has been used. DOE considers this criterion closed-pending additional documentation of expert judgement. Expert elicitation was not used
- Acceptance Criterion 5: "Quality Assurance" Not addressed at this Technical Exchange

Current Subissue Status

- **Radionuclide Transport Issue Resolution Status Report, Rev. 02 indicates this subissue is OPEN:**
  - Determination of reasonable values of K_d for neptunium (Np)
  - Additional work is required to establish defensible K_d values for plutonium (Pu)
  - Eliminate the possibilities that processes other than sorption contribute to uranium (U) removal
  - Flow through column tests have not been performed with U
- **NOTE: Saturated zone models include radionuclide attenuation in the fractured rock matrix and alluvium, therefore, where the acceptance criteria in this subissue address radionuclide attenuation, a response will be provided for saturated zone. Otherwise, DOE considers this subissue applicable only to the unsaturated zone model**

Acceptance Criterion 1a

- **Acceptance Criterion 1a: DOE has determined, through sensitivity analysis, whether radionuclide attenuation processes such as sorption, precipitation, radioactive decay, and colloidal filtration are important to performance**
- **Action or information needs identified**
  - None identified

Acceptance Criterion 1a
(Continued)

- **Basis for closure**
  - Processes of hydrodynamic dispersion, matrix diffusion, sorption (solutes), filtration (colloids), and radioactive decay are considered important to performance for the unsaturated zone and are all explicitly modeled in the unsaturated zone transport model abstraction
  - For the purposes of radionuclide attenuation, the saturated zone models do not consider any of the geologic media to be porous rock
  - IRSR, Rev. 2 indicates that this acceptance criterion has been met for radionuclides important to performance

Acceptance Criterion 1a
(Continued)

- **References**
  - Analysis and Model Report *Particle Tracking Model and Abstraction of Transport Processes* (ANL-NBS-HS-000026 REV 00)
- **Performance assessment calculations have been used to determine whether radionuclide attenuation processes are important to performance**
- **No additional work is required, DOE considers this acceptance criterion closed**

Acceptance Criterion 1b

- **Acceptance Criterion 1b: DOE has (i) Assumed K_d is zero and radionuclides travel at the rate of groundwater flow, if it has been found that radionuclide attenuation is unimportant to performance and it can be demonstrated that this assumption is conservative; no other acceptance criteria for this subissue need be met, or, (ii) demonstrated that criterion 2 or 3 has been met, if radionuclide attenuation in porous rock is important to performance or if an assumption that K_d is zero in porous rock is not conservative**
- **Action or information needs identified**
  - None identified

Acceptance Criterion 1b
(Continued)

- **Basis for closure**
  - In porous rock and fractured rock matrix, C, Tc, and I are assigned a K_d of zero
  - Because C, Tc, and I do not participate in colloid transport, the zero K_d assumption is conservative
  - Other radionuclides important to performance where K_d is not zero are discussed under Acceptance Criterion 2
  - IRSR, REV 02 indicates that this acceptance criterion has been met

Acceptance Criterion 1b
(Continued)

- **References**
  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00)
  - *Total System Performance Assessment for the Site Recommendation* (TDR-WIS-PA-000001 REV 00)
- **Assumption that K_d is zero has been demonstrated to be conservative**
- **No additional work is required, DOE considers this acceptance criterion closed**

Acceptance Criterion 2a

- **Acceptance Criterion 2a: For the valid application of the constant K_d approach, equation (1) $R_f = 1 + \rho_b K_d / n$, (or $R_f = 1 + \rho_b K_d / \theta$), DOE has: Demonstrated that the portion of the flow path to which equation (1) applies acts as a single continuum porous medium**
- **Action or information needs identified**
  - Nonwelded vitric rock behaves as single-continuum porous media
  - Demonstrate that Busted Butte is an appropriate analog for the CHnv below the potential repository block
  - Show that the effects of the PTn on flow beneath the potential repository are appropriately considered

Acceptance Criterion 2a
(Continued)

- **Basis for closure**
  - For the unsaturated zone, Busted Butte field test results to date indicate that the CHnv acts as a single-continuum porous medium
  - Busted Butte is considered a distal extension of the Calico Hills beneath the potential repository block - not an analog
  - For Total System Performance Assessment, Rev. 0, DOE conservatively allows for a small portion of flow and transport in the fracture continuum of the CHnv and PPv

Acceptance Criterion 2a
(Continued)

- **References**
  - *Unsaturated Zone Flow and Transport Model Process Model Report* (TDR-NBS-HS-000002 REV 00 ICN 02)
  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00)
  - Analysis and Model Report *Calibrated Properties Model* (MDL-NBS-HS-000003 REV 00)
  - Analysis and Model Report *Development of Numerical Grids for UZ Flow and Transport Modeling* (ANL-NBS-HS-000015 REV 00)
  - Analysis and Model Report *Analysis of Hydrologic Properties Data* (ANL-NBS-HS-000002 REV 00)

Acceptance Criterion 2a
(Continued)

- Existing measurements support the conclusion that the nonwelded vitric rock in the unsaturated zone behaves as a single-continuum porous medium
- DOE considers this acceptance criterion closed. Completion of the Busted Butte testing and data analyses is expected to confirm lines of evidence and reduce uncertainty

Conclusions

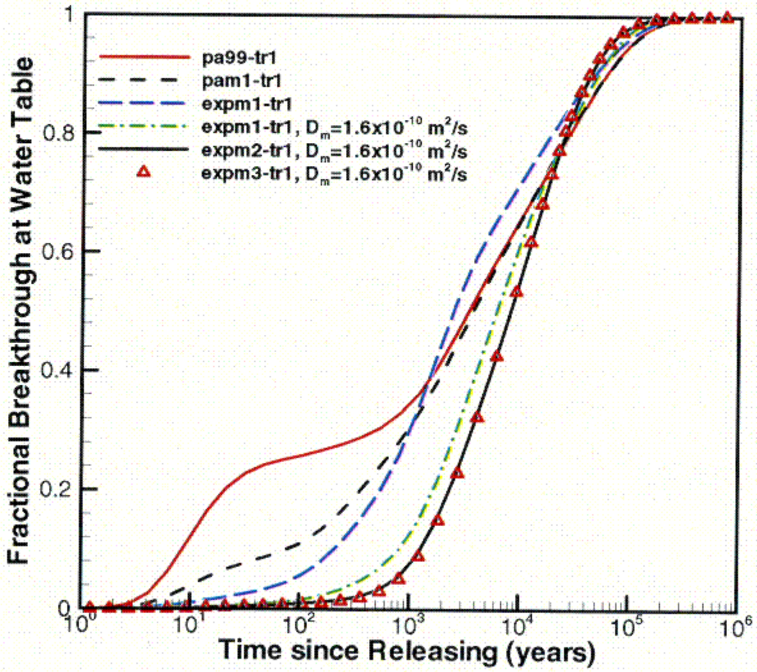
- Evidence for single-continuum behavior has been obtained from the Busted Butte field tests
- Analyses indicate that the Calico Hills rocks exposed at Busted Butte are a distal extension of the formation located beneath the potential repository block
- The effects of the PTn on flow beneath the potential repository have been appropriately modeled for radionuclide transport

Single-Continuum Porous Medium

- **Busted Butte observations**
  - Busted Butte testing showed that even when injection occurs immediately adjacent to a fracture, water appears to be imbibed quickly into the surrounding matrix
  - Phase 1-B transport times observed immediately below the injection point were on the order of 30 days, whereas pure fracture flow would have resulted in travel times of minutes to hours at this flow rate
  - Tracer injection has stopped - data collection and analyses are being completed this fiscal year

Single-Continuum Porous Medium
(Continued)

- **From the perspective of importance to performance, sub-system sensitivity studies for radionuclide transport indicate that the effects of fracture flow in the CHnv are not important because matrix flow dominates**



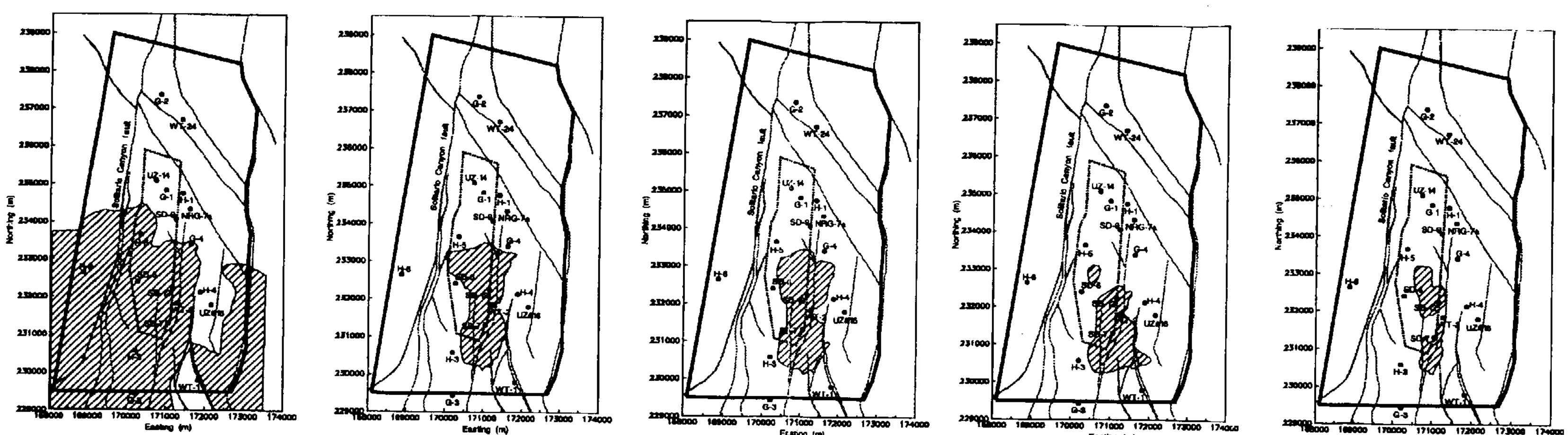
pa99-tr1: present-day mean, PA model; without perched water
pam1-tr1: perched water #1
expm1-tr1: perched water #1, no fracture in vitric
expm1-tr1: base expected case
expm2-tr1: 10x fracture higher perm in zeolites
expm3-tr1: 100x higher perm in zeolites

C-8

Reference: Work in progress

Single-Continuum Porous Medium
(Continued)

- **One reason for the lack of sensitivity is that the CHnv does not underlie a large fraction of the potential repository block. Therefore, a large fraction of potential radionuclide releases do not encounter the CHnv**



(a) ch1 (b) ch2 (c) ch3 (d) ch4 (e) ch5

NOTE: White areas indicate "zeolitic" material.

Figure 5. Extent of Vitric Region (indicated by the blue diagonal lines) in FY 99 UZ Model Layers (a) ch1, (b) ch2, (c) ch3, (d) ch4, and (e) ch5.

Reference: ANL-NBS-HS-000015

Busted Butte Applicability

- **Applicability to potential repository block**
  - Calico Hills rocks exposed at Busted Butte are a distal extension of the formation located beneath the potential repository horizon - not an analog
  - Mineralogic characteristics of Busted Butte are similar to that found in core and drill cuttings from the vitric Calico Hills Formation in boreholes USW H-5 and USW SD-6

	USW H-5	USW SD-6	Busted Butte
◆ Glass	85% (70-95%)	78% (71-81%)	81% (65-97%)
◆ Feldspar	8% (5-20%)	11% (7-16%)	10% (1-18%)
◆ Quartz	3% (1-5%)	5% (2-8%)	5% (1-8%)
◆ Cristobalite /Opal-CT	2% (0-5%)	2% (2-3%)	0.8% (0-1%)
◆ Clinoptilolite	1% (0-6%)	2% (1-4%)	0.4% (0-1%)
◆ Smectite	0.4% (0-3%)	1% (0-4%)	3% (0-6%)

Reference: Work in progress

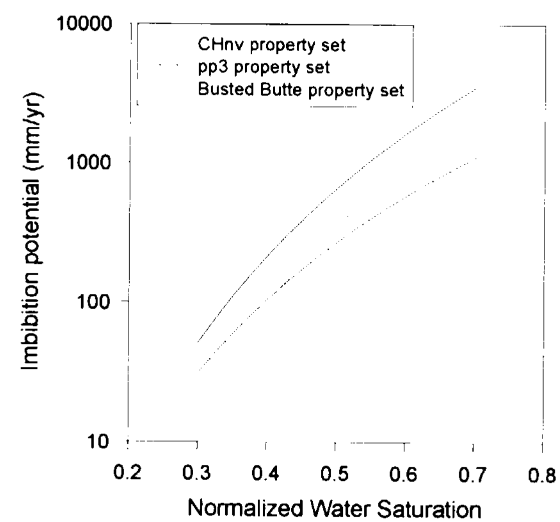
Busted Butte Applicability

- **Applicability to potential repository block** **(Continued)**
  - Hydrogeologic parameters

	Calibrated Properties Model (avg. CHnv)	(avg. pp3)	Busted Butte
Porosity	0.33	0.30	0.35
Permeability (m^2)	$3x10^{-13}$	$2x10^{-14}$	10^{-12}
Capillary Pressure (m^{-1})	0.36	0.17	0.8
Shape parameter (n)	1.5	1.6	1.3

Imbibition potential = effective permeability x capillary pressure gradient

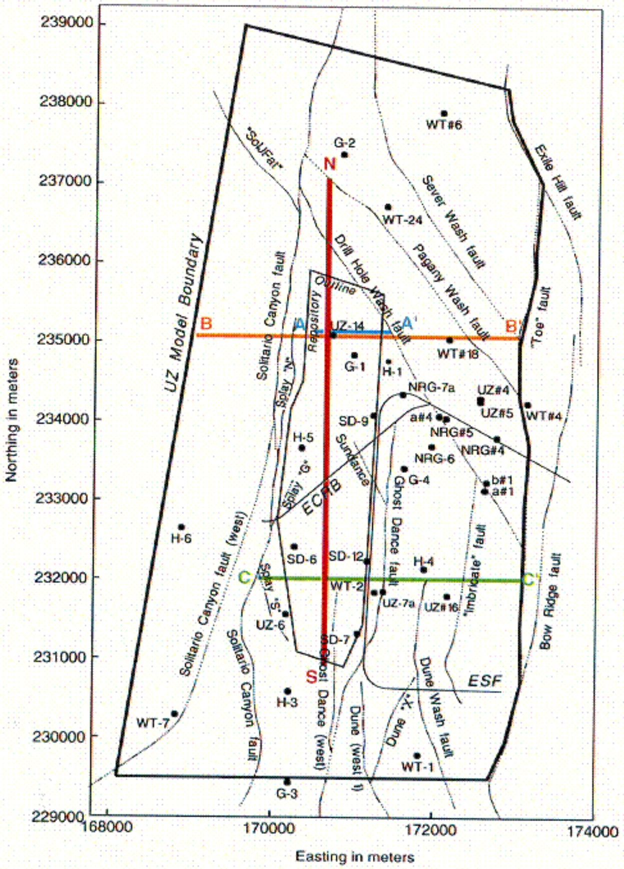
Comparison of Imbibition Potential



References (data): MDL-NBS-HS-000003, ANL-NBS-HS-000019

Effects of PTn on Flow
(Continued)

- **A different aspect related to transport modeling concerns the effects of the PTn on flow patterns beneath the potential repository horizon**



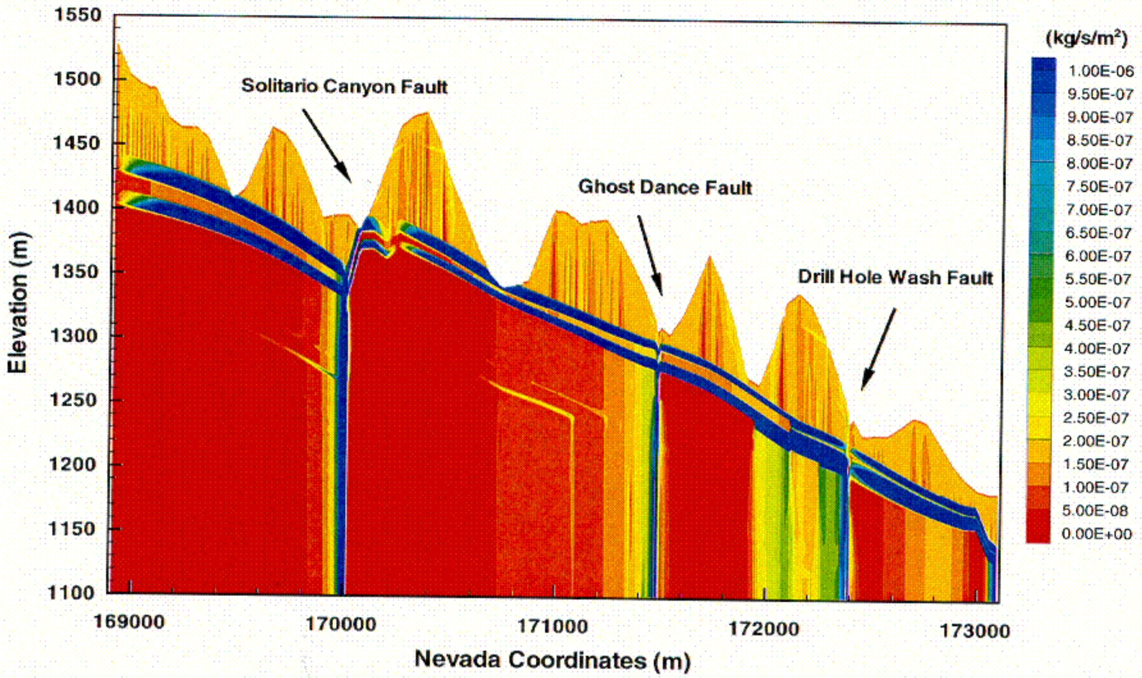
Two-dimensional simulations were carried out using a fine-grid model for A-A' and B-B'

C-9

Reference: Work in progress

Effects of PTn on Flow
(Continued)

- **The PTn is important for two reasons:**
  - The PTn/TSw interface results in a capillary barrier that diverts some of the infiltration flux

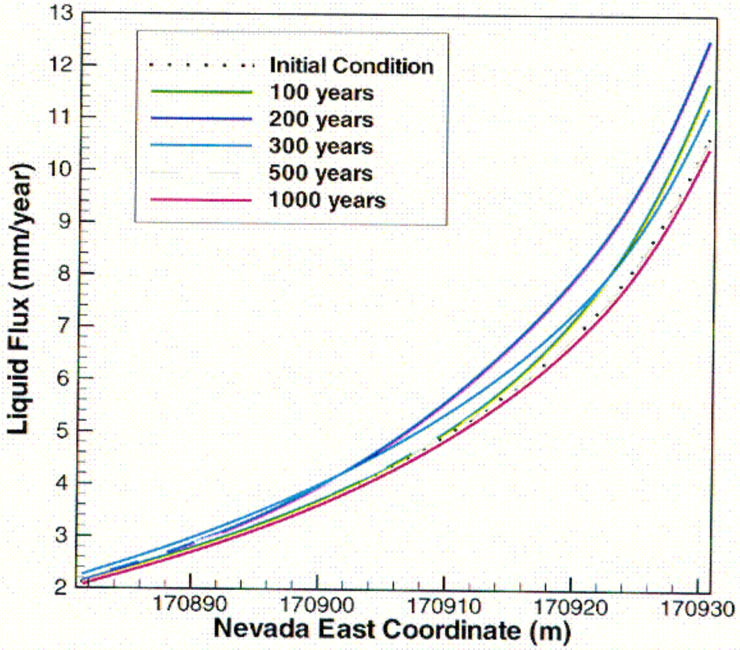


Magnitude of simulated 2-D vectors of mass flux (kg/s/m^2) along B-B' using the refined grid and uniform surface infiltration.

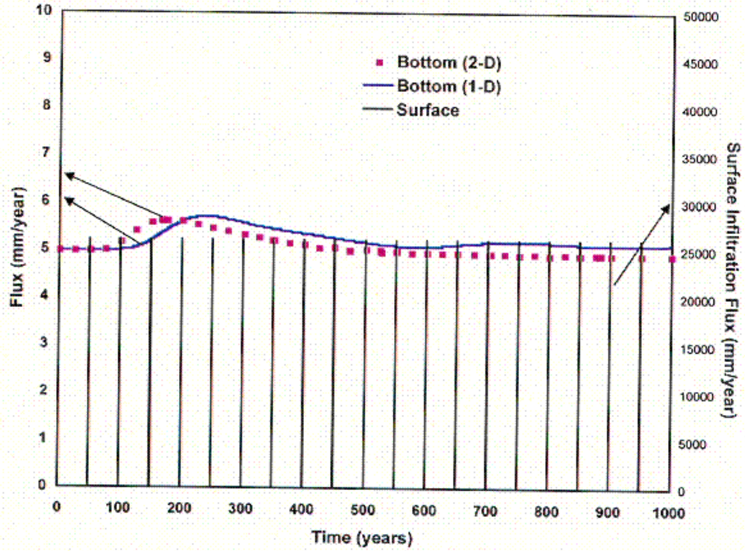
C-10

Effects of PTn on Flow
(Continued)

- The PTn damps out episodic flow behavior resulting in (nearly) steady flow behavior at and below the potential repository horizon



Simulated vertical percolation fluxes at different times across the PTn-TSw interface along a 50 m long E-W cross-section (A-A')



Simulated variations in total percolation fluxes versus times at the bottom of the PTn unit of the 2-D (A-A') and1-D (Easting 170,906 m) models

Reference: Work in progress

C-11

Acceptance Criterion 2b

- **Acceptance Criterion 2b: For the valid application of the constant K_d approach, equation (1) $R_f = 1 + \rho_b K_d / n$, (or $R_f = 1 + \rho_b K_d / \theta$), DOE has: Determined appropriate values for parameters, K_d, n or θ, and ρ_b**
- **Action or information needs identified**
  - Demonstrate sorption coefficients were determined with appropriate methodologies for radionuclides important to performance
    - Batch sorption tests
    - Sorption tests using site specific materials
    - Crushed tuff flow-through column experiments
    - Intact rock flow-through column experiments
    - Diffusion experiments
    - Unsaturated flow experiments
    - Process models to determine constant K_d

Acceptance Criterion 2b
(continued)

- **Basis for closure**
  - Parameters relevant to retardation (K_d, n, ρ_b) have been measured on site-specific materials for radionuclides of importance to performance
  - Laboratory measurements of n and ρ_b have been performed on core samples
  - Laboratory measurements of K_d have been performed using batch sorption techniques and confirmed with crushed tuff column experiments using site specific materials

Acceptance Criterion 2b
(continued)

- **References**
  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties* (U0100) (ANL-NBS-HS-000019 REV 00)
- **Existing test data for n, ρ_b, and most (except Pu) of the K_d values are considered adequate to meet this acceptance criterion**
- **DOE considers this acceptance criterion closed-pending. Additional sensitivity studies and a review of available data will be used to evaluate the adequacy of the data**

Conclusions

- Aqueous compositions and radionuclide concentrations used in batch sorption tests are appropriate for determinations of K_d
- Crushed tuff column experiments for Np have confirmed batch sorption results. Experiments for Pu have shown kinetic effects that make the high flow rates used for the column tests non-representative. Additional sensitivity studies and a review of available data will be used to evaluate the adequacy of the data
- Diffusion measurements for sorbing radionuclides have been conservatively bounded by diffusion coefficients selected for performance assessment

Sorption Coefficients

- **Radionuclides of Importance to Performance**
  - C, I, Tc ⇒ Non-sorbing (K_d = 0.0 ml/g)
  - Np, U ⇒ Moderately sorbing (K_d << 100 ml/g)
  - Sr, Cs, Pa ⇒ Moderately highly sorbing ($K_d \geq$ 100 ml/g)
  - Am, Pu, Th ⇒ Highly sorbing, transported only in colloidal phase. May desorb from colloidal phase and sorb onto matrix and vice versa (K_d > 100 ml/g)
  - Ra, Pb ⇒ Not transported (in secular equilibrium with Th)
  - Ac ⇒ Not transported (in secular equilibrium with Pa)

(Reference: ANL-WIS-MD-000006, Rev. 00, ICN 1)

Batch Sorption Tests

- **Comment: K_ds for Pb, Ac, Sm and Zr were not determined on site specific materials therefore these K_ds are "much less certain for application to performance assessment calculations than those determined using site-specific materials"**
  - Response: Pb, Ac, Sm and Zr are not on list of radionuclides to be considered for far-field transport calculations
- **Comment: Problems with batch K_ds for Th, Nb, Sn, Ac, Am, Sm, Ce, and Eu involving colloidal particles in batch sorption experiment solutions**
  - Response: The presence of colloidal particles in the batch sorption experiment solutions would tend to bias the K_d obtained to lower, and thereby conservative, values

Batch Sorption Tests
(Continued)

- **Comment: Batch sorption experiments for Pa using site-specific materials have been obtained only at pH values 6.3 and 6.7. Sorption experiments using site-specific materials and a higher pH are needed if Pa is judged to be important to performance**
  - Response: The sensitivity of performance assessment results to Pa sorption will be investigated to evaluate adequacy of data

Sorption Tests Using Site Specific Materials

- **Comment: Some of the batch sorption experiments carried out with U may have been oversaturated with a U phase such as soddyite**
  - Response: Although experiments carried out at the high end of the range of concentrations (8 X 10^{-8} to 1 X 10^{-4} M/l) used may have been supersaturated with soddyite, the bulk of the experiments were not. This is supported by isotherm data (Triay et al. 1997)

- **Comment: Batch sorption experiments for Ni were carried out over a limited pH range of 8.3 to 9.0**
  - Response: Ni is not on the list of radionuclides of importance to performance

Sorption Tests Using Site Specific Materials (Continued)

- **Comment: Batch sorption experiments using site-specific materials were not carried out for Pb, Sm, Zr, and Ac**
  - Response: These are not on the list of radionuclides to be considered for far-field transport

- **Comment: Some of the batch sorption experiments carried out with Np may have precipitated a Np phase (i.e., were supersaturated)**
  - Response: Although a limited number of batch sorption experiments may have been supersaturated with a Np phase, most of them were not. Isotherm data support this conclusion (Triay et al. 1997)

Sorption Tests Using Site Specific Materials (Continued)

- **Comment: Certain combinations of groundwaters (e.g., UE-25 p#1) and solids (e.g., zeolitic tuff) used in the batch experiments may have been unnatural and not expected in the Yucca Mountain environment**
  - Response: Although contacting UE-25 p#1 groundwater with a zeolitic tuff may alter the composition of the groundwater, it is expected that similar alteration of the groundwater composition would occur in the natural Yucca Mountain environment based on the variation in the composition of zeolites vertically in the zeolitic zones (Broxton et al. 1986)
- **Comment: Batch experiments need to be designed and conducted to analyze for the presence of colloids**
  - Response: Batch experiments are not the preferred way to investigate the presence of colloids. Column experiments are better suited for this. Some column experiments carried out with insoluble nuclides such as Am and Pu do suggest the presence of an early breakthrough fraction that may be composed of colloids (Triay et al. 1997)

Crushed Tuff Flow-Through Column Experiments

- **Comment: Column experiments have been performed with Pu, Np, and Tc. However, column experiments with Am, U, Cs, Sr and Ba have not been carried out even though these were specified in the Site Characterization Plan**
  - Response: Early planning for site characterization has been updated based on performance assessment results. Column experiments with Ba, Cs, and Sr were performed early in the project. Column experiments with Am were carried out by J. Thompson (1989). These experiments suggested the presence of an early breakthrough fraction (~1%) possibly colloidal in nature. Sensitivity analyses will be performed to evaluate the adequacy of the data

Crushed Tuff Flow-Through Column Experiments (Continued)

- **Comment: The experimental technique used in the crushed tuff column experiments described in Triay (1997) is not adequately described**
  - Response: The experimental technique was to add the radionuclide-bearing solution as a pulse and not continuously. Refer to *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00) for additional details

Crushed Tuff Flow-Through Column Experiments (Continued)

- **Comment: The criterion to confirm the K_d determined in static tests (that) are appropriate for calculating retardation in dynamic systems has not been met for plutonium. Further, the proposal that batch sorption tests provide information for conservatively estimating plutonium transport appears to be unsupported**
  - Response: We will consider the effects of Pu sorption on performance in sensitivity studies and also review external information concerning Pu sorption to evaluate the adequacy of the data

Crushed Tuff Flow-Through Column Experiments (Continued)

- **Comment: Laboratory transport experiments using intact rock samples were performed for Se. These experiments indicated that the potential effect of disturbed sorption sites on crushed material was not observed for Se. Similar experiments have not been performed using other radionuclides**
  - Response: Intact rock column experiments were carried out using Ba, Cs, and Sr tracers. The results show that batch K_ds can be used to model the breakthrough of these tracers. To successfully model the results, a time-dependent dispersion coefficient was used (Rundberg et al. 1989)

    Evidence that "disturbed sorption sites on crushed material" are not an issue is also provided by the results of sorption experiments on rock samples crushed to different grain sizes (Rogers and Chipera, 1993). In these experiments, the K_d obtained for a given radionuclide was shown to be largely independent of the grain size used in the experiment

    These data indicate that crushed rock material can be used in batch tests in lieu of solid rock material in column tests to obtain sorption coefficients for use in performance assessment

Diffusion Experiments

- **Comment: The results of diffusion experiments carried out with Cs in an intact tuff beaker are not entirely consistent with predictions based on transport calculations. The predictions could perhaps be improved by inclusion of cesium isotherm data**
  - Response: The implementation of diffusion in performance assessment for cationic species conservatively bounds the effects of matrix diffusion found in laboratory tests

    The predictions would not likely be improved by inclusion of Cs isotherm data because data suggest a higher degree of sorption than modeled by the batch test results

Process Models to Determine Constant K_d

- **Comment: Geochemical sorption models can be used to calculate K_d values under conditions beyond the limited set of conditions for which batch or column experimental data are available**
  - Response: Surface complexation models for heterogeneous media (e.g., complex mineralogy, unknown surface compositions and structures) are not sufficiently developed at the present time to be reliably used to predict K_d values outside the range of conditions addressed in the experimental program carried out by DOE

Acceptance Criterion 2c

- **Acceptance Criterion 2c: For the valid application of the constant K_d approach, equation (1) $R_f = 1 + \rho_b K_d / n$, (or $R_f = 1 + \rho_b K_d / \theta$), DOE has: Demonstrated that the three implicit assumptions (i.e., linear isotherm, fast reversible sorption reaction, and constant bulk chemistry) are valid**
- **Action or information needs identified**
  - Demonstrate that assumptions are valid
    - Linear isotherm
    - Fast reversible sorption reaction
    - Constant bulk chemistry

Acceptance Criterion 2c
(Continued)

- **Basis for closure**
  - Isotherms have been found to be either linear or nonlinear with a convex upward shape. In either case, a K_d approach can be used to conservatively predict transport
  - Fast, reversible sorption reactions have been demonstrated in crushed tuff column experiments for Np. Similar experiments for Pu have found kinetic effects, but the flow rates used were orders of magnitude larger than the expected flow rates at Yucca Mountain. Rate dependence in the laboratory tests for Pu demonstrate convergence to equilibrium behavior at lower flow rates
  - The effects of variations in bulk chemistry are incorporated into the range of values for K_d used in performance assessment

Acceptance Criterion 2c
(Continued)

- **References** (Continued)

  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00)
  - Broxton, D.E.; Warren, R.G.; Hagan, R.C.; and Luedemann, G. 1986. Chemistry of Diagenetically Altered Tuffs at a Potential Nuclear Waste Repository, Yucca Mountain, Nye County, Nevada. LA-10802-MS ACC: MOL.19980527.0202
  - Rogers, P.S. and Chipera, S.J. 1993. "Sorption Characteristics of Yucca Mountain Tuffs as a Function of Sample Particle Size, Surface Area, and Water Composition," Los Alamos Manuscript Series Report TWS-INC-03-93-04 ACC: MOL.20000622.0021
  - Rundberg, R.S.; Mitchell, A.J.; Ott, M.A.; Thompson, J.L.; and Triay, I.R. 1989. "Laboratory Studies of Radionuclide Migration in Tuff." Proceedings of the American Nuclear Society Topical Meeting on Nuclear Waste Isolation in the Unsaturated Zone. 248-255 TIC: 222644

Acceptance Criterion 2c
(Continued)

- **References** (Continued)

  - Thompson, J.L. 1989. "Actinide Behavior on Crushed Rock Columns." Journal of Radioanalytical and Nuclear Chemistry, Articles, 130, (2), 353-364 TIC: 222698
  - Triay, I.R.; Meijer, A.; Conca, J.L.; Kung, K.S.; Rundberg, R.S.; Strietelmeier, B.A.; and Tait, C.D. 1997. Summary and Synthesis Report on Radionuclide Retardation for the Yucca Mountain Site Characterization Project. Eckhardt, R.C., ed. LA-13262-MS ACC: MOL.19971210.01
  - Analysis and Model Report *Inventory Abstraction* (ANL-WIS-MD-000006, REV 00., ICN1)

Acceptance Criterion 2c
(Continued)

- The existing data and methods for implementing the K_d model in performance assessment account for the three implicit assumptions that underlie a K_d approach to sorption
- DOE considers this acceptance criterion closed-pending. Sensitivity analyses and a review of available data will be used to evaluate the adequacy of the data

Linear Isotherms

- **Comment: Sorption isotherms have been obtained for Pu, U, Np, Cs, Sr, Ce and Eu. Because the isotherms are either linear (Np, Tc) or convex upward, they can be used to estimate retardation. Radionuclides with isotherms that are convex upward tend to form self-sharpening fronts and can be used to predict breakthrough**
  - Response: No additional response required

Fast Reversible Sorption

- **Comment: It is inappropriate to use a K_d to model the removal of a radionuclide from solution through a co-precipitation reaction**
  - Response: It is acknowledged that a co-precipitation mechanism should not be modeled with a K_d, however, the lack of equilibration in experiments involving Np sorption onto hematite and calcite was not necessarily due to a co-precipitation mechanism

Fast Reversible Sorption
(Continued)

- **Comment: Batch and column experiments with plutonium indicate retardation reactions are not instantaneous on the time scale of the experiments**
  - Response: We will consider the effects of Pu sorption on performance in sensitivity studies and also review external information concerning Pu sorption. These results will be used to evaluate the need for additional experiments with Pu. Although batch and column experiments with Pu indicate the sorption reactions are not fast and reversible, these reactions are considered sufficiently fast to reach equilibrium under the flow conditions in the saturated zone at the site

Constant Bulk Chemistry

- **Comment: Studies have shown that water chemistry in the vicinity of Yucca Mountain can vary significantly with regard to parameters such as pH, ionic strength and CO_3^{2-} that might affect radionuclide retardation. Although attempts have been made to include the effects of these variations in deriving PDFs for retardation coefficients, process models may be useful in demonstrating the sensitivity of retardation coefficients to these variations**
  - Response: Although process models may, in theory, be useful in demonstrating the sensitivity of retardation coefficients to variations in water chemistry, the presently available models are not sufficiently sophisticated to allow such a demonstration without a series of untested assumptions about the nature of the sorption substrate. Therefore, DOE has chosen not to take this approach, but rather is using the minimum K_d approach

Acceptance Criterion 3a

- **Acceptance Criterion 3a: For the valid application of process models affecting radionuclide transport such as surface complexation, ion exchange, precipitation/dissolution, and processes involving colloidal material, DOE has: demonstrated that a portion of the flow path acts as an isotropic homogeneous porous medium**
- **Action or information needs identified**
  - None
- **Basis for closure**
  - Process-model methods to quantify sorption, ion exchange, precipitation/dissolution, colloidal interactions, or other factors that affect radionuclide transport were not used in performance assessment calculations to quantify transport parameters

Acceptance Criterion 3b

- **Acceptance Criterion 3b: For the valid application of process models affecting radionuclide transport such as surface complexation, ion exchange, precipitation/dissolution, and processes involving colloidal material, DOE has: demonstrated that appropriate values are used in process models**
- **Action or information needs identified**
  - None
- **Basis for closure**
  - Process-model methods to quantify sorption, ion exchange, precipitation/dissolution, colloidal interactions, or other factors that affect radionuclide transport were not used in performance assessment calculations to quantify transport parameters

Acceptance Criterion 3c

- **Acceptance Criterion 3c: For the valid application of process models affecting radionuclide transport such as surface complexation, ion exchange, precipitation/ dissolution, and processes involving colloidal material, DOE has: (i) Demonstrated that the three implicit assumptions (as in 2c) are realized, if process models are intended to yield a constant K_d for use in the retardation equation (equation 1); otherwise, determined transport in a dynamic reactive transport system model (e.g., PHREEQC, MULTIFLO, HYDROGEOCHEM, etc.)**

Acceptance Criterion 3c
(Continued)

- **Action or information needs identified**
  - None
- **Basis for closure**
  - Process-model methods to quantify sorption, ion exchange, precipitation/dissolution, colloidal interactions, or other factors that affect radionuclide transport were not used in performance assessment calculations to quantify transport parameters

Acceptance Criteria 3a, b, c

- **References**
  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00)
  - *Unsaturated Zone Flow and Transport Model Process Model Report* (TDR-NBS-HS-000002 REV 00 ICN 02)
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 01)
- **Process-model methods to quantify sorption, ion exchange, precipitation/dissolution, colloidal interactions, or other factors that affect radionuclide transport were not used in performance assessment calculations to quantify transport parameters. Therefore, DOE considers this criterion closed**

Acceptance Criterion 4

- **Acceptance Criterion 4: Where data are not reasonably or practicably obtained, expert judgement has been used and expert elicitation procedures have been adequately documented. If used, expert elicitations were conducted and documented in accordance with the guidance in NUREG-1563 or other acceptable approaches**
- **Action or information needs identified**
  - The process used to define distributions for sorption coefficients used in performance assessment are not fully documented
- **Basis for closure**
  - Additional documentation will be provided to explain how sorption coefficient distributions used for performance assessment were derived

Acceptance Criterion 4
(Continued)

- **References**
  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00)
- **Additional documentation will be provided to explain how sorption coefficient distributions used for performance assessment were derived. Therefore, DOE considers this criterion closed-pending**

Conclusions

- DOE has met Criteria 1a, 1b, 3a, 3b, and 3c
- Criterion 2a will be met by completion of the Busted Butte testing and data analyses
- Sensitivity analyses and a review of the available data will be performed to meet Criteria 2b and 2c.
- Additional documentation of analyses will be provided to meet Criterion 4
- Therefore, this subissue is closed-pending

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

Radionuclide Transport Key Technical Issue, Subissue 3, Radionuclide Transport in Fractured Rock

Presented to:
DOE-NRC Technical Exchange on the Radionuclide Transport Key Technical Issue

Presented by:
Al Aziz Eddebbarh, Ph.D, Bo Bodvarsson, Ph.D
George Moridis, Ph.D, Paul Reimus, Ph.D
Edward Kwicklis, Ph.D
Civilian Radioactive Waste Management System Management and Operating Contractor

December 5-7, 2000
Lawrence Berkeley N[illegible]
Berkeley, CA

YUCCA MOUNTAIN PROJECT

Outline

- **Presentation Objectives**
- **Current Subissue Status**
- **For items identified in the Radionuclide Transport Issue Resolution Status Report Rev. 02, this presentation will:**
  - Summarize technical basis for item resolution
  - Identify basis documents (References)
  - Summarize technical adequacy of basis
- **Conclusions**

NOTE: Additional details are provided in the "delta" analysis

Presentation Objectives

- **Describe the basis for resolving Subissue 3, Radionuclide Transport in Fractured Rock, of the Radionuclide Transport Issue Resolution Status Report Rev. 02**
  - Acceptance Criterion 1a: "Processes important to performance are included in Total System Performance Assessment"
    Performance assessment calculations have been used to determine whether radionuclide attenuation processes are important to performance. DOE considers this criterion closed
  - Acceptance Criterion 1b: "Determine if radionuclide attenuation is important to performance"
    C, I, and Tc have a K_d of zero. However, attenuation due to matrix diffusion is important to performance and is included in all radionuclide transport calculations. Therefore, DOE considers this acceptance criterion not applicable

Presentation Objectives
(Continued)

- **Describe the basis for resolving Subissue 3, Radionuclide Transport in Fractured Rock, of the Radionuclide Transport Issue Resolution Status Report Rev. 02 (Continued)**
  - Acceptance Criterion 1c: "Justify flow path length"
    Flow paths lengths are generally the shortest paths between source and receptor except for lateral diversion pathways in the unsaturated zone. However, the range of potential flow paths investigated has been shown to have relatively small effects on transport behavior. DOE considers this criterion closed
  - Acceptance Criterion 2a: "Demonstrate ability to predict breakthrough curves". Breakthrough curves of reactive and non-reactive, and colloidal tracers have been developed from field tests. These breakthrough curves are documented in the Saturated Zone Process Model Report, the planned C-well testing report and the Unsaturated Zone Process Model Report. DOE considers this criterion closed-pending results from Alcove 8/Niche 3 testing and predictive modeling

Presentation Objectives
(Continued)

- **Describe the basis for resolving Subissue 3, Radionuclide Transport in Fractured Rock, of the Radionuclide Transport Issue Resolution Status Report Rev. 02 (Continued)**
  - Acceptance Criterion 2b: "Demonstrate tracers are appropriate homologues for radionuclides". DOE expects to show that non-radioactive tracers used in field tests are appropriate homologues for radio-elements. DOE considers this criterion closed-pending documentation of Busted Butte and C-wells data
  - Acceptance Criterion 2c: "Justify flow path length"
    Same as acceptance criterion 1c
  - Acceptance Criterion 3: "Expert elicitation"
    Expert elicitation is not used. DOE considers this criterion closed
  - Acceptance Criterion 4: "Quality Assurance"
    Not addressed at this Technical Exchange

Current Subissue Status

- **Radionuclide Transport Issue Resolution Status Report, Rev. 02 indicates this subissue is OPEN:**
  - Demonstrate capability to predict breakthrough curves of reactive, non-reactive, and colloidal material
  - Justify length of flow path affected by fracture-dominated transport
  - Credit for sorption within fractures in current Total System Performance Assessment models

Acceptance Criterion 1a

- **Acceptance Criterion 1a: DOE has determined through Performance Assessment calculations whether radionuclide attenuation processes such as sorption, precipitation, radioactive decay, and colloidal filtration are important to performance**
- **Action or information needs identified**
  - None identified

Acceptance Criterion 1a
(Continued)

- **Basis for closure**
  - Radionuclide transport attenuation processes such as sorption, colloidal filtration, and radionuclide decay are important to performance and are included in the transport models
  - IRSR, Rev. 2 indicates that this acceptance criterion has been met

Acceptance Criterion 1a
(Continued)

- **References**
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 01)
  - *Unsaturated Zone Flow and Transport Model Process Model Report* (TDR-NBS-HS-000002 REV 00 ICN 02)
- **No further work required, DOE considers this acceptance criterion closed. Performance assessment calculations have been used to determine whether radionuclide attenuation processes are important to performance**

Acceptance Criterion 1b

- **Acceptance Criterion 1b: DOE has assumed K_d (or K_A) is zero and that radionuclides travel at the velocity of groundwater flow through fractures, if it has been found that radionuclide attenuation in fractures is unimportant to performance, and it can be demonstrated that this assumption is conservative**
- **Action or information needs identified**
  - None identified

Acceptance Criterion 1b
(Continued)

- **Basis for closure**
  - DOE does not assume that radionuclides travel at the velocity of groundwater in fractures. Therefore, this criterion is not applicable

- **References**
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 01)
  - *Unsaturated Zone Flow and Transport Model Process Model Report* (TDR-NBS-HS-000002 REV 00 ICN 02)

Acceptance Criterion 1b
(Continued)

- No further work required. Although K_d is assumed to be zero for some radionuclides, DOE does not assume that radionuclides travel at the velocity of groundwater in fractures. Therefore, DOE considers this criterion not applicable

Acceptance Criterion 1c

- **Acceptance Criterion 1c: For the estimation of radionuclide transport through fractured rock, DOE has: justified the length of flowpath to which these fracture transport conditions apply**
- **Action or information needs identified**
  - Justify length of flow path affected by fracture-dominated transport

Acceptance Criterion 1c
(Continued)

- **Basis for closure - Unsaturated Zone**
  - For the unsaturated zone, the path lengths through the various units are generally the shortest distance between the potential repository and the water table
    - The only case where this is not true is where there is lateral diversion due to perched water or lower permeability zeolitic rock
  - The sensitivity of transport to different models of perched water (and hence lateral diversion) demonstrates that transport time to the water table is not significantly affected by the path length
    - The major influence on transport time to the water table is the amount of matrix flow and transport that occurs

Conclusions - Unsaturated Zone

- **Basis for resolution:**
  - Transport behavior in the unsaturated zone is not sensitive to alternative transport pathways resulting from alternative flow paths that are consistent with the data and known flow processes
  - DOE considers this acceptance criterion closed

Justify Length of Flow path

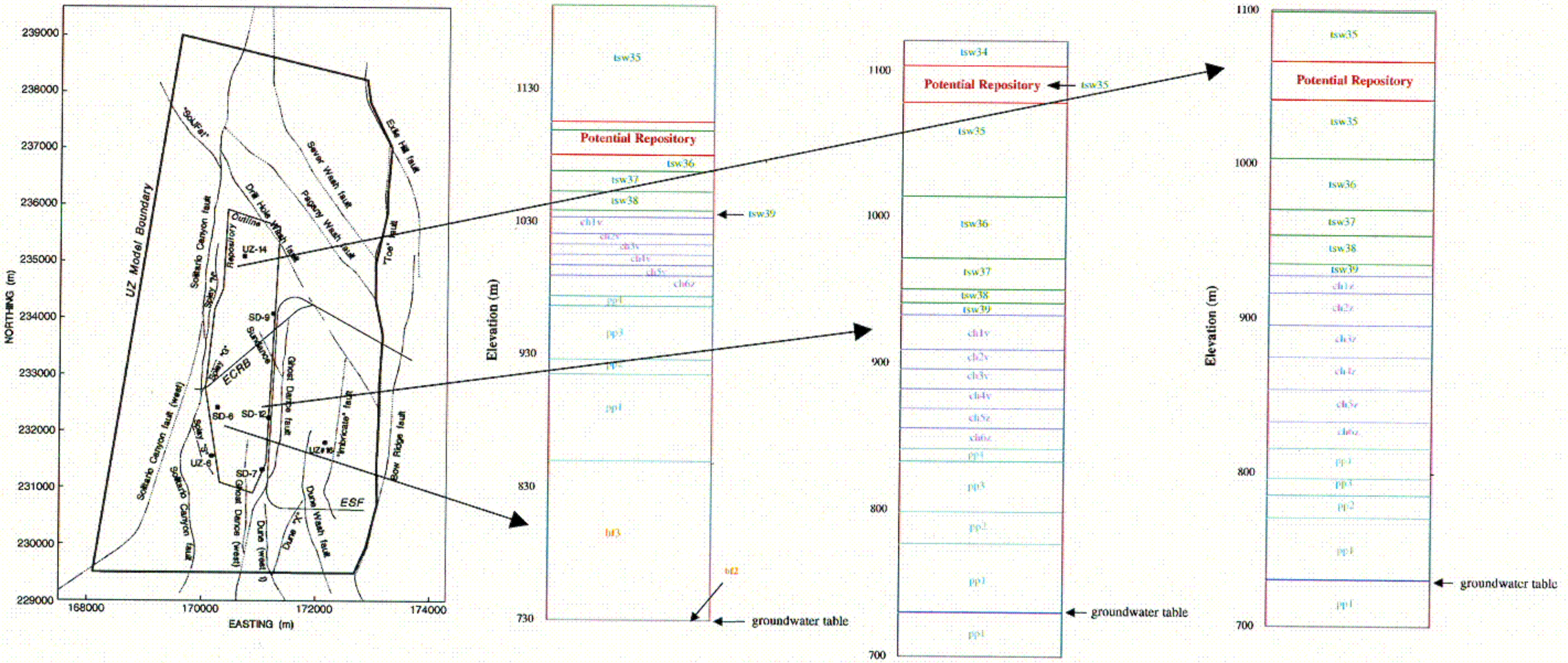
- Fractures are the main pathways of radionuclide transport in the unsaturated zone
- Diffusion from the fractures into the matrix is the main retardation process in radionuclide transport
- Sorption onto the matrix retards the migration of sorbing radionuclides
- Transport in the TSw hydrogeologic unit is strongly dependent on the thickness of the unit and its spatial variability over the area of the potential repository

Justify Length of Flow path
(Continued)

- **Flow and transport in the CHn hydrogeologic unit are strongly dependent on the spatial variability of the distribution of the vitric and zeolitic layers**
  - Zeolitic: fracture-dominated flow, fast advective transport
  - Vitric: porous medium behavior, effective barriers to radionuclide transport
- **Radionuclide transport appears to be practically uninhibited in the top zeolitic layers (pp4) of the PP hydrogeologic unit, but is effectively retarded by the underlying devitrified layers**

Justify Length of Flow path

Two-dimensional Tc-99 Transport Studies - Uniform flow



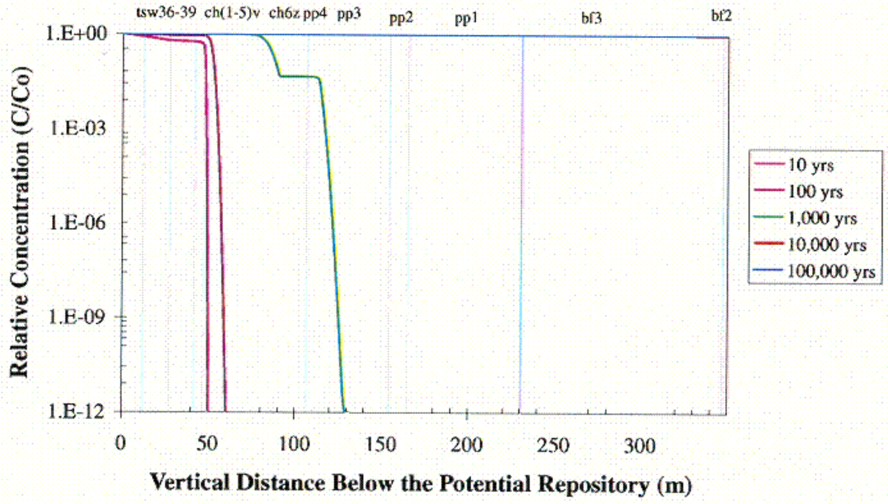
C-12

Reference: MDL-NBS-HS-000008

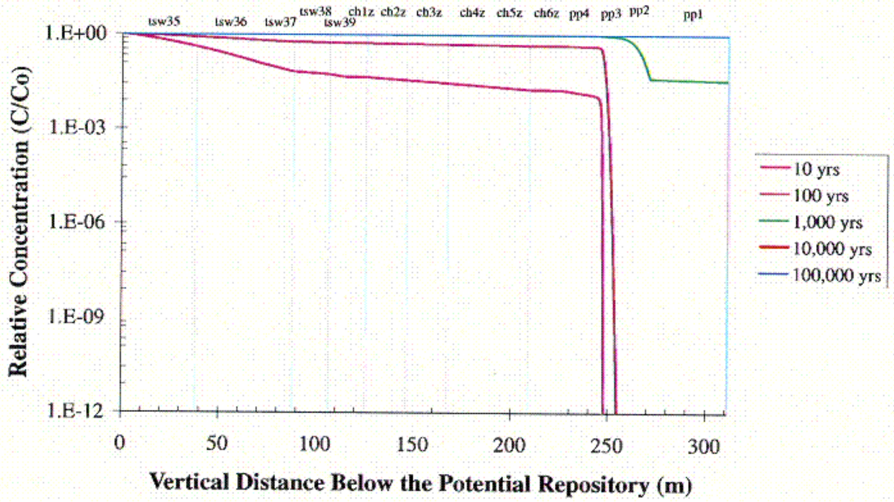
Justify Length of Flow path

Two-dimensional Tc-99 Transport Studies - Uniform flow

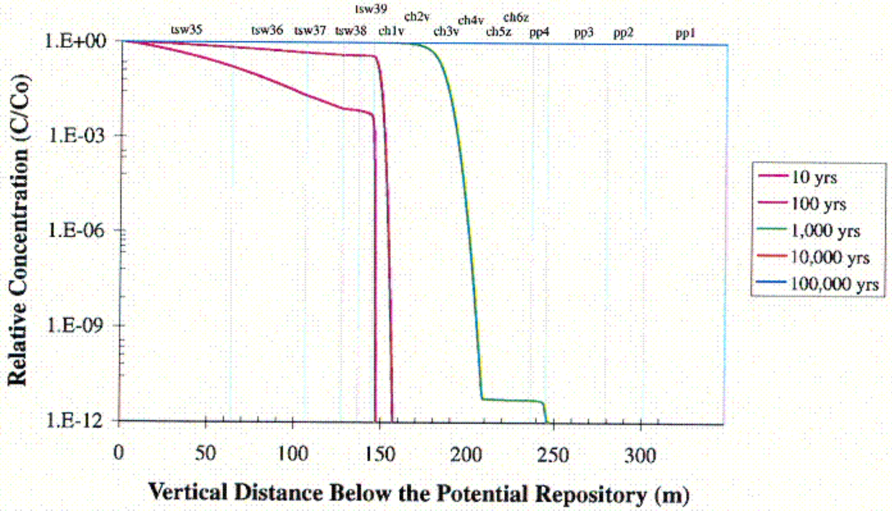
Cross Section 1



Cross Section 3



Cross Section 2

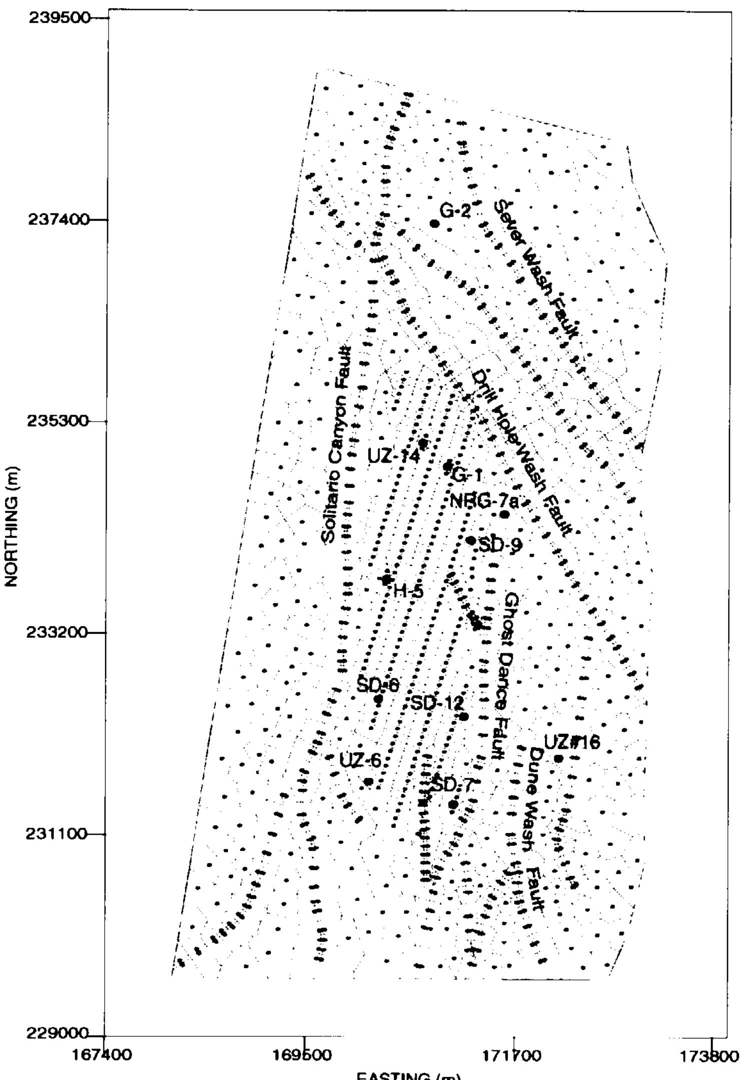


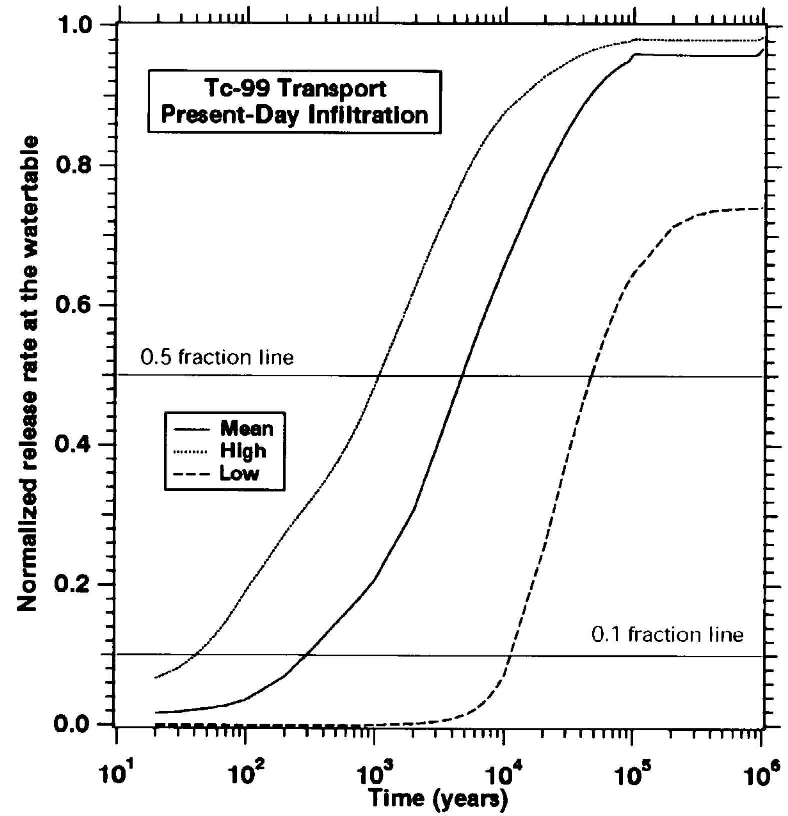
C-13

Reference: MDL-NBS-HS-000008

Justify Length of Flow path

Three-dimensional Site-Scale Simulations of Flow and Transport





Comparison of the two-dimensional and three-dimensional results for the non-sorbing Tc-99 indicates differences. These are attributed to the effect of flow patterns (fast pathways, flow diversion, flow focusing)

Reference: TDR-NBS-HS-000002

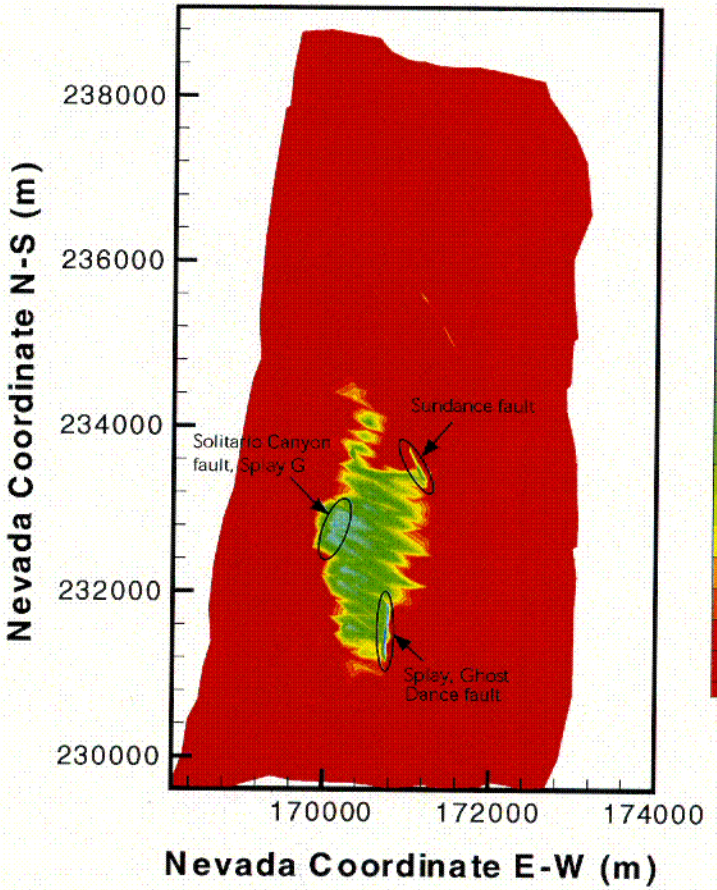
Justify Length of Flow path

- **Flow and Transport Issues**
  - Three-dimensional site-scale simulations indicate that radionuclide transport is both dominated and controlled by the faults. These provide fast pathways to downward migration to the water table, but also limit lateral transport past them
  - Radioactive solutes from the potential repository appear to reach the water table earlier and over a larger area in the southern part of the potential repository. Four reasons:
    - Infiltration and percolation patterns
    - Presence of faults (Splay G of the Solitario Canyon fault, Ghost Dance fault splay, Sundance fault, the Drill Hole Wash fault, main Ghost Dance fault)
    - Flow focusing due to contraction of the areal extent of the vitrified tuffs in the southern part
    - Low-permeability zones at the TSw-CHn interface in the northern part

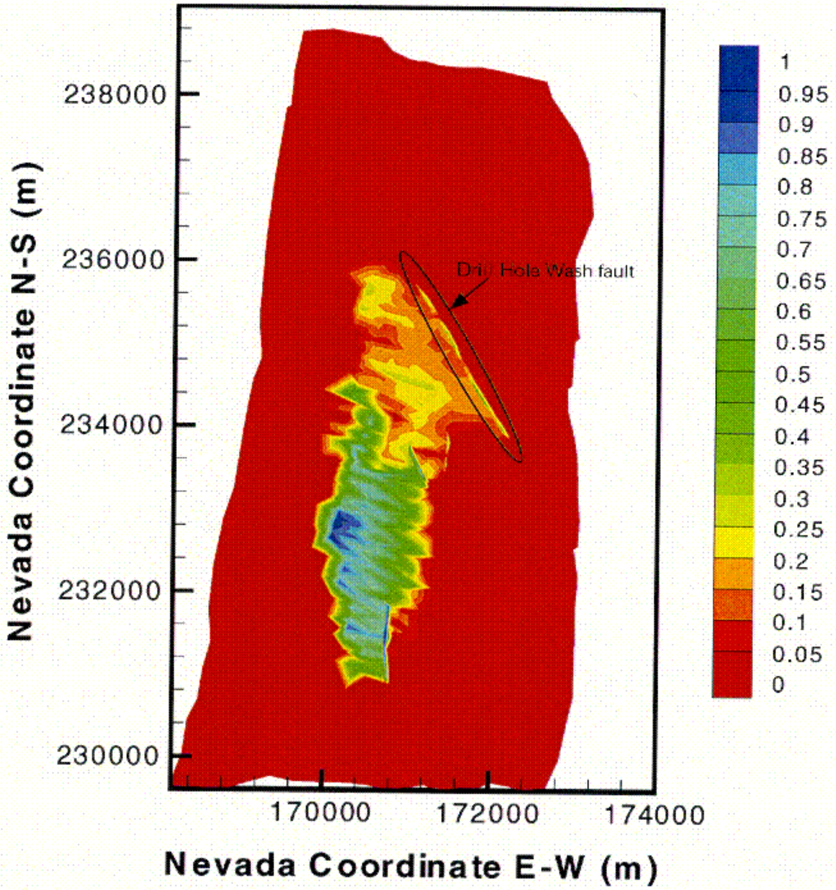
Justify Length of Flow path

Tc-99 Transport Below the Potential Repository

Fracture Mass Fraction at Bottom of TSw
(for Tc at 100 years)



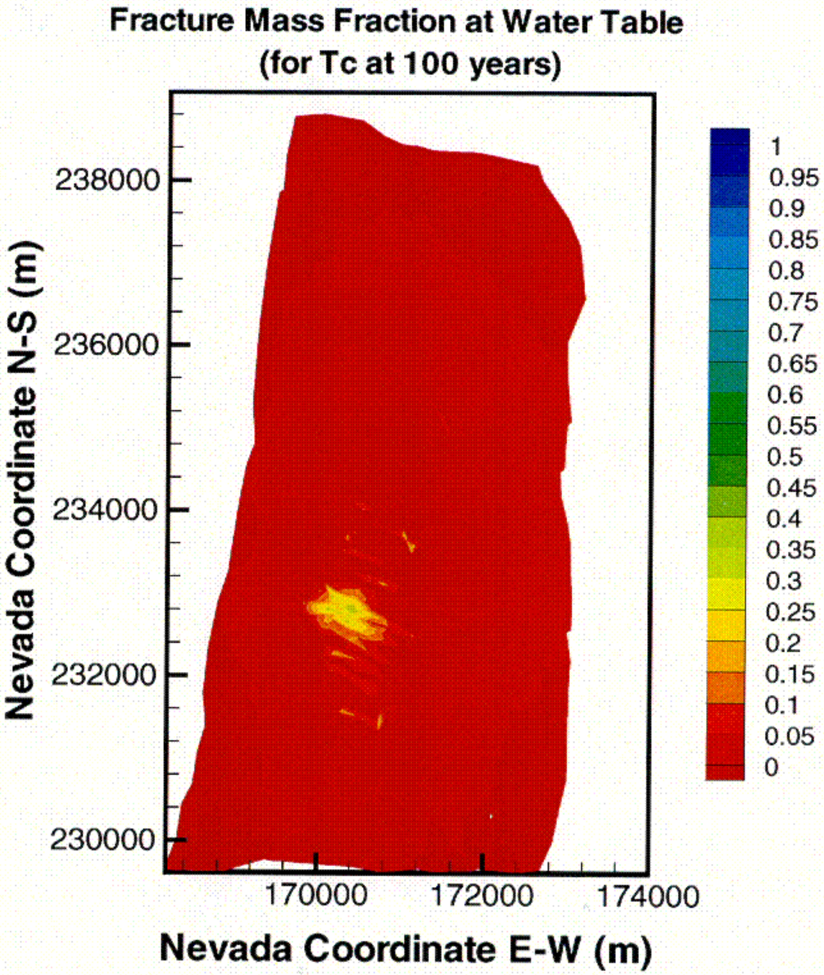
Fracture Mass Fraction at Bottom of TSw
(for Tc at 1000 years)

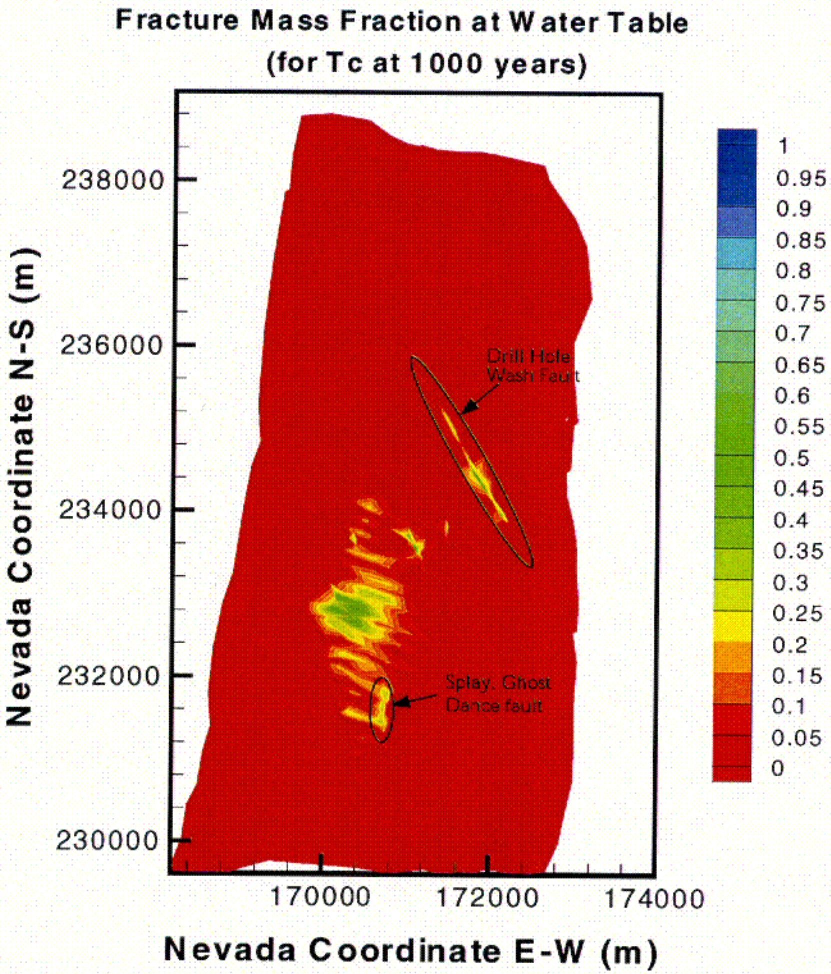


C-14

Justify Length of Flow path

Tc-99 Transport at the Water Table

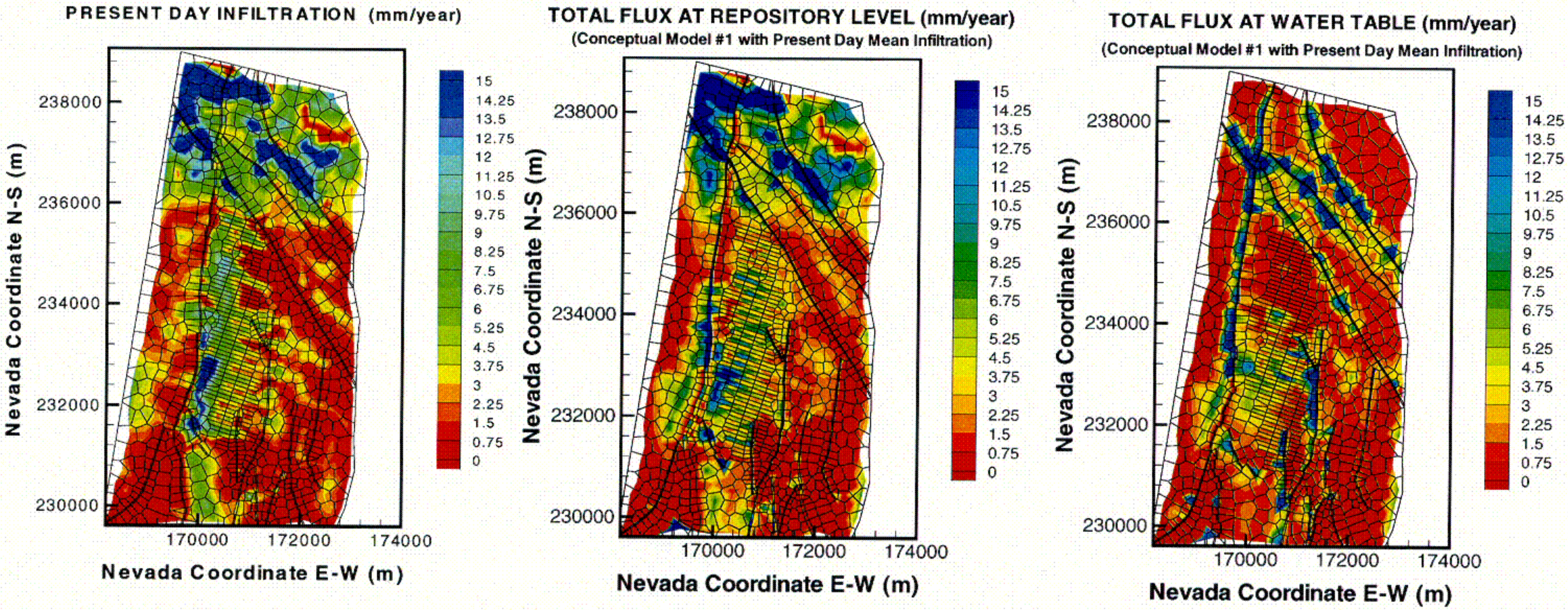




Reference: TDR-NBS-HS-000002

Justify Length of Flow path

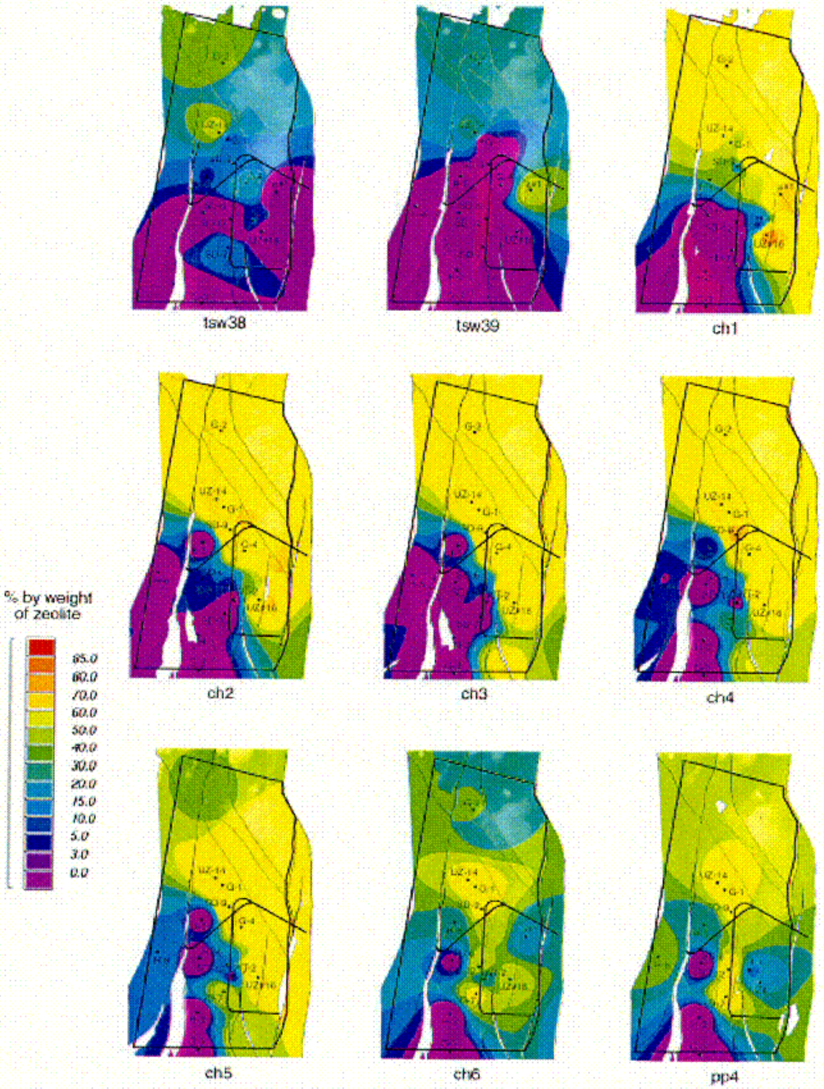
Infiltration and Flow Patterns Below the Potential Repository



Very strong correlation between flow patterns and transport patterns

Justify Length of Flow path

Vitric Unit Distribution Pattern - Flow Focusing

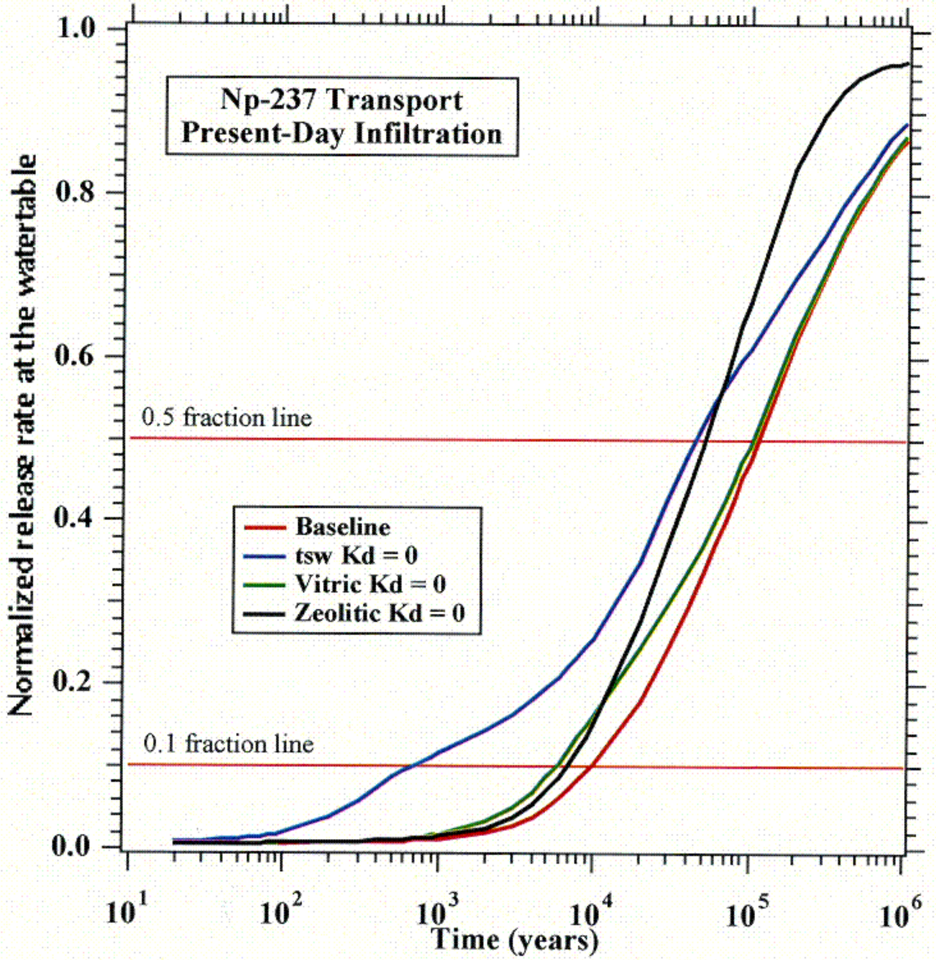


Reference: MDL-NBS-HS-000008

C-17

Justify Length of Flow path

- **Relative Importance of Hydrogeologic Units - *Targeting of Flow & Transport Studies***



TSw units appear to be the most important to early arrival at the water table

Zeolitic units are more important for later arrival

In terms of relative importance, TSw > zeolitic > vitric

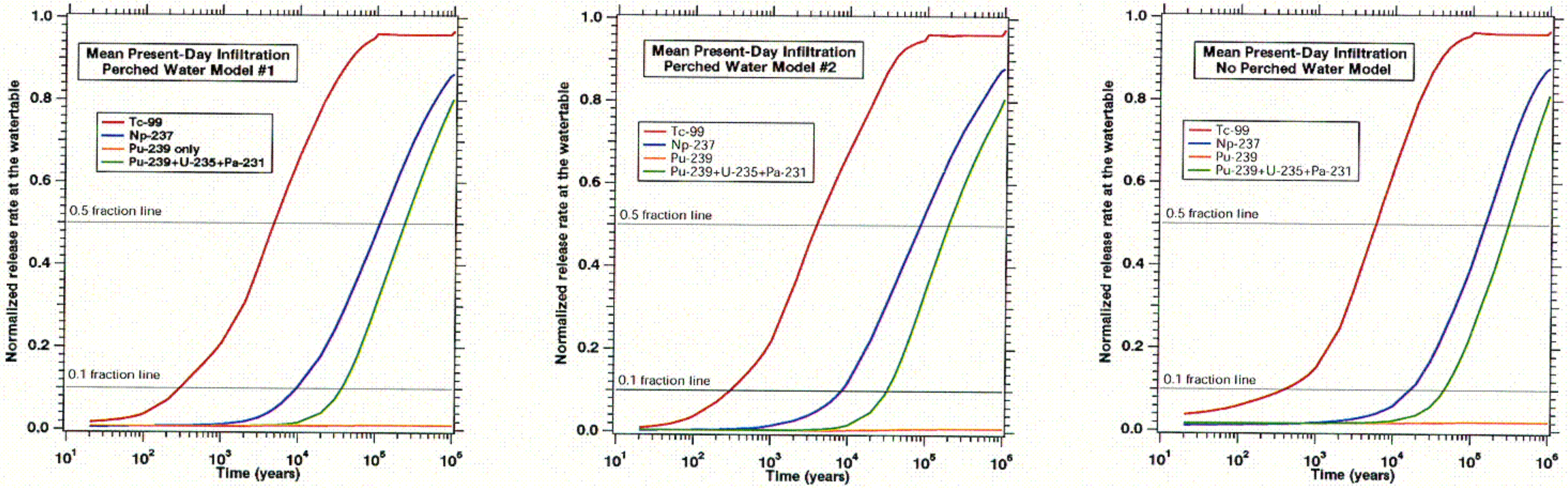
Reference: work in progress

Justify Length of Flow path

- **Different Perched Water Models**
  - Perched water bodies observed in formations overlaying relatively impermeable matrix material, such as the Topopah Spring basal vitrophyre. Although the vitrophyre is extensively fractured, many of the fractures have been filled with zeolitic material, thus limiting flow. The blockage of fracture flow which occurs in these perched water bodies can lead to lateral diversion of radionuclide migration if the percolation flux is sufficiently large
  - Three perched water models:
    - No perched water model
    - Perched water model #1 (flow through the perched water)
    - Perched water model #2 (flow bypassing the perched water)

Justify Length of Flow path

- **Effects of Different Perched Water Models**



Differences in the perched water conceptual models do not appear to appreciably affect cumulative radionuclide transport to the water table

Reference: MDL-NBS-HS-000008

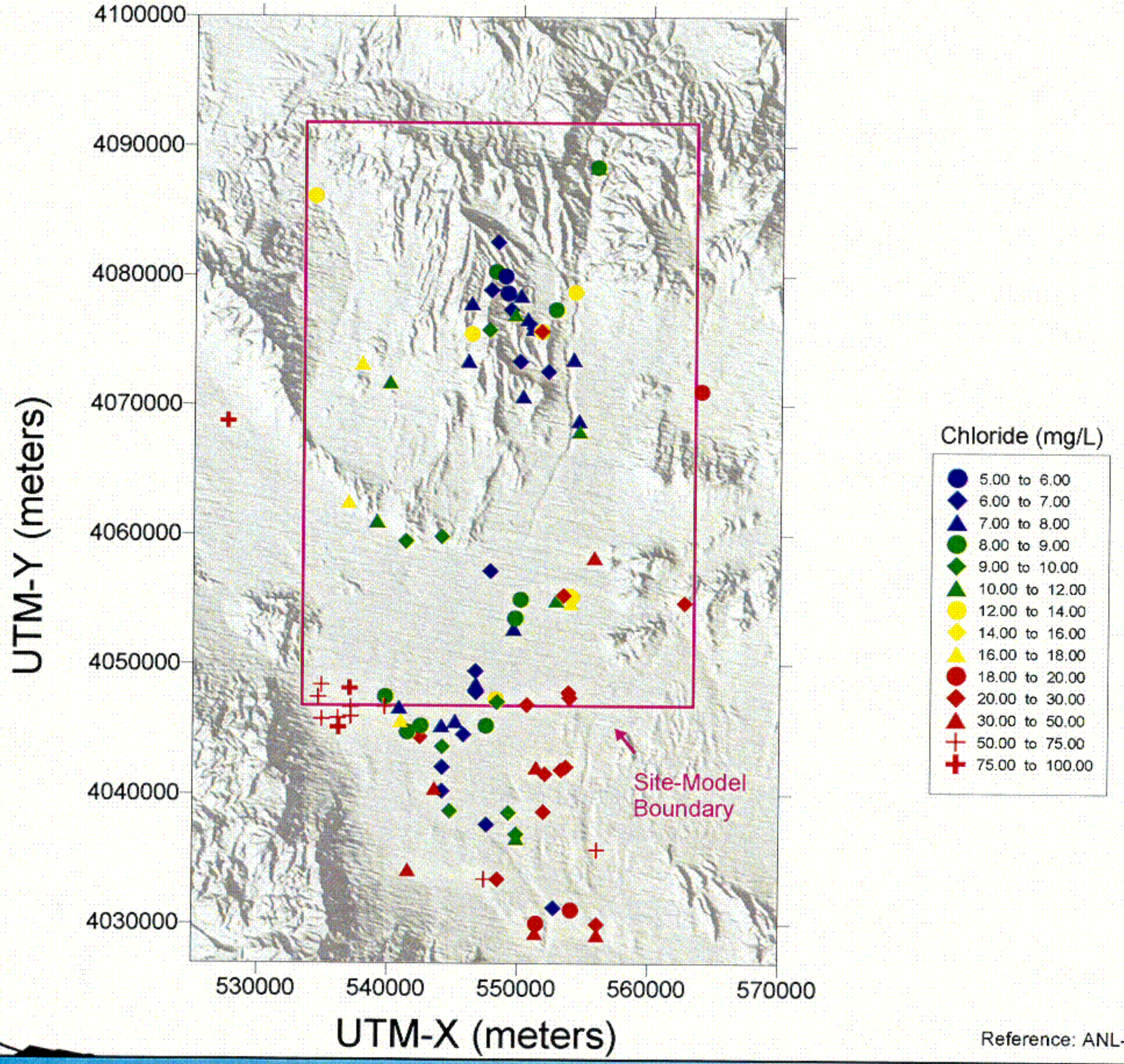
Acceptance Criterion 1c

- **Basis for closure - Saturated Zone**
  - For the saturated zone, the uncertainty related to the lengths of flow paths in the tuff and in the alluvium was discussed at the Saturated Zone Technical Exchange October 31, 2000
    - DOE agreed at the technical exchange to provide additional information, including Nye County data, to further justify the uncertainty distribution of flow path lengths in alluvium in updates to the *Uncertainty Distribution Stochastic Parameters* AMR - additional information was provided at this meeting

Regional Flow Paths

- **Basis for resolution:**
  - Link upgradient areas with distinct chemical and isotopic compositions to downgradient areas with similar compositions
  - Multiple chemical and isotopic species are used to identify compositionally distinct areas
- **Approach assumes that**
  - (1) δD, $\delta^{18}O$, SO_4^{2-}, Cl^-, Na^+, and Ca^{2+} are sufficiently conservative that they can be used as tracers
  - (2) The effects of local recharge on chemical and isotopic compositions are negligible
  - (3) There is no vertical mixing between aquifers

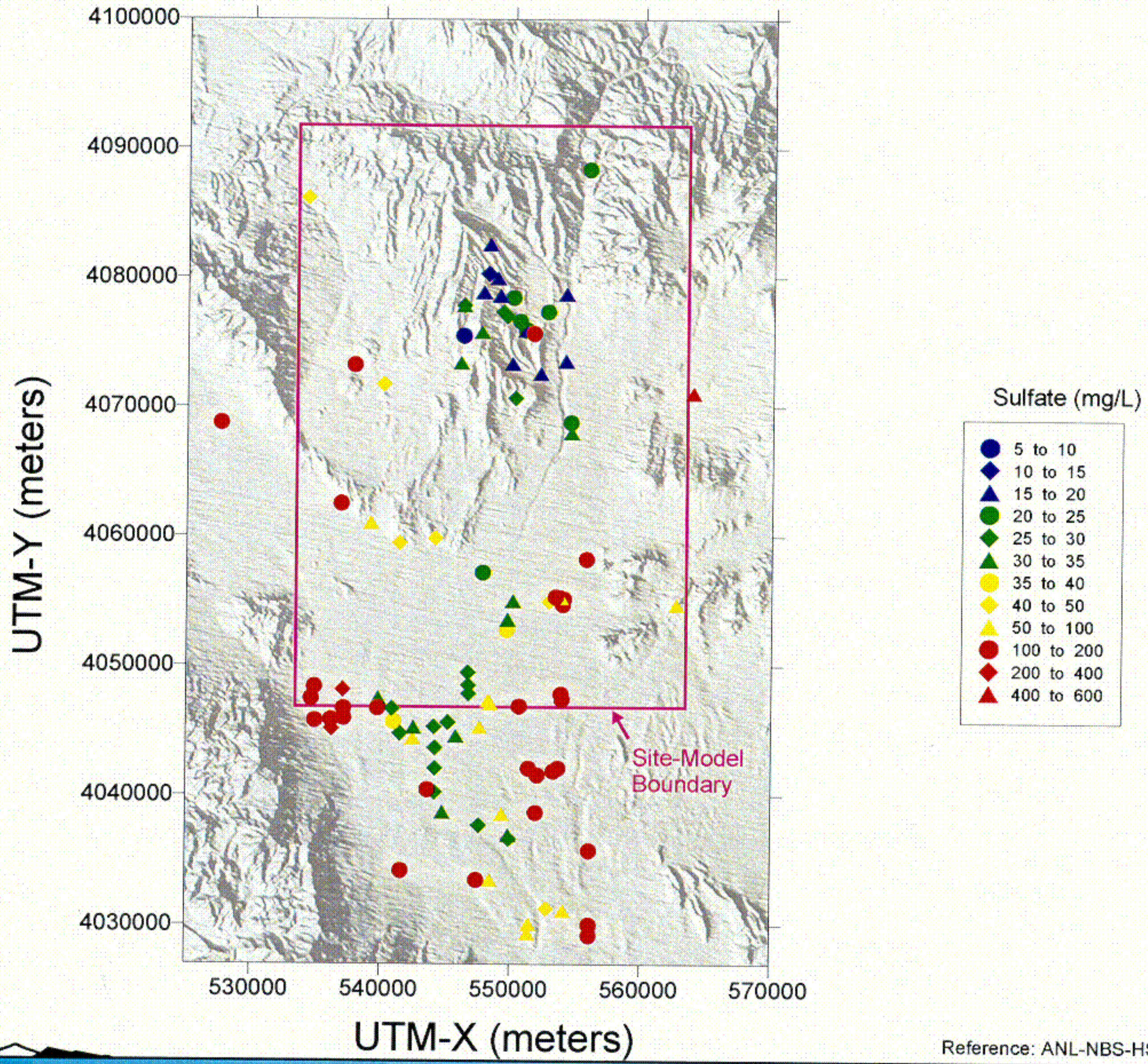
Dissolved chloride concentrations (mg/L)



C-20

Reference: ANL-NBS-HS-000021

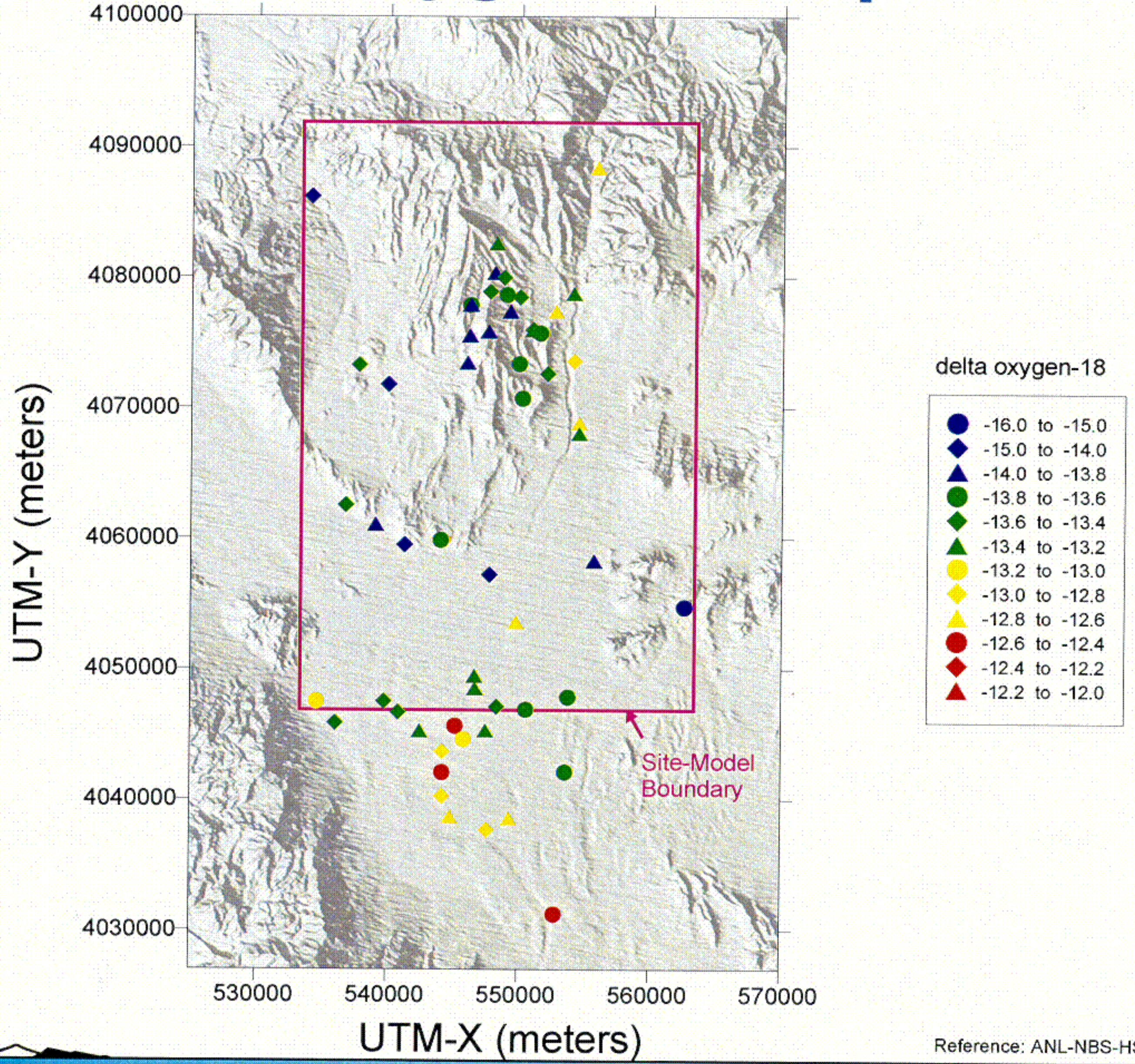
Dissolved sulfate concentrations (mg/L)



C-21

Reference: ANL-NBS-HS-000021

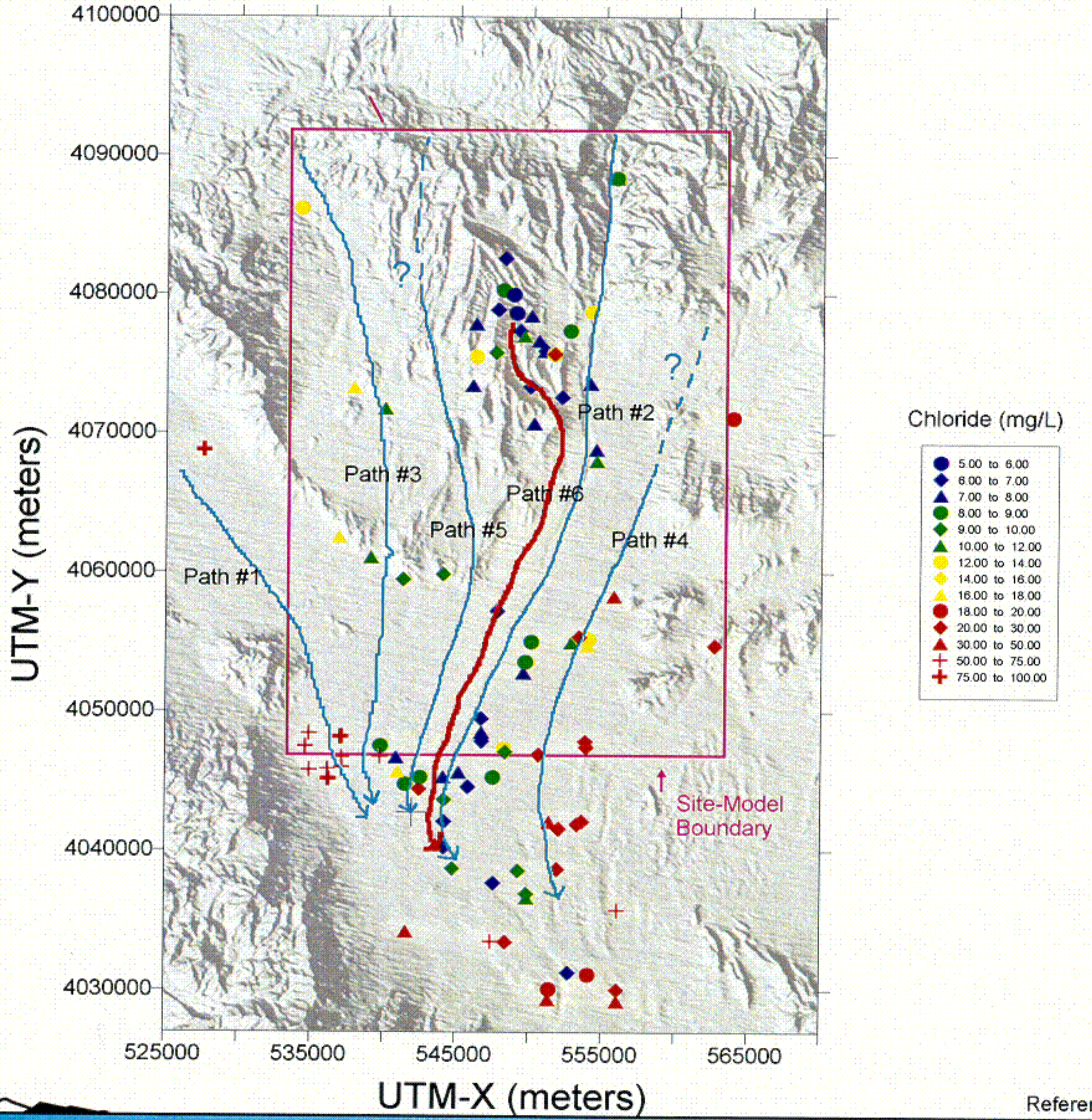
Delta oxygen-18, in per mil



C-22

Reference: ANL-NBS-HS-000021

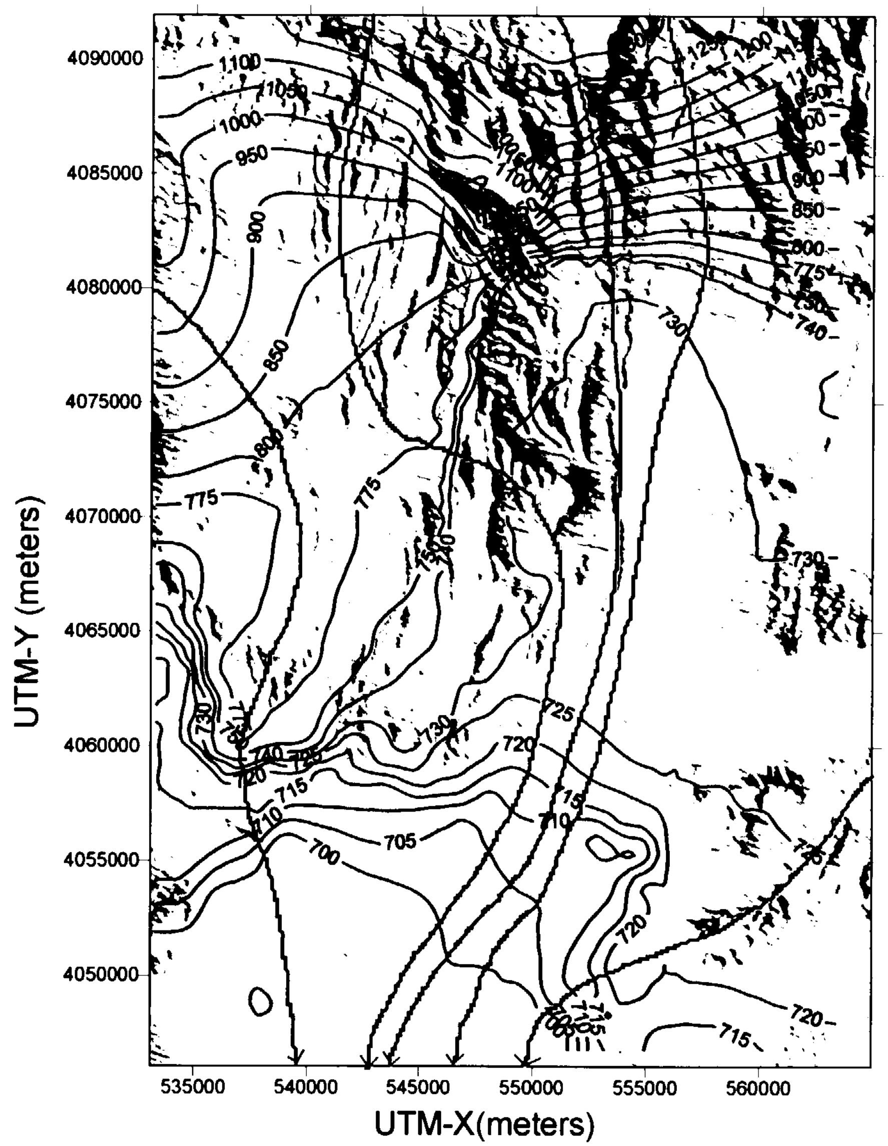
Inferred flow paths based on hydrochemical and isotopic data



Reference: ANL-NBS-HS-000021

C-23

Inferred flow paths based on the potentiometric surface



Reference: ANL-NBS-HS-000021

Comparison of flow paths inferred from hydrochemical and hydraulic data

- **Regional flow paths constructed from hydrochemical data are generally consistent with flow paths inferred from hydraulic data, but have a stronger north-south component in eastern Crater Flat**

- **The stronger north-south component in flow directions inferred from hydrochemical data could be reflecting**
  - (1) the general north-south structural fabric of the rock
  - (2) the inability of the hydrochemical method to account for chemical mixing due to recharge or aquifer mixing
  - (3) the sparseness of data in certain areas

Acceptance Criterion 1c
(Continued)

- **References**
  - Analysis and Model Report *Radionuclide Transport Models Under Ambient Conditions* (MDL-NBS-HS-000008, REV 00)
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 01)
  - *Unsaturated Zone Flow and Transport Model Process Model Report* (TDR-NBS-HS-000002 REV 00 ICN 02)
  - Analysis and Model Report *Uncertainty Distributions for Stochastic Parameters* (ANL-NBS-MD-000011)
  - Analysis and Model Report *Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing, and Recharge at Yucca Mountain, Nevada* (ANL-NBS-HS-000021)

Acceptance Criterion 1c
(Continued)

- **No additional work required, DOE considers this acceptance criterion closed**
  - Flow path length in the unsaturated zone is a function of lateral diversion. However, sensitivity of transport behavior to diversion has been shown to be negligible
  - Additional information from Nye County wells is expected to further justify saturated zone flow path lengths

Acceptance Criterion 2a

- **Acceptance Criterion 2a: If credit is to be taken for radionuclide attenuation in fractured rock, DOE has demonstrated capability to predict breakthrough curves of reactive, nonreactive, and colloidal tracers in field tests**
- **Action or information needs identified**
  - Demonstrate capability to predict breakthrough curves of reactive, non-reactive, and colloidal material

Acceptance Criterion 2a
(Continued)

- **Basis for closure - Unsaturated Zone**
  - DOE has developed breakthrough curves for nonsorbing tracer transport in fractured, welded tuff based on Alcove 1 data. Additional tests are being conducted in Alcove 8/Niche 3 which will include nonsorbing and moderately sorbing tracers
  - Predictive models are being developed for the Alcove 8/Niche 3 tests as discussed at the Structural Deformation and Seismicity Technical Exchange October 11, 2000. This is the subject of an agreement made at the Structural Deformation and Seismicity Key Technical Issue meeting

Conclusions - Unsaturated Zone

- **Field testing in 3 alcoves, 5 niches, and along Exploratory Studies Facility Main Drift and Cross Drift provides data for Unsaturated Zone flow and transport modeling and assessment of fractured tuff units**
- **Simulated breakthrough curves match the tracer concentration data in the Alcove 1 tracer test, indicating**
  - The continuum approach is valid for modeling flow and transport in unsaturated fractured rock
  - Use of an active fracture model can capture the major features of fingering flow and transport in fractures

Conclusions - Unsaturated Zone
(Continued)

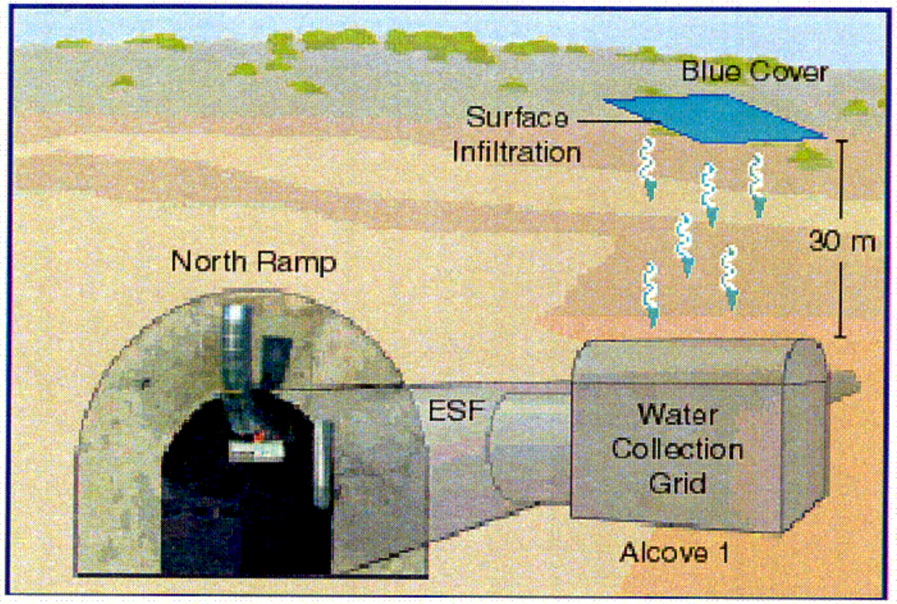
- **Ongoing tracer test at Alcove 8/Niche 3 will further evaluate predictive modeling of transport in fractured rock**
- **Potential future testing of reactive transport in fractured rock at the repository horizon (both middle nonlithophysal unit and lower lithophysal unit); more on this will be discussed for Criterion 2b**

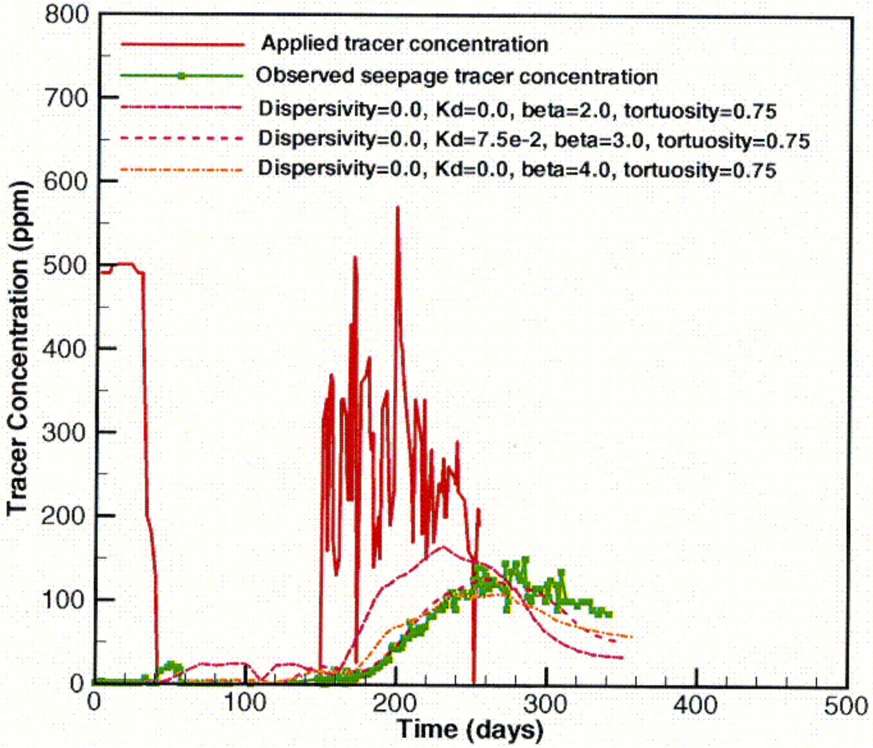
Predict Breakthrough Curves

- **Exploratory Studies Facility and Cross-Drift Tests**
  - Alcove 1 Tracer Test
  - Chloride Distribution
  - Construction Water Migration
  - Alcove 8/Niche 3 Tracer Test
  - Alcove 6 Tracer Test
  - Systematic Hydrological Characterization
  - Niche Seepage Tests

Predict Breakthrough Curves

- **Alcove 1 Tracer Test (TCw)**





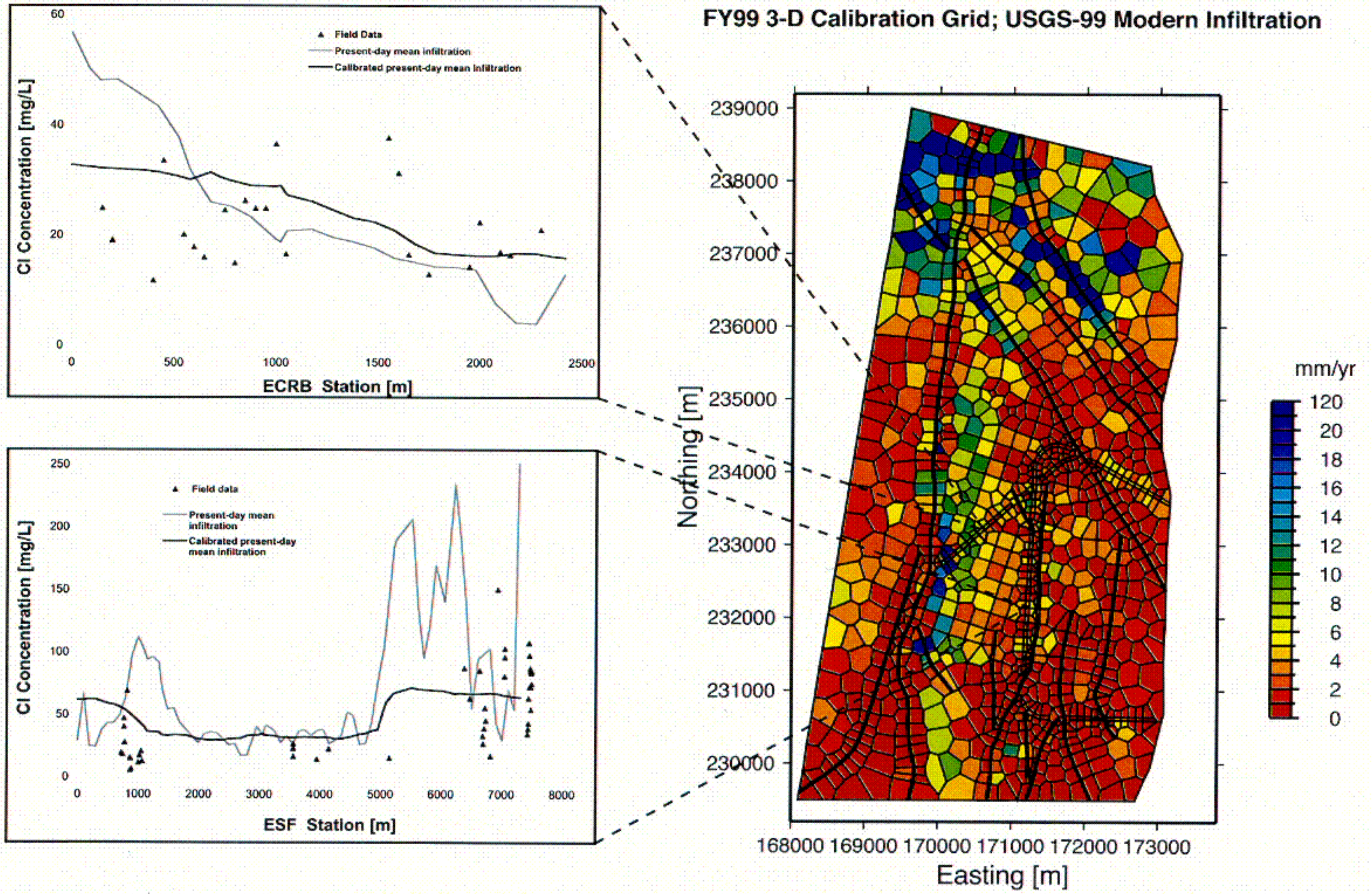
- **Dual-permeability, active fracture flow and transport model with three matrix continua in the Multiple Interacting Continuum method are used for seepage and bromide tracer observed 30 m below surface**

- **Strong matrix diffusion is identified as a main transport mechanism**

Reference: TDR-NBS-HS-000002

Predict Breakthrough Curves

- **Calculated and Measured Chloride Concentrations in Cross Drift and Exploratory Studies Facility**



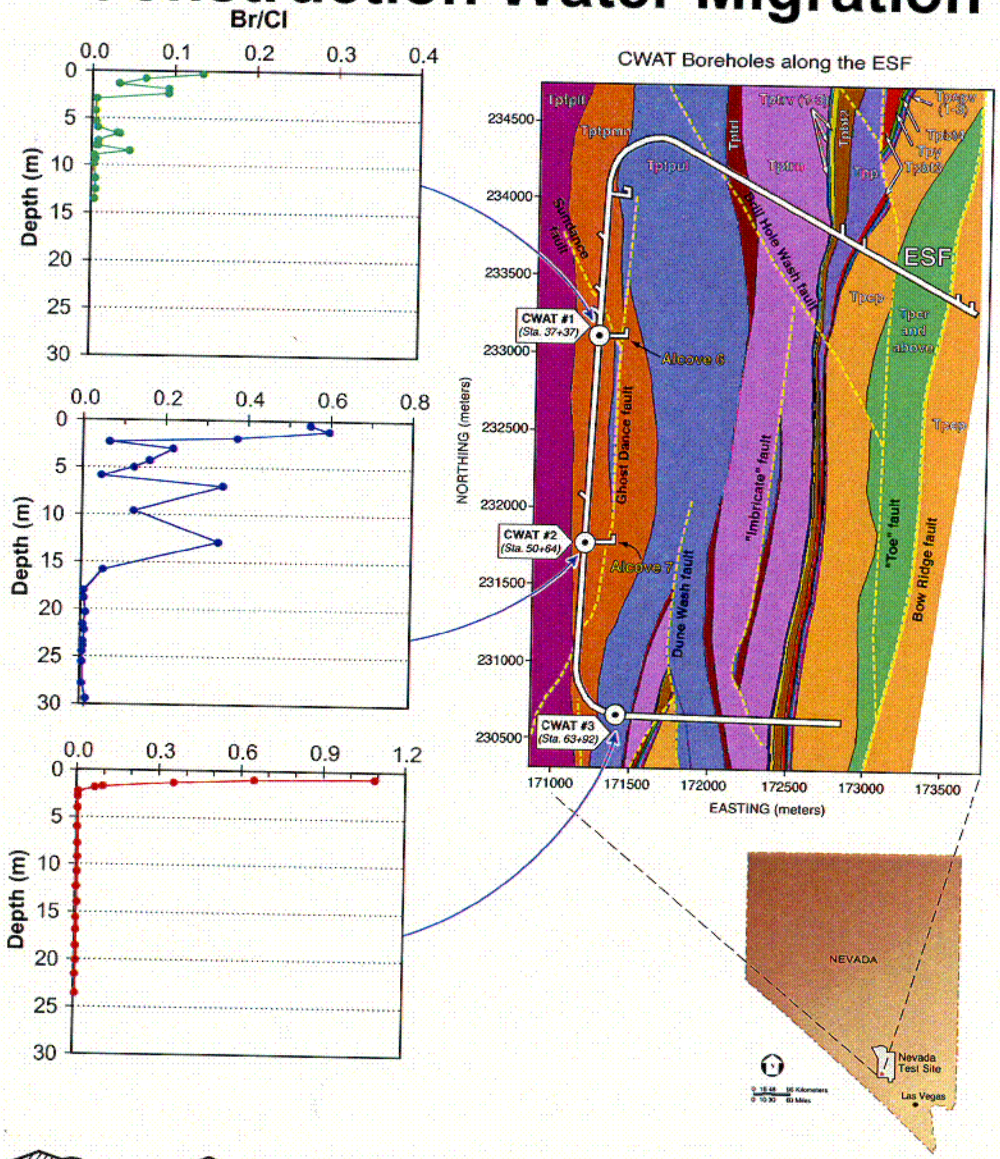
C-25

Unsaturated Zone site scale flow and transport model is used to interpret Cl distribution with modified infiltration model or PTn lateral diversion mechanism

Reference: TDR-NBS-HS-000002

Predict Breakthrough Curves

- **Construction Water Migration**



Heterogeneous fracture model with Multiple Interacting Continuum matrix to interpret Br distribution in middle nonlithophysal cores

CWAT#3, Cross Drift starter tunnel slant borehole, and cross-over point monitoring during Cross Drift excavation provided migration data for releases in upper lithophysal tuff

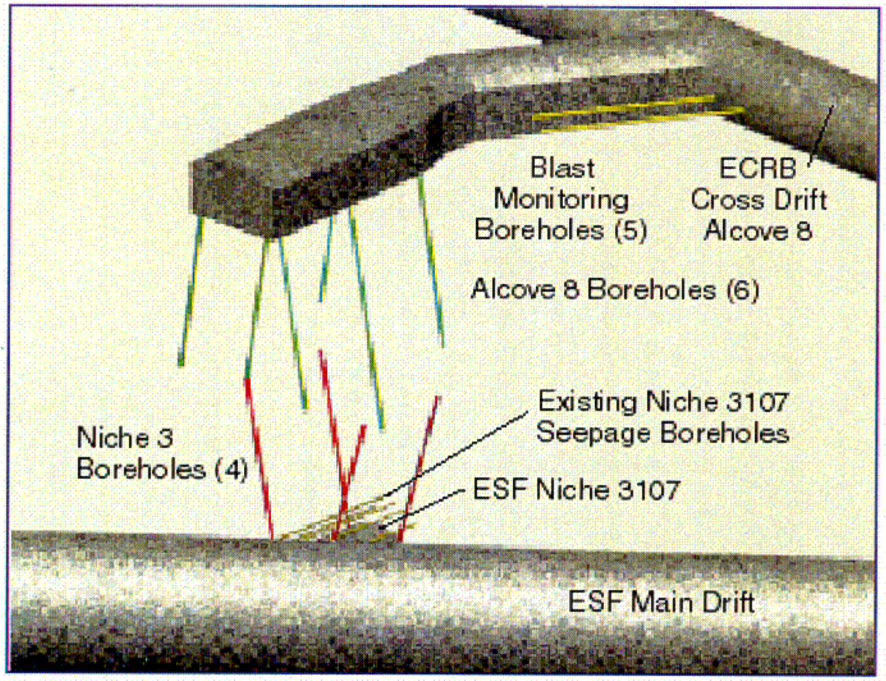
Results sensitive to released amount

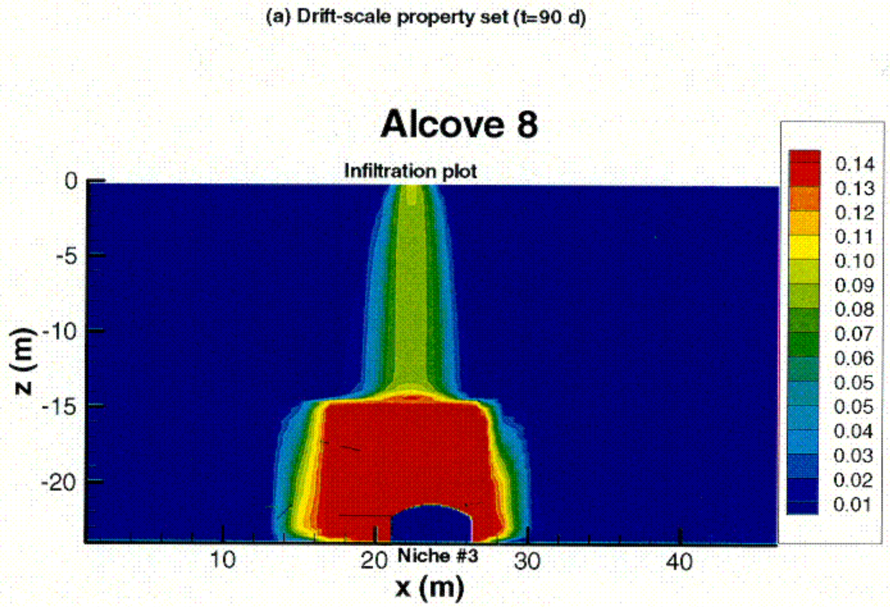
C-2a

Reference: TDR-NBS-HS-000002

Predict Breakthrough Curves

- **Additional Testing at Alcove 8/Niche 3**





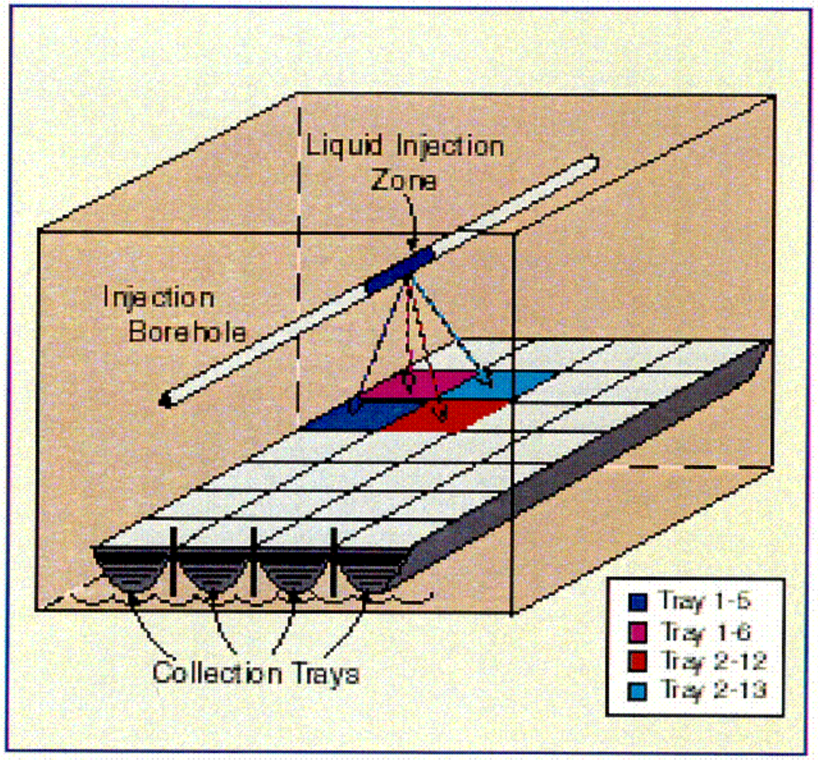
- **The Multiple Interacting Continuum model with drift scale properties is used for pretest prediction for migration of water and tracers introduced at Alcove 8 about 20 m above Niche 3**
- **Pairs of nonsorbing tracers of contrasting diffusivities will be used to demonstrate the importance of matrix diffusion and evaluate the effective fracture/matrix interaction area**

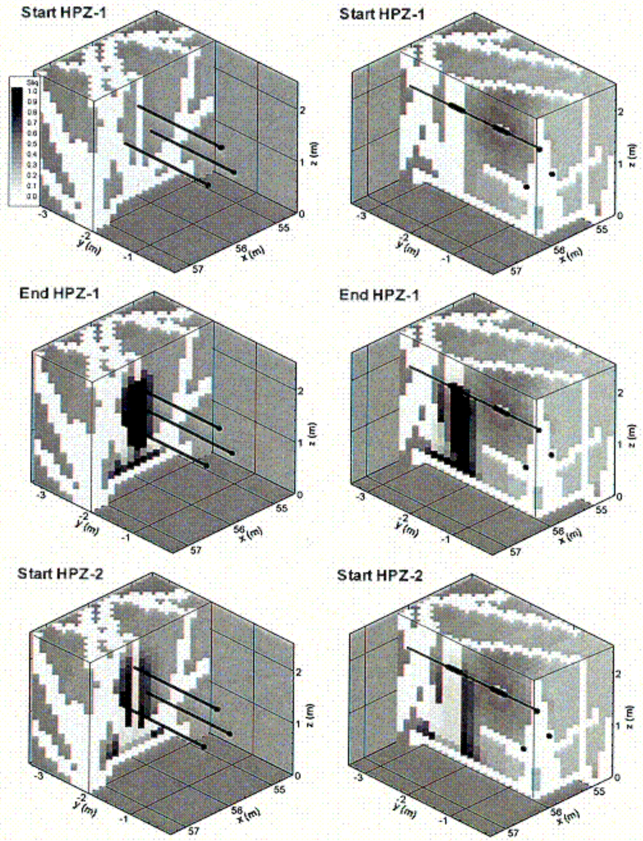
Reference: TDR-NBS-HS-000002

C-27

Predict Breakthrough Curves

- **Alcove 6 Tracer Test**



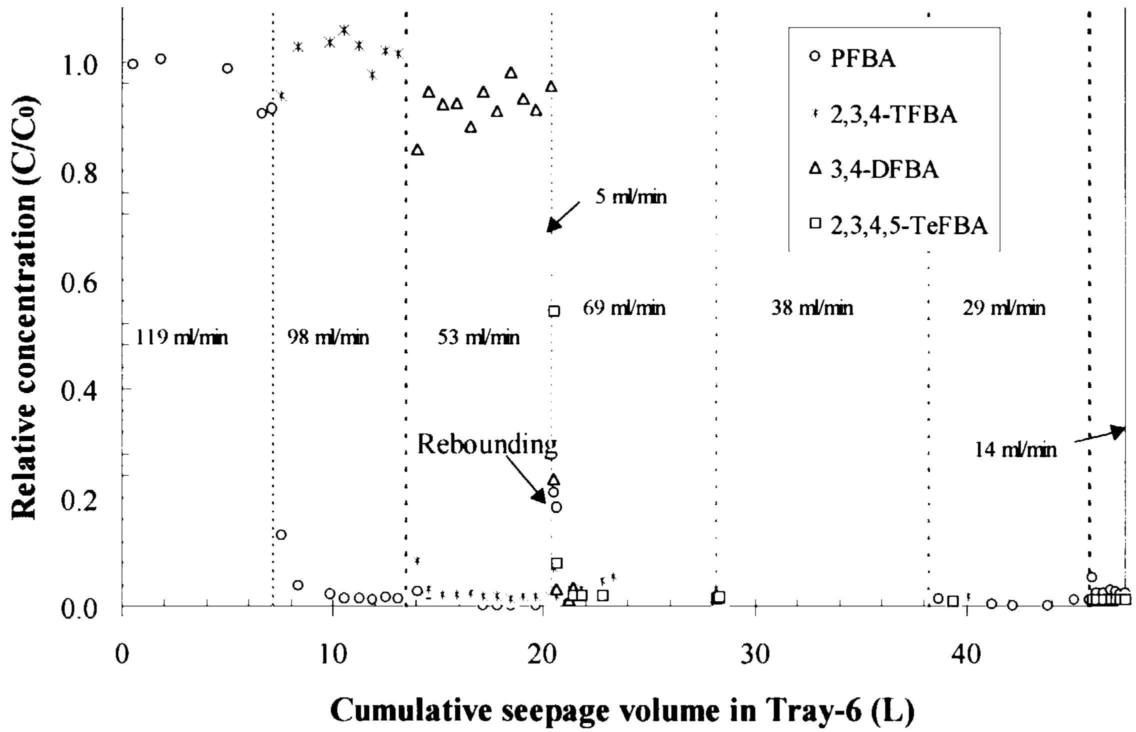


- Test conducted in the TSw welded tuff, interpreted with quasi-explicit fracture network 3-D model
- Use a slot (1.6 m below the injection borehole) to capture seepage
- Test conducted in two phases, each phase with four tests of different injection rates (from high to low); each test has a separate tracer

Reference: TDR-NBS-HS-000002

Predict Breakthrough Curves

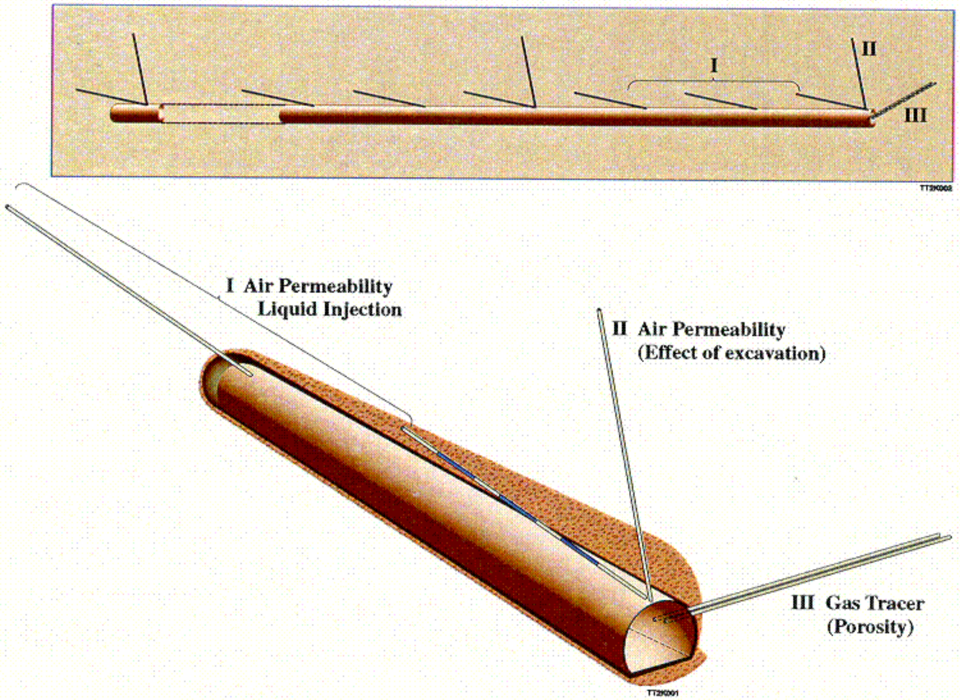
- **Alcove 6 Tracer Test**
  - Under high injection rates: fractures as the predominant conducting pathways, with limited fracture-matrix interaction
  - Under low injection rates: fracture flow comparatively less dominant, with a noticeable contribution from matrix flow
  - Concentration rebounding observed after flow interruption: mass exchange between the fast-flowing fractures and slow- or non-flowing regions

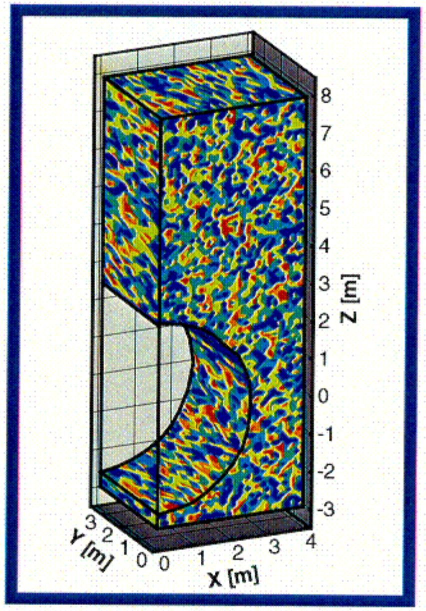


Reference: TDR-NBS-HS-000002

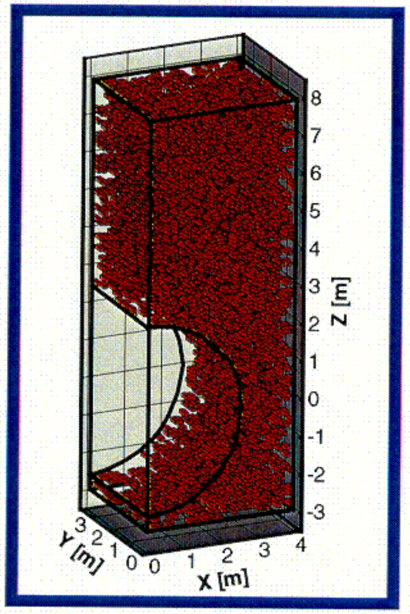
Predict Breakthrough Curves

- **Systematic Hydrological Characterization - Cross Drift**





Fracture Permeability



Lithophysal Cavities

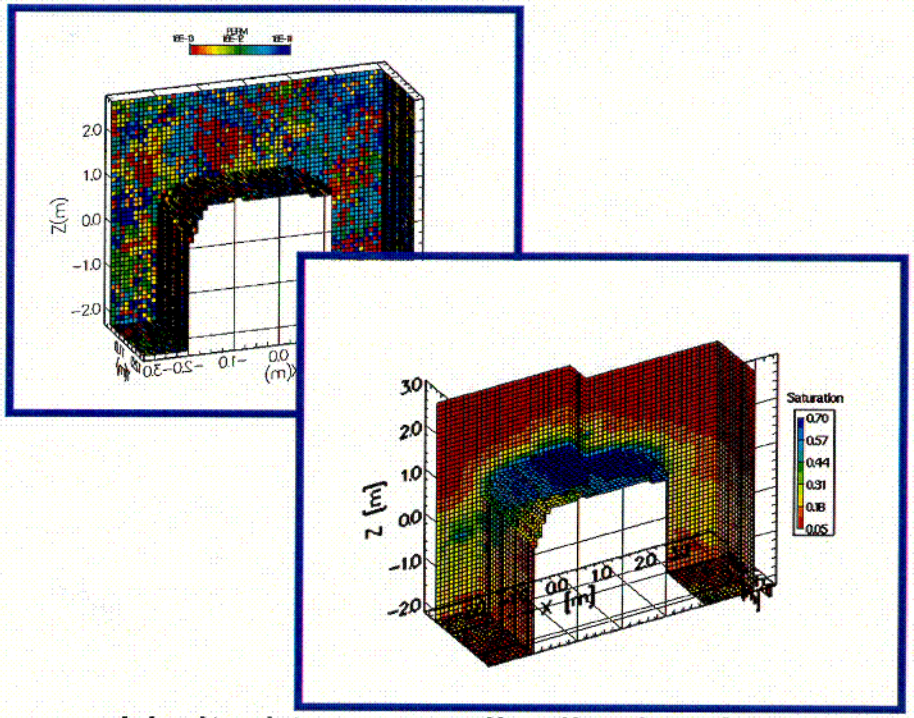
- Seepage Calibration Model is calibrated and validated with data from three zones in the Systematic Hydrological Characterization boreholes
- Ventilation effect is identified as an important process for quantification of seepage potential in open drifts

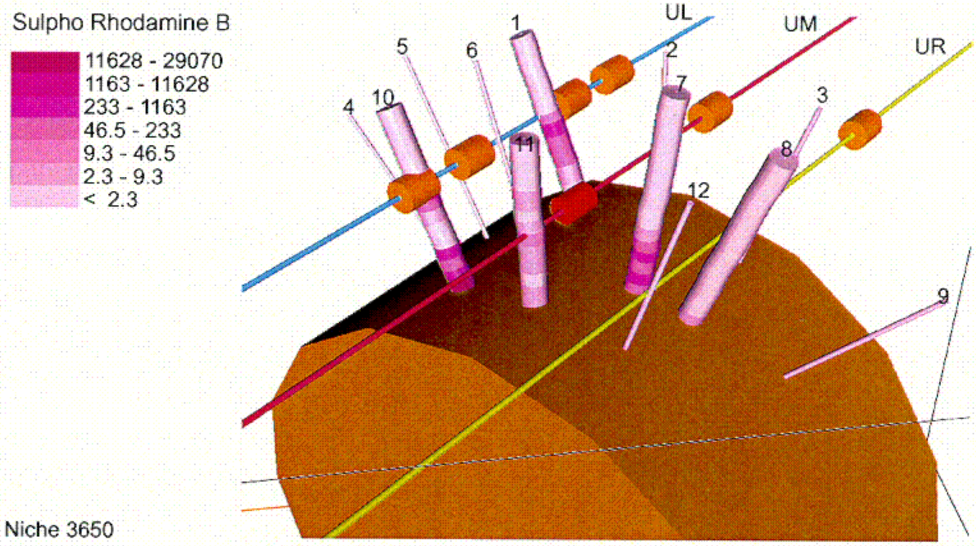
C-29

Reference: TDR-NBS-HS-000002

Predict Breakthrough Curves

- **Niche Seepage Tests in Middle Nonlithophysal Tuff**



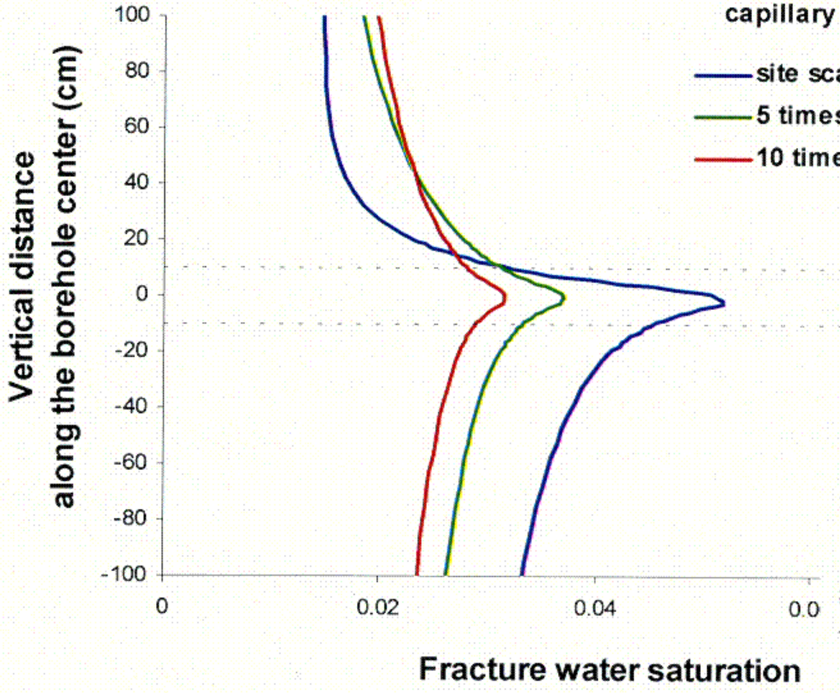


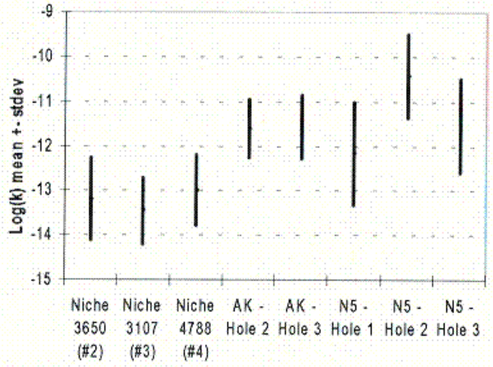
  - Limited tracer redistribution for pulse releases at Niche 4788
  - Seepage Calibration Model is used to calibrate against seepage data from nine long-term seepage experiments in Niches 3107 and 4788 (with ventilation and relative humidity controlled)
  - Validation against data from forty-nine seepage experiments in Niches 3107, 3650, and 4788

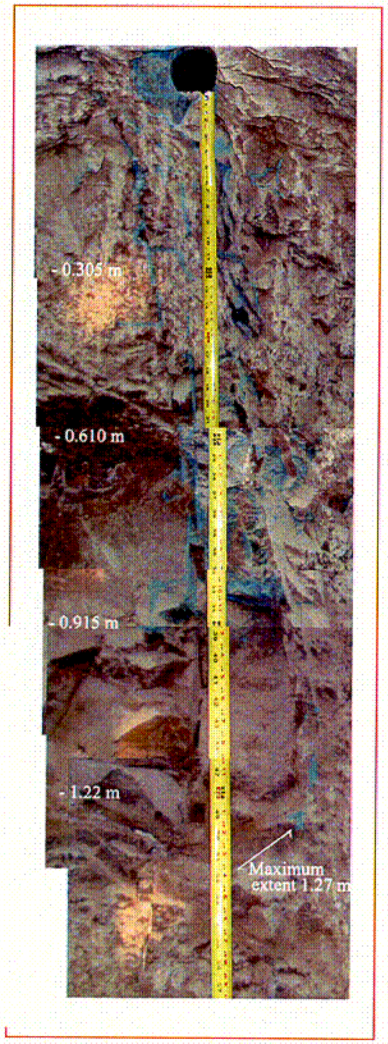
Reference: TDR-NBS-HS-000002

Predict Breakthrough Curves

- **Niche Seepage Tests in lower lithophysal tuff**
  - Potentially high seepage threshold with strong capillary strength and high permeability







Reference: TDR-NBS-HS-000002

Acceptance Criterion 2a
(Continued)

- **Basis for closure - Saturated Zone**
  - DOE has developed breakthrough curves based on C-well data. These curves were used to identify and confirm conceptual models of transport processes
  - The envelope from the uncertainty distribution for the transport parameters is sufficiently large to address the scaling of the parameters derived from the C-well data
    - Sensitivity analyses have been performed on the matrix diffusion and spanned the entire spectrum from zero to complete matrix diffusion
    - The total population in the uncertainty distribution is skewed towards negligible matrix diffusion
    - The range of matrix diffusion in the sensitivity analysis is within the uncertainty distribution range used in the performance assessment
  - Predictive modeling was completed for the C-well testing and will be documented in the upcoming C-well report
    - The predictions relative to tracer responses were consistent with the field results

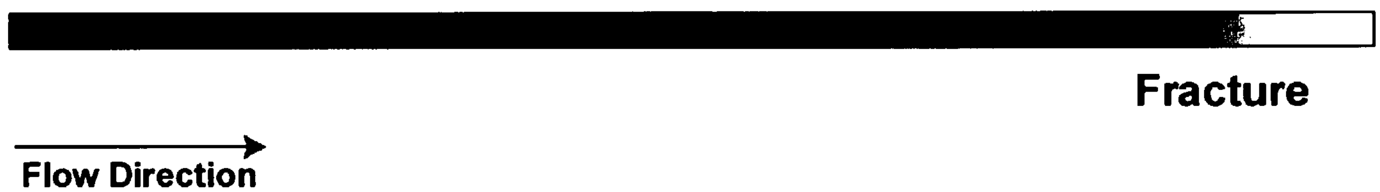
Conclusions - Saturated Zone

- **Field testing at the C-well complex provides data for saturated zone flow and transport modeling and assessment of fractured tuff units**
- **Simulated breakthrough curves match the tracer concentration data in the C-well tests**
  - The dual porosity continuum approach is valid for modeling flow and transport in saturated fractured rock

Reference: ANL-NBS-HS-000019, TDR-NBS-HS-000001, ANL-NBS-HS-000031, and work in progress

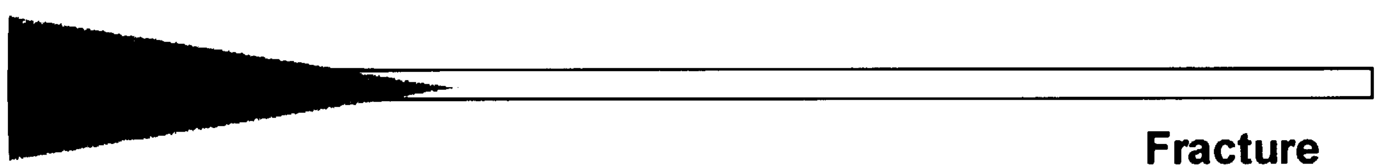
Saturated Zone Conceptual Transport Model(s)

No Matrix Diffusion



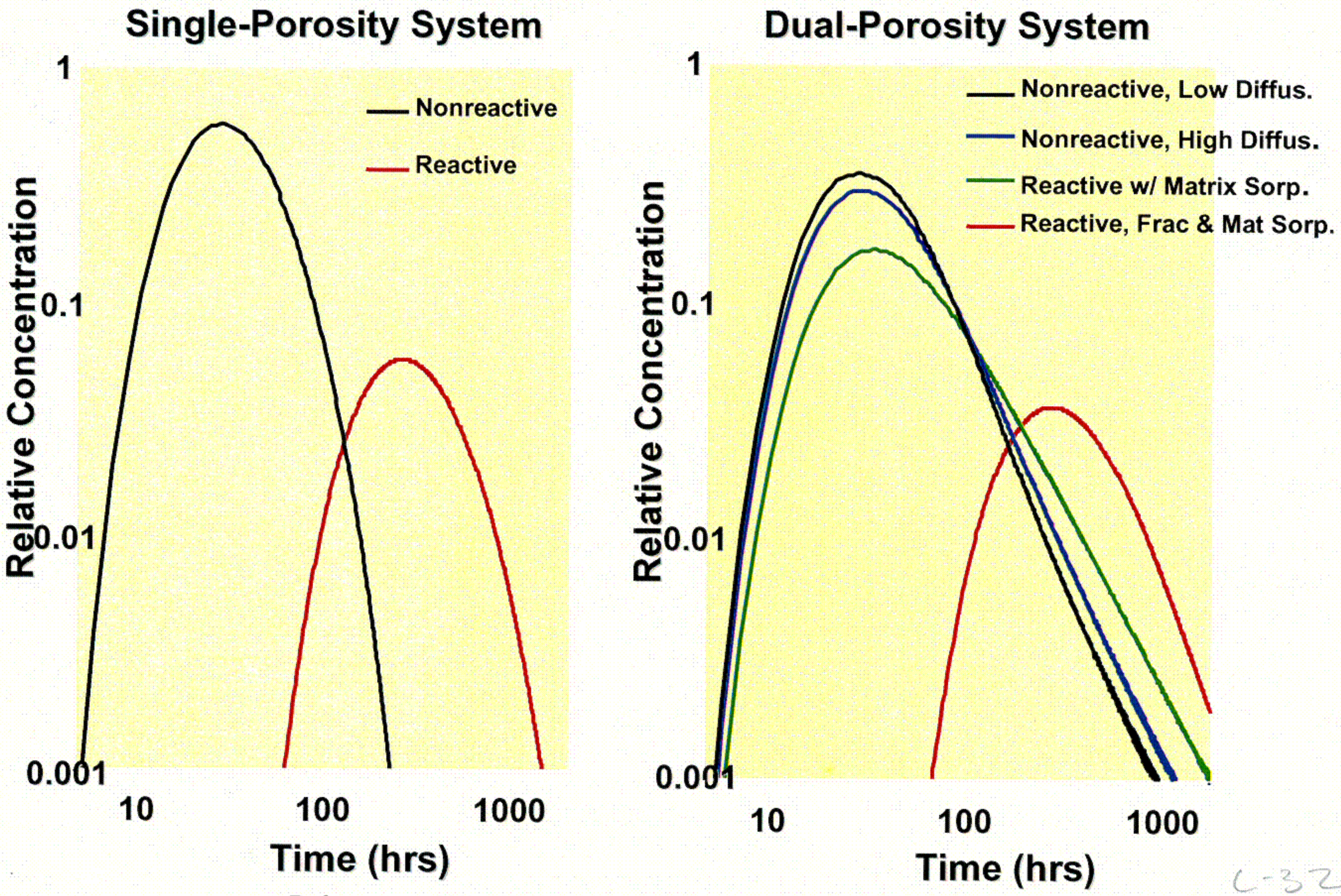
Matrix Diffusion - No Sorption

Sorption and Matrix Diffusion



Reference: ANL-NBS-HS-000019, TDR-NBS-HS-000001, and work in progress

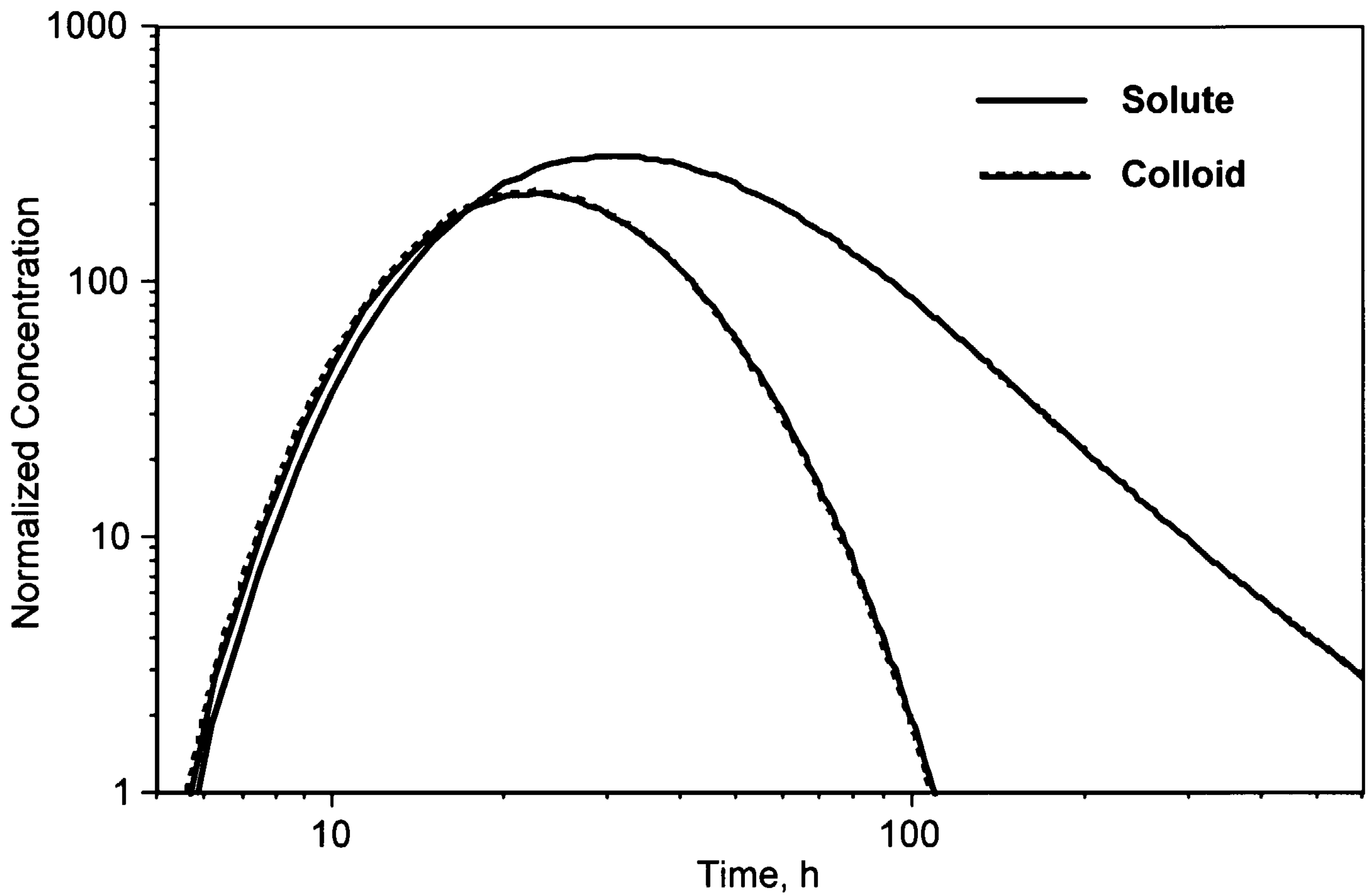
Saturated Zone Pre-Test Predictions - Solutes



C-32

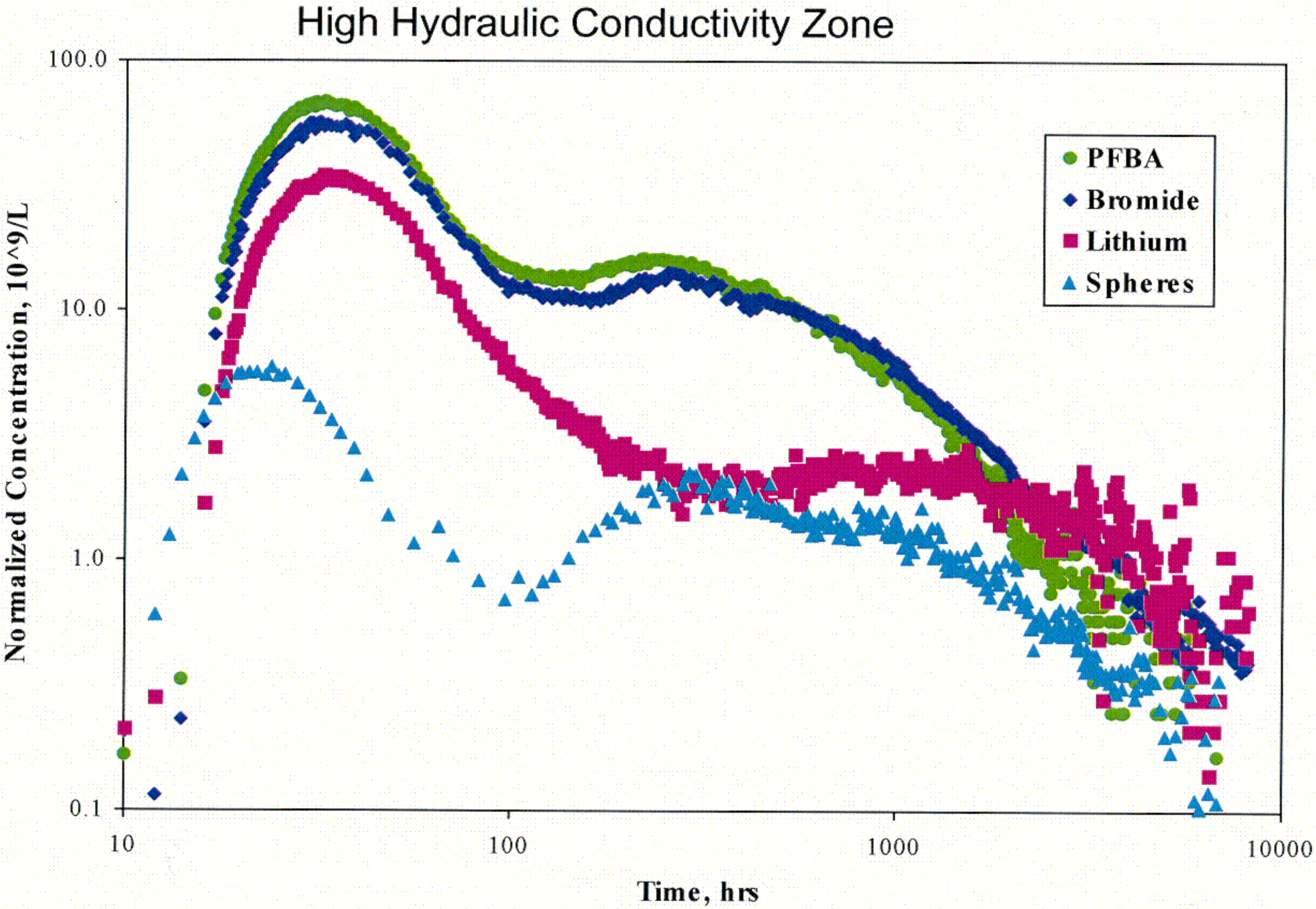
Reference: ANL-NBS-HS-000019, TDR-NBS-HS-000001, and work in progress

Saturated Zone Pre-Test Predictions - Colloids



Reference: work in progress

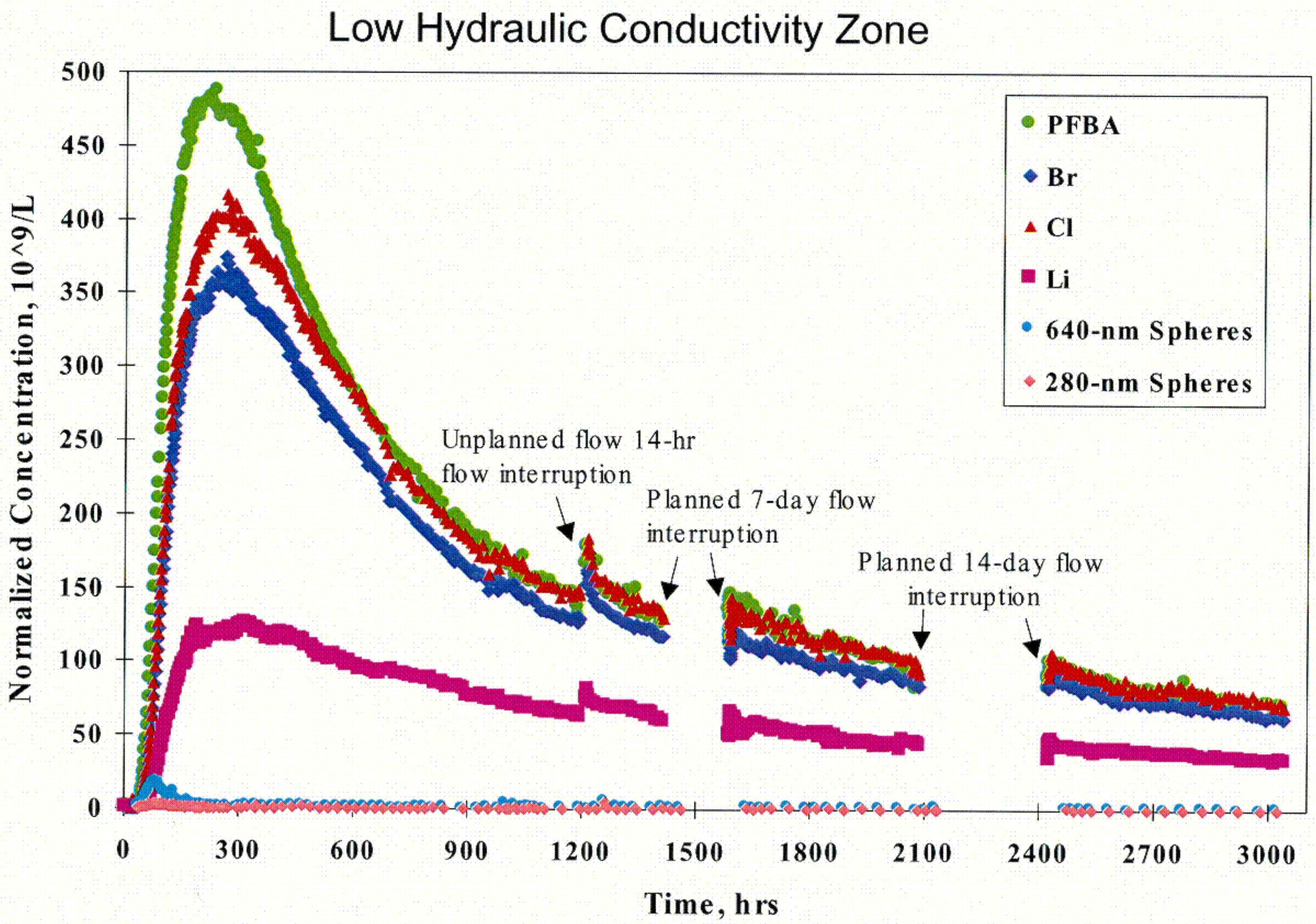
Saturated Zone Field Test Results – Bullfrog Tuff



Reference: ANL-NBS-HS-000019, TDR-NBS-HS-000001, and work in progress

C-33

Saturated Zone Field Test Results – Prow Pass Tuff

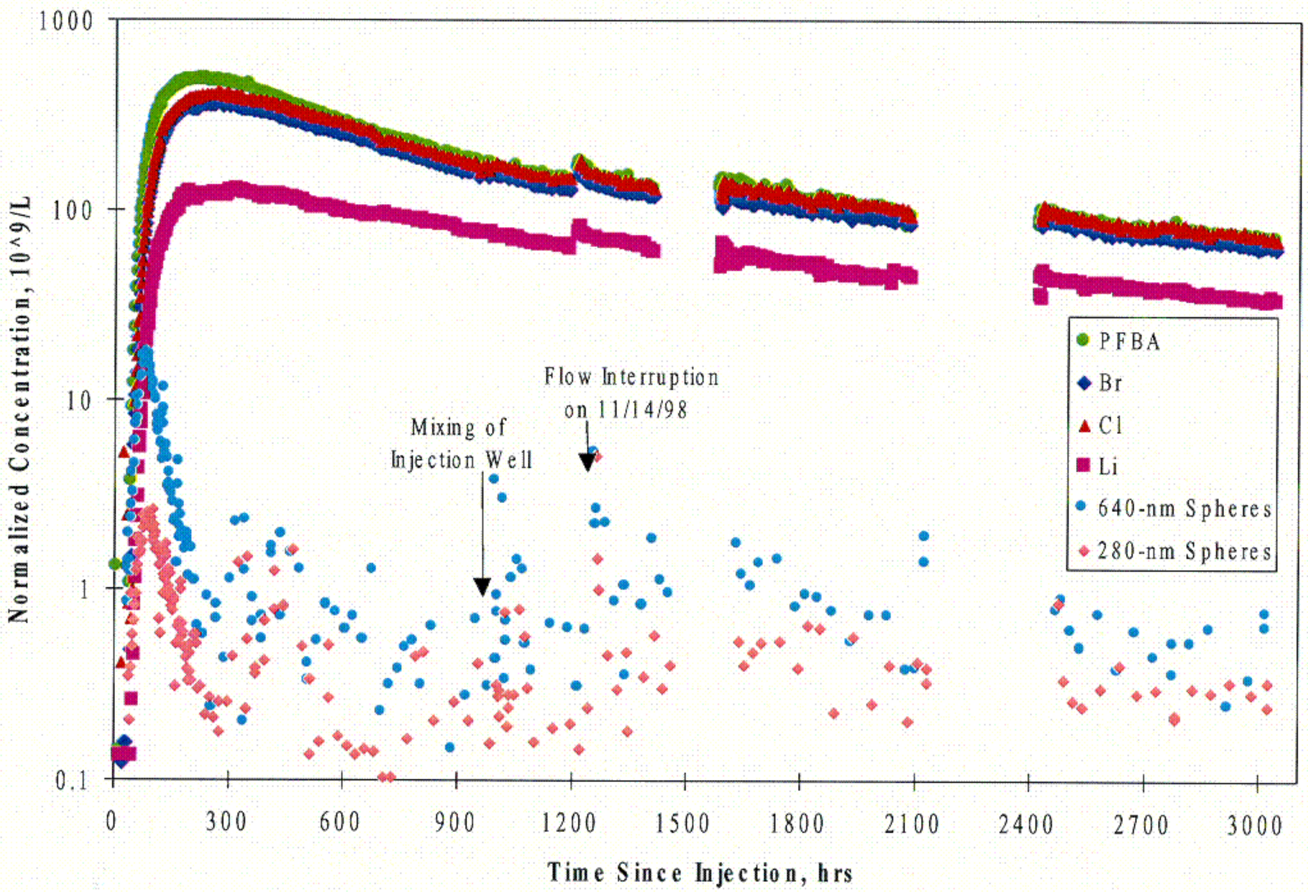


Reference: ANL-NBS-HS-000019, TDR-NBS-HS-000001, and work in progress

C-34

Predict Breakthrough Curves - Saturated Zone

C-Wells Prow Pass, Log Responses

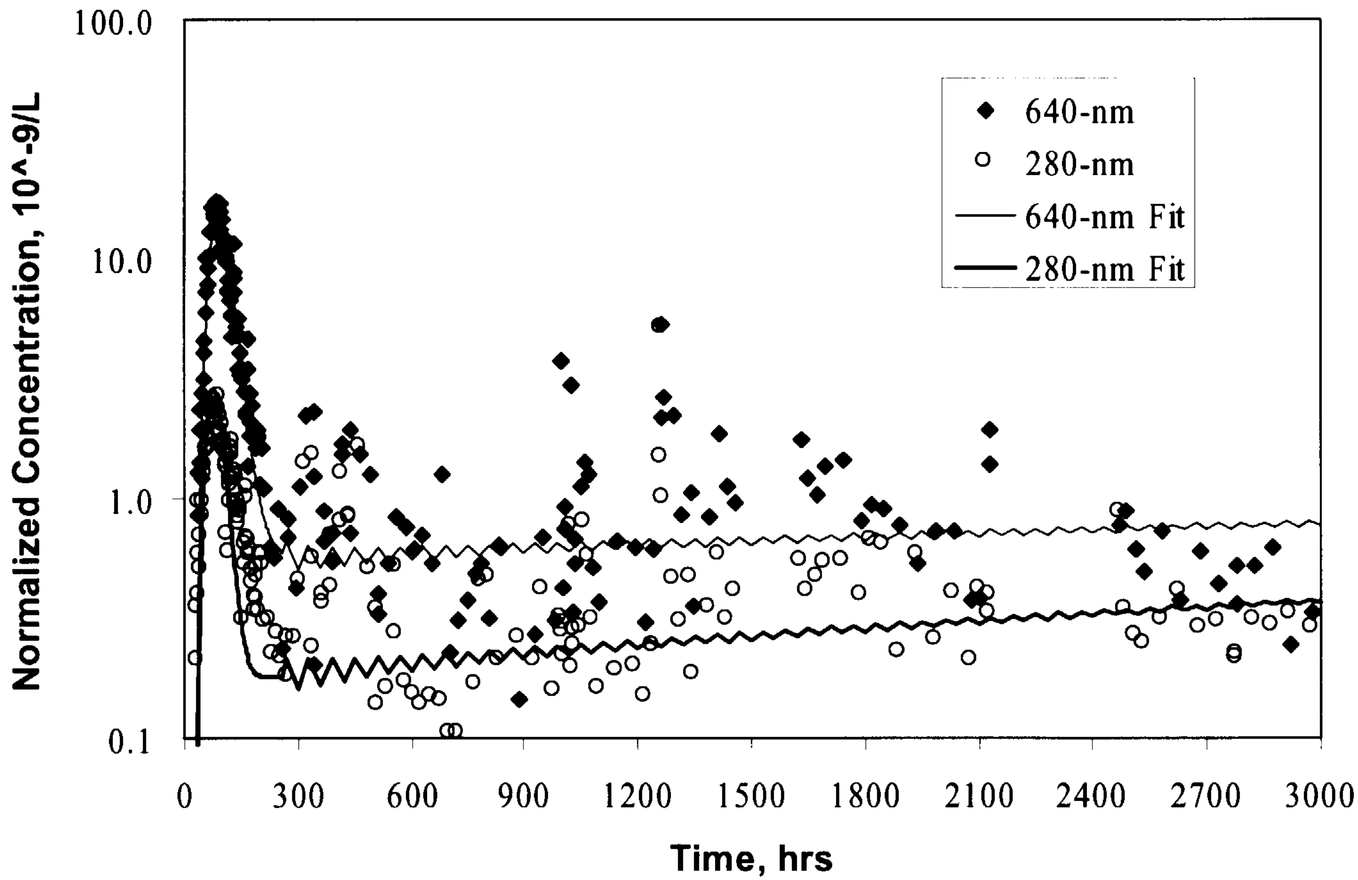


C-35

Reference: ANL-NBS-HS-000019, TDR-NBS-HS-000001, and work in progress

Predict Breakthrough Curves - Saturated Zone

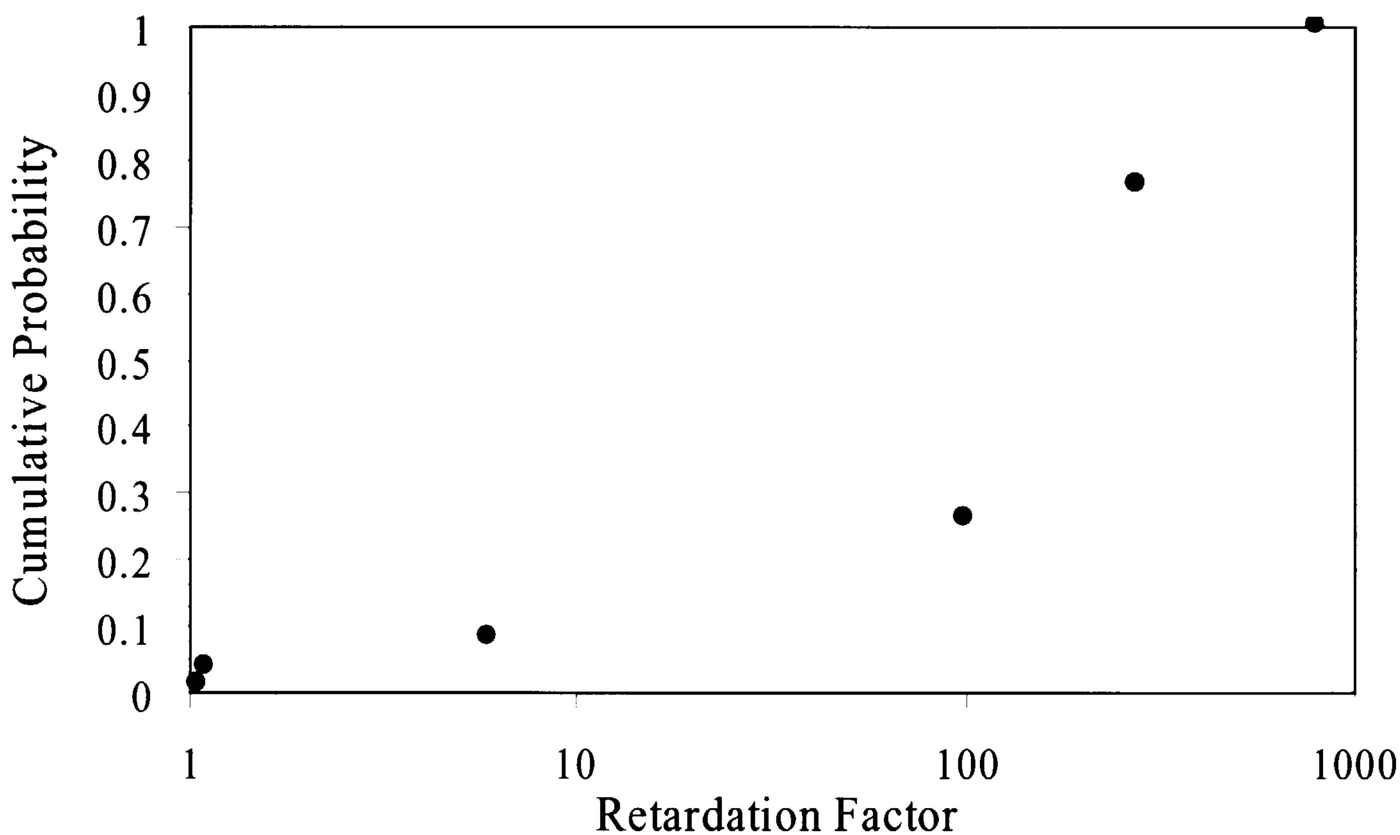
Model Fits to Prow Pass Microsphere Data



Reference: ANL-NBS-HS-000031

Predict Breakthrough Curves - Saturated Zone

Cumulative Distribution Function of Colloid Retardation Factor from C-Wells Field Tests



Reference: ANL-NBS-HS-000031

Acceptance Criterion 2a
(Continued)

- **References**
  - *Unsaturated Zone Flow and Transport Model Process Model Report* (TDR-NBS-HS-000002 REV 00 ICN 02)
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 01)
  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00)
  - Analysis and Model Report *Saturated Zone Colloid-Facilitated Transport* (ANL-NBS-HS-000031 REV 00)
- **Predictive models for transport in fractured rock in the saturated zone have been shown to adequately represent C-well test data**

Acceptance Criterion 2a
(Continued)

- DOE considers this acceptance criterion closed-pending completion of Alcove 8/Niche 3 testing and predictive modeling for the unsaturated zone

Acceptance Criterion 2b

- **Acceptance Criterion 2b: If credit is to be taken for radionuclide attenuation in fractured rock, DOE has: demonstrated nonradioactive tracers used in field tests are appropriate homologues for radioelements**
- **Action or information needs identified**
  - Demonstrate that tracers used are appropriate for characterization of radionuclide and colloidal transport

Acceptance Criterion 2b
(Continued)

- **Basis for closure - Unsaturated Zone**
  - The aqueous Br^- tracer used for Alcove 1 testing has sorption and ion size characteristics representative of I. Therefore, it is a suitable homologue for ^{129}I
  - Transport tests are being conducted in Alcove 8/Niche 3 using tracers that are representative of nonsorbing and moderately sorbing tracers in the potential repository host rock
    - Fluorobenzoic acids are nonsorbing anions with larger ion sizes similar to TcO_4^- Therefore they are suitable homologues for aqueous ^{99}Tc
    - Aqueous Li has been found to have sorption characteristics similar to moderately sorbing radionuclide isotopes of Np and U

Conclusions - Unsaturated Zone

- **Alcove 1 tests using Br^- are representative of ^{129}I behavior in fractured, welded tuff**
- **Ongoing testing at Alcove 8/Niche 3 will provide transport data using a suite of tracers representative of conservative and weakly sorbing radionuclides**

Tracers for Transport Testing

- **Alcove 8/Niche 3 Tracer Test**
  - Test objective
  - Test approaches
  - Proposed test sequence
  - Homologue tracers to be used

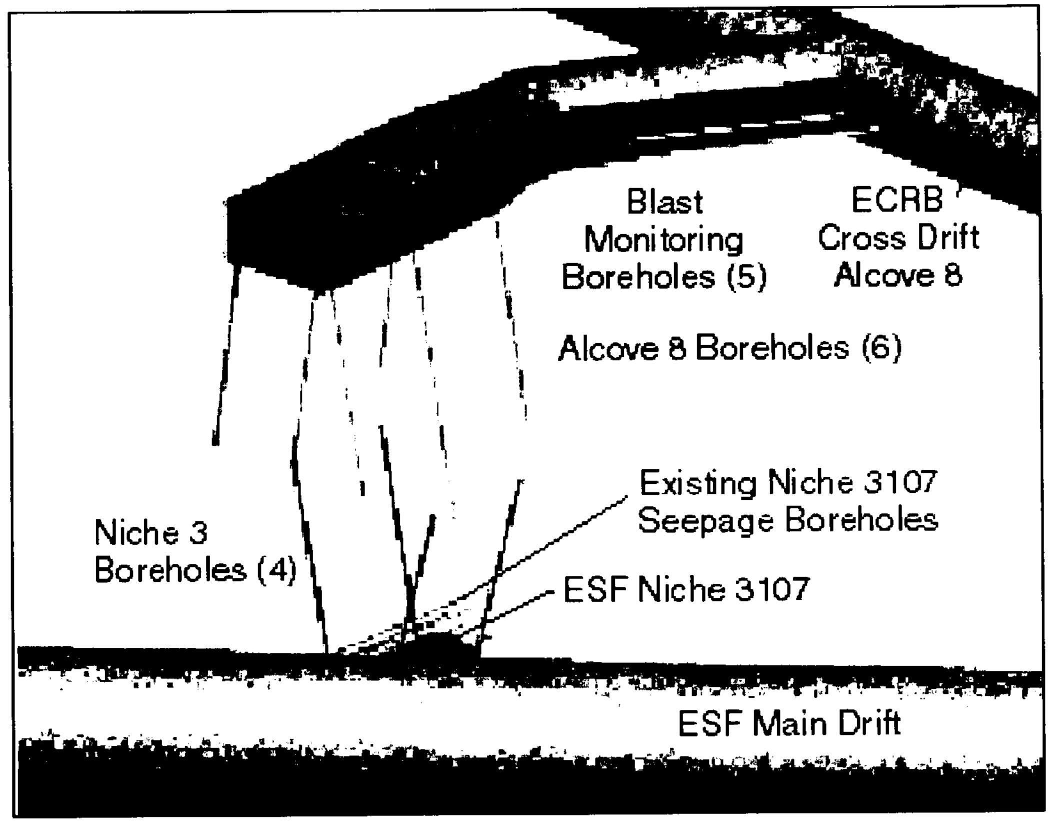
Tracers for Transport Testing

- **Objectives of Alcove 8/Niche 3 Test**
  - Evaluate flow and transport processes across an lithophysal-nonlithophysal interface
  - Quantify large-scale infiltration and seepage processes in the potential repository horizons
  - Determine fault flow and transport properties (e.g., liquid permeability, fracture characteristic curves, fracture porosity)
  - Fully demonstrate the importance of the matrix diffusion by using conservative tracers of multiple diffusivity
  - Estimate fracture/matrix interface area under both saturated and unsaturated conditions

Tracers for Transport Testing

- **Alcove 8/Niche 3 Test**

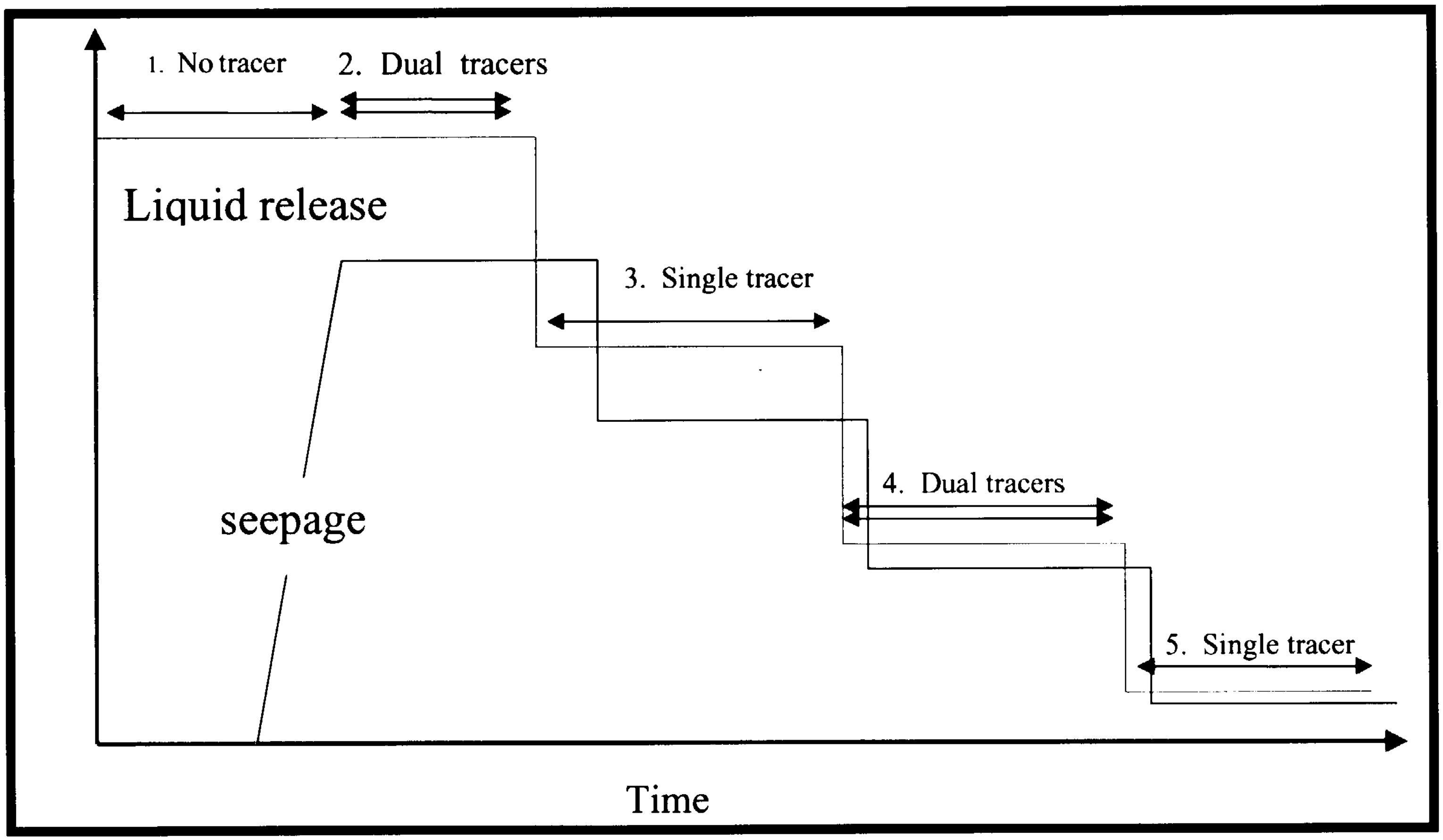
- Liquid release in Alcove 8/Niche 3 instrumented with seepage collectors and wetting front sensors
- Pre-test predictive modeling
- Analyses of tracer breakthrough curves
- Model calibration of flow and transport properties



Reference: TDR-NBS-HS-000002

Tracers for Transport Testing

- **Proposed Test Sequence at Alcove 8/Niche 3**



Reference: Work in progress - Alcove 8/Niche 3 plan

Tracers for Transport Testing

- **Tracer Application Design**

Liquid release	Tracer chemicals	Aqueous diffusion coefficient (m^2/s, 10^{-10})
Phase 1	None	NA
Phase 2	LiBr + PFBA	Br^-: 20.8; PFBA: 7.6
Phase 3	2,4-DFBA	8.1
Phase 4	Iodide + 2,6-DFBA	I^-: 20.5; 2,6-DFBA: 8.1
Phase 5	2,3,4,5-TEFBA	7.8

PFBA: pentafluorobenzoic acid
TEFBA: tetra-fluorobenzoic acid
DFBA: di-fluorobenzoic acid

Reference: Work in progress - Alcove 8/Niche 3 plan

Tracers for Transport Testing

- **Homologue Tracers at Alcove 8/Niche 3**
  - Anionic Br^- and I^- are homologues for ^{129}I. Fluorobenzoic acids are homologues for radioelements and ^{99}Tc (in the form of TcO_4^-)
  - Li is a reactive tracer and homologue for moderately sorbing radioelements (such as Np, U)
  - Other considerations
    - The main focus of Alcove 8/Niche 3 test is to address matrix diffusion, with conservative tracers mainly employed
    - Choice among sixteen derivatives of fluorinated benzoic acid tracers in different liquid release phases where multiple tracers of similar physical properties are needed
    - Similar tracers have been used in C-wells and Busted Butte tests with success

Acceptance Criterion 2b
(Continued)

- **Basis for closure - Saturated Zone**
  - C-wells tests have been conducted using PFBA, Br^-, Li, and microspheres that are representative of conservative radionuclides, sorbing radionuclides, and colloids

Conclusions - Saturated Zone

- **Dual-porosity conceptual transport model validated**
- **Laboratory-derived Li K_d values in good agreement with field K_d values (with tendency to be conservative)**

↓

- **Defensible basis for using dual-porosity transport model and laboratory-derived radionuclide K_d values for field-scale transport predictions**

Reference: ANL-NBS-HS-000019, TDR-NBS-HS-000001, and work in progress

Laboratory Batch Sorption Experiments - Comparison of Radionuclides and Homologues

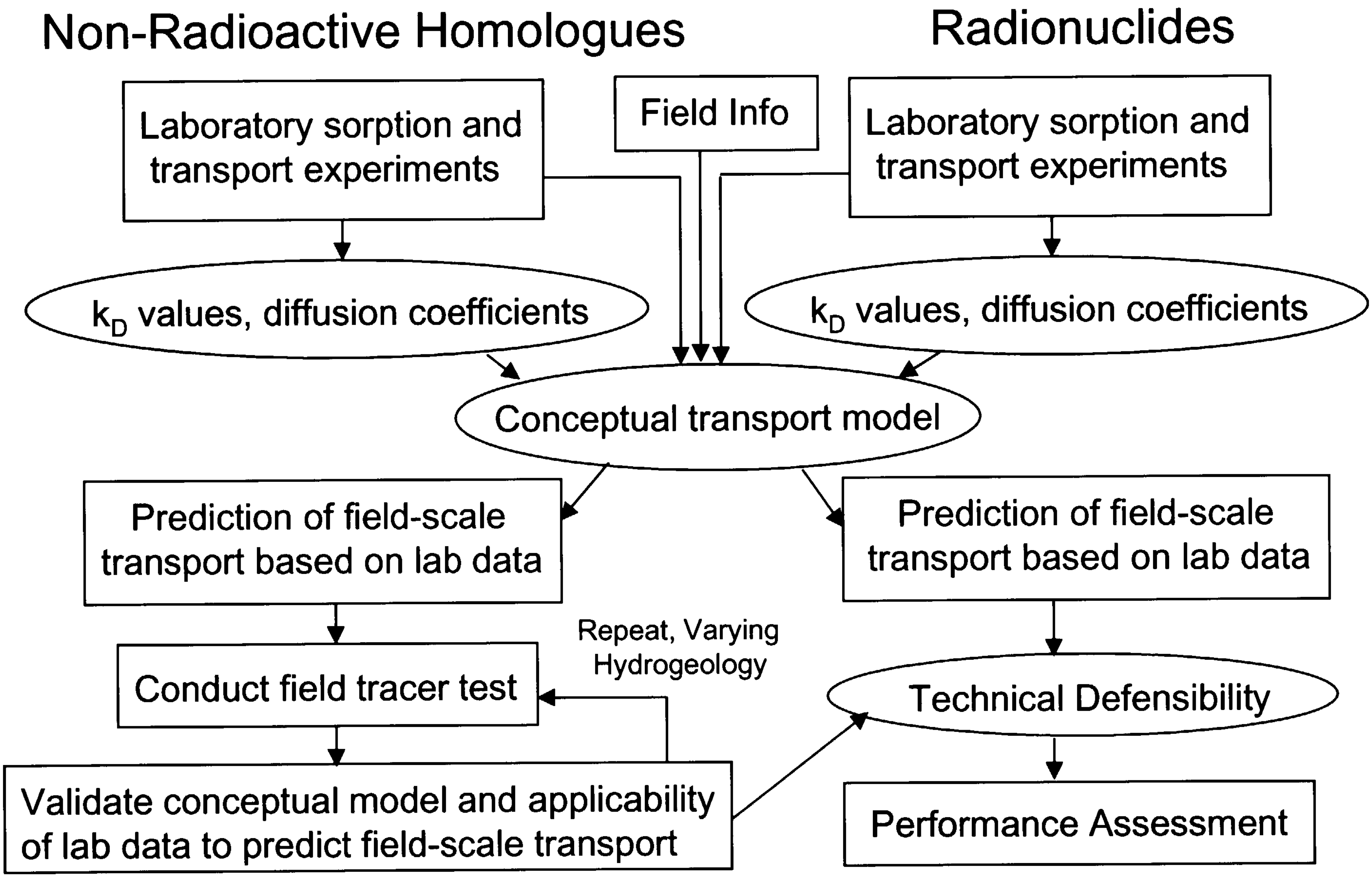
Busted Butte Laboratory Batch Sorption Test Data:

Species	*Li*	*Mn*	*Ni*	*Co*	*Np*	*Am*	*Pu*
	Approximate K_d (mL/g)						
Tptpv2	0.9	86	430	910	1.1	460	960
Tptpv1	0.4	15	48	120	0.3	360	18
Tac	1.3	98	670	1600	1.4	460	2500

- Li and Np have comparable K_ds
- Co comparable to Pu (Mn comparable for Tptpv1)
- Ni comparable to Am

Reference: ANL-NBS-HS-000019, work in Progress

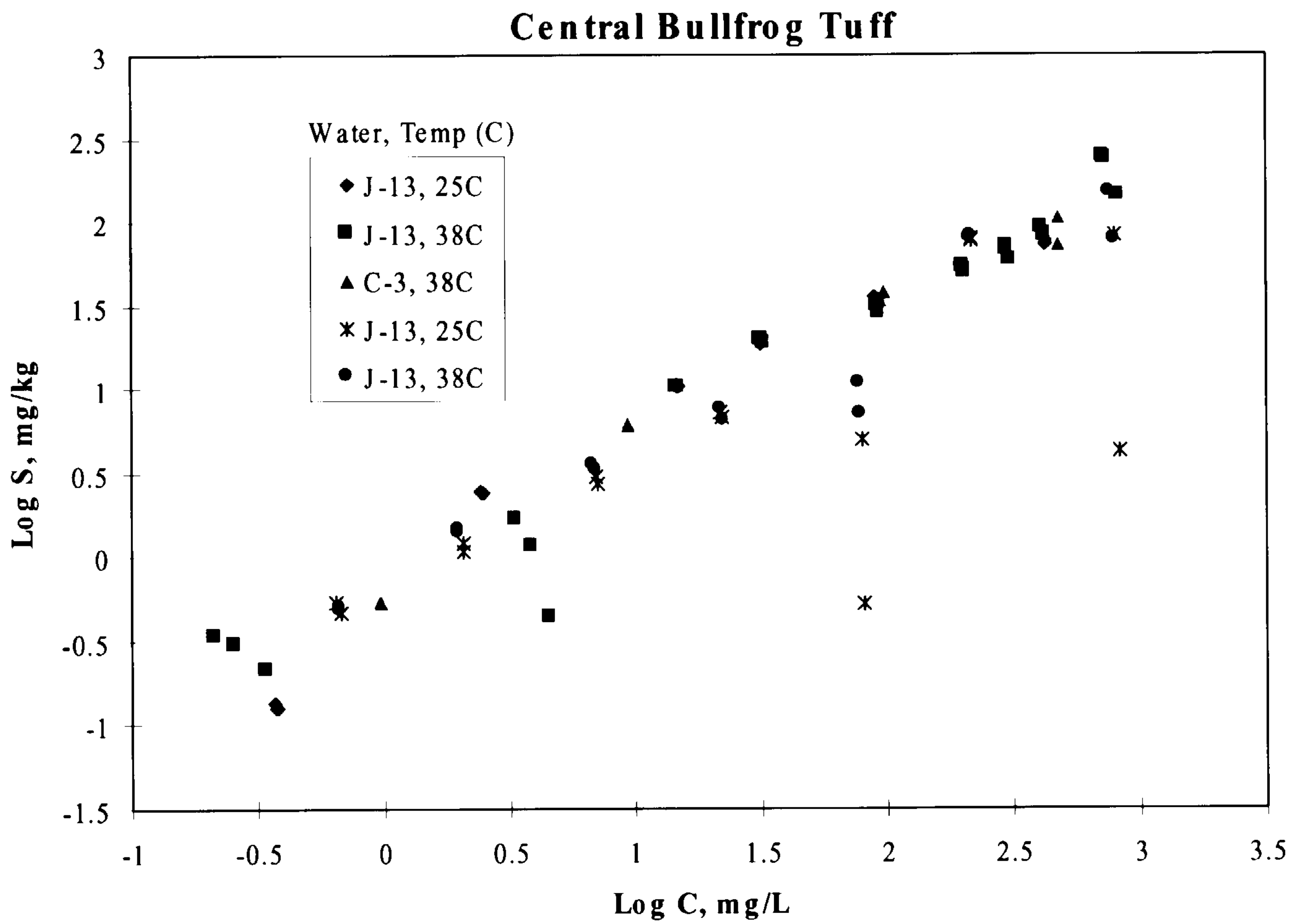
SZ Strategy for Resolution



Reference: ANL-NBS-HS-000019, TDR-NBS-HS-000001, and work in progress

Tracers for Transport Testing - Saturated Zone

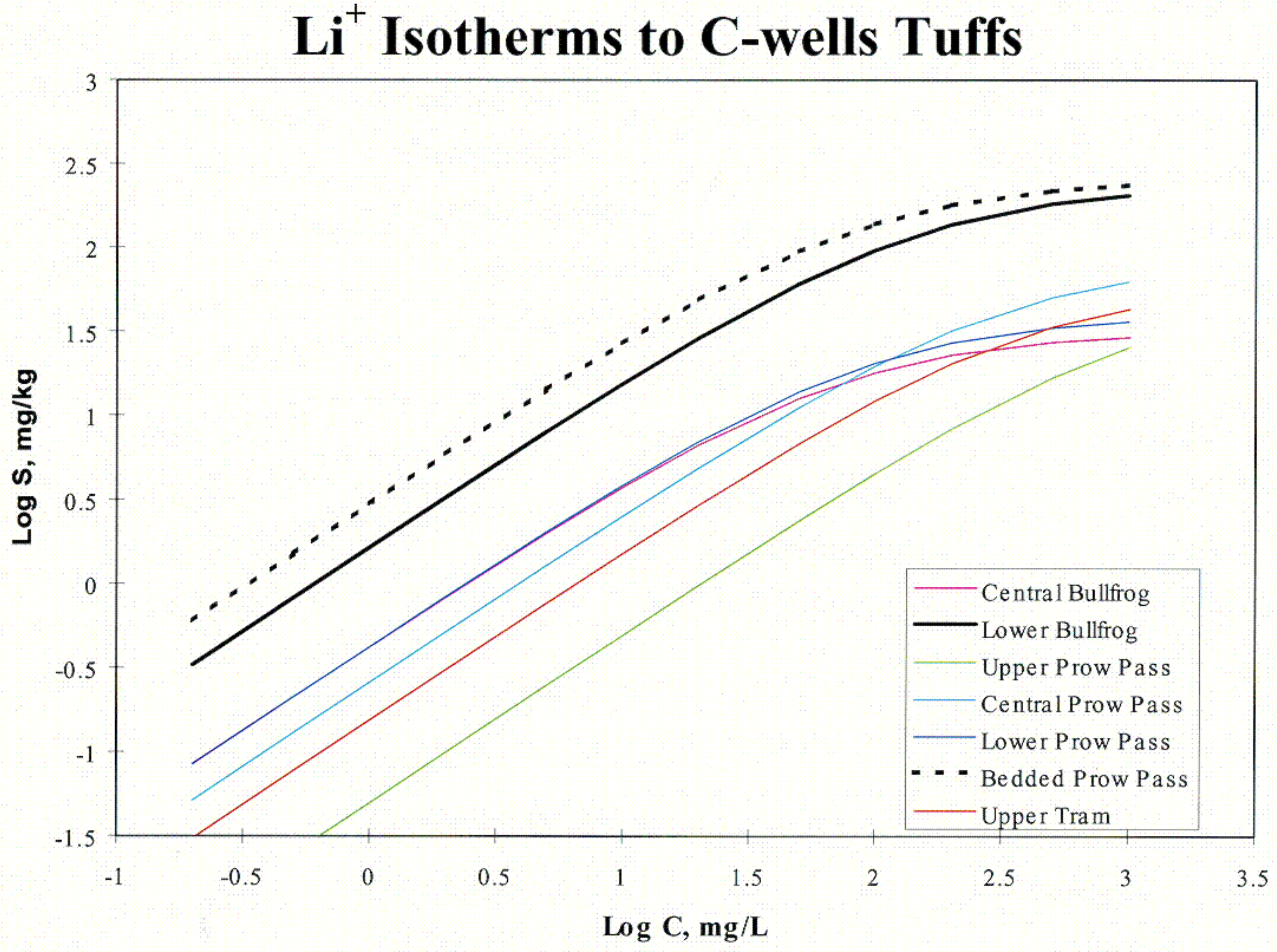
Li$^+$ Batch Sorption Test Results



S=sorbed concentration; C=concentration in solution

Reference: work in progress

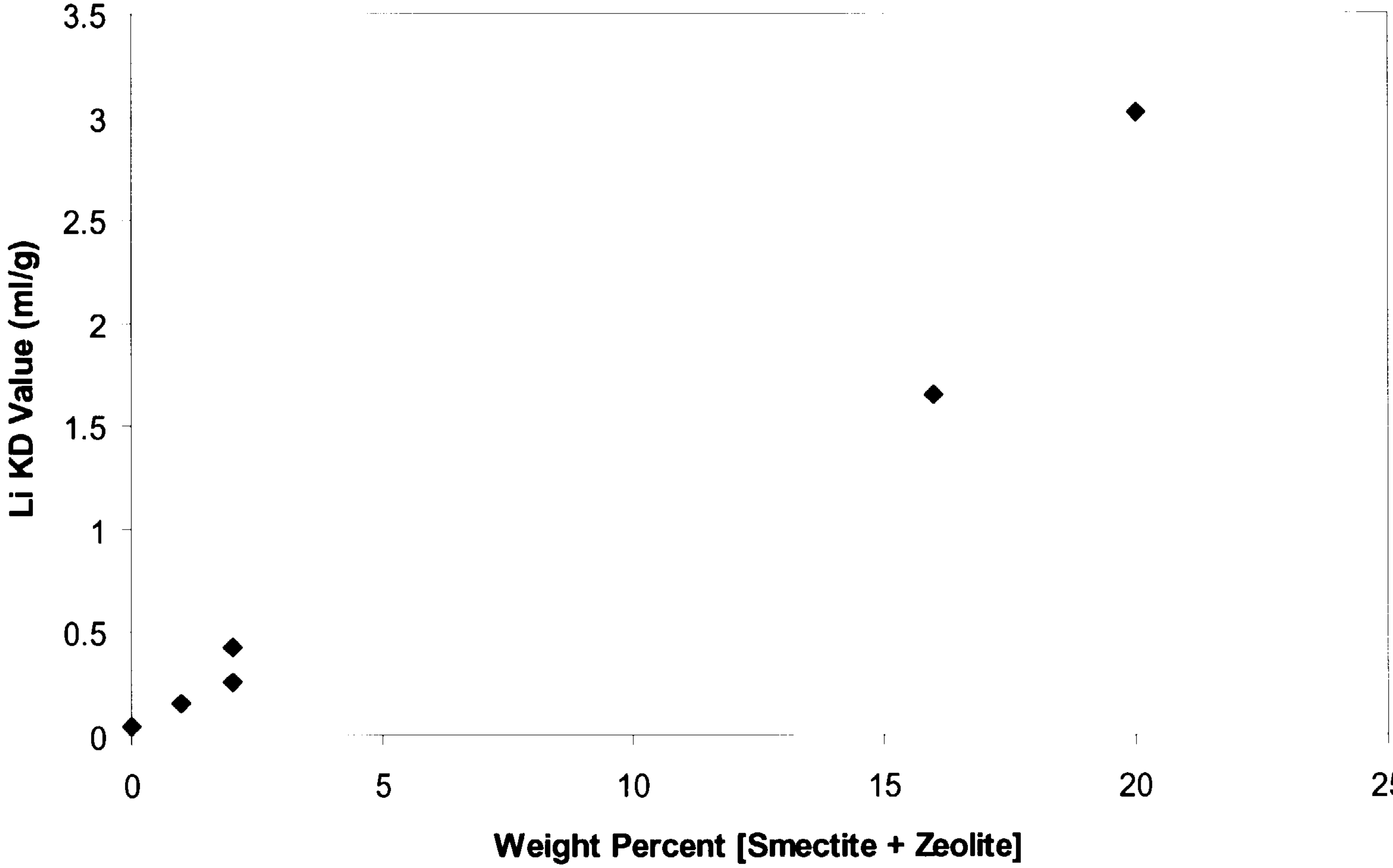
Tracers for Transport Testing - Saturated Zone



S=sorbed concentration; C=concentration in solution

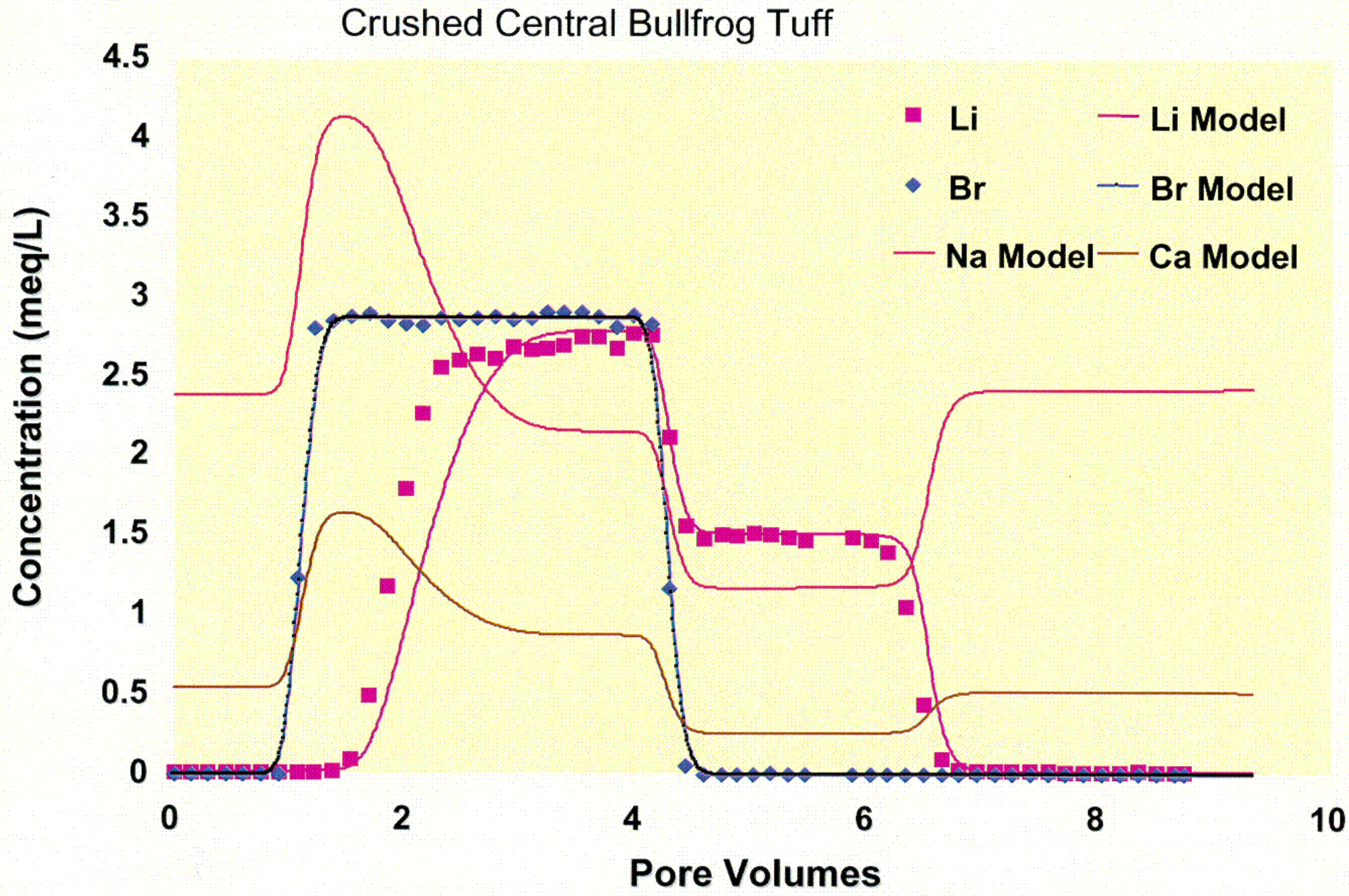
Reference: work in progress

Dependence of Li^+ Sorption on Mineralogy



Reference: ANL-NBS-HS-000019, TDR-NBS-HS-000001, and work in progress

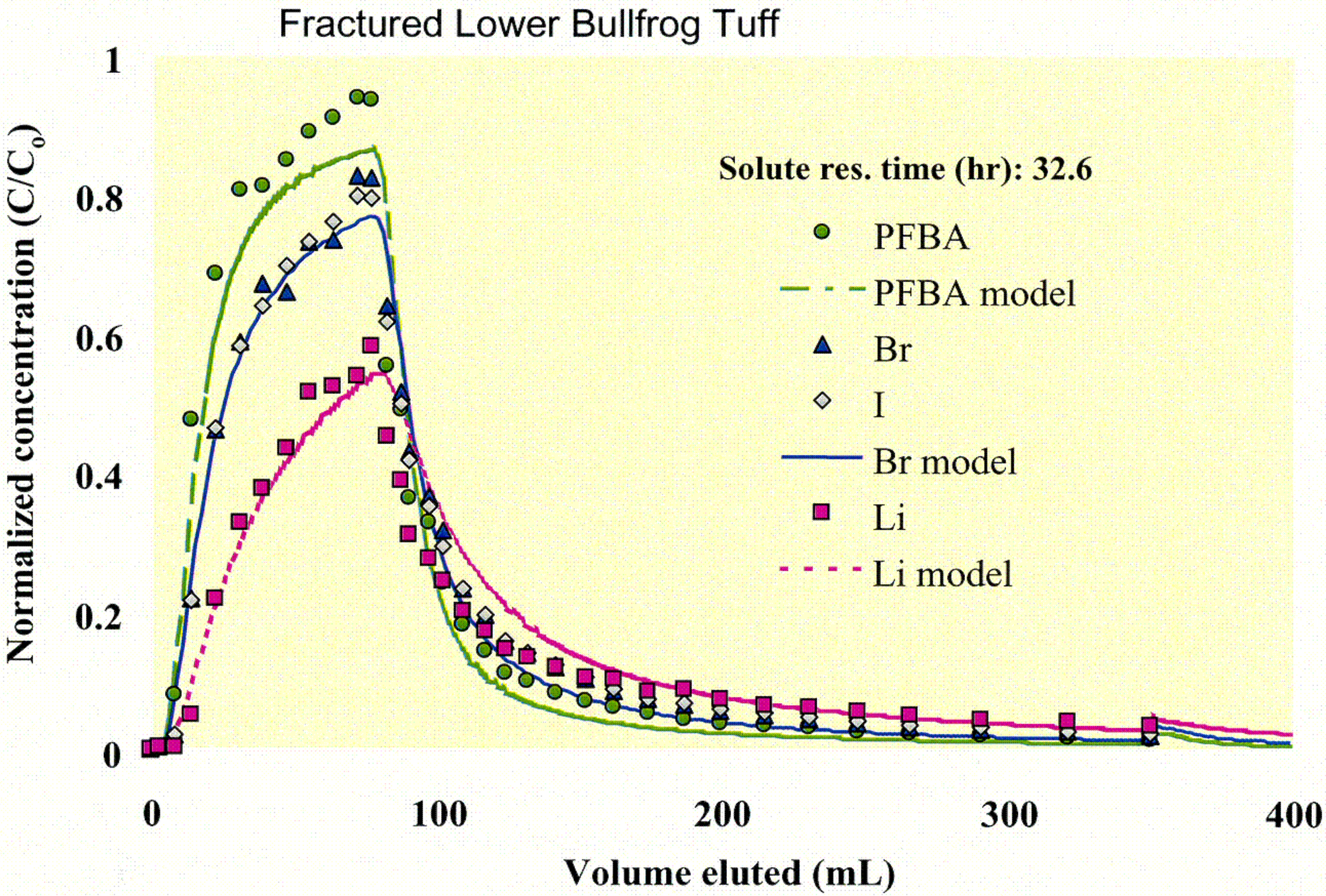
Laboratory Column Experiments - Li^+



Reference: work in progress

C-37

Laboratory Column Experiments - Li^+

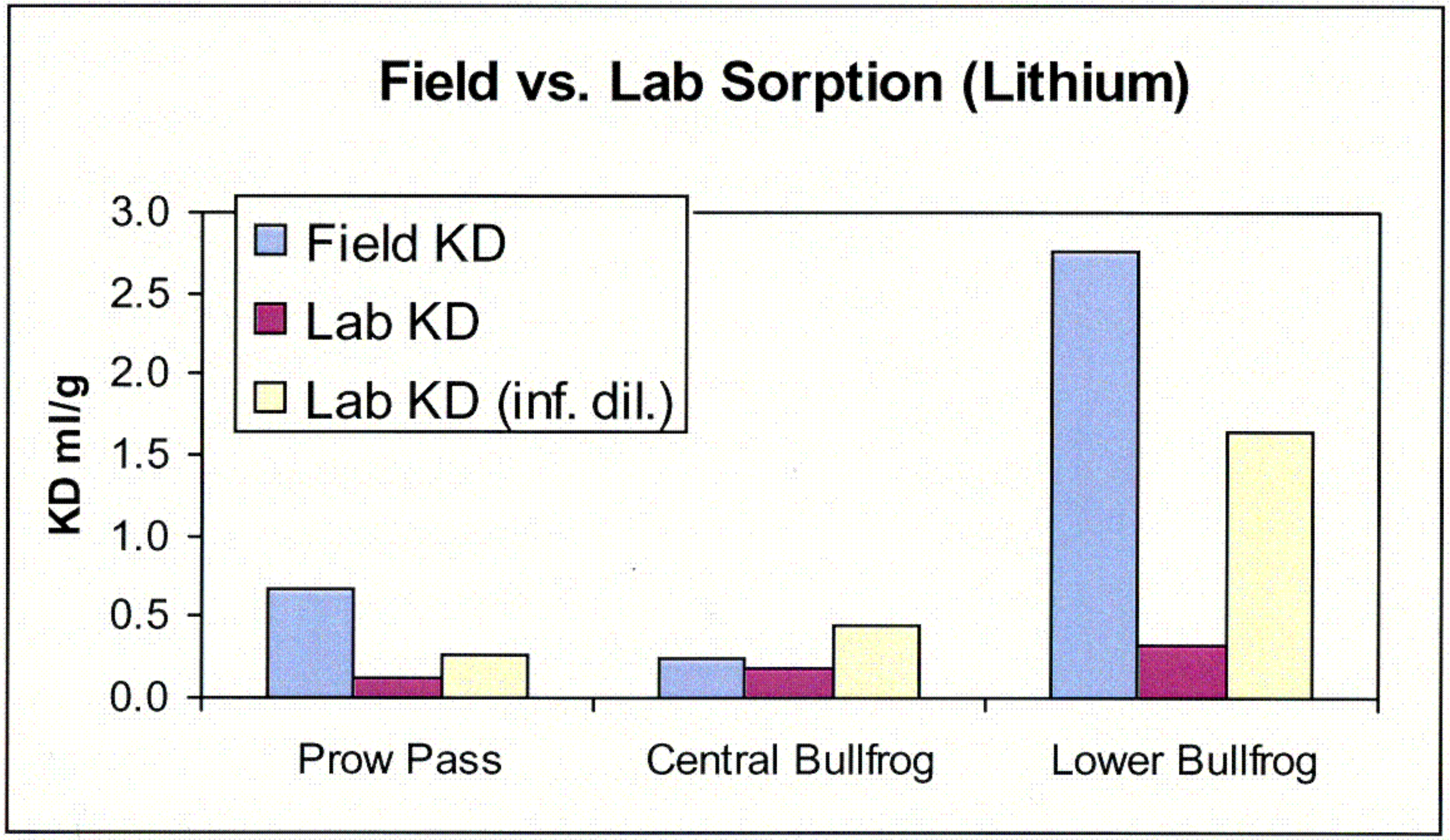


Tracers for Transport Testing - Saturated Zone

- **Procedure for Estimating Field K_ds**
  - Obtain mean residence time, dispersivity, and matrix diffusion parameters for conservative tracers based on simultaneous fit to tracer responses
  - Assume these parameters apply to Li, with the exception that the matrix diffusion parameter is twice that of PFBA and 2/3rds that of Br^-
  - Adjust matrix retardation factor, R_m, to obtain a fit to the Li response
  - Obtain estimate of Li K_d from $K_d = \phi(R_m-1)/\rho_b$ using best estimates of ϕ and ρ_b from available data

Tracers for Transport Testing - Saturated Zone

Comparison of C-wells Lab and Field K_ds



C-39

Acceptance Criterion 2b
(Continued)

- **References**
  - *Unsaturated Zone Flow and Transport Model Process Model Report* (TDR-NBS-HS-000002 REV 00 ICN 02)
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 01)
  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00)

- **Appropriate tracers have been identified for use in testing to represent transport of non-sorbing and sorbing radionuclides and colloids**

- **Tests using these tracers have been conducted at C-wells, Busted Butte, and Alcove 1. Similar tracer tests are being conducted at Alcove 8/Niche 3. DOE considers this criterion closed**

Acceptance Criterion 2c

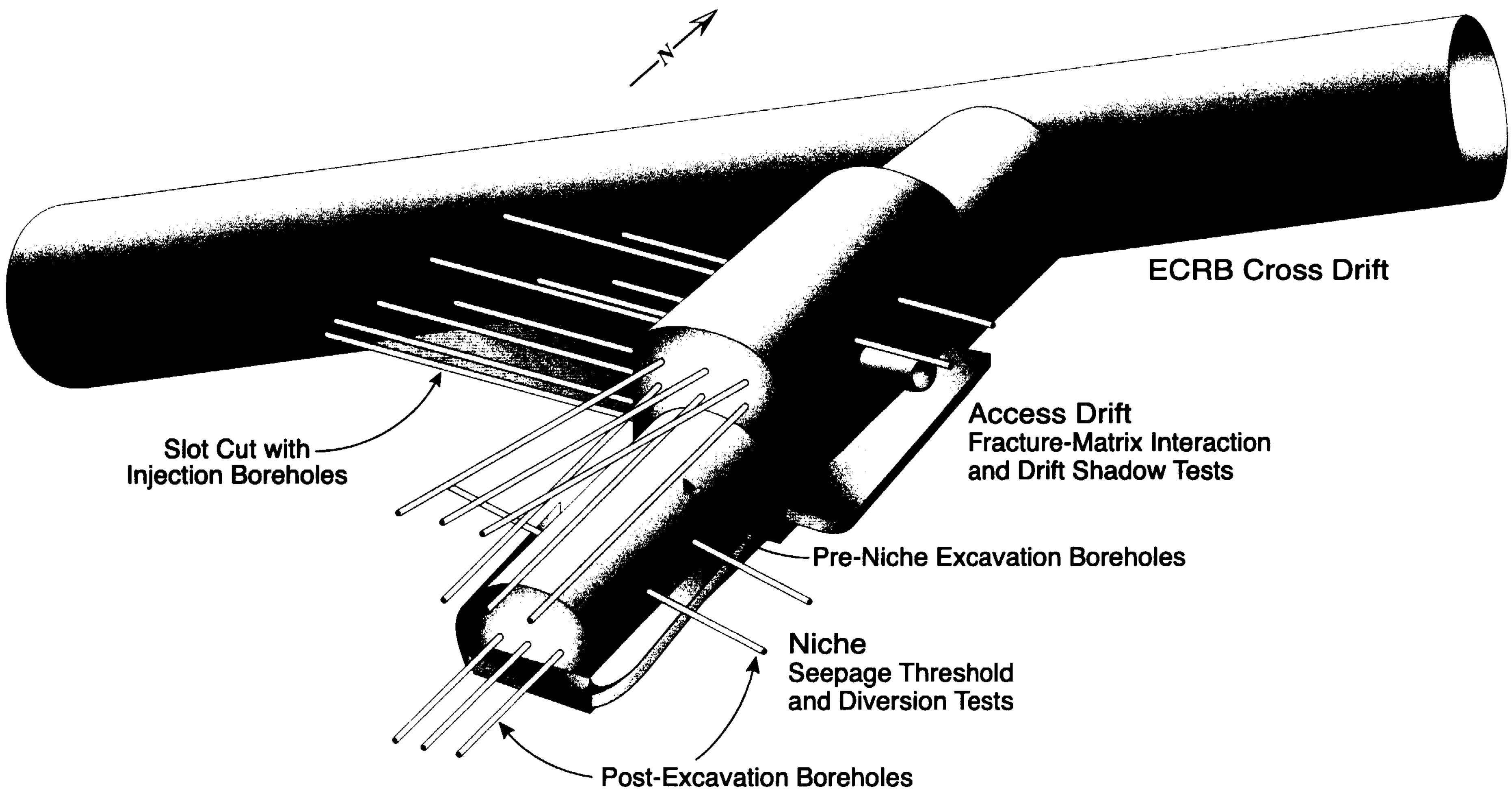
- **Acceptance Criterion 2c: For the estimation of radionuclide transport through fractured rock, DOE has: justified the length of flowpath to which these fracture transport conditions apply**
- **Action or information needs identified**
  - Justify length of flow path affected by fracture dominated transport
- **Basis for closure**
  - This is the same as Acceptance Criterion 1C. Refer to discussions for Acceptance Criterion 1C

Acceptance Criterion 3

- **Acceptance Criterion 3: Where data are not reasonably or practicably obtained, expert judgement has been used and expert elicitation procedures have been adequately documented. If used, expert elicitations were conducted and documented in accordance with the guidance in NUREG-1563 or other acceptable approaches**
- **Action or information needs identified**
  - None
- **Basis for closure**
  - DOE based conclusions regarding radionuclide transport in fractured rock on laboratory and field testing, as well as on models. Expert elicitation and expert judgement were not used
- **DOE considers this criterion closed**

Conclusions

- DOE has met criteria 1a, 1b, 1c, 2b, 2c, and 3
- Additional testing is planned to meet criterion 2a for the unsaturated zone in Alcove 8/Niche 3
- For the saturated zone, criterion 2a is considered closed-pending completion of the C-wells report
- Therefore, DOE considers this subissue closed-pending


N
ECRB Cross Drift
Access Drift
Fracture-Matrix Interaction
and Drift Shadow Tests
Slot Cut with
Injection Boreholes
Pre-Niche Excavation Boreholes
Niche
Seepage Threshold
and Diversion Tests
Post-Excavation Boreholes

AT01-003

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

Radionuclide Transport Key Technical Issue, Subissue 2, Radionuclide Transport Through Alluvium

Presented to:
DOE-NRC Technical Exchange on the Radionuclide Transport Key Technical Issue

Presented by:
Al Aziz Eddebbarh, Ph.D
Paul Reimus, Ph.D
Arend Meijer, Ph.D
Civilian Radioactive Waste Management System Management and Operating Contractor

December 5-7, 2000
Lawrence Berkeley National Laboratory
Berkeley, CA

YUCCA MOUNTAIN PROJECT

Outline

- **Presentation Objectives**
- **Current Subissue Status**
- **For items identified in the Radionuclide Transport Issue Resolution Status Report Rev. 02, this presentation will:**
  - Summarize technical basis for item resolution
  - Identify basis documents (References)
  - Summarize technical adequacy of basis
- **Conclusions**

Note: Additional summary information is provided in the "delta analysis"

Presentation Objectives

- **Describe the basis for resolving Subissue 2, Radionuclide Transport Through Alluvium, of the Radionuclide Transport Rev. 02**
  - Acceptance Criterion 1a: Department of Energy (DOE) has determined through Performance Assessment calculations that attenuation processes such as sorption, radioactive decay and colloidal filtration are important to performance. DOE considers this criterion closed
  - Acceptance Criterion 1b: DOE has (i) assumed K_d is zero or (ii) demonstrated that Criteria 2 or 3 has been met. K_d for Tc and I are not statistically different from zero. DOE considers this criterion closed

Presentation Objectives
(Continued)

- **Describe the basis for resolving Subissue 2, Radionuclide Transport Through Alluvium, of the Radionuclide Transport Rev. 02 (Continued)**
  - Acceptance Criterion 2a: DOE has demonstrated that the flow path acts as a single continuum. DOE determined that the alluvium acts as a single continuum porous medium. DOE considers this criterion closed-pending tests at the Alluvium Testing Complex to confirm hydraulic and transport parameters for the alluvium
  - Acceptance Criterion 2b: DOE has demonstrated that appropriate parameters have been adequately considered. DOE considers this criterion closed-pending tests at the Alluvium Testing Complex to experimentally obtain hydraulic and transport parameters for the alluvium
  - Acceptance Criterion 2c: DOE demonstrated that assumptions are valid. DOE considers this criterion closed-pending column and batch experiments to confirm the use of linear isotherm

Presentation Objectives

(Continued)

- **Describe the basis for resolving Subissue 2, Radionuclide Transport Through Alluvium, of the Radionuclide Transport Rev. 02 (Continued)**
  - Acceptance Criterion 3a: "Process model approach" Method not used. DOE considers this criterion closed
  - Acceptance Criterion 3b: "Process model approach" Method not used. DOE considers this criterion closed
  - Acceptance Criterion 3c: "Process model approach" Method not used. DOE considers this criterion closed
  - Acceptance Criterion 4: Expert Elicitation - DOE did not use expert elicitation for development of K_ds for the alluvium. DOE considers this criterion closed-pending additional documentation of expert judgement
  - Acceptance Criterion 5: Quality Assurance - Not addressed at this Technical Exchange

Current Subissue Status

- **Radionuclide Transport Issue Resolution Status Report, Rev. 02 indicates this Subissue is OPEN:**
  - Data gaps exist with respect to important transport characteristics of the alluvium
  - The potential for preferential pathways requires additional study
  - Confirmation is needed that the alluvium behaves as a continuum porous medium

NOTE: This subissue is applicable only to the saturated zone models

Acceptance Criterion 1a

- **Acceptance Criterion 1a: DOE has determined through Performance Assessment calculations whether radionuclide attenuation processes such as sorption, precipitation, radioactive decay, and colloidal filtration are important to performance**
- **Action or information needs identified**
  - None identified

Acceptance Criterion 1a
(Continued)

- **Basis for closure**
  - DOE has determined through performance assessment that radionuclide attenuation processes such as sorption, radioactive decay, and colloidal filtration are important to performance
  - The estimation of radionuclide transport through the alluvium and its importance to performance is documented in Total System Performance Assessment-Site Recommendation, Rev. 0, the Saturated Zone Process Model Report and related analysis model reports
  - Issue Resolution Status Report, Rev. 2 indicates that this Acceptance Criterion has been met for radionuclides important to performance

Acceptance Criterion 1a
(Continued)

- **References**
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 02)
  - Analysis and Model Report *Uncertainty Distributions for Stochastic Parameters* (ANL-NBS-MD-000011)
  - Analysis and Model Report *Input and Results of the Base Case Saturated Zone Flow and Transport Model for TSPA* (ANL-NBS-HS-000030)
- **No further work required, DOE considers this acceptance criterion closed. Performance assessment calculations have been used to determine whether radionuclide attenuation processes are important to performance**

Acceptance Criterion 1b

- **Acceptance Criterion 1b: DOE has (i) Assumed K_d is zero and radionuclides travel at the rate of the groundwater flow, if it has been found that radionuclide attenuation is unimportant to performance and it can be demonstrated that this assumption is conservative in which case, Acceptance Criteria 2 and 3 do not have to be met or, (ii) demonstrated that Criterion 2 or 3 has been met, if radionuclide attenuation in porous rock {sic: Alluvium} is important to performance, or if an assumption that K_d is zero in porous rock {sic: Alluvium} is not conservative**
- **Action or information needs identified**
  - Describe plans to confirm K_d values for Np, Tc, and I

Acceptance Criterion 1b
(Continued)

- **Basis for closure**
  - Ongoing and planned testing at the Alluvium Testing Complex will help confirm applicability of laboratory transport parameters used for Np, as addressed under Acceptance Criterion 2
  - Total System Performance Assessment for the Site Recommendation, Rev. 00 used K_d values that were greater than zero, but very small (less than 1 ml/gm) based on preliminary data for Tc and I
  - Ongoing experimental data have determined that K_d values for Tc and I as measured in the alluvium are not statistically different from zero under oxidizing conditions
  - Based on the newer data, DOE is planning to use values of zero for Tc and I under oxidizing conditions in Total System Performance Assessment for the Site Recommendation, Rev. 01

Acceptance Criterion 1b
(Continued)

- **References**
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 01)
  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00)
  - Analysis and Model Report *Uncertainty Distributions for Stochastic Parameters* (ANL-NBS-MD-000011)
  - Analysis and Model Report *Input and Results of the Base Case Saturated Zone Flow and Transport Model for TSPA* (ANL-NBS-HS-000030)
- **No further work needed, DOE considers this acceptance criterion closed. Tc and I will be treated as having K_d values of zero in Total System Performance Assessment- Site Recommendation, Rev. 01**
- **Np will be addressed under Acceptance Criterion 2**

Acceptance Criterion 2a

- **Acceptance Criterion 2a: For the valid application of the constant K_d approach, equation (1) $R_f=1+\rho_b K_d/n$, (or $R_f=1+\rho_b K_d/\theta$), DOE has: Demonstrated that the flow path acts as a single continuum porous medium. If the flow can not be shown to be a single continuum porous medium, then the acceptance criteria for radionuclide transport in fractured rock apply**
- **Action or information needs identified**
  - DOE needs to justify the assumption of homogeneity

Acceptance Criterion 2a
(Continued)

- **Basis for closure**
  - For the purpose of Total System Performance Assessment and over large scales, the alluvium can be modeled as a single continuum porous medium. This will be confirmed by testing at the Alluvium Testing Complex
- **References**
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 01)
  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00)
  - Analysis and Model Report *Uncertainty Distributions for Stochastic Parameters* (ANL-NBS-MD-000011)
  - Analysis and Model Report *Input and Results of the Base Case Saturated Zone Flow and Transport Model for TSPA* (ANL-NBS-HS-000030)

Acceptance Criterion 2a
(Continued)

- **No further work beyond the ongoing and planned testing at the Alluvium Testing Complex is required**
- **DOE considers this acceptance criterion closed-pending completion of ongoing and planned Alluvium Testing Complex testing**

Assumption of Homogeneity for Alluvium

- **Basis for resolution**
  - The heterogeneity in the medium is incorporated through the use of the distribution of the effective porosity in the alluvium which is less than total porosity. The use of the effective porosity reflects the channelization of flow caused by heterogeneity
- **References**
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 01)
  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00)
  - Analysis and Model Report *Uncertainty Distributions for Stochastic Parameters* (ANL-NBS-MD-000011)
  - Analysis and Model Report *Input and Results of the Base Case Saturated Zone Flow and Transport Model for TSPA* (ANL-NBS-HS-000030)
- **This information need is resolved because DOE treats this medium as heterogeneous**

Acceptance Criterion 2b

- **Acceptance Criterion 2b: For the valid application of the constant K_d approach, equation (1)$R_f=1+\rho_b K_d/n$, (or $R_f = 1 + \rho_b K_d/\theta$), DOE has demonstrated that appropriate values for parameters, K_d, n or θ, and ρ_b have been adequately considered (e.g., experimentally determined or measured)**
- **Action or information needs identified**
  - Need to verify that K_d values from batch sorption experiments provide realistic (or conservative) predictions of field-scale transport of sorbing radionuclides

Acceptance Criterion 2b
(Continued)

- **Basis for closure**
  - DOE is using preliminary transport parameter values derived from lab measurements for use in performance assessment analyses. DOE will refine and confirm these parameter values after multiple well tracer testing of radionuclide surrogates at the Alluvium Testing Complex and after laboratory column radionuclide transport studies
- **References**
  - Alluvium Testing Complex work planning document
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 01)
  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00)
  - Analysis and Model Report *Uncertainty Distributions for Stochastic Parameters* (ANL-NBS-MD-000011)
  - Analysis and Model Report *Input and Results of the Base Case Saturated Zone Flow and Transport Model for TSPA* (ANL-NBS-HS-000030)

Acceptance Criterion 2b
(Continued)

- **No further work beyond the ongoing and planned testing at the Alluvium Testing Complex is required**
- **DOE considers this acceptance criterion closed-pending completion of ongoing and planned Alluvium Testing Complex testing and laboratory transport studies**

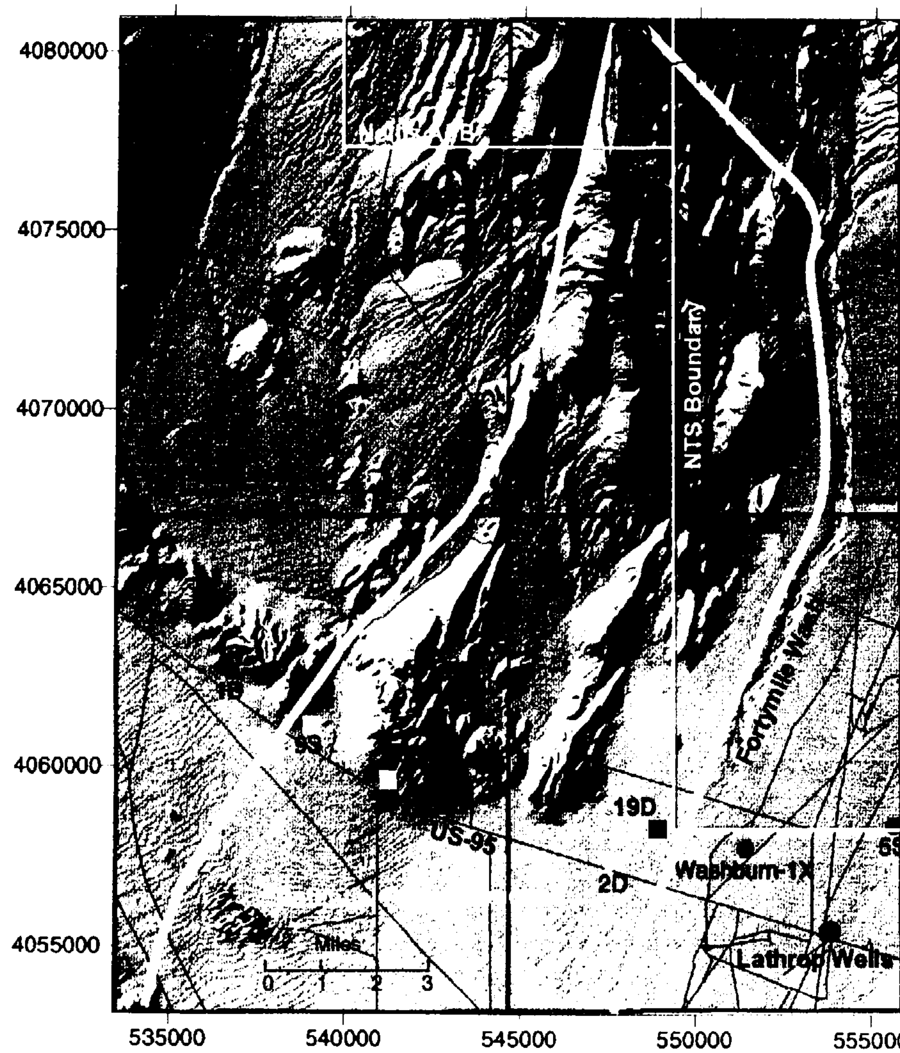
Conclusions from Alluvium Batch and Column Studies

- No I^- or TcO_4^- sorption to alluvium under oxidizing conditions
- NpO_2^+ sorption highly dependent on clay (smectite) and zeolite (clinoptilolite) content of alluvium
- Column experiments demonstrate potential for less retardation under flowing conditions than may be deduced from batch experiments

Reference: ANL-NBS-HS-000019 and work in progress

Alluvium K_d Values Derived From Lab Studies

- **Alluvium from three Nye County wells**
- **Water from EWDP-03s**
- **Batch studies with I^-, TcO_4^-, and NpO_2^+**
- **Column studies (three nuclides) in two columns packed with EWDP-03s material**



Reference: ANL-NBS-HS-000019

Experimental Matrix - Batch Studies

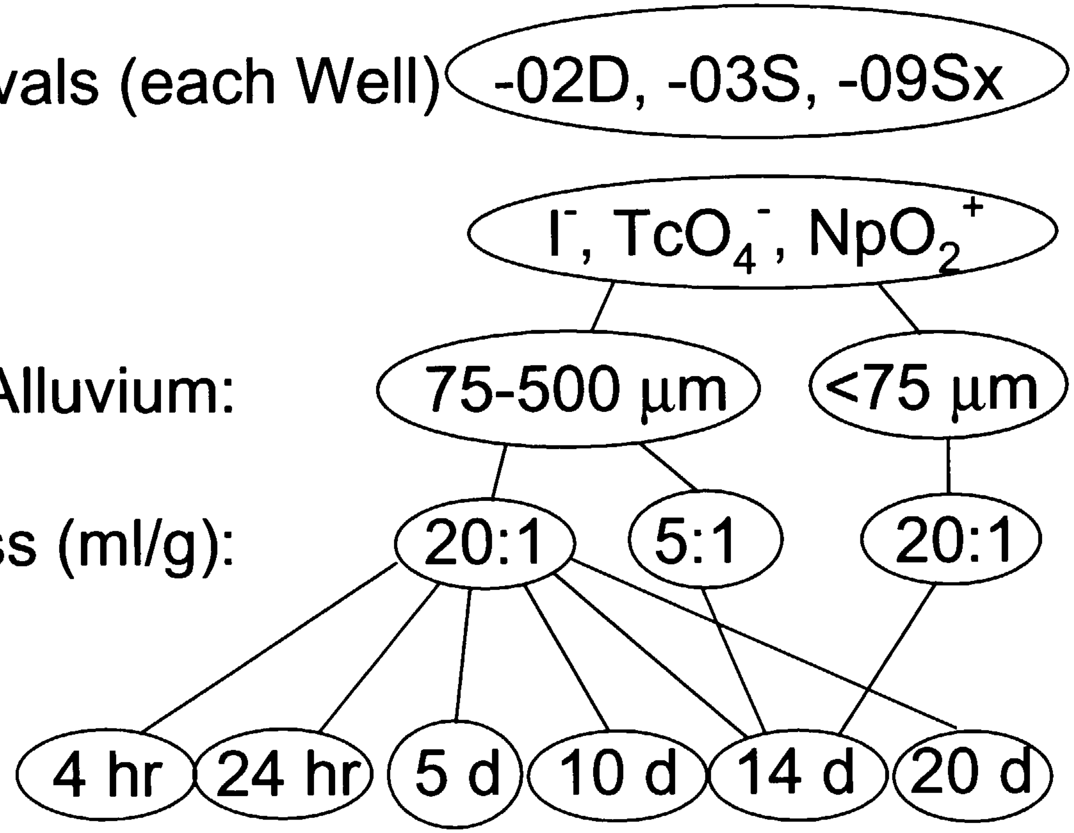
4 Adjacent 5-ft Intervals (each Well)

3 Radionuclides:

2 Size Fractions of Alluvium:

Soln. Vol./Rock Mass (ml/g):

Sorption Kinetics



Water from EWDP-03S used in all experiments
- All experiments performed in duplicate

Reference: ANL-NBS-HS-000019 and work in progress

Alluvium Column Studies

- **2 Columns**
  - 1-centimeter diameter X 60-centimeter long
  - Material from EWDP-03S, 65-70 feet below land surface
  - 75-500 μm, wet sieved
  - Column porosity = 0.45
  - Water from EWDP-03S
- **^{3}HHO used as conservative tracer with each radionuclide (I^-, TcO_4^-, NpO_2^+) in each column**
  - Flow rate of about 2 ml/hr (~10-hr residence time), reduced to 0.5 ml/hr late in test

Reference: ANL-NBS-HS-000019 and work in progress

EWDP-03S Groundwater Chemistry

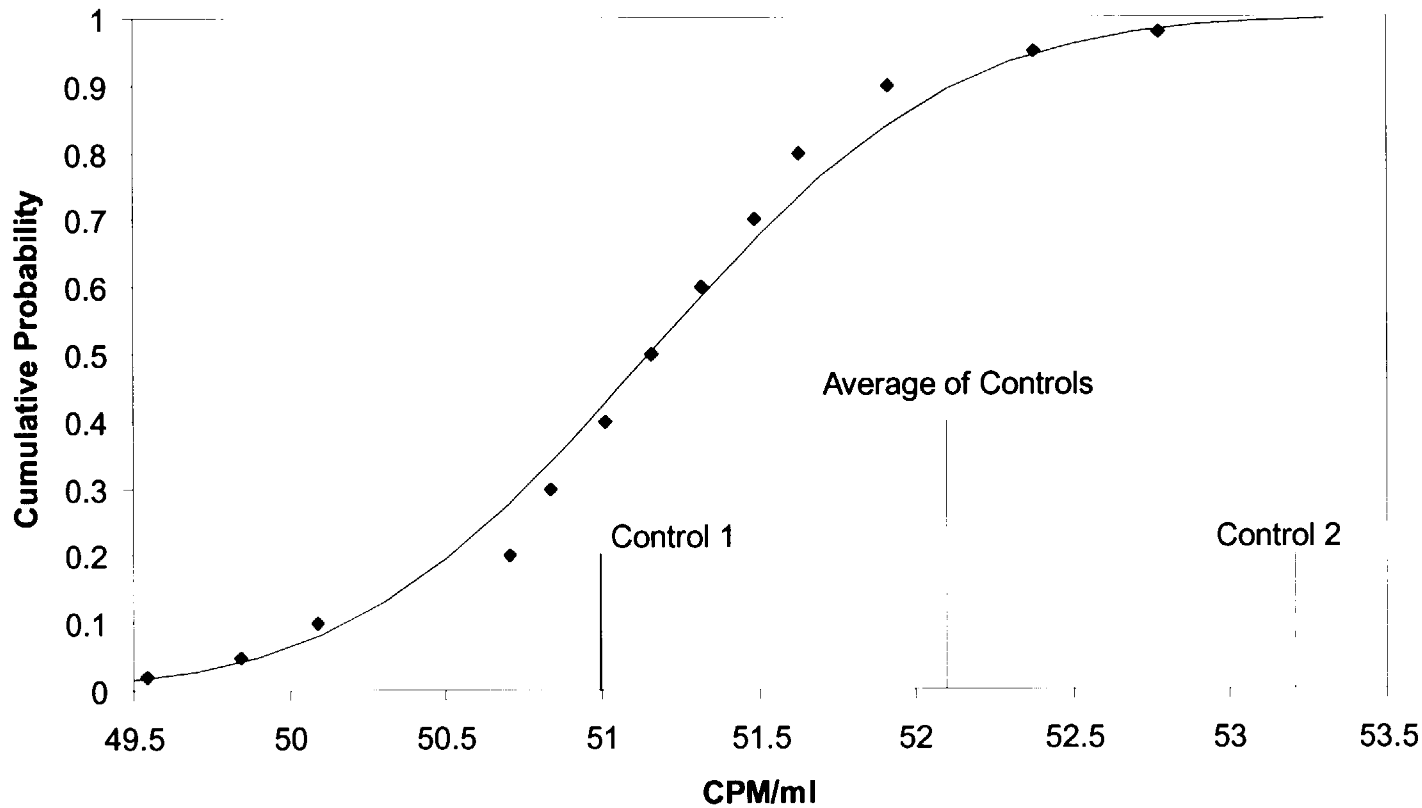
NC-EWDP-03S Groundwater Chemistry (results based on the original water filtered through 0.45 μm filter paper)

Cations		Anions		pH	Eh (mv)	DO (mg/L)	EC (μs/cm)
Elements	(mg/L)	Elements	(mg/L)				
Na	128.45	Cl^-	9.20	8.67	202	0.02	625.3
Si	26.42	Br^-	0.05				
K	4.04	F^-	2.08				
Ca	1.18	NO_3^-	3.25				
Li	0.29	PO_4^{3-}	< 0.10				
Fe	< 0.40	SO_4^{2-}	49.81				
Mg	< 0.40						
Mn	< 0.08						

Balance of anions assumed to be HCO_3^- (~260 mg/L)

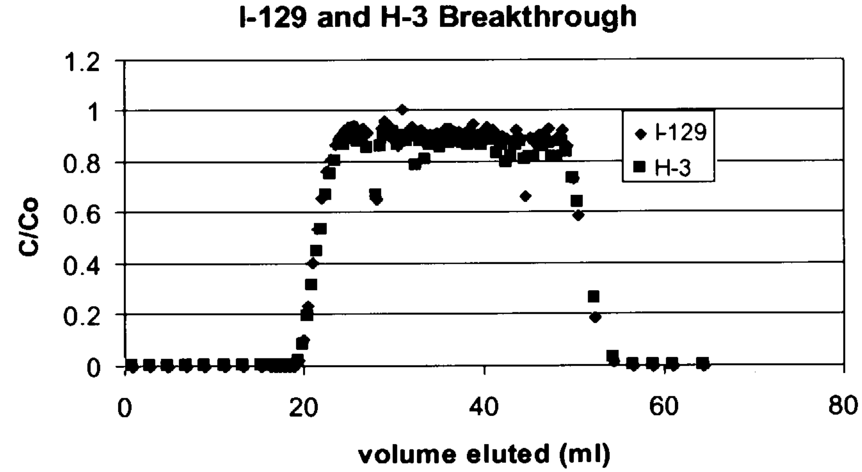
Reference: ANL-NBS-HS-000019 and work in progress

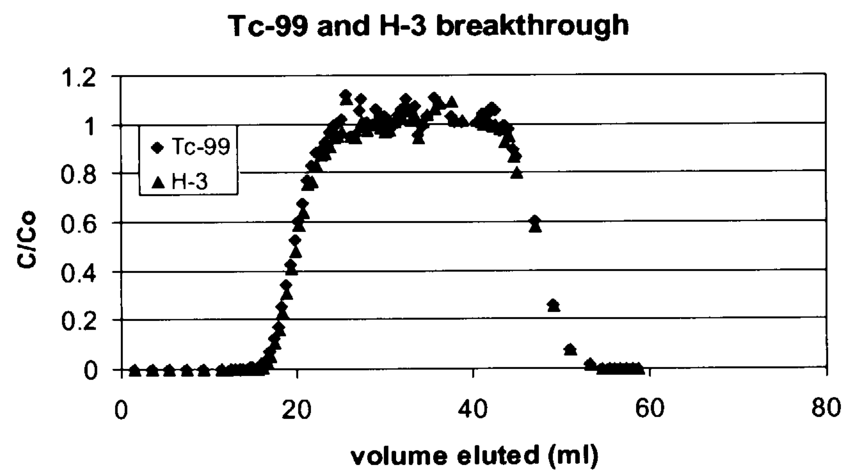
Results: Statistically Insignificant I^- and TcO_4^- Sorption



Reference: ANL-NBS-HS-000019 and work in progress

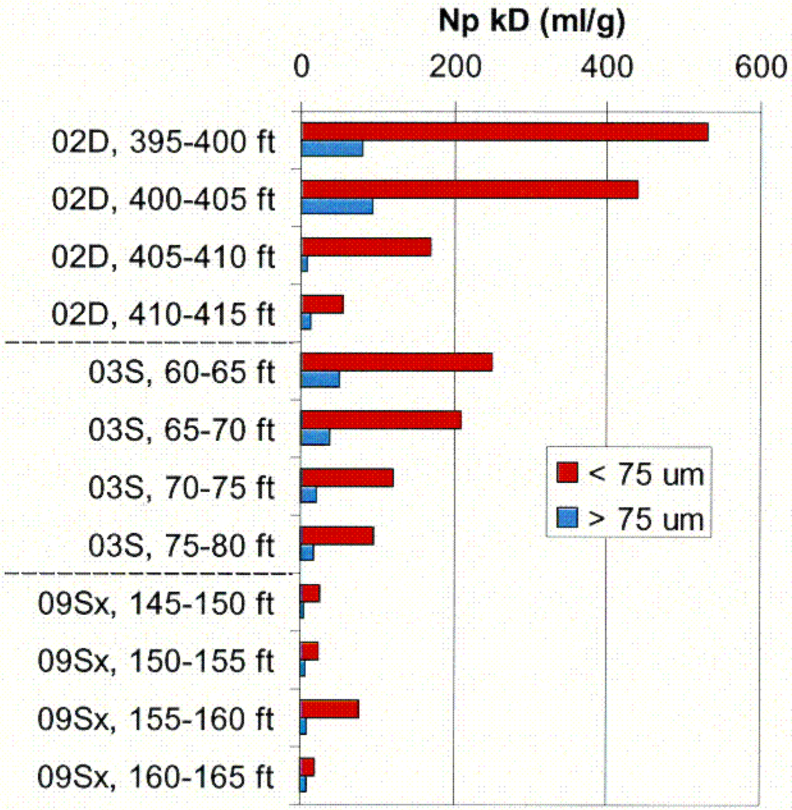
Column Results: Confirm no I^- and TcO_4^- Sorption

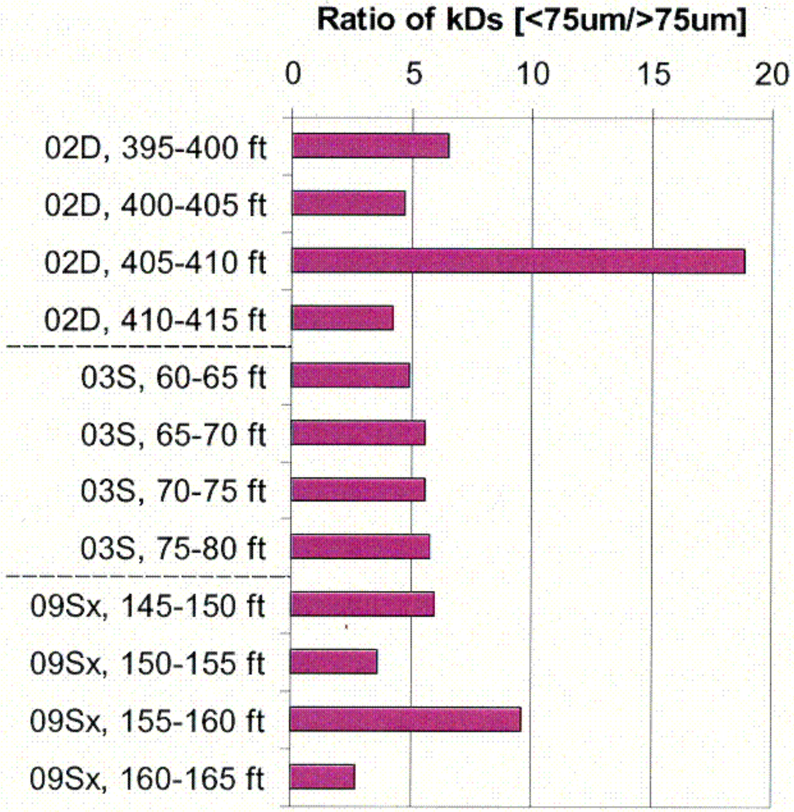




Reference: ANL-NBS-HS-000019 and work in progress

Np Sorption as a Function of Interval and Size Fraction – Batch Studies

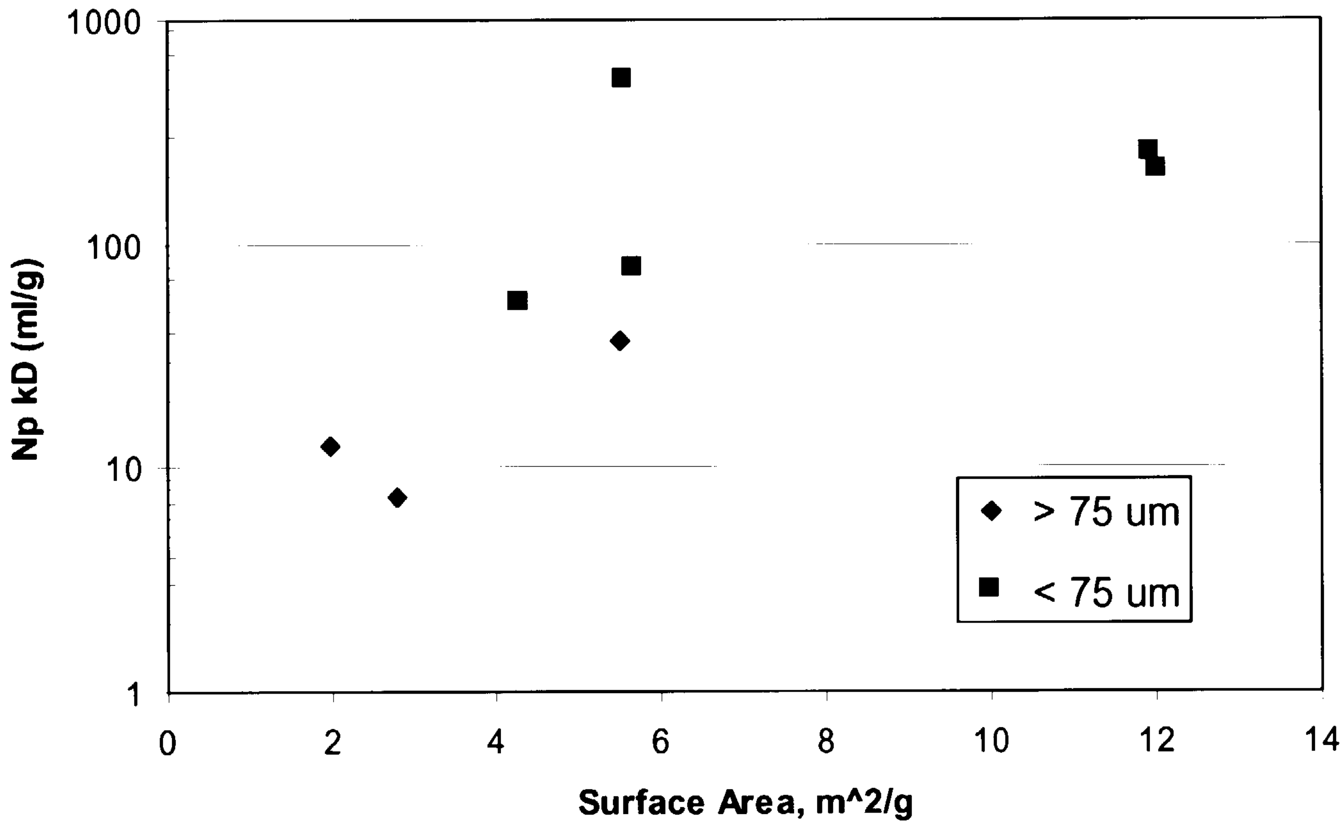




C-40

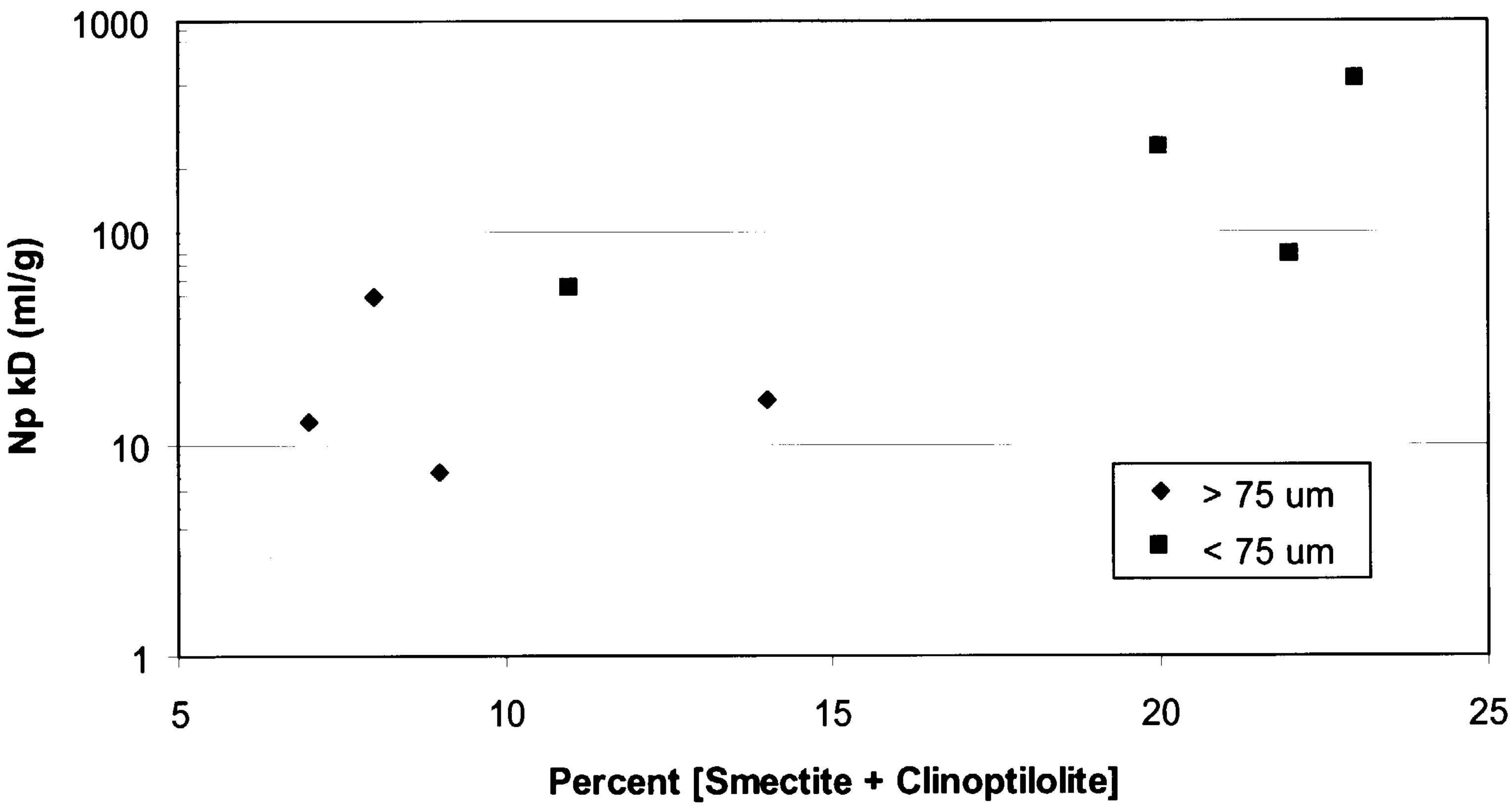
Reference: ANL-NBS-HS-000019 and work in progress

Np Sorption as a Function of Surface Area



Reference: ANL-NBS-HS-000019 and work in progress

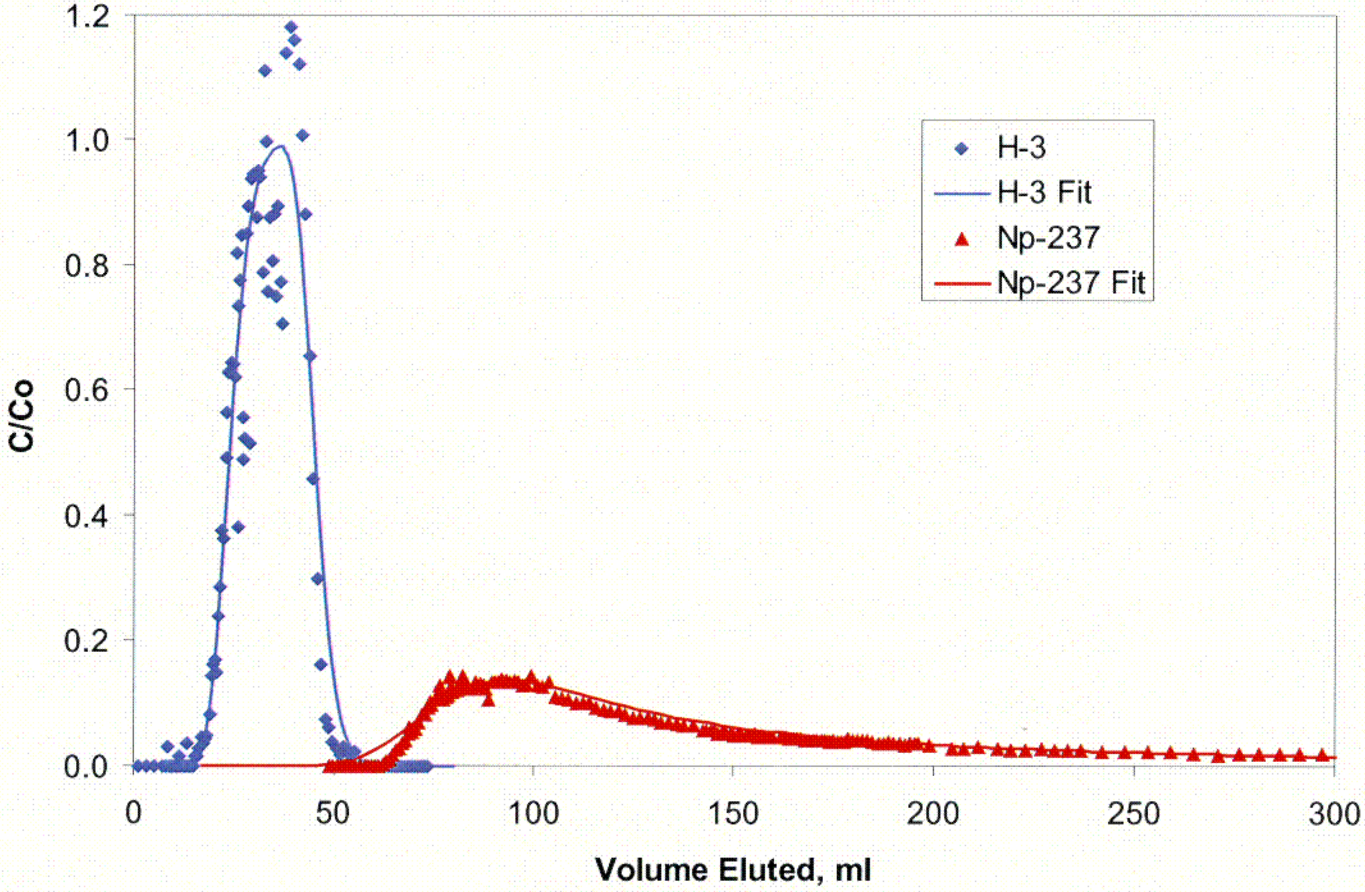
Np Sorption as a Function of Clay and Zeolite Content



- Mineralogy determined by Quantitative X-Ray Diffraction

Reference: ANL-NBS-HS-000019 and work in progress

Column Results: Less Np Sorption Than in Batch Tests



C-41

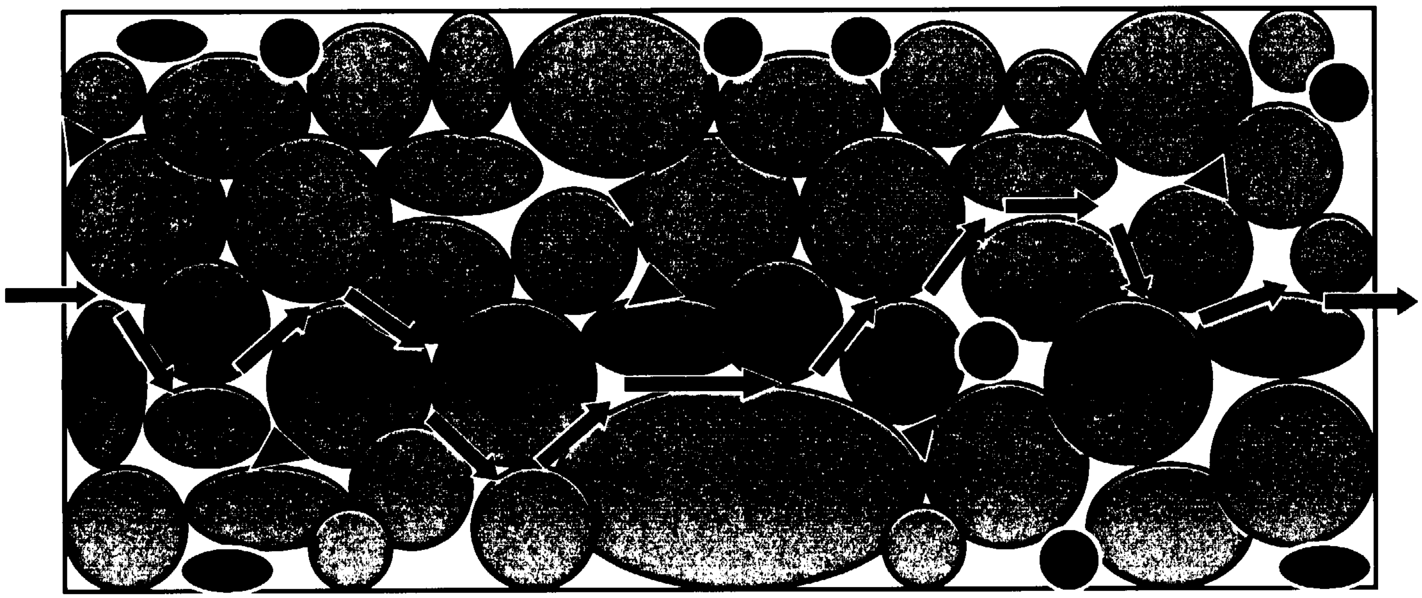
Reference: ANL-NBS-HS-000019 and work in progress

Column Experiments: Preliminary Interpretations

- Np first arrival matched by K_d = 0.5 ml/g (vs. K_d = 6.3 ml/g in batch tests with same material)
- Long Np tail suggests that some NpO_2^+ sorbed for extended period of time onto a portion of the column material
- Interpretive model assumes mass transfer step between bulk column material (where K_d = 0.5 ml/g) and sorptive phases (K_d > 100 ml/g)

Column Experiments: Conceptual Model

Column packed with wet-sieved 75-500 μm material



● Grains - primarily silica (quartz, feldspar)

◀ Clays and zeolites

➡ Path of an ion that doesn't "see" much clay and zeolite

Reference: ANL-NBS-HS-000019 and work in progress

Acceptance Criterion 2c

- **Acceptance Criterion 2c: For the valid application of the constant K_d approach, equation (1) $R_f=1+\rho_b K_d/n$, (or $R_f = 1 + \rho_b K_d/\theta$), DOE has: Demonstrated that the three implicit assumptions (i.e., linear isotherm, fast reversible sorption reaction, and constant bulk chemistry) are valid**
- **Action or information needs identified**
  - Confirm constant K_d approach
    - Fast desorption kinetics assumption needs to be verified in column experiments at varying flow rates
    - Constant bulk chemistry assumption needs to be verified in additional batch and column experiments - primarily reducing conditions, although K_ds are expected to increase under these conditions

Acceptance Criterion 2c
(Continued)

- **Basis for closure**
  - Linear isotherm assumption are considered valid given the very low expected molar concentrations of radionuclides
  - Fast sorption kinetics has been demonstrated for Np; fast desorption kinetics will be verified in planned laboratory testing
  - Batch and column testing of Tc and Np under reducing conditions is planned; saturated zone performance is expected to improve under reducing conditions; therefore, current approach is conservative
- **References**
  - Planned Alluvium Testing Complex report
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 01)
  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00)

Acceptance Criterion 2c
(Continued)

- **References** **(Continued)**
  - Analysis and Model Report *Uncertainty Distributions for Stochastic Parameters* (ANL-NBS-MD-000011)
  - Analysis and Model Report *Input and Results of the Base Case Saturated Zone Flow and Transport Model for TSPA* (ANL-NBS-HS-000030)
- **No further work beyond planned laboratory testing is required. DOE considers this acceptance criterion closed-pending completion of testing**

Confirm Constant K_d Approach

- **Basis for resolution**
  - The constant K_d (linear isotherm) approach is considered valid at low molar radionuclide concentrations. Confirmation of the constant K_d approach will require additional batch experiments
    - Planned column testing will address the assumption of fast desorption kinetics
    - Planned laboratory testing under reducing conditions will address the assumption of constant bulk chemistry
  - Preliminary work to confirm constant K_d approach has been performed. Additional work to confirm will be done using column experiments

Confirm Constant K_d Approach
(Continued)

- **References**
  - Planned Alluvium Testing Complex report
  - *Saturated Zone Flow and Transport Process Model Report* (TDR-NBS-HS-000001 REV 00 ICN 01)
  - Analysis and Model Report *Unsaturated Zone and Saturated Zone Transport Properties (U0100)* (ANL-NBS-HS-000019 REV 00)
  - Analysis and Model Report *Uncertainty Distributions for Stochastic Parameters* (ANL-NBS-MD-000011)
  - Analysis and Model Report *Input and Results of the Base Case Saturated Zone Flow and Transport Model for TSPA* (ANL-NBS-HS-000030)

Confirm Constant K_d Approach
(Continued)

- **No further work beyond planned laboratory testing is required. DOE considers this acceptance criterion closed-pending completion of testing**

Acceptance Criterion 3a

- **Acceptance Criterion 3a: For the valid application of process models affecting radionuclide transport such as surface complexation, ion exchange, precipitation/dissolution, and processes involving colloidal material, DOE has demonstrated that a portion of the flow path acts as an isotropic homogeneous porous medium**
- **Action or information needs identified**
  - None identified

Acceptance Criterion 3a
(Continued)

- **Basis for closure**
  - Process models approach for determination of K_d is not being used in the alluvium and therefore, the acceptance criterion is not applicable
- **References**
  - Not applicable
- **No further work required. DOE considers this acceptance criterion closed**

Acceptance Criterion 3b

- **Acceptance Criterion 3b: For the valid application of process models affecting radionuclide transport such as surface complexation, ion exchange, precipitation/dissolution, and processes involving colloidal material, DOE has demonstrated that appropriate values are used in process models**
- **Action or information needs identified**
  - None identified

Acceptance Criterion 3b
(Continued)

- **Basis for closure**
  - Process models approach for determination of K_d is not being used in the alluvium and therefore, the acceptance criterion is not applicable
- **References**
  - Not applicable
- **No further work required. DOE considers this acceptance criterion closed**

Acceptance Criterion 3c

- **Acceptance Criterion 3c: For the valid application of process models affecting radionuclide transport such as surface complexation, ion exchange, precipitation/dissolution, and processes involving colloidal material, DOE has: (i) Demonstrated that the three implicit assumptions are valid, if process models are intended to yield a constant K_d approach for use in the retardation equation; or (ii) determined transport in a dynamic reactive transport system (e.g., PHREEQC, MULTIFLO, HYDROCHEM, etc.)**
- **Action or information needs identified**
  - None identified

Acceptance Criterion 3c
(Continued)

- **Basis for closure**
  - Process models approach for determination of K_d is not being used in the alluvium and therefore, the acceptance criterion is not applicable
- **References**
  - Not applicable
- **No further work required. DOE considers this acceptance criterion closed**

Acceptance Criterion 4

- **Acceptance Criterion 4: Where data are not reasonably or practicably obtained, expert judgement has been used and expert elicitation procedures have been adequately documented. If used, expert elicitations were conducted and documented in accordance with the guidance in NUREG-1563 or other acceptable approaches**
- **Action or information needs identified**
  - Clarify use of expert judgement for sorption coefficient distributions

Acceptance Criterion 4
(Continued)

- **Basis for closure**
  - This is covered under Subissue 1
- **References**
  - Not applicable
- **Additional documentation will be provided to explain how sorption coefficient distributions used for performance assessment were derived. Therefore, DOE considers this acceptance criterion closed-pending**

Conclusions

- **DOE considers the status of Subissue 2, Radionuclide Transport Through Alluvium, closed-pending completion of ongoing and planned Alluvium Testing Complex testing and laboratory testing**

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

Features, Events, and Processes for Unsaturated Zone and Saturated Zone Transport

Presented to:
DOE-NRC Technical Exchange on the Radionuclide Transport Key Technical Issue

Presented by:
Jim Houseworth, Ph.D
Civilian Radioactive Waste Management System Management and Operating Contractor

December 5-7, 2000
Lawrence Berkeley National Laboratory
Berkeley, CA

YUCCA MOUNTAIN PROJECT

Outline

- Presentation Objectives
- Definition and Classification
- Included Features, Events, and Processes
- Excluded Features, Events, and Processes
- Examples of Screening Arguments
- References
- Conclusions

Presentation Objectives

- **Explain how features, events, and processes are classified and analyzed**
- **Give the status of unsaturated zone and saturated zone features, events, and processes related to radionuclide transport**
  - Indicate where analyses are changing in Revision 01

Definition and Classification

- **Features, events, and processes are supposed to capture every possible feature, event, or process important to performance**
  - Over 1,700 features, events, and processes on master list
- **Out of 128 primary features, events, and processes in the unsaturated zone and saturated zone there are 35 related to unperturbed radionuclide transport**
  - 28 are included
  - Seven are excluded

Definition and Classification
(Continued)

- **Features, events, and processes classification**
  - Included features, events, and processes: those that are modeled in Total System Performance Assessment either directly or indirectly
    - Directly model matrix diffusion
    - Indirectly model variability in ambient geochemistry (through distribution for K_d)

Features, Events, and Processes Relevant to Transport

- **Included features, events, and processes**
  - Fractures (existing only) (1.2.02.01.00)
  - Faulting (existing only) (1.2.02.02.00)
  - Suspension of Particles Larger than Colloids (2.1.09.21.00)
  - Stratigraphy (2.2.03.01.00)
  - Rock Properties of Host Rock and Other Units (2.2.03.02.00)
  - Unsaturated Groundwater Flow in Geosphere (2.2.07.02.00)
  - Focusing of Unsaturated Flow (Fingers, Weeps) (2.2.07.04.00)
  - Perched Water Develops (2.2.07.07.00)
  - Fracture Flow in the Unsaturated Zone (2.2.07.08.00)
  - Matrix Imbibition in the Unsaturated Zone (2.2.07.09.00)

Features, Events, and Processes Relevant to Transport (Continued)

- **Included features, events, and processes (Continued)**
  - Saturated Groundwater Flow (2.2.07.12.00)
  - Water-Conducting Features in the Saturated Zone (2.2.07.13.00)
  - Advection and Dispersion (2.2.07.15.00)
  - Dilution of Radionuclides in Groundwater (2.2.07.16.00)
  - Diffusion in the Saturated Zone (2.2.07.17.00)
  - Groundwater Chemistry/Composition in Unsaturated Zone and Saturated Zone (existing only) (2.2.08.01.00)
  - Geochemical Interactions in the Geosphere (existing only) (2.2.08.03.00)
  - Complexation in the Geosphere (existing only) (2.2.08.06.00)
  - Matrix Diffusion in Geosphere (2.2.08.08.00)
  - Sorption in Unsaturated Zone and Saturated Zone (2.2.08.09.00)

Features, Events, and Processes Relevant to Transport (Continued)

- **Included features, events, and processes (Continued)**
  - Colloidal Transport in Geosphere (2.2.08.10.00)
  - Distribution And Release of Nuclides from the Geosphere (2.2.08.11.00)
  - Microbial Activity in Geosphere (unperturbed only) (2.2.09.01.00)
  - Infiltration and Recharge (Hydrologic and Chemical Effects) (2.3.11.03.00)
  - Radioactive Decay and Ingrowth (3.1.01.01.00)
  - Natural Geothernal Effects (2.2.10.03.00)
  - Undetected Features (2.2.12.00.00)
  - Isotopic Dilution (3.2.07.01.00)

Features, Events, and Processes Relevant to Transport (Continued)

- **Excluded features, events, and processes**
  - Open Site Investigation Boreholes (1.1.01.01.00)
  - Loss of Integrity of Borehole Seals (1.1.01.02.00)
  - Abandoned and Undetected Boreholes (1.4.04.02.00)
  - Flow and Transport in the Unsaturated Zone from Episodic Infiltration (2.2.07.05.00)
  - Episodic / Pulse Release from Repository (2.2.07.06.00)
  - Density Effects on Groundwater Flow (Concentration) (2.2.07.14.00)
  - Groundwater Discharge to the Surface (2.3.11.04.00)

Discussion of Screening Approach

- **Excluded features, events, and processes: screened out due to**
  - Low probability (or not relevant)
    - Low probability arguments not used for unperturbed radionuclide transport issues

Discussion of Screening Approach
(Continued)

- **Excluded features, events, and processes: screened out due to**
  - Low consequence
    - Open Site Investigation Boreholes (1.1.01.01.00)
      - » This exclusion is partially based on a bounding argument concerning a sudden release of perched water through boreholes. The maximum quantity of water that could be released by perched water drainage through boreholes is generally less than the equivalent of a few years of total flux through the potential repository. It is smaller than the release that could result from a 1 m rise in the water table beneath the potential repository. Therefore, the effects of boreholes on performance can be neglected. This argument also applies to features, events, and processes 1.1.01.02.00 and 1.4.04.02.00
    - Flow and Transport in the UZ from Episodic Infiltration (2.2.07.05.00)
      - » Relies on observed and modeled behavior of the PTn to dampen episodic flow as discussed in presentation on porous rock. This argument also applies to features, events, and processes 2.2.07.06.00

Discussion of Screening Approach
(Continued)

- **Excluded features, events, and processes: screened out due to**
  - Low consequence
    - Density Effects on Groundwater Flow (Concentration) (2.2.07.14.00)
      - » No credit is taken for possible incomplete capture of the plume in a well at the accessible environment. Mixing is assumed to be dominated by the redistribution of water upon uptake in a well. Therefore, dynamic effects caused by the density of water entering the saturated zone from the unsaturated zone can be neglected
    - Groundwater Discharge to the Surface (2.3.11.04.00)
      - » Groundwater discharge points at the surface are currently located at Franklin Lake Playa and Ash Meadows, beyond the 20 km radius. Modeling of future groundwater behavior also indicates that such discharge points will remain well outside the 20 km radius. Therefore, the effects of such discharge can be neglected at the compliance point

References

- **Analysis and Model Report *Features, Events, and Processes in UZ Flow and Transport* (ANL-NBS-MD-000001)**
- **Analysis and Model Report *Features, Events, and Processes in SZ Flow and Transport* (ANL-NBS-MD-000002)**

Conclusions

- **All features, events, and processes have been addressed**
- **The majority of features, events, and processes relevant to transport are included**
- **Some transport-related features, events, and processes have been excluded on the basis of low consequence**

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 1: Radionuclide Transport Through Porous Rock		
Importance to System Performance: Radionuclide delay through the unsaturated zone is a principal factor of the postclosure safety case. The porous rocks of the unsaturated zone contribute to the delay and dilution of radionuclide concentrations provided by the natural barriers.		
Acceptance Criterion (AC) 1a: For the estimation of radionuclide transport through porous rock, DOE has determined, through sensitivity analysis, whether radionuclide attenuation processes such as sorption, precipitation, radioactive decay, and colloidal filtration are important to performance.		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
Acceptance Criterion Status: CLOSED The radionuclides for which the boxes are checked have been evaluated in previous PAs (see Section 3.2). This criterion is included to allow DOE to determine the importance of a given radionuclide without having to perform laboratory experiments. For example, radionuclides with short half-lives and small inventories may contribute so little to the dose that they need not be considered. The use of sensitivity analysis to eliminate from further consideration the retardation of certain radionuclides requires greater reliance on other aspects of the repository performance. It is anticipated that this approach, however, will not be used to the extreme, whereby all the reliance is placed on one aspect of repository performance to the exclusion of all others. The staff considers that this acceptance criterion has been met for radionuclides important to performance. However, as processes, conditions, and conceptual models are revised based on new site characterization information and repository designs, it is expected that new sensitivity analyses would be needed. The only situation where this criterion would not be met would occur if DOE failed to consider a radionuclide in its PA that the NRC staff considered to be important.	DOE believes this criterion is CLOSED. For the purposes of radionuclide attenuation, the SZ models do not consider any of the geologic media to be porous rock. The SZ models include radionuclide attenuation in the fractured rock matrix and alluvium. Therefore, where the acceptance criteria in this subissue address radionuclide attenuation, a response will be provided for SZ. Otherwise, DOE does not consider this subissue applicable to the SZ model (CRWMS M&O 2000a). All the processes stated above, except precipitation, have been included in the UZ radionuclide transport model. Excluding precipitation from the transport model is conservative from a dose standpoint. Hydrodynamic dispersion is not important to UZ or SZ radionuclide transport, although it is included in the model. All other processes are important to UZ performance. (CRWMS M&O 2000b; CRWMS M&O 2000a).	No additional work is needed.

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 1: Radionuclide Transport Through Porous Rock		
DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "The processes of hydrodynamic dispersion, matrix diffusion, sorption (solutes), filtration (colloids), and radioactive decay are considered important to performance for the UZ and are all explicitly modeled in the UZ transport model abstraction." In response, the NRC staff considers this criterion has been met as previously described in Revision 1 of the RT IRSR. However, the list of processes DOE considers important to performance includes matrix diffusion, which, by definition, is a process that may occur in fractured, not porous rock (NRC 2000)		

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 1: Radionuclide Transport Through Porous Rock		
Acceptance Criterion (AC) 1b: For the estimation of radionuclide transport through porous rock, DOE has (i) Assumed K_d is zero and radionuclides travel at the rate of groundwater flow, If it has been found that radionuclide attenuation Is unimportant to performance and it can be demonstrated that this assumption is conservative; no other acceptance criteria for this subissue need be met, or, (ii) demonstrated that criterion 2 or 3 has been met, if radionuclide attenuation in porous rock is important to performance or if an assumption that K_d is zero in porous rock is not conservative.		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
Acceptance Criterion Status: CLOSED This criterion has been used for carbon, technetium, iodine, and chlorine, which occur predominately as anions and, as such, experience limited attraction to the negatively charged surfaces of the minerals along the flowpath. The staff agrees with the selection of C, Tc, I, and Cl as having a K_d of zero, for use in PAs. The staff recognizes, however, that there may be other elements or species that, under certain situations, have a K_d of zero. There are examples where multiple species of a single radionuclide exist in solution at the same time. Some species can be cations and others, anions. The retardation of the species varies as a function of their charge and size. A classic example, occurred at the Cambric site where ruthenium, with a nonzero K_d, was observed at a sampling well before it was expected. It was later discovered that ruthenium is present in both cationic and anionic forms, and the negatively-charged ruthenate ion contributed to the early breakthrough. Plutonium is another radionuclide with multiple species, including cationic as well as anionic and colloidal forms. Triay, et al. (1997) and Thompson (1989) show that some plutonium travels unretarded in crushed tuff column experiments. The plutonium	DOE believes this criterion is CLOSED. For radionuclides with a non-zero K_d value, DOE has met criterion 2 as discussed under criterion 2. Criterion 3 is not applicable to RT models as explained under criterion 3. In porous rock and fractured rock matrix, C, Tc, and I are assigned a K_d of zero (CRWMS M&O 2000d). Because C, Tc, and I do not participate in colloid transport, the zero K_d assumption is conservative Cl is not currently modeled in TSPA, as discussed in the inventory abstraction AMR (CRWMS M&O 2000e). The basis for selecting the radionuclides for TSPA-SR calculations will be the subject of discussions at the TSPAI technical exchange and not at the RT Technical Exchange. For the UZ, negatively charged radionuclide species are assigned smaller diffusion coefficients based on the laboratory measurements of diffusion for pertechnetate. For UZ and SZ, colloidal forms are conservatively assumed not to diffuse (CRWMS M&O 2000b and CRWMS M&O 2000a). The early breakthrough for Pu found in crushed-tuff dynamic sorption tests was shown to be rate dependent. As the experiment flow rate was reduced, the degree of early breakthrough was significantly reduced. Therefore, DOE believes that the early-breakthrough behavior is a rate effect that is dependent on the kinetic rates for Pu sorption mechanisms. The flow rates used were orders of magnitude larger than the expected flow rates at Yucca Mountain. (see CRWMS M&O 2000d for a discussion of the crushed tuff	No additional work is needed.

and ruthenium examples demonstrate the importance of performing flow-through column tests for identifying mobile species (see status of Methodology 2b3 below). DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "K_d is assumed to be zero for C, Tc, I, and Cl." In response, the NRC staff considers this criterion has been met as previously described in Revision 1 of the RT IRSR. Caveats identified in Revision 1 remain (NRC 2000).	column experiments). Multiple species for Pu and other radionuclides, as applicable, are discussed under Acceptance Criterion 2. C, Tc, and I which are assumed to have a K_d of zero do not transport as colloids and hence the caveats indicated in Revision 1 of the RT KTI IRSR (NRC 1999) are not applicable for these nuclides (CRWMS M&O 2000l).	

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 1: Radionuclide Transport Through Porous Rock		
Acceptance Criterion (AC) 2a: For the valid application of the constant K_d approach, equation (1) $R_f = 1 + \rho_b K_d / n$, (or $R_f = 1 + \rho_b K_d / \theta$), DOE has: Demonstrated that the portion of the flow path to which equation (1) applies acts as a single continuum porous medium		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
Acceptance Criterion Status: OPEN This criterion is generally independent of the radionuclide migrating through the medium. However, radionuclide size and charge can exclude certain radionuclide species from the isotropic homogeneous medium in favor of the heterogeneous features. The C-Well tests provide an example that suggests a portion of the flow path is not acting as a single continuum porous medium. Currently, the only portions of the flowpath considered to be a single continuum porous medium in the NRC's TPA are the nonwelded vitric unit of the Calico Hills and the alluvium (See Subissue 2, Radionuclide Transport through Alluvium). The reason the vitric unit is considered a porous medium is because its matrix permeability is considered high enough to accommodate the percolation rates expected for YM. On the other hand, the nonwelded zeolite unit of the Calico Hills has a matrix permeability that may accommodate only a relatively small portion of the percolation rate. Consequently, most of the water bypasses the zeolite unit in fractures. Finally, it remains to be demonstrated that the Calico Hills nonwelded vitric unit and the alluvium behave as a single continuum porous media. Phase II of the UZ Field Transport Test at Busted Butte involve identifying possible "fast pathways" within the Calico Hills block and performing cross hole tracer tests using conservative and reactive	DOE believes this criterion is CLOSED. For the SZ transport model in the fractured tuff, flow is modeled as occurring only in the fractures. No credit for sorption is taken in the fractures. Sorption occurs in the rock matrix after diffusion. Therefore, this Acceptance Criterion is not applicable to the SZ transport models in the fractured tuff (CRWMS M&O 2000a). Present transport models in the UZ represent flow and transport through all units using a dual-continuum approach. Most, but not all, of the flow and transport through the CHnv is in the matrix. In the TSw and CHnz, most, but not all, of the flow and transport occur in the fractures. Retardation is only applicable to the matrix component of transport – sorption is assumed to not occur in the fracture continuum (CRWMS M&O 2000b). The flow path over which the K_d model is applied is variable. In general, it is a function of the fracture/matrix flow behavior and matrix diffusion. Variability of the retardation factor is accounted for in the parameter distribution for K_d and the variation in matrix porosity and rock density for model layers within each unit. In the TSw and CHnz, radionuclide transport pathways in the matrix are a function of where radionuclides enter and leave the matrix via flow and diffusion mechanisms. The transport pathways are primarily through the fractures, but a small portion of the transport occurs in the matrix., Observations at Busted Butte indicate that fracture flow and transport does not occur in the Calico Hill nonwelded vitric. All flow and transport occurs in the matrix, as a single-continuum. The current flow and transport model conservatively allows for a small amount of flow and transport in this unit. Due to the strong advective exchange, matrix diffusion in this unit is not important (CRWMS M&O 2000b).	No additional work is needed.

tracers. The effect of variable flow rates on tracer breakthrough will be determined. The NRC staff considers this type of experiment important for demonstrating transport through porous rock. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 20 00 that "The vitric portion of the Calico Hills hydrogeologic units behaves as a porous medium and provides an effective barrier to radionuclide transport. The upper units of the Prow Pass hydrogeologic unit also behaves as a porous medium." In response, the NRC staff notes the DOE comment does not include the term "single continuum." If this omission is intentional, and the units identified are not expected to act as single continua but as dual continua, then DOE would have to demonstrate its capability to predict breakthrough curves (NRC 2000).	For the unsaturated zone, Busted Butte field test results to date indicate that the CHnv acts as a single-continuum porous medium Busted Butte is considered a distal extension of the Calico Hills beneath the potential repository block -- not an analog For TSPA, DOE conservatively allows for a small portion of flow and transport in the fracture continuum of the CHnv and PPv Existing measurements support the conclusion that the nonwelded vitric rock in the Unsaturated Zone behaves as a single-continuum porous medium This acceptance criterion is closed. Completion of the Busted Butte testing and data analyses is expected to confirm lines of evidence and reduce uncertainty	

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 1: Radionuclide Transport Through Porous Rock		
Acceptance Criterion (AC) 2b: For the valid application of the constant K_d approach, equation (1) $R_f = 1 + \rho_b K_d / n$, (or $R_f = 1 + \rho_b K_d / \theta$), DOE has: Determined appropriate values for parameters, K_d ,n or θ, and ρb.		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
Acceptance Criterion Status: OPEN Criterion 2b has been subdivided in Table 5-1 into seven methodologies to record the multiple approaches that can be used to determine and validate appropriate values for K_d. The NRC staff considers the batch sorption experiment using site-specific materials along with the crushed tuff column experiment constitute the minimum set of experiments to demonstrate an appropriate value for K_d. Experiments involving intact tuff, diffusion, unsaturated, and fractured tuff can provide useful supplemental information. This strategy for the validation of batch sorption data is described by Triay et al., 1992. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "Details of the experimental program are provided in the Yucca Mountain Site Description." The NRC instead reviewed the Summary and Synthesis Report on Radionuclide Retardation for the Yucca Mountain Site Characterization Project (Triay et al., 1997) for details of the experimental program. If the Yucca Mountain Site Description contains additional details of the experimental program that would eliminate NRC concerns, the staff requests DOE identify this supporting information. In the letter from Brocoum to Reamer, Mar. 22, 2000, on DOE's Review of the RT IRSR, there were a total of 23 comments. Only one comment pertained to Section 5 of the RT IRSR Rev 1, where the NRC staff describes the status of	DOE believes this criterion is CLOSED-PENDING. Existing test data for n, ρ_b, and most (except Pu) of the K_d values are considered adequate to meet this acceptance criterion K_d, n, and ρ_b of the rock matrix are determined through laboratory measurements using site-specific materials for radionuclides of importance to performance. Laboratory measurements of n and ρ_b have been performed on core samples. Laboratory measurements of K_d have been performed using batch sorption techniques and confirmed with crushed tuff column experiments using site specific materials. Bulk density and porosity parameters are referenced in the Integrated Site Model PMR (CRWMS M&O 2000c). K_d and related information are included in the Unsaturated Zone and Saturated Zone Transport Properties AMR (CRWMS M&O 2000d). Aqueous compositions and radionuclide concentrations used in batch sorption tests are appropriate for determinations of K_d. Crushed tuff column experiments for Np have confirmed batch sorption results. Experiments for Pu have shown kinetic effects that make the high flow rates used for the column tests non-representative. Diffusion measurements for sorbing radionuclides have been conservatively bounded by diffusion coefficients selected for performance assessment The Inventory Abstraction AMR (CRWMS M&O 2000e) identifies the following nuclides as important to performance assessment calculations. The following categorization is described in Uncertainty Distribution for Stochastic Properties AMR (CRWMS M&O 2000f): C, Tc, I ⇒ Non-sorbing ($K_d \sim 0.0$ ml/g) Np, U ⇒ Moderately Sorbing ($K_d << 100$ ml/g)	Sensitivity studies and a review of available data will be used to evaluate the need for additional Pu column tests. As discussed in the following subsections of acceptance criterion 2b.

the DOE experimental program in light of the acceptance criteria. The NRC staff interprets the relatively small number of comments on Section 5 to mean DOE did not find fault with the NRC observations on the status of this subissue (NRC 2000).	Sr, Cs, Pa ⇒ Moderately Strongly Sorbing ($K_d \geq 100$ ml/g) Am, Pu, Th, ⇒Highly Sorbing, transported only in colloidal phase. May desorb from colloidal phase and sorb onto matrix and vice versa ($K_d > 100$ ml/g) Ra, Pb, ⇒ Not transported (in secular equilibrium with Th) Ac ⇒ Not transported (in secular equilibrium with Pa) Discussions of K_d are provided in the following methodology discussions of acceptance criterion 2b and address NRC issues.	

Subissue 1: Radionuclide Transport Through Porous Rock		
Methodology 2b1. Sorption Coefficient Has Been Determined Using a Batch Sorption Test		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
In Table 5-1, any radionuclide for which an experimentally determined K_d has been determined using a batch sorption test has this box checked in the table above. This includes radionuclides whose batch sorption tests have not involved site-specific materials, along with radionuclides whose batch sorption tests have. The radionuclides for which nonsite-specific batch sorption tests have been performed are lead, actinium, samarium, and zirconium. The NRC staff considers the sorption coefficients determined from nonsite-specific batch sorption experiments much less certain for application to YM PA calculations than those determined using site-specific materials (NRC 2000)	Pb, Ac, Sm and Zr are not on list of radionuclides to be considered for far-field transport calculations. This methodology was used for all sorbing nuclides to provide ranges of probability distributions where testing with site-specific materials was insufficient to establish the full K_d distribution range. All sorbing radionuclides that undergo some aspect of aqueous transport have batch sorption measurements using site-specific materials (method 2b2) (CRWMS M&O 2000d).	No additional work is needed.

Subissue 1: Radionuclide Transport Through Porous Rock		
Methodology 2b2. Sorption Coefficient Has Been Determined From Sorption Test Using Site-Specific Materials		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
Batch sorption experiments using site-specific materials have been performed yielding K_d values for americium, plutonium, uranium, thorium, radium, neptunium, protactinium, tin, nickel, cesium, strontium, niobium, technetium, selenium, cerium, and europium.	Radionuclides with site-specific batch sorption measurements used in TSPA for aqueous transport are Am, Np, U, Pu, Th, Pa, Cs, and Sr (CRWMS M&O 2000d). Ac, Ra, and Pb are only included through secular equilibrium at the accessible environment, therefore, this methodology is not applicable to these nuclides (CRWMS M&O 2000l). Tc, I ,and C are assigned a K_d of zero (CRWMS M&O 2000d).	No additional work is needed.
Triay, et al. (1997) states that batch sorption experiments involving protactinium and site-specific materials have only been performed at pH values 6.3 to 6.7. Consequently, the report recommends that sorption experiments involving protactinium be performed at pH values between 7 and 9 to match the expected pH of waters at YM. The NRC staff agrees with this recommendation if protactinium is shown to be important to performance.	Regarding Pa, additional batch sorption measurements at pH levels between 7 and 9 have not been performed using site-specific materials, K_d values for these pH ranges were obtained from SKB data (CRWMS M&O 2000d). The sensitivity of performance assessment results to Pa sorption will be investigated. Available data will be used to evaluate the need for additional Pa sorption measurements at higher pH.	No additional work is needed.
Plutonium batch sorption experiments have been performed using site-specific materials. These materials included rocks such as zeolitic tuff, vitric tuff, devitrified tuff, minerals such as clinoptilolite, albite, quartz, synthetic hematite, montmorillonite, calcite, gibbsite, and groundwaters including J-13 and UE-25p#1.	DOE concurs with NRC staff analysis.	No additional work is needed.
Sorption experiments involving selenium have only used J-13 water. Triay, et al. (1997) states that changes in divalent ion concentration may affect selenium sorption more than changes in pH. The NRC staff agrees with the recommendation in that report that additional experiments using groundwaters with higher divalent ion concentrations (e.g., UE-25p#1) should be performed if sensitivity analysis indicates selenium sorption could be important to performance.	Selenium is not on the list of radioelements important to performance.	No additional work is needed.

Sorption of uranium in J-13 well water onto YM tuffs has been described by Triay, et al. (1997). The concentrations of uranium in the initial solutions range from 8x10 -8 to 1x10 -4 M (19 ppb to 24 ppm). The silica concentration is 57 ppm, and the final pH ranges from 6.9 to 8.6, depending upon whether the experiments were performed in a glovebox maintaining elevated CO_2 pressure or at atmospheric pressure. The NRC staff performed equilibrium calculations using PHREEQC with the WATEQ4F.DAT database and the log K for the dissolution reaction of soddyite from the EQ3/EQ6 database. The results of these calculations suggest that the initial solutions for the sorption experiments may have been supersaturated with respect to soddyite. Appendix D includes the output of the PHREEQC simulation in which uranium is added to J-13 water resulting in a groundwater with a uranium concentration of 1×10^{-4} M. The pCO_2 is maintained at $10^{-2.99}$ atm. The species $(UO_2)_2\,CO_3\,(OH)^{3-}$, and $UO_2\,(OH)_2$ were added to the database in an attempt to match the species considered by Triay et al., 1997. Triay, et al. (1997) explain the importance of ensuring that a sorption experiment involves sorption and not precipitation. If precipitation has occurred, the resulting partition coefficient is not a K_d to be used in equation (1). It is possible that the precipitation of soddyite is inhibited. Sorption of uranium onto the solid could be occurring without the precipitation reaction also occurring. However, if precipitation reactions are kinetically inhibited, the use of solubility limits calculated using thermodynamic data to constrain radionuclide concentrations would be brought into question. The Generic Technical Position on Radionuclide Solubilities (Brooks, et al., 1984) recommends constraints on radionuclide concentrations be based on solubility experiments that approach equilibrium from both undersaturation	The sorption curves for U do not indicate any precipitation threshold where the apparent sorption would be expected to increase suddenly with increased U solution concentration. The smooth behavior of sorbed U vs increasing U solution concentration indicates that precipitation is not occurring. Although experiments carried out at the high end of the range of concentrations (8×10^{-8} to 1×10^{-4} M/L) used may have been supersaturated with soddyite, the bulk of the experiments were not. This is supported by isotherm data. Further, nucleation and precipitation kinetics for phases such as soddyite are generally slow (Triay et al. 1997).	No additional work is needed.

and oversaturation, but neglected the possibility of supersaturated solutions. The staff recognizes that supersaturated solutions are possible, especially at low temperatures, but reasoned that if solubility experiments are performed using site-specific materials under site conditions, kinetic effects could be identified and factored into radionuclide concentration estimates. In a batch sorption experiment, the nucleation of a phase with which the solution is saturated should be enhanced by the presence of nucleation sites on the crushed tuff. Sorption of uranium as a function of radionuclide concentration was determined resulting in sorption isotherms. Since the dissolution of soddyite depends on pH, uranyl, and silica concentration in solution, the nonvertical isotherm for uranium does not necessarily preclude the possibility of precipitation of soddyite. If silica activity and pH are held constant, and the initial uranium concentration is increased, precipitation of soddyite would produce a vertical isotherm (i.e., constant final uranium concentration in the liquid). However, variations in uranyl concentration could be compensated for by variations in pH and silica concentration, and the solution could still be in equilibrium with soddyite. Chemical analyses of the steady-state groundwater could be used to eliminate the precipitation process as a cause for uranium partitioning between the solid and the liquid. Another possible explanation for the suggestion of supersaturation with respect to soddyite is that the thermodynamic parameters used for calculating the dissolution of soddyite are incorrect. The database of EQ3/EQ6 uses the estimated free energy of formation of soddyite from Hemingway (1982). Two more recent studies have yielded much higher free energies of formation of soddyite. Nguyen, et al. (1992) and Moll, et al. (1996) experimentally		

determined synthetic soddyite solubility. These solubility experiments approached equilibrium from undersaturation. The final equilibrated solutions were analyzed for their uranyl and silica concentrations and the Gibbs free energy of formation was calculated. However, the measured silica concentrations (300 ppm) in the final equilibrated solutions exceed solubility of amorphous silica. Consequently, the results of these studies can be challenged. Triay, et al. (1997) note that unsaturated zone water that is relatively high in calcium and magnesium, may produce low K_d values for uranium, due to competing ions for sorption sites. The NRC staff agrees with the recommendation in the Triay, et al. (1997) report that experiments using high calcium and magnesium, low carbonate, unsaturated zone water composition with pH ranging from 6 to 9, and batch sorption experiments involving high total carbonate and high calcium and magnesium (e.g., UE-25p#1) should be performed.		
Thorium sorption experiments involving site-specific materials were reported by Rundberg, et al. (1985) and Thomas (1988). Triay, et al. (1997) suggests that fine colloidal particles in solution may have contributed to uncertainty in the K_d values for thorium. Such a suggestion would indicate confirmatory tests are needed.	The discussion in Triay et al. 1997 concerning Th sorption and the potential effects of colloidal material in the aqueous solution was only a speculative remark in light of the large range of observed K_ds (140 ml/g to 23,800 ml/g). Care in preparation of the Th solutions used for sorption measurements were taken to keep Th in the aqueous phase and no observations of colloidal material in the batch sorption experiments were reported. In TSPA, the upper limit for K_d is 2000 ml/g in devitrified rock, therefore the higher range of K_d observed are not used in TSPA. The presence of colloidal particles in the batch sorption experiment solutions would tend to bias the K_d obtained to lower, and thereby, conservative values.	No additional work is needed.
Wolfsberg (1978) describes sorption-desorption studies of NTS alluvium that included experiments with niobium. The NRC staff considers these experiments involved material that may approximate material expected to be encountered in the alluvial portion of the flowpath from the repository. Sorption of niobium on other site-specific material using	Niobium was not determined to be important to performance assessment calculations as determined in the inventory abstraction AMR (CRWMS M&O 2000e).	No additional work is needed.

appropriate groundwaters has not been performed. Triay, et al. (1997) suggests that fine colloidal particles in solution may contribute to uncertainty in the K_d values for niobium. Such a suggestion would indicate that confirmatory tests are needed.		
Tin sorption experiments have been performed using site-specific rock samples and J-13 and UE-25p#1 groundwaters. Consequently, Criteria 2b1 and 2b2 have been met for tin. However, as with thorium, Triay, et al. (1997) states the large range in sorption coefficients may reflect the presence of colloidal-size particles in the solution phase. Such a suggestion would indicate that confirmatory tests are needed.	Tin was not determined to be important to performance assessment calculations as determined in the inventory abstraction AMR (CRWMS M&O 2000e).	No additional work is needed.
Triay, et al. (1997) groups actinium, americium, and samarium together, along with cerium and europium, due to the similarities in their chemical speciation in aqueous solution and their sorption reactions. All exist in the +3 oxidation state and form carbonate, phosphate, and hydroxide complexes. Sorption coefficients for cerium, europium, and americium were determined for a variety of Yucca Mountain rock samples and J-13 and UE-25p#1 groundwaters. Triay, et al. (1997) states that "the main uncertainty regarding the surficial behavior of americium appears to be the degree to which it is mobilized through colloidal transport (for example, Penrose, et al., 1990)." Such a suggestion would indicate confirmatory tests are needed.	Of the list of radionuclides identified here by the NRC staff analysis, only americium is included in transport calculations for PA. Therefore, confirmatory tests for the suggested grouping are not needed.	No additional work is needed.
Triay, et al. (1997) groups cesium, radium, and strontium together because they exist as simple ions. Their sorption reactions largely involve ion exchange. The batch sorption tests for these radionuclides were performed using site-specific solids and groundwaters including J-13 and UE-25p#1. The NRC staff considers this criterion has been met for these radionuclides.	DOE concurs with the NRC staff analysis.	No additional work is needed.
Nickel sorption has been determined on YM materials including devitrified, zeolitic and vitric tuff from several groundwaters in the pH range from 8.3 to 9.0. The limited range in pH for the nickel	Nickel was not determined to be important to performance assessment calculations as determined in the inventory abstraction AMR (CRWMS M&O 2000e).	No additional work is needed.

experiments is the reason the NRC staff considers this criterion only partially met for nickel. However, it may be possible to calculate the sorption coefficient at lower pH values.		
Sorption of lead, samarium, zirconium, and actinium have not been determined using site-specific materials. Consequently, the criterion has not been met for these elements.	These are not on the list of radionuclides of concern in relation to far-field transport (CRWMS M&O 2000l).	No additional work is needed.
Neptunium sorption has been determined using site-specific materials. They include devitrified, vitric and zeolitic tuff, clinoptilolite, hematite, calcite, albite and quartz, J-13 and UE-25p#1 well waters at pH values of 7, 8.5 and 9.0. Initial neptunium concentrations in some batch sorption tests ranged from 1 X 10^{-7} to 3 X10^{-5}. However, Efurd et al., 1997 found that neptunium solubility approached from undersaturation was only (1.5±0.6) X 10^{-5} at pH = 8.5 and 25 °C. Consequently, sorption experiments carried out at this condition may have precipitated a neptunium phase.	Although a limited number of batch sorption experiments may have been supersaturated with a neptunium phase, most of them were not. Isotherm data supports this conclusion (Triay et al. 1997). If Np sorption measurements were significantly affected by precipitation, then the isotherms would not show the smooth behavior observed. Once a solubility threshold was exceeded, a large increase in the apparent sorption would be observed. Most of the experiments were performed below the solubility limit and the few that were above showed definite indications that precipitation occurred (CRWMS M&O 2000d).	No additional work is needed.
A general concern of the NRC staff is that although site-specific materials may be used in the batch sorption tests, certain combinations of groundwaters and solids may be unnatural and not expected in the YM environment. For example, it is reasonable to assume that the carbonate groundwater, UE25p#1, is in equilibrium with the Paleozoic carbonates, but would that water ever be found in equilibrium with zeolitic tuff? What is the composition of the initial groundwater in the batch sorption experiment, when 20 mL of UE25p#1 is contacted with 1 g of pre-treated zeolite? If the UE25p#1 and the pre-treated zeolite are out of equilibrium initially, what affect might this have on the partitioning of radionuclide between solid and groundwater?	In general, the use of equilibration of solutions with the sample prior to sorption testing brings the sorption tests closer to chemical disequilibrium between the sample and the solution. Compositional changes that may occur are going to be seen in the natural environment. Although contacting UE25p#1 groundwater with a zeolitic tuff may alter the composition of the groundwater, it is expected that similar alteration of the groundwater composition would occur in the natural YM environment.	No additional work is needed.

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Subissue 1: Radionuclide Transport Through Porous Rock		
Methodology 2b3. Performed Crushed Tuff Flow-through Column Experiment		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
Column experiments have been performed to confirm batch sorption K_d values for plutonium, neptunium, and technetium. The criterion has not been met for any other elements listed in the Table 5-1. The DOE Site Characterization Plan (SCP) (U.S. Department of Energy, 1988) originally called for these tests to be performed with plutonium, americium, neptunium, uranium, technetium, cesium, strontium and barium.	For the radionuclides identified as important to performance, identified under Acceptance Criterion 2b, the results of batch and column experiments (where both were performed) are consistent, with the exception of Pu. Column experiments were not done for Pa, Th, Am. Th and Am are not amenable to time efficient column studies. Th and Am exist in only one oxidation state and are highly insoluble, therefore, the batch test is considered sufficient. Pa is considered to behave analogously to Pu. Early planning for site characterization has been updated based on performance assessment results. Column experiments with Ba, Cs and Sr were performed early in the project. Column experiments with Am were carried out by J. Thompson (1989). These experiments suggested the presence of an early breakthrough fraction (~1%) possibly colloidal in nature. Available data will be used to evaluate the need for additional column experiments with U	No additional work is needed.
For those radionuclides that may be mobilized as colloids (e.g., americium, plutonium, thorium, neptunium, tin, actinium, samarium, niobium, cerium, and europium), meeting this criterion has added importance, since the K_d from the batch test may have provided an inaccurate measure of the mobility of the radionuclide. Batch experiments need to be designed and conducted, however, to analyze for the presence of colloids. Additionally, for radionuclides that exist as multiple species in solution, the crushed tuff column experiment can be used to determine if the different species can migrate at different rates in an advective system.	DOE does not consider batch experiments as the preferred way to investigate the presence of colloids. Column experiments are better suited for this. Some column experiments carried out with insoluble nuclides such as Am and Pu suggest the presence of an early breakthrough fraction that may be composed of colloids (Triay et al. 1997).	No additional work is needed.
Triay, et al. (1996a) demonstrated that the K_d from batch sorption experiments could be used to predict breakthrough for neptunium through crushed zeolitic, devitrified, and vitric tuffaceous material. The	DOE concurs with the NRC staff analysis.	No additional work is needed.

apparent dispersivity of the neptunium elution curves through the zeolitic and vitric tuffs led Triay, et al. (1996a) to suggest that "sorption is either nonlinear, irreversible, or noninstantaneous, which means the transport cannot be completely described using a sorption distribution coefficient." However, the report continues that "the use of a batch sorption distribution coefficient to calculate neptunium transport through YM tuffs would result in conservative values for neptunium release." Consequently, the NRC staff considers that this methodology has been successful for determining the retardation of neptunium.		
The NRC staff concludes that, although crushed tuff flow-through column experiments have been performed, as recognized in Table 5-1, the criterion to confirm the K_d determined in static tests are appropriate for calculating a retardation in dynamic systems has not been met for plutonium. This conclusion is based on the observations that the thermodynamic calculations using EQ3 do not agree with observed speciation, the recognition that multiple species do exist, including colloidal forms, and K_d values from batch sorption tests ranging from 20 mL/g (for devitrified tuff) to 2,000 mL/g (for vitric tuff) are inconsistent with crushed tuff column experiments where significant portions of plutonium are eluted unretarded. Triay, et al. (1997) state (page 144) that "The shape of the elution curves for plutonium indicates that use of K_d values to predict plutonium transport through YM tuffs will predict plutonium releases conservatively." On the same page, Figure 98 shows 85% of the plutonium eluting unretarded. Therefore, the proposal that batch sorption tests provide information for conservatively estimating plutonium transport appears to be unsupported (NRC 2000)	The early breakthrough found in crushed-tuff dynamic sorption tests for Pu was shown to be rate dependent. As the experiment flow rate was reduced, the degree of early breakthrough was significantly reduced. Therefore, DOE believes that the early-breakthrough behavior is a rate effect that is dependent on the kinetic rates for Pu sorption mechanisms. The flow rates used were orders of magnitude larger than the expected flow rates at Yucca Mountain. The behavior of Pu in dynamic sorption studies requires further evaluation using dynamic sorption experiments. The experimental technique was to add the radionuclide-bearing solution as a pulse and not continuously. The ordinate on the figures should be labeled "Cumulative Relative Mass." Refer to Unsaturated Zone and Saturated Zone Transport Properties (U0100) (ANL-NBS-HS-000019 REV 00) for additional details	DOE will consider the effects of Pu sorption on performance in sensitivity studies and also review external information concerning Pu sorption. The results of the sensitivity analysis will be used to evaluate the need for additional experiments with Pu.

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Methodology 2b4. Performed Intact Rock Flow-through Column Experiment		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
Conca and Triay (1996) describes a study of selenium migration through unsaturated intact rock. It was demonstrated that the migration of selenium could be estimated conservatively from batch sorption tests. The advantage of this type of experiment over that of batch sorption test is that the sorbing surfaces are likely to be in a more natural state. This methodology successfully demonstrated that the potential effect of disturbed sorption sites on crushed material was not observed for selenium. Similar experiments have not been performed using any of the other radionuclides (NRC 2000).	Selenium has not been identified as a nuclide important to performance assessment calculations (CRWMS M&O 2000e). Intact rock column experiments were carried out using Ba, Cs, and Sr tracers. The results show that batch K_ds can be used to model the breakthrough of these tracers. To successfully model the results, a time-dependent dispersion coefficient was used (Rundberg et al. 1989) Evidence that "disturbed sorption sites on crushed material" are not an issue is also provided by the results of sorption experiments on rock samples crushed to different grain sizes (Rogers and Chipera, 1993). In these experiments, the K_d obtained for a given radionuclide was shown to be largely independent of the grain size used in the experiment These data indicate that crushed rock material can be used in batch tests in lieu of solid rock material in column tests to obtain sorption coefficients for use in performance assessment. Intact rock flow-through column experiments were not fully investigated because of the minimum K_d method used. These tests are considered to be confirmatory in nature to batch tests. Selenium was evaluated using all three methods and demonstrated similar results. Tests were conducted with crushed tuff using different grain sizes. These tests with moderately sorbing nuclides (Np and Sr) indicate that the crushing from 1 cm to micron size did not affect values obtained for K_d (CRWMS M&O 2000d).	No additional work is needed.

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Methodology 2b5. Performed Diffusion Experiment		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Diffusion experiments have been performed for tritium, technetium, neptunium, americium, strontium, cesium, and barium. The advantage of this experimental approach is that the sorbing surfaces are likely to be undisturbed. Consequently, there should be little concern normally associated with crushing, such as generating greater surface areas, and creating fresh surfaces that may be unnaturally sorptive. Figure 132 of Triay, et al. (1997) illustrates a comparison between calculated cesium concentration in a system in which diffusion and sorption are occurring and the actual observed concentrations. The calculated concentrations assumed reversible, instantaneous, linear sorption. The discrepancy between the observed and calculated concentrations suggests that one or more of the assumptions are incorrect. Since isotherms have been measured for cesium (See Criterion 2c1), it may be possible to adjust this comparison.	Matrix diffusion coefficients have been measured on rock samples. Anionic species are assumed to follow the lower rate of diffusion determined for Tc. Cationic species were found to diffuse more rapidly than anionic species and were found to be faster than diffusion of tritium. Therefore, diffusion for cationic species are conservatively bounded by measured diffusion coefficient for tritium. The implementation of diffusion in performance assessment for cationic species conservatively bounds the effects of matrix diffusion found in laboratory tests The predictions would not likely be improved by inclusion of Cs isotherm data because data suggest a higher degree of sorption than modeled by the batch test results NOTE: Matrix diffusion was addressed at the UZ Technical Exchange August 16, 2000 and at the SZ Technical Exchange October 31, 2000. These issues were determined closed-pending upon issuance of documentation and did not identify any new analytical studies.	No additional work is needed.

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Methodology 2b6. Performed Unsaturated Flow Experiment

NRC Staff Analysis	DOE Status	DOE Proposed Path Forward
Conca and Triay (1996) describe solid-rock column unsaturated flow experiments performed using the unsaturated flow apparatus (UFA). The methodology has been successfully applied to the retardation of selenium. The Busted Butte Unsaturated Transport tests are expected to provide additional important information on unsaturated flow and transport in the Topopah Spring and Calico Hills tuffs at the field scale (Bussod and Turin, 1999). Tracers injected during Phase 1 and Phase 2 have included fluorescein and bromide as conservative elements, lithium, and five separate polyfluorinated benzoic acids. Polystyrene latex microspheres are being injected to investigate colloid movement, and a number of reactive tracers such as nickel, cobalt, manganese, samarium, and cerium are being injected as analogs for radionuclide transport (Bussod and Turin, 1999; U.S. Department of Energy, 1998c, Volume 1, Appendix C).	DOE is currently conducting unsaturated flow field experiments at Busted Butte, Alcove 8/Niche 3, and Alcove 1. The results of the Busted Butte testing will be provided in a future revision to the *Unsaturated Zone and Saturated Zone Transport Properties AMR* (CRWMS M&O 2000d). The alcove testing will be documented in a future revision to the *Radionuclide Transport Models Under Ambient Conditions AMR* (CRWMS M&O 2000g) and the *In Situ Field Testing of Processes AMR* (CRWMS M&O 2000h). Given that water saturations are relatively high (approximately 90%) in the welded and zeolitic rock in the unsaturated zone, dynamic sorption experiments under saturated conditions are expected to give representative results given the high degree of saturation.	Complete currently scheduled unsaturated zone field experiments.

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Methodology 2b7. Used Process Model to Determine Constant K_d

NRC Staff Analysis	DOE Status	DOE-Proposed Path Forward
Experimental evidence indicates that sorption behavior is dependent on the physicochemical conditions in the system of interest. Geochemical sorption models to describe these dependencies, and the necessary model parameters, have been summarized and described in several reports (e.g., Davis and Kent, 1990; Serne, et al., 1990; Turner, 1993; Paviet-Hartmann and Triay, 1997). These include ion exchange and surface complexation approaches to sorption, both of which have been used to describe radionuclide sorption mechanisms and characterize the geochemical dependence of radionuclide sorption (e.g., Turner, 1995; Triay, et al., 1997; Paviet-Hartmann and Triay, 1997). Process models have been applied to some extent to sorption of several radioelements of interest in PA, including: neptunium, plutonium, uranium, americium, carbon, cesium, iodine, and selenium (Bradbury and Baeyens, 1993; Dzombak and Morel, 1990; Turner, 1995; Triay, et al., 1997; Paviet-Hartmann and Triay, 1997). The model parameters are calibrated against a set of well-constrained experiments. Process models typically use thermodynamic data for the radioelement of interest to calculate aqueous speciation and determine the amount of radioelement dissolved in solution and the amount sorbed onto the solid. This output can then be used to calculate K_d as a function of chemistry. Calibrated process models can be used to calculate K_d values under conditions beyond the limited set of conditions for which batch or column experimental sorption data are available (Turner, 1998; Turner, et	This method has been used to help qualitatively explain sorption behavior, but is not used to quantitatively establish K_d. Surface complexation models for heterogeneous media (e.g., complex mineralogy, unknown surface compositions and structures) are not sufficiently developed at the present time to be reliably used to predict K_d values outside the range of conditions addressed in the experimental program carried out by DOE. The assumptions required to apply the (few) existing models developed for heterogeneous media are considered difficult to defend. DOE does not use the same constant K_ds in each performance calculation. The K_ds used are randomly selected from probability distributions for a given realization. These distributions are based on expert judgement regarding the influence of the many variables that can affect the sorption coefficient for a given radionuclide.	No additional work is needed.

al., 1998b, 1999). Even in extrapolating model results, however, the application of the K_d approach is subject to the same conditions as the use of batch sorption results. As discussed previously, the assumption of a constant K_d in PA implies that the physicochemical system does not change significantly over the time period of interest. It also requires that the physicochemical conditions remain constant at the level of discretization of the PA model abstraction.		

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Acceptance Criterion (AC) 2c: For the valid application of the constant K_d approach, using equation (1) $R_f = 1 + \rho_b K_d / n$, (or $R_f = 1 + \rho_b K_d / \theta$), DOE has: Demonstrated that the three implicit assumptions (i.e., linear isotherm, fast reversible sorption reaction, and constant bulk chemistry) are valid		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: OPEN DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "The AMR on radionuclide transport models under ambient conditions provides the supporting rationale for these assumptions." The DOE comment suggests that there is information in the AMR that would demonstrate these assumptions are valid. To demonstrate the first two assumptions are valid, multiple sorption experiments would have to be performed where initial radionuclide concentration were varied and the duration of the sorption experiments varied, respectively. The NRC staff intends to review this AMR in FY 01 (NRC 2000)	DOE believes this criterion is CLOSED-PENDING Discussions of K_d related assumptions (i.e., linear isotherm, fast reversible sorption reaction, and constant bulk chemistry) are provided in the following subsections of acceptance criterion 2c. The existing data and methods for implementing the K_d model in performance assessment account for the three implicit assumptions that underlie a K_d approach to sorption	Sensitivity analyses and a review of available data will be used to evaluate the need for additional testing.

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Methodology 2c1. Demonstrated Linear Isotherm by Determining K_d as a Function of Radionuclide Concentration		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Sorption isotherms have been determined for plutonium, uranium, neptunium, cesium, strontium, cerium, and europium. In comparison, the SCP (U.S. Department of Energy, 1988) had listed only four radioelements for which isotherms would be determined. These radioelements were plutonium, uranium, neptunium, and americium. The sorption isotherm for europium, a homologue for americium, but with a lower specific activity, and, thus, less of a problem experimentally, has been determined instead of the isotherm for americium. Triay, et al., (1997) state that the sorption isotherms for plutonium "are generally nonlinear." The nonlinearity in the isotherms is expressed as a curve with the convex side up. As discussed in Section 4, isotherms with convex side up produce self-sharpening fronts and can be used to predict breakthrough. Consequently, the results of this methodology do not preclude the constant K_d for plutonium retardation. The isotherms for neptunium are generally linear. Only near the solubility limit for neptunium is there some nonlinearity. Uranium isotherms are nonlinear but convex up and so can be used to estimate retardation. Isotherms for cesium, strontium, cerium, and europium are best fitted to a nonlinear Freundlich isotherm, with convex side up (NRC 2000)	Isotherms have been found to be either linear or nonlinear with a convex upward shape. In either case, a K_d approach can be used to conservatively predict transport. Given that the sorption behavior is either linear or nonlinear with the convex side up shape, this issue is addressed in CRWMS M&O 2000d.	No additional work is needed.

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Methodology 2c2. Demonstrated Fast Ion Exchange or Adsorption Reaction		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
Triay, et al. (1996a) investigated the kinetics of sorption of neptunium and found these reactions to be fast when the sorbing materials are tuff or clinoptilolite. When the solid was calcite or hematite, steady state had not been reached in 30 days of contact (experiment duration). It is suggested by Triay, et al. (1996a) that coprecipitation is the process that removes neptunium from solution when in contact with calcite. The NRC staff considers that, although the coprecipitation process will remove neptunium from the groundwater, it is inappropriate to use a K_d from the batch tests in formulating a retardation factor. A comparison of batch tests and column tests for neptunium sorption (Triay, et al., 1996b) indicated that the batch sorption distribution coefficient could be used to predict arrival time. However, the elution curves showed dispersivity, which may suggest the isotherm is nonlinear, sorption is irreversible, or noninstantaneous. These column experiments did not involve significant calcite. Batch sorption tests for plutonium failed to reach steady state in 32 days (experiment duration). Likewise, crushed tuff column experiments resulted in some of the plutonium eluting unretarded. Variation in the flow rate resulted in different proportions of the plutonium moving unretarded through the column. At fast flow rates, larger proportions moved unretarded; at slow flow rates, smaller proportions moved unretarded.	The lack of equilibration in experiments involving neptunium sorption onto hematite and calcite was not necessarily due to a coprecipitation mechanism. However, it is acknowledged that a coprecipitation mechanism should not be modeled with a K_d. For non-sorbing and moderately sorbing nuclides, this methodology has been proven conservative as demonstrated in CRWMS M&O (2000d). For Pu, this was not the case and is considered an effect of multiple oxidation states. Fast, reversible sorption reactions have been demonstrated in crushed tuff column experiments for Np. Similar experiments for Pu have found kinetic effects, but the flow rates used were orders of magnitude larger than the expected flow rates at Yucca Mountain. Rate dependence in the laboratory tests for Pu demonstrate convergence to equilibrium behavior at lower flow rates The early breakthrough found in crushed-tuff dynamic sorption tests for Pu was shown to be rate dependent. As the experiment flow rate was reduced, the degree of early breakthrough was significantly reduced. Therefore, DOE believes that the early-breakthrough behavior is a rate effect that is dependent on the kinetic rates for Pu sorption mechanisms. DOE will consider the effects of Pu sorption on performance in sensitivity studies and also review external information concerning Pu sorption. These results will be used to evaluate the need for additional experiments with Pu. Although batch and column experiments with Pu indicate the sorption reactions are not fast and reversible, these reactions are considered sufficiently fast to reach equilibrium under the flow conditions in the saturated zone at the site	Sensitivity analyses and a review of available data will be used to evaluate the need for additional testing.

Triay, et al. (1997) states that "It is noteworthy that the experimentally determined redox behavior of plutonium in solution was quite distinct from the behavior predicted on the basis of EQ3 calculations (Nitsche, 1991)." The report goes on to say "the uncertainties in our knowledge of the solution behavior of plutonium will make it difficult to properly interpret the sorption behavior of that element." The NRC staff considers that this criterion has not been met for plutonium. Neither has the removal of plutonium from solution been shown to be the result of an ion exchange or adsorption reaction nor has the reaction been shown to be fast. The crushed tuff column experiments for studying the elution of plutonium involved adding a pulse of plutonium-contaminated groundwater to the system and flushing through with uncontaminated groundwater. Some unknown reaction reduced the amount of plutonium exiting the column. It is possible that a precipitation reaction could have produced this result. If the experiments were performed with a continuous source instead of a pulse, the experiment might better simulate the situation expected at YM, where the plutonium source term should be continuous after the waste packages are breached. Technetium has been eluted through crushed tuff columns at different flow rates. The flow rate did not affect breakthrough. There was little or no interaction with the solid as technetium moved through the column unretarded, so flow rates should have had no effect as observed (NRC 2000).		

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Methodology 2c3. Demonstrated Constant Bulk Chemistry		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
As discussed previously (Section 4.1.2.2.3.3), an implicit assumption in using K_d to describe radionuclide sorption is that the chemistry of the groundwater is constant at the scale of discretization used in the transport model. Many of the sorption experiments discussed previously (e.g., Meijer, 1990) are performed using water from tuff aquifers in well J-13 in Jackass Flat and carbonate aquifers in well UE-25p#1. A number of studies, however, have Demonstrated that water chemistry in the vicinity of Yucca Mountain can vary significantly with regard to parameters such as pH, ionic strength, and CO_3^{2-} concentration that may affect radionuclide retardation (Yang et al., 1996a,b; Perfect, et al., 1995; Turner, et al., 1999). Both DOE and NRC have made an effort to account for the effects of this changing chemistry in developing the PDFs used in TSPA-VA (Triay et al., 1997; Civilian Radioactive Waste Management System, Management and Operations, 1998a; U.S. Department of Energy, 1998c; Turner, et al., 1999). It also may be possible to demonstrate, through the use of process models, that the observed variability in geochemical conditions will produce minimal changes in K_d .Another approach is to simulate transport using a dynamic reactive transport system model (e.g., PHREEQC, MULTIFLO, HYDROGEOCHEM, etc.) to evaluate the effects of chemical heterogeneity on transport (NRC 2000).	This criterion has been addressed using a range of water compositions and a distribution of K_ds for TSPA. Two water compositions (UE-25p#1 and J-13) were used with variations in pH, ionic strength, and carbonate concentration have been used. Perched waters in the UZ fall within the range of the water from these two wells. Pore water is also within the range from these wells, except for pH which is adjusted during the experiment (CRWMS M&O 2000d) The models identified by NRC as an alternative are not considered sufficiently sophisticated for use on the project at this time. DOE uses a minimum K_d approach that is conservative and does not rely on process models. Although the approach may have potential, useful process models generally require detailed data for the sorption processes and phases to be modeled. Such data is typically not available particularly for heterogeneous systems. A modeling effort in which model parameters are "estimated" simply to force the model to replicate a limited data set does not necessarily clarify the understanding of the processes involved nor does it necessarily provide reliable predictions of sorption behavior outside the limitations of the experimental data set.	No additional work is needed.

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Acceptance Criterion (AC) 3a: For the valid application of process models affecting radionuclide transport such as surface complexation, ion exchange, precipitation/dissolution, and processes involving colloidal material, DOE has: demonstrated that a portion of the flow path acts as an isotropic homogeneous porous medium [see USFIC IRSR (Nuclear Regulatory Commission, 1998b) on deep percolation]		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
Acceptance Criterion Status: OPEN Same as Criterion 2a. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "The vitric portion of the Calico Hills hydrogeologic units behaves as a porous medium and provides an effective barrier to radionuclide transport. The upper units of the Prow Pass hydrogeologic unit also behaves as a porous medium." The NRC staff notes that the DOE comment does not include the term "single continuum." If this omission is intentional, and the units identified are not expected to act as single continua but as dual continua, then DOE would have to demonstrate its capability to predict breakthrough curves (NRC 2000).	DOE believes this criterion is CLOSED. Process-model methods to quantify sorption, ion exchange, precipitation/dissolution, colloidal interactions, or other factors that affect radionuclide transport were not used in performance assessment calculations to quantify transport parameters.	No additional work is needed.

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Acceptance Criterion (AC) 3b: For the valid application of process models affecting radionuclide transport such as surface complexation, ion exchange, precipitation/dissolution, and processes involving colloidal material, DOE has: demonstrated that appropriate values are used in process models		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
Acceptance Criterion Status: OPEN Table 5-2 shows that process models have been applied to some extent to sorption of several radioelements of interest in PA including: neptunium, plutonium, uranium, americium, carbon, cesium, iodine, and selenium (Bradbury and Baeyens, 1993; Dzombak and Morel, 1990; Turner, 1995; Triay, et al., 1997; Paviet-Hartmann and Triay, 1997). These models typically use thermodynamic data for the radioelement of interest to calculate aqueous speciation, and to determine the amount of radioelement dissolved in solution and the amount sorbed onto the solid. This outputcan then be used to calculateKd as a function of chemistry. Although process models can be applied over a wide set of geochemical conditions, it is recognized that determining the necessary model parameters relies on calibration against a set of well-constrained experiments. To provide additional confidence in the model results, the experiments used to calibrate the model should cover a range in critical parameters such as pH, ionic strength, and radionuclide concentration. The experimental variation in these Parameters should span the range expected over the time period of interest at the scale of discretization in the PA abstraction. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "UZ Transport parameters are summarized in Section 3.11.2 of the UZ F&T PMR." In response, the NRC staff intends to review the UZ F&T PMR in FY01 (NRC 2000).	DOE believes this criterion is CLOSED. Process-model methods to quantify sorption, ion exchange, precipitation/dissolution, colloidal interactions, or other factors that affect radionuclide transport were not used in performance assessment calculations to quantify transport parameters.	No additional work is needed.

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Acceptance Criterion (AC) 3c: For the valid application of process models affecting radionuclide transport such as surface complexation, ion exchange, precipitation/dissolution, and processes involving colloidal material, DOE has: (i) Demonstrated that the three implicit assumptions (as in 2c) are realized, if process models are intended to yield a constant K_d for use in the retardation equation (equation 1); otherwise, determined transport in a dynamic reactive transport system model (e.g., PHREEQC, MULTIFLO, HYDROGEOCHEM, etc.)		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
Acceptance Criterion Status: OPEN Turner (1998) uses groundwater compositions from Perfect, et al. (1995) to suggest the possibility of a significant range of K_d values for neptunium and uranium for the YM region. However, the variation in groundwater composition in the portion of the pathway that is considered to be an isotropic homogeneous porous medium may be less than that over the whole region, which includes significant fractured rock. The limited availability of groundwater analyses for the porous rock units will likely result in a limited range of calculated K_d values. One additional concern stems from the evidence that in some wells, groundwater compositions have varied over time. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "The AMR on radionuclide transport models under ambient conditions provides the supporting rationale for these assumptions." The NRC staff intends to review this AMR in FY01 (NRC 2000).	DOE believes this criterion is CLOSED. Process-model methods to quantify sorption, ion exchange, precipitation/dissolution, colloidal interactions, or other factors that affect radionuclide transport were not used in performance assessment calculations to quantify transport parameters.	No additional work is needed.

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 1: Radionuclide Transport Through Porous Rock		
Acceptance Criterion (AC) 4: Where data are not reasonably or practicably obtained, expert judgement has been used and expert elicitation procedures have been adequately documented. If used, expert elicitations were conducted and documented in accordance with the guidance in NUREG-1563 (Nuclear Regulatory Commission, 1996) or other acceptable approaches		
NRC Staff Analysis	**DOE Status**	**DOE Proposed Path Forward**
Acceptance Criterion Status: OPEN The NRC staff considers K_d values from batch sorption tests, confirmed by crushed tuff column or other experiments, can be reasonably or practicably obtained. Consequently, expert elicitation would not appear to be appropriate, as a general matter, to use in place of experimentally determined sorption coefficients. This applies only to those radionuclides whose sorption characteristics affect performance. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "No expert elicitation was conducted." With regard to expert elicitation, the NRC staff considers this acceptance criterion has been met. However, the staff needs clarification on the use of expert judgement in radionuclide transport. For example, how are the distributions of sorption parameters determined? Triay et al., 1997 state that "sorption coefficient distributions are inferred from data..." NRC staff requests that the term "inferred" be clarified (NRC 2000).	DOE believes this criterion is CLOSED-PENDING. Expert judgement was not used in place of experimentally developed values. The experimentally determined values are only applicable under the conditions which the experiment was performed. However, the number of parameters that affect the K_d is so large and the number of experiments that would have to be performed to address the number of permutations involved is not practicable. Therefore, the TSPA uses a distribution range of K_d values for performance assessment calculations (Wilson et al. 1994 and CRWMS M&O 2000d). Expert judgement was used to help define the distributions for K_ds used in TSPA. These judgements were based on the experimentally available sorption data as well as published literature.	Additional documentation will be provided to explain how sorption coefficient distributions used for performance assessment were derived.

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

<table>
<tr><th colspan="3">Subissue 1: Radionuclide Transport Through Porous Rock</th></tr>
<tr><td colspan="3">Acceptance Criterion (AC) 5: Data and models have been collected, developed, and documented under acceptable QA procedures (e.g., Altman, et al., 1988), or if data were not collected under an established QA program, they have been qualified under appropriate QA procedures</td></tr>
<tr><th>NRC Staff Analysis</th><th>DOE Status</th><th>DOE-Proposed Path Forward</th></tr>
<tr><td>Acceptance Criterion Status: OPEN

The Total System Performance Assessment—Viability Assessment (TSPA-VA) indicates that the K_d values for plutonium, uranium, and neptunium are Q-listed. All other K_d s and K_d distributions have Not Qualified (NQ) QA status.

DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "Activities associated with this work were determined to be subject to the quality assurance program as described in the Quality Assurance Requirements Description (QARD) document." In response, the NRC staff considers the status unchanged. Values of K_d for plutonium, uranium, and neptunium are Q-listed. All other K_ds and K_d distributions have Not Qualified QA status.</td><td>DOE believes this criterion is CLOSED-PENDING.

The Unsaturated Zone Flow and Transport Process Model Report, Saturated Zone Flow and Transport Process Model Report, and their supporting AMRs were completed under acceptable quality assurance procedures. The status of technical inputs may be confirmed by review of the Document Input Reference System (DIRS) database. The DIRS database will be updated to indicate changes to the QA status of these data.</td><td>80% of the data related to the subject of this KTI have been qualified as of 7/31/00. A list of unqualified data supporting the Site Recommendation Consideration Report will be provided to the NRC with the report. These unqualified data will be qualified by 6/25/01</td></tr>
</table>

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 2: Radionuclide Transport Through Alluvium		
Importance to System Performance: Radionuclide delay through the saturated zone is a principal factor of the postclosure safety case. The alluvium of the saturated zone contributes to the delay and dilution of radionuclide concentrations provided by the natural barriers.		
Acceptance Criterion 1a: For the estimation of radionuclide transport through alluvium, DOE has determined through PA calculations whether radionuclide attenuation processes such as sorption, precipitation, radioactive decay, and colloidal filtration are important to performance.		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: CLOSED DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "SZ performance assessment calculations indicate these processes are important." In response, the NRC staff considers this acceptance criterion has been met.	DOE believes this criterion is CLOSED. Performance assessment calculations have been used to determine that radionuclide attenuation processes are important to performance	No additional work is needed.

Subissue 2: Radionuclide Transport Through Alluvium

Acceptance Criterion 1b: For the estimation of radionuclide transport through alluvium, DOE has (i) Assumed K_d is zero and radionuclides travel at the rate of the groundwater flow, if it has been found that radionuclide attenuation is unimportant to performance and it can be demonstrated that this assumption is conservative in which case, Acceptance Criteria 2 and 3 do not have to be met or, (ii) demonstrated that Criterion 2 or 3 has been met, if radionuclide attenuation in alluvium is important to performance, or if an assumption that K_d is zero in alluvium is not conservative.

NRC Staff Analysis	DOE Status	DOE-Proposed Path Forward
Acceptance Criterion Status: OPEN DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "K_d is assumed to be zero for C and Cl." The NRC staff notes that Tc and I are not assumed to have K_d value of zero as was assumed in the porous rock. The presentation at the Technical Exchange included results of recent batch sorption experiments for Np, Tc, and I. The values of K_d were nonzero for all three elements. The staff requests that DOE describe plans to confirm the K_d values.	DOE believes this criterion is CLOSED.. For the 14 nuclides of interest, TSPA-SR Rev. 0 used K_d values that were greater than zero, but very small (less than 1 ml/gm) based on preliminary data. Ongoing experimental data have determined that K_d values for Tc and I as measured in the alluvium are not statistically different from zero under oxidizing conditions. Based on the newer data, Tc and I will be treated as having K_d values of zero in Total System Performance Assessment- Site Recommendation Rev. 01. Np will be addressed under Acceptance Criterion 2	No additional work is needed.

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

<table>
<tr><th colspan="3">Subissue 2: Radionuclide Transport Through Alluvium</th></tr>
<tr><td colspan="3">Acceptance Criterion 2a: For the valid application of the constant K_d approach, equation (1) $R_f = 1 + \rho_b K_d / n$, (or $R_f = 1 + \rho_b K_d / \theta$), DOE has: Demonstrated that the flow path acts as a single continuum porous medium. If the flow can not be shown to be a single continuum porous medium, then the acceptance criteria for radionuclide transport in fractured rock apply.</td></tr>
<tr><th>NRC Staff Analysis</th><th>DOE Status</th><th>DOE-Proposed Path Forward</th></tr>
<tr><td>Acceptance Criterion Status: OPEN

DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "SZ fluid flow in the alluvium is likely to be well represented using a porous continuum conceptual model. Data to quantify the alluvial portion of the flow path are sparse, and hydrologic parameters used in numerical models should be considered to be bounding."

Additionally, this acceptance criterion was identified in the Technical Exchange presentation as an area of potential disagreement. This point was also made in the letter from Brocoum to Reamer, 03/22/00. In the presentation, it is stated that "homogeneity of porous rock or alluvium does not need to be demonstrated at all scales." Instead DOE suggests that "Homogeneity only needs to be addressed at the level of assumed homogeneity in the model, for example, the grid discretization or level of heterogeneity modeled."

In the letter from Brocoum to Reamer, it is stated that "DOE believes that, consistent with the intent of proposed 10 CFR Part 63, IRSR discussions should not impose prescriptive requirements and should not call for additional DOE work not clearly linked to repository performance. We believe in this case that qualitative arguments should suffice (e.g., alluvium is unconsolidated sediment) to justify treating alluvium as a porous medium."</td><td>DOE believes this criterion is CLOSED-PENDING.

For the purpose of Total System Performance Assessment and over large scales the alluvium can be modeled as a single continuum porous medium. This will be confirmed by testing at the Alluvium Testing Complex (ATC).

The heterogeneity in the medium is incorporated through the use of the distribution of the effective porosity in the alluvium which is less than total porosity. The use of the effective porosity reflects the channelization of flow caused by heterogeneity. (CRWMS M&O 2000f).</td><td>Continue the testing at ATC and the Nye County wells to further reduce uncertainty in hydrologic parameters. Prepare hydrostratigraphic cross sections using Nye County data. (Note that this work is the subject of Agreements 3, 4, and 5 under Subissue 5 from the Saturated Zone Technical Exchange).</td></tr>
</table>

In response, the NRC staff is unconvinced that the alluvium can be considered homogeneous on the scale of grid discretization, which has been reported to 500 m. Logging of Nye County EWDP holes suggests heterogeneity in a vertical sense. Cross-hole correlation of the lithologic logs from the EWDP could provide information on heterogeneity in a horizontal sense on scales of tens of meters and greater. Furthermore, recent pump tests suggest heterogeneity of hydraulic parameters in single well. The NRC staff agrees with DOE that homogeneity only need be demonstrated on the scale modeled. However, the method by which this can be accomplished on blocks 500 m on a side is unclear. Qualitative arguments will not suffice if retardation in the alluvium is important to performance. Performance assessment calculations by the NRC staff suggest the alluvium can be an important component of the geologic barrier.		

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 2: Radionuclide Transport Through Alluvium		
Acceptance Criterion 2b: For the valid application of the constant Kd approach, equation (1) $R_f = 1 + \rho_b K_d / n$, (or $R_f = 1 + \rho_b K_d / \theta$), DOE has: Demonstrated that appropriate values for the parameters, K_d, n or θ, and ρ_b have been adequately considered (e.g., experimentally determined or measured).		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: OPEN DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "SZ transport of sorbing solutes in porous media is a subject that has been well studied. Therefore, it is reasonable to assume that the transport velocities of sorbing radionuclides in the alluvium can be conservatively represented using an equilibrium sorption coefficient. Sorption coefficients onto alluvium from the Nye County wells have been measured for a few key radionuclides; for the remaining radionuclides, sorption coefficients have been estimated based on the corresponding values measured for crushed tuff. Recent evaluations of K_d for Np, Tc, and I have been accomplished for alluvium." The NRC staff agrees that sorption of solutes in porous media has been the subject of considerable study. Sorption onto alluvial materials is new. It is likely that information from crushed tuff experiments can be applied to the alluvial system. However, this would require comparing the solid phases present in the alluvium with phases in the crushed tuff experiments. The fact that Tc and I have nonzero K_d values for the alluvium and not the porous rock suggest some differences.	DOE believes this criterion is CLOSED-PENDING. DOE is using preliminary transport parameter values derived from lab measurements for use in performance assessment analyses (CRWMS M&O 2000d).. DOE will refine and confirm these parameter values after multiple well tracer testing of radionuclide surrogates at the Alluvium Testing Complex and after laboratory column radionuclide transport studies. DOE presented plans to the NRC for obtaining these parameters at the SZ technical exchange October 31, 2000. This work is being tracked under the USFIC KTI.	No further work beyond the ongoing and planned testing at the ATC is required. DOE presented plans to the NRC for obtaining these parameters at the SZ technical exchange October 31, 2000. This work is being tracked under the USFIC KTI.

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 2: Radionuclide Transport Through Alluvium		
Acceptance Criterion 2c: For the valid application of the constant K_d approach, using equation (1) $R_f = 1 + \rho_b K_d / n$, (or $R_f = 1 + \rho_b K_d / \theta$), DOE has: Demonstrated that the following assumptions (i.e., linear isotherm, fast reversible sorption reaction, and constant bulk chemistry) are valid.		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: OPEN DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "Sorption is incorporated into the site-scale SZ flow and transport model using a linear isotherm model." In response, the NRC staff considers the constant K_d approach should be confirmed through the use of column experiments. This approach is recommended by Triay et al., 1996b.	DOE believes this criterion is CLOSED-PENDING. Linear isotherm assumption are considered valid given the very low expected molar concentrations of radionuclides Fast sorption kinetics has been demonstrated for Np; fast desorption kinetics will be verified in planned laboratory testing Batch and column testing of Tc and Np under reducing conditions is planned; Saturated Zone performance is expected to improve under reducing conditions; therefore, current approach is conservative.	Complete planned laboratory column experiments.

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 2: Radionuclide Transport Through Alluvium		
Acceptance Criterion 3a: For the valid application of process models affecting radionuclide transport such as surface complexation, ion exchange, precipitation/dissolution, and processes involving colloidal material, DOE has: Demonstrated that the flow path acts as a single continuum porous medium.		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: OPEN DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "SZ fluid flow in the alluvium is likely to be well represented using a porous continuum conceptual model. Data to quantify the alluvial portion of the flow path are sparse, and hydrologic parameters used in numerical models should be considered to be bounding." In response, the NRC staff considers this the same as for 2a.	DOE believes this criterion is CLOSED. Process models approach for determination of K_d is not being used in the alluvium and therefore, the acceptance criterion is not applicable.	No additional work is needed.

Subissue 2: Radionuclide Transport Through Alluvium		
Acceptance Criterion 3b: For the valid application of process models affecting radionuclide transport such as surface complexation, ion exchange, precipitation/dissolution, and processes involving colloidal material, DOE has: Demonstrated that appropriate values are used in the process models.		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: OPEN DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "SZ transport of sorbing solutes in porous media is a subject that has been well studied. Therefore, it is reasonable to assume that the transport velocities of sorbing radionuclides in the alluvium can be conservatively represented using an equilibrium sorption coefficient. Sorption coefficients onto alluvium from the Nye County wells have been measured for a few key radionuclides; for the remaining radionuclides, sorption coefficients have been estimated based on the corresponding values measured for crushed tuff. Recent evaluations of K_d for Np, Tc, and I have been accomplished for alluvium." In response, the NRC staff considers this the same as for 2b.	DOE believes this criterion is CLOSED. Process models approach for determination of K_d is not being used in the alluvium and therefore, the acceptance criterion is not applicable.	No additional work is needed

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 2: Radionuclide Transport Through Alluvium		
Acceptance Criterion 3c: For the valid application of process models affecting radionuclide transport such as surface complexation, ion exchange, precipitation/dissolution, and processes involving colloidal material, DOE has: (i) Demonstrated that the three implicit assumptions are valid, if process models are intended to yield a constant K_d approach for use in the retardation equation; or (ii) determined transport in a dynamic reactive transport system (e.g., PHREEQC, MULTIFLO, HYDROCHEM, etc.)		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: OPEN DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "Sorption is incorporated into the site-scale SZ flow and transport model using a linear isotherm model." In response, the NRC staff considers this the same as 2c.	DOE believes this criterion is CLOSED. Process models approach for determination of K_d is not being used in the alluvium and therefore, the acceptance criterion is not applicable.	No additional work is needed

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

<table>
<tr><th colspan="3">Subissue 2: Radionuclide Transport Through Alluvium</th></tr>
<tr><td colspan="3">Acceptance Criterion 4: Where data are not reasonably or practicably obtained, expert judgement has been used and expert elicitation procedures have been adequately documented. If used, expert elicitations were conducted and documented in accordance with the guidance in NUREG-1563 (Nuclear Regulatory Commission, 1996) or other acceptable approaches. However, the NRC staff considers Kd values from batch sorption tests, confirmed by crushed tuff column or other experiments can be reasonably or practicably obtained. Consequently, expert elicitation would not appear appropriate to use in place of experimentally determined sorption coefficients.</td></tr>
<tr><th>NRC Staff Analysis</th><th>DOE Status</th><th>DOE-Proposed Path Forward</th></tr>
<tr><td>Acceptance Criterion Status: OPEN

DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "No expert elicitation was conducted." With regard to expert elicitation, the NRC staff considers this acceptance criterion has been met. However, the staff needs clarification on the use of expert judgement in radionuclide transport. For example, how are the distributions of sorption parameters determined? Triay et al., 1997 state that "sorption coefficient distributions are inferred from data..." the term "inferred" needs to be clarified.</td><td>DOE believes this criterion is CLOSED-PENDING

Expert judgement was used to help define the distributions for K_ds used in TSPA. These judgements were based on the experimentally available sorption data as well as published literature.</td><td>Additional documentation will be provided to explain how sorption coefficient distributions used for performance assessment were derived.</td></tr>
</table>

Subissue 2: Radionuclide Transport Through Alluvium		
Acceptance Criterion 5: Data and models have been collected, developed and documented under acceptable QA procedures (e.g., Altman et al., 1988), or if data were not collected under an established QA program, they have been qualified under appropriate QA procedures.		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: OPEN DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "Activities associated with this work were determined to be subject to the quality assurance program as described in the Quality Assurance Requirements Description (QARD) document." In response, the NRC staff considers the status unchanged. Values of K_d for plutonium, uranium, and neptunium are Q-listed. All other K_d s and K_d distributions have a Not Qualified QA status.	DOE believes this criterion is CLOSED-PENDING The Unsaturated Zone Flow and Transport Process Model Report, Saturated Zone Flow and Transport Process Model Report, and their supporting AMRs were completed under acceptable quality assurance procedures. The status of technical inputs may be confirmed by review of the Document Input Reference System (DIRS) database. The DIRS database will be updated to indicate changes to the QA status of these data.	80% of the data related to the subject of this KTI have been qualified as of 7/31/00. A list of unqualified data supporting the Site Recommendation Consideration Report will be provided to the NRC with the report. These unqualified data will be qualified by 6/25/01.

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 3: Radionuclide Transport in Fractured Rock		
Importance to System Performance: Radionuclide delay through the unsaturated zone and saturated zone are principal factors of the postclosure safety case. The fractured rocks of the unsaturated zone and saturated zone contribute to the delay and dilution of radionuclide concentrations provided by the natural barriers.		
Acceptance Criterion 1a: For the estimation of radionuclide transport through fractured rock, DOE has: determined, through PA calculations, whether radionuclide attenuation processes such as sorption, precipitation, and radioactive decay, and colloidal transport are important to performance		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: CLOSED DOE has used performance assessment calculations to determine whether radionuclide attenuation processes are important to performance. Consequently, this criterion has been met. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "Performance assessment calculations have determined that such processes are important. Sorption in the fractures is neglected in the PA transport evaluations because of limited data and the conservative nature of the assumption." In response, the NRC staff considers this criterion has been met.	DOE believes this criterion is CLOSED. Radionuclide transport attenuation processes have been determined to be important to performance and are included in the transport models. (CRWMS M&O 2000a and CRWMS M&O 2000b).	No additional work is needed.

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 3: Radionuclide Transport in Fractured Rock		
Acceptance Criterion 1b: For the estimation of radionuclide transport through fractured rock, DOE has: assumed K_d (or K_A) is zero and that radionuclides travel at the velocity of groundwater flow through fractures, if it has been found that radionuclide attenuation in fractures is unimportant to performance, and it can be demonstrated that this assumption is conservative		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: OPEN Current performance assessment models assume radionuclides are not sorbed in fractures. However, it appears that matrix diffusion will be considered as an attenuation processes affecting radionuclide transport in fractured rock. Consequently, this criterion has not been met. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "K_d is assumed to be zero for C and Cl. Sorption in the fractures is neglected in the PA transport evaluations because of limited data and the conservative nature of the assumption." The NRC notes that K_d for I and Tc are assumed to be zero in the porous rock but here in fractured rock their K_ds are considered to be nonzero. This apparent discrepancy needs to be clarified.	DOE believes this criterion is CLOSED. Matrix diffusion is important to performance and is included in the dual-continuum model. However, this is a topic covered by the USFIC KTI and was discussed at the Technical Exchange for Unsaturated Zone, August 16, 2000. K_ds for Tc and I are only (potentially) considered to be nonzero in alluvium. K_ds for Tc, I, C are zero for the UZ. (Cl is not among the fourteen nuclides modeled in TSPA) (CRWMS M&O 2000a and CRWMS M&O 2000b). Matrix diffusion is important to performance and is included in the saturated zone flow and transport model. This topic was addressed at the USFIC Technical Exchange for the Saturated Zone, October 31, 2000. K_ds for Tc, C, and I in the rock matrix of the fractured rock are zero. No sorption credit is taken in the fractures for any nuclide (CRWMS M&O 2000a and CRWMS M&O 2000b). Due to the inclusion of matrix diffusion, DOE does not assume that radionuclides travel at the velocity of groundwater in fractures. Therefore, this criterion is not applicable.	No additional work is needed

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 3: Radionuclide Transport in Fractured Rock		
Acceptance Criterion 1c: For the estimation of radionuclide transport through fractured rock, DOE has: justified the length of flowpath to which these fracture transport conditions apply		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: OPEN Geostatistical analysis of tracer tests as suggested in Criterion 2a can provide support for establishing the length of the flowpath to which fracture transport conditions apply. Lacking a geostatistical analysis, estimation of the fractured pathway length should err on the side of conservatism. This criterion has not been met. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "Chloride hydrochemical groundwater data, as well as other chemical and isotopic data and the potentiometric surface map have been used to constrain SZ flowpaths. Sorption in the fractures is neglected in the PA transport evaluations because of limited data and the conservative nature of the assumption." The NRC staff will review the AMR describing the use of hydrochemical data to constrain SZ flowpaths in FY01. This acceptance criterion is intended to apply to both the SZ and UZ fracture rock flow systems.	DOE believes this criterion is CLOSED. The path lengths through the various units in the UZ are generally the shortest distance between the potential repository and the water table (CRWMS M&O 2000b and CRWMS M&O 2000i). The only case where this is not true is where there is lateral diversion due to perched water. The sensitivity of transport to more or less perched water (and hence lateral diversion) demonstrates that transport time to the water table is not significantly affected by the path length (CRWMS M&O 2000j). The major influence on transport time to the water table is the amount of matrix flow and transport that occurs. The uncertainty related to the lengths of flow paths in the saturated tuff and in the alluvium was discussed at the Saturated Zone Technical Exchange October 31, 2000. Uncertainty related to the lengths of flow paths in the saturated tuff and in the alluvium is documented in (CRWMS M&O 2000k). DOE agreed at the technical exchange to provide additional information, including Nye County data, to further justify the uncertainty distribution of flow path lengths in alluvium in updates to the *Uncertainty Distribution for Stochastic Parameters AMR* (Agreement 4 under Subissue 5).Therefore, this criterion is considered closed within the RT KTI and is tracked in the USFIC KTI.	No additional work is needed.

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 3: Radionuclide Transport in Fractured Rock		
Acceptance Criterion 2a: If credit is to be taken for radionuclide attenuation in fractured rock, DOE has: demonstrated capability to predict breakthrough curves of reactive, nonreactive, and colloidal tracers in field tests		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: OPEN Unlike the estimation of transport in porous media, which is supported by 50 years of chemical engineering experience in chromatographic separation techniques, the estimation of transport through fractured rock is relatively untested. The C-hole reactive tracer test is the only field test the NRC staff is aware of in the SZ at YM that provides direct information on the transport of reactive, nonreactive, and colloidal material. The C-hole breakthrough curves (concentration and travel time) could not be quantitatively predicted using the laboratory experiments including batch sorption, crushed tuff column, diffusion, and fractured rock column tests, alone, or in concert with the hydraulic pump tests in the C-holes. Consequently, this criterion is not met. The NRC staff considers the cross hole reactive tracer tests, like those at the C-hole complex and the Busted Butte facility to be crucial to demonstrate the capability to predict transport. The use of field tests to compare back to the laboratory experiments is a logical extension to the strategy proposed by Triay et al., 1992 to validate the batch sorption data. Geostatistical analysis of multiple tracer tests could be used to demonstrate the capability to predict radionuclide transport in fractured rock. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "SZ model of fracture flow and matrix diffusion consistent with	DOE believes this criterion is CLOSED-PENDING. For the Unsaturated Zone, non-sorbing tracer tests have been conducted in fractured welded tuff (Alcove 1) and additional tests are being conducted in Alcove 8/Niche 3. Predictive models are being developed for the Alcove 8/Niche tests as discussed at the SDS Technical Exchange October 11, 2000. Agreement 2 of Subissue 3 is being tracked by the SDS KTI. Field testing in 3 alcoves, 5 niches, and along Exploratory Studies Facility Main Drift and Cross Drift provides data for Unsaturated Zone flow and transport modeling and assessment of fractured tuff units. Simulated breakthrough curves match the tracer concentration data in the Alcove 1 tracer test, indicating: the continuum approach is valid for modeling flow and transport in unsaturated fractured rock use of an active fracture model can capture the major features of fingering flow and transport in fractures. Ongoing tracer test at Alcove 8/Niche 3 will further evaluate predictive modeling of transport in fractured rock. Potential future testing of reactive transport in fractured rock at the repository horizon (both middle nonlithophysal unit and lower lithophysal unit); more on this will be discussed for Criterion 2b For the Saturated Zone, the C-well data was used to identify and confirm conceptual models of transport processes. The envelope from the uncertainty distribution for the transport parameters is sufficiently large to address the scaling of the parameters derived from the C well data. Sensitivity analyses have been performed on the matrix diffusion and spanned the entire spectrum from zero to	Complete Alcove 8/Niche 3 testing and predictive modeling for the Unsaturated Zone.

data. Sorbing tracer (Li) breakthrough consistent with combined matrix diffusion/sorption model. Microspheres breakthrough slightly earlier than solutes, but are attenuated. Sorption in the fractures is neglected in the PA transport evaluations because of limited data and the conservative nature of the assumption." The NRC staff questions the appropriateness of developing an SZ model that extends tens of kilometers based on a test that extends only tens of meters. The C-well test was an excellent experiment that provided important information on transport in a fractured system on the scale of 30 meters. However, extrapolation to larger scales is untested. If processes other than pure matrix diffusion are occurring in a tracer test (e.g., Becker and Shapiro, 2000), extrapolation using inappropriate abstract models could lead to miscalculations of breakthrough curves. The NRC staff is unclear how credit can be taken for matrix diffusion but sorption in fractures is neglected in PA transport evaluations because of limited data. In the TSPA VA it is stated that "surfaces of fractures, often lined with minerals that differ from the bulk of the rock matrix may be capable of sorbing many of the radionuclides (Triay et al., 1997). However, there has been limited characterization of the distribution of the fracture-lining materials and sorptive interactions with these minerals." The NRC staff requests that DOE explain this apparent inconsistency. In the letter from Brocoum to Reamer, 3/22/00, on reviewing this acceptance criterion, the DOE comment states that "The TSPA models are not designed to be predictive or to represent transport on the scale of a few meters and over the timeframe of days. The models are designed to bound the potential transport rates over some 20 km and over periods of 10,000 years or more. Given these constraints, it	complete matrix diffusion. The total population in the uncertainty distribution is skewed towards negligible matrix diffusion. The range of matrix diffusion in the sensitivity analysis is within the uncertainty distribution range used in the performance assessment (CRWMS M&O 2000f). Predictive modeling was completed prior to the C-well testing and is documented in Robinson (1994) and Reimus (1995). The predictions relative to tracer responses were consistent with the field results. These predictions will also be summarized in the planned C-wells report.	

would be unrealistic to require the same models to predict tracer transport on much smaller time scales." The NRC staff agrees that the TSPA models are not suited for predictions of small scale systems. However, DOE made predictions of transport in column tests from the results of batch tests. The characterization program has been based on a principle of testing simple systems first and using the results to predict more complex systems. Can DOE predict breakthrough curves of field experiments? Also, in the letter it was stated that this work is not clearly related to repository performance. The staff disagrees. The C-well work should be repeated in other localities with efforts to predict the breakthrough preceding the tests.		

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 3: Radionuclide Transport in Fractured Rock		
Acceptance Criterion 2b: If credit is to be taken for radionuclide attenuation in fractured rock, DOE has: demonstrated nonradioactive tracers used in field tests are appropriate homologues for radioelements		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: CLOSED Considerable effort has been expended in identifying reactive tracers that mimic the properties of radionuclides. The use of "cocktails" of tracers is an innovative approach at characterizing transport processes in the field. The NRC staff considers this criterion is being met with regard to the Busted Butte and C-hole complex tests. The NRC staff will continue to track the tests to assure this criterion is met. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "SZ model of fracture flow and matrix diffusion consistent with data. Sorbing tracer (Li) breakthrough consistent with combined matrix diffusion/sorption model. Microspheres breakthrough slightly earlier than solutes, but are attenuated. Sorption in the fractures is neglected in the PA transport evaluations because of limited data and the conservative nature of the assumption." The NRC staff considers this criterion has been met, but will continue to track the tests to assure reasonable tracers are used.	DOE believes this criterion is CLOSED. Work with a variety of tracers has been conducted at Busted Butte, including weakly sorbing Li. Both nonsorbing and strongly sorbing tracers have also been tested at Busted Butte. A variety of nonsorbing tracers with different diffusion coefficients are planned for use in the Alcove 8/Niche 3 testing program. The same applies to the saturated zone testing at the C-wells. Batch sorption experiment were completed to test the sorption behavior of the tracer homologues and the radionuclides. The results indicated that the tracers used were homologues to the radionuclides. The aqueous Br^- tracer used for Alcove 1 testing has sorption and ion size characteristics representative of I. Therefore, it is a suitable homologue for ^{129}I Transport tests are being conducted in Alcove 8/Niche 3 using tracers that are representative of nonsorbing and moderately sorbing tracers in the potential repository host rock. Fluorobenzoic acids are nonsorbing anions with larger ion sizes similar to TcO_4^- Therefore they are suitable homologues for aqueous ^{99}Tc. Aqueous Li has been found to have sorption characteristics similar to moderately sorbing radionuclide isotopes of Np and U. Appropriate tracers have been used in the C-wells testing to represent transport of non-sorbing and sorbing radionuclides and colloids in the saturated zone.	No additional work is needed

Subissue 3: Radionuclide Transport in Fractured Rock		
Acceptance Criterion 2c: For the estimation of radionuclide transport through fractured rock, DOE has: justified the length of flowpath to which these fracture transport conditions apply		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: OPEN Same as Criterion 1c. Geostatistical analysis of tracer tests as suggested in Criterion 2a can provide support for establishing the length of the flowpath to which fracture transport conditions apply. Lacking a geostatistical analysis, estimation of the fractured pathway length should err on the side of conservatism. This criterion has not been met. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "Chloride hydrochemical groundwater data, as well as other chemical and isotopic data and the potentiometric surface map have been used to constrain SZ flowpaths. Sorption in the fractures is neglected in the PA transport evaluations because of limited data and the conservative nature of the assumption." In response, the NRC staff consider this is the same as 1c.	DOE believes this criterion is CLOSED. The path lengths through the various units in the UZ are generally the shortest distance between the potential repository and the water table (CRWMS M&O 2000b and CRWMS M&O 2000i). The only case where this is not true is where there is lateral diversion due to perched water. The sensitivity of transport to more or less perched water (and hence lateral diversion) demonstrates that transport time to the water table is not significantly affected by the path length (CRWMS M&O 2000j). The major influence on transport time to the water table is the amount of matrix flow and transport that occurs. The uncertainty related to the lengths of flow paths in the saturated tuff and in the alluvium was discussed at the Saturated Zone Technical Exchange October 31, 2000. Uncertainty is documented in (CRWMS M&O 2000k). DOE agreed at the technical exchange to provide additional information, including Nye County data, to further justify the uncertainty distribution of flow path lengths in alluvium in updates to the *Uncertainty Distribution for Stochastic Parameters AMR* (Agreement 4 under Subissue 5).Therefore, this criterion is considered closed within the RT KTI and is tracked in the USFIC KTI.	No additional work is needed

Analysis of the Resolution Status for the Key Technical Issue on Radionuclide Transport

Subissue 3: Radionuclide Transport in Fractured Rock		
Acceptance Criterion 3: Where data are not reasonably or practicably obtained, expert judgement has been used and expert elicitation procedures have been adequately documented. If used, expert elicitations were conducted and documented in accordance with the guidance in NUREG-1563 (Nuclear Regulatory Commission, 1996) or other acceptable approaches. Expert elicitation and sensitivity analyses should not be used as a replacement for experimental and field data, where such data can be reasonably obtained		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: OPEN If expert judgement or elicitation is used to address radionuclide transport through fractured rock, the NRC staff would expect those people elicited would have a proven track record of predicting tracer breakthrough curves in fractured rock. Further, it would have to be demonstrated that this expertise can be applied to the fracture systems in the YM region. This approach has not been taken by the DOE so the NRC staff has no comment. A discussion of the status of meeting this criterion is not applicable. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "No expert elicitation was conducted." With regard to expert elicitation, the NRC staff considers this acceptance criterion has been met. However, the staff needs clarification on the use of expert judgement in radionuclide transport. For example, how are the distributions of parameters important to transport determined?	DOE believes this criterion is CLOSED. DOE based conclusions regarding radionuclide transport in fractured rock on laboratory and field testing, as well as on models. Expert elicitation and expert judgement were not used	No additional work is needed

Subissue 3: Radionuclide Transport in Fractured Rock		
Acceptance Criterion 4: Data and models have been collected, developed and documented under acceptable QA procedures (e.g., Altman, et al., 1988), or if data were not collected under an established QA program, they have been qualified under appropriate QA procedures		
NRC Staff Analysis	**DOE Status**	**DOE-Proposed Path Forward**
Acceptance Criterion Status: OPEN The NRC has expressed concerns about the DOE's QA program (U. S. Nuclear Regulatory Commission, 1999). Status of this criterion is to be determined. DOE commented in the Technical Exchange on Prelicensing Issues on April 22, 2000 that "Activities associated with this work were determined to be subject to the quality assurance program as described in the Quality Assurance Requirements Description (QARD) document." In response, the NRC staff considers the status is open.	DOE believes this criterion is CLOSED-PENDING. The Unsaturated Zone Flow and Transport Process Model Report, Saturated Zone Flow and Transport Process Model Report, and their supporting AMRs were completed under acceptable quality assurance procedures. The status of technical inputs may be confirmed by review of the Document Input Reference System (DIRS) database. The DIRS database will be updated to indicate changes to the QA status of these data.	80% of the data related to the subject of this KTI have been qualified as of 7/31/00. A list of unqualified data supporting the Site Recommendation Consideration Report will be provided to the NRC with the report. These unqualified data will be qualified by 6/25/01

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