U.S. DEPARTMENT OF ENERGY
OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT

NUCLEAR WASTE TECHNICAL REVIEW BOARD
FULL BOARD MEETING

SUBJECT: TSPA-1995 PREDICTED RADIONUCLIDE RELEASE AND DOSE AT THE ACCESSIBLE ENVIRONMENT, YUCCA MOUNTAIN, NEVADA

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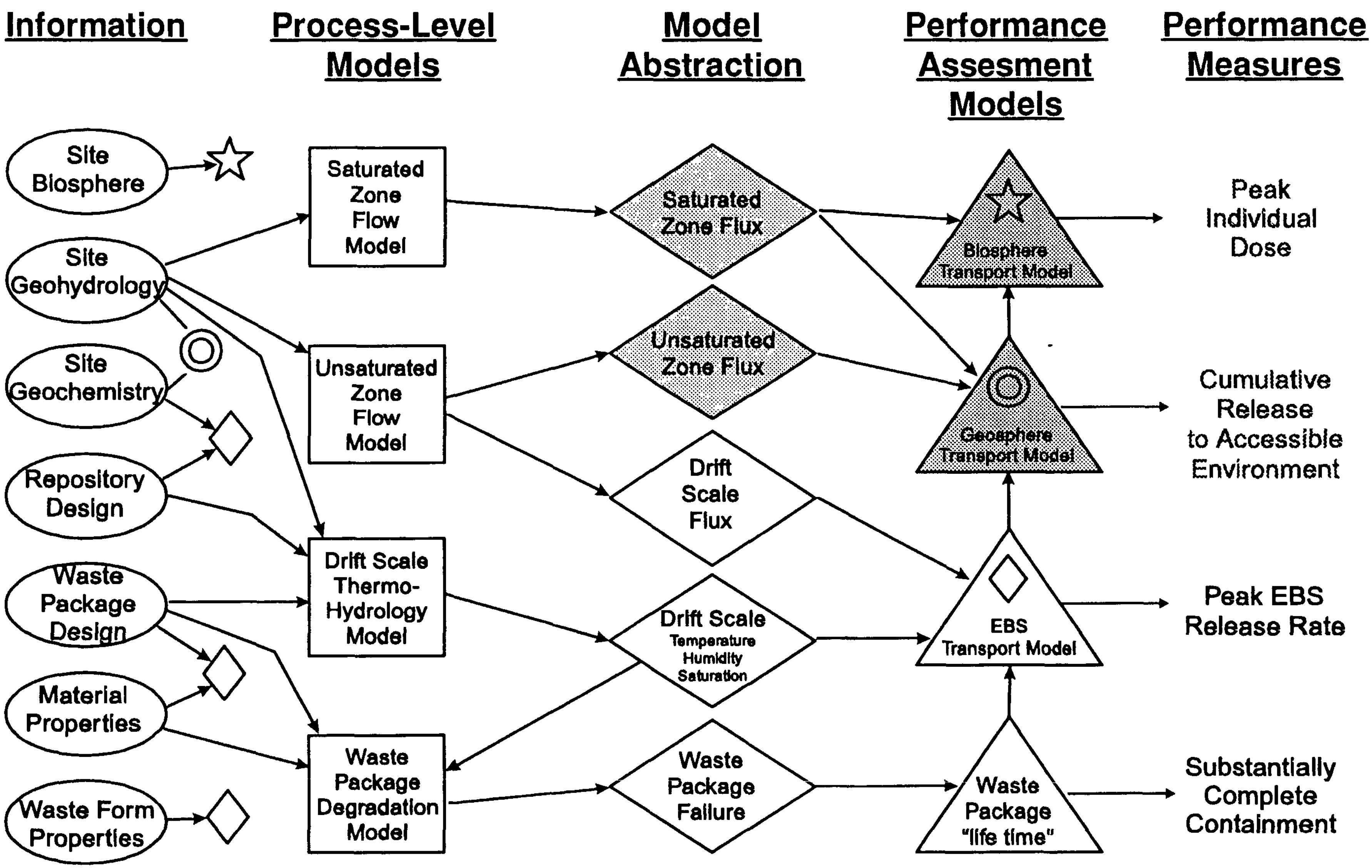
Outline

- TSPA models for unsaturated zone (UZ) and saturated zone (SZ) radionuclide transport, based on
  - » Process-level abstractions
  - » Experiments
  - » Direct incorporation of simplified analytical models into TSPA code
- Release and dose exposure at accessible environment (AE)
  - » Performance over two time periods: 10,000 years and 1,000,000 years
  - » Sensitivity analyses for
    - – Various conceptual models of geosphere transport
    - – Various conceptual models of near-field (WP/EBS) environment
    - – Various repository designs
- Comparison of Subsystem Performance

TSPA-1995 Information Flow Diagram

Radionuclide Transport to Accessible Environment



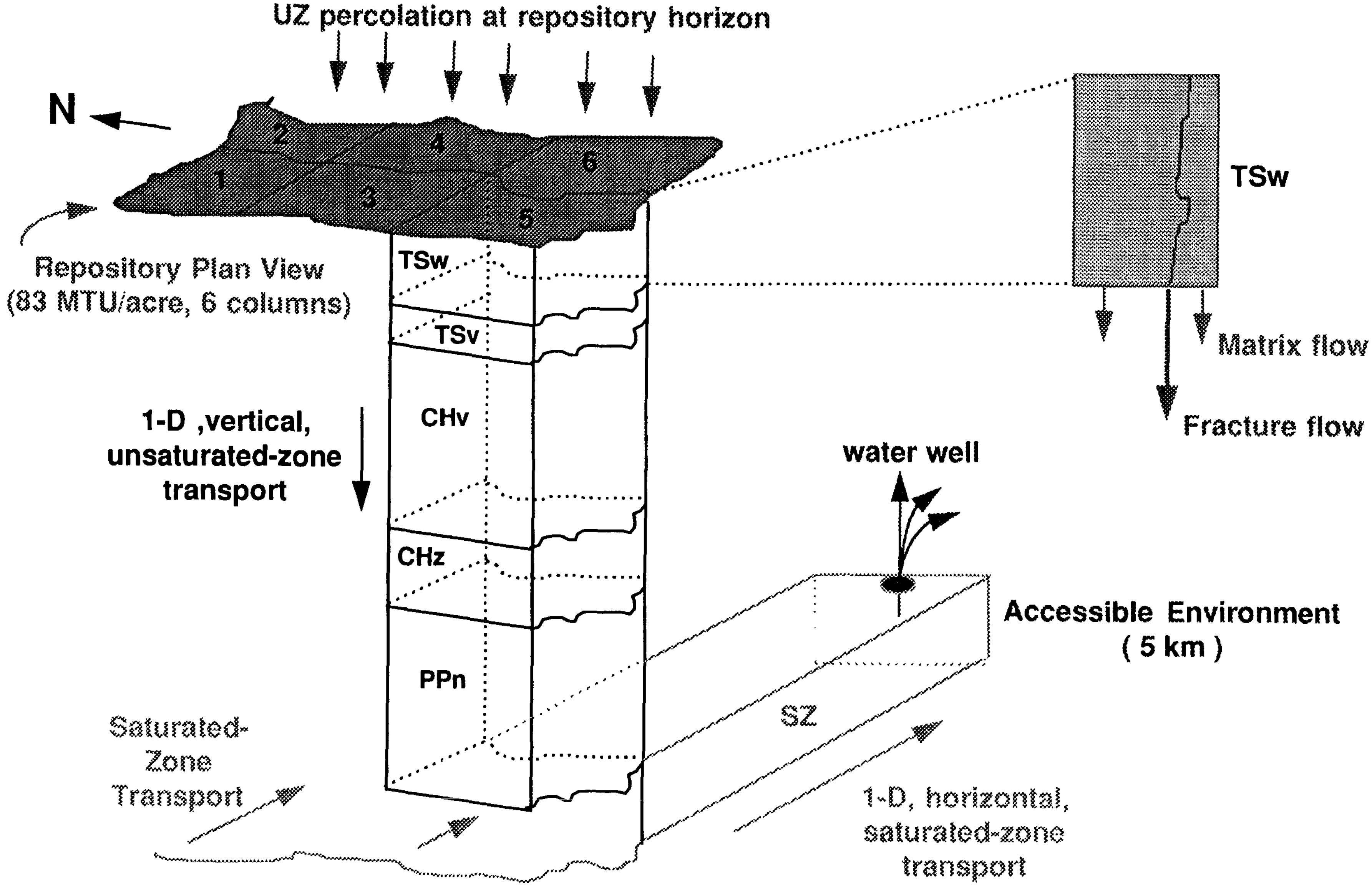
UZ Aqueous Transport Model

- TSPA stochastic model: RIP (Golder, 1994)
- Transport-pathway geometry
- Dual-continua representation: fracture - matrix
- How much nuclide mass in each continuum
- How fast nuclide mass travels through each continuum

UZ Aqueous Transport Model

- **TSPA stochastic model: RIP (Golder, 1994)**
- **Transport-pathway geometry**
  - » Radionuclide transport with decay through a series of 1-D pathways
  - » 3-D UZ geometry represented as either 6 or 10 parallel columns, with 5 pathways per column representing the TSw, TSv, CHnv, CHnz, and PPn
- **Dual-continua representation: fracture - matrix**
- **How much nuclide mass in each continuum**
- **How fast nuclide mass travels through each continuum**

UZ and SZ Pathway Geometry

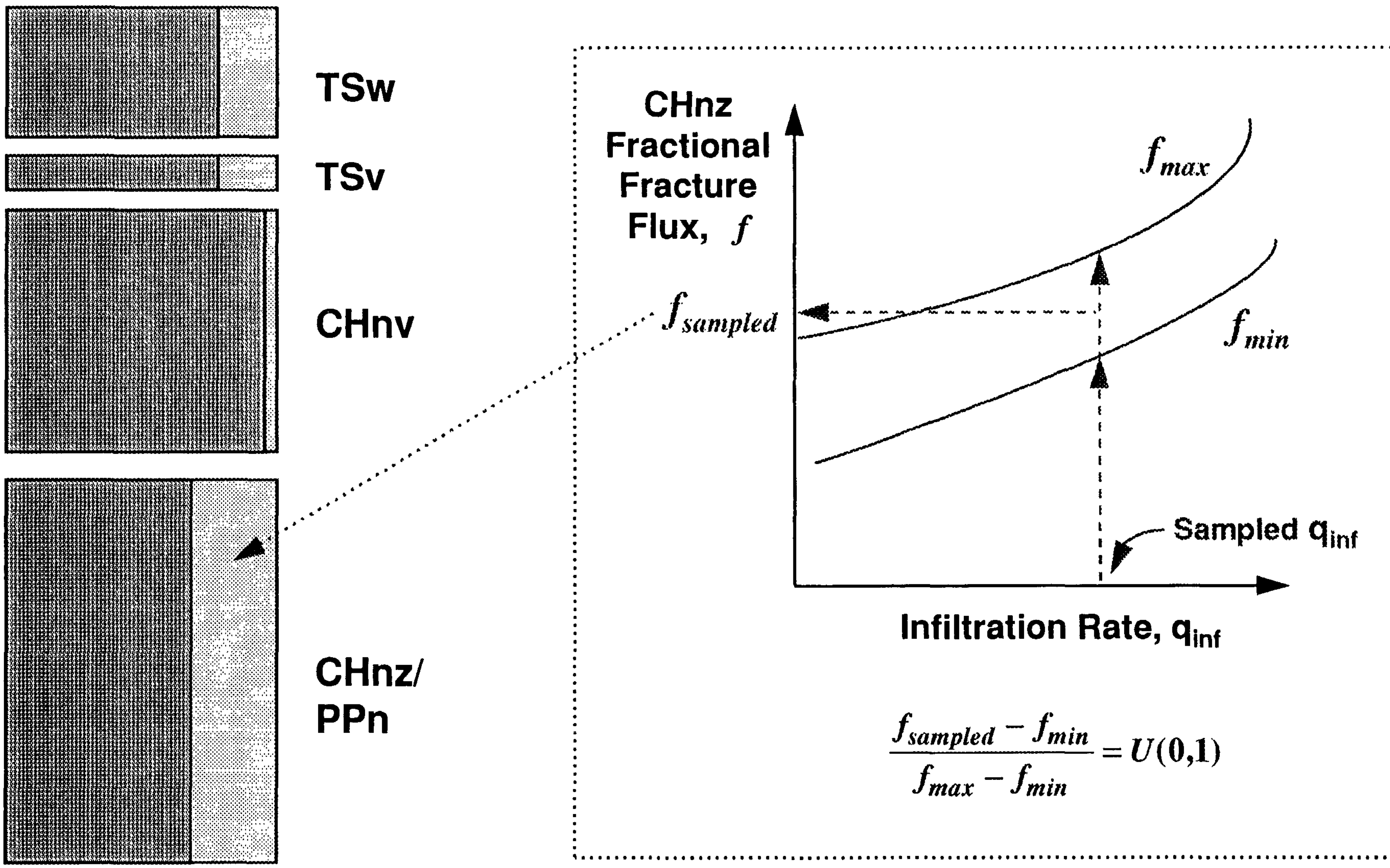


UZ Aqueous Transport Model

- TSPA stochastic model: RIP (Golder)
- Transport-pathway geometry
- Dual-continua representation: fracture - matrix
- How much nuclide mass in each continuum:
  - » Fracture flow fraction (from process-level model abstractions)
- How fast nuclide mass travels through each continuum:
  - » Unretarded matrix-velocity abstractions (from process-level models)

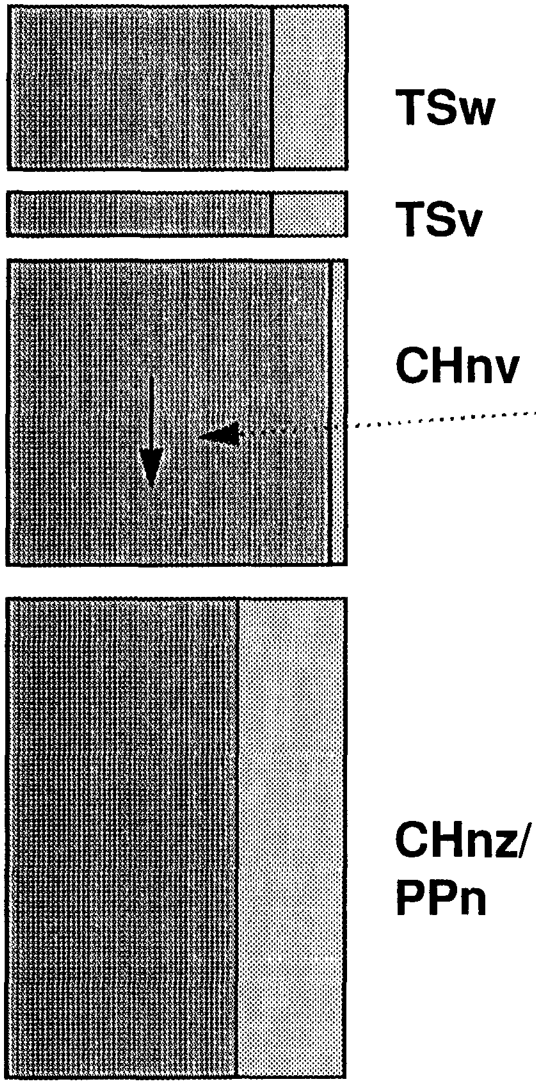
How Much?

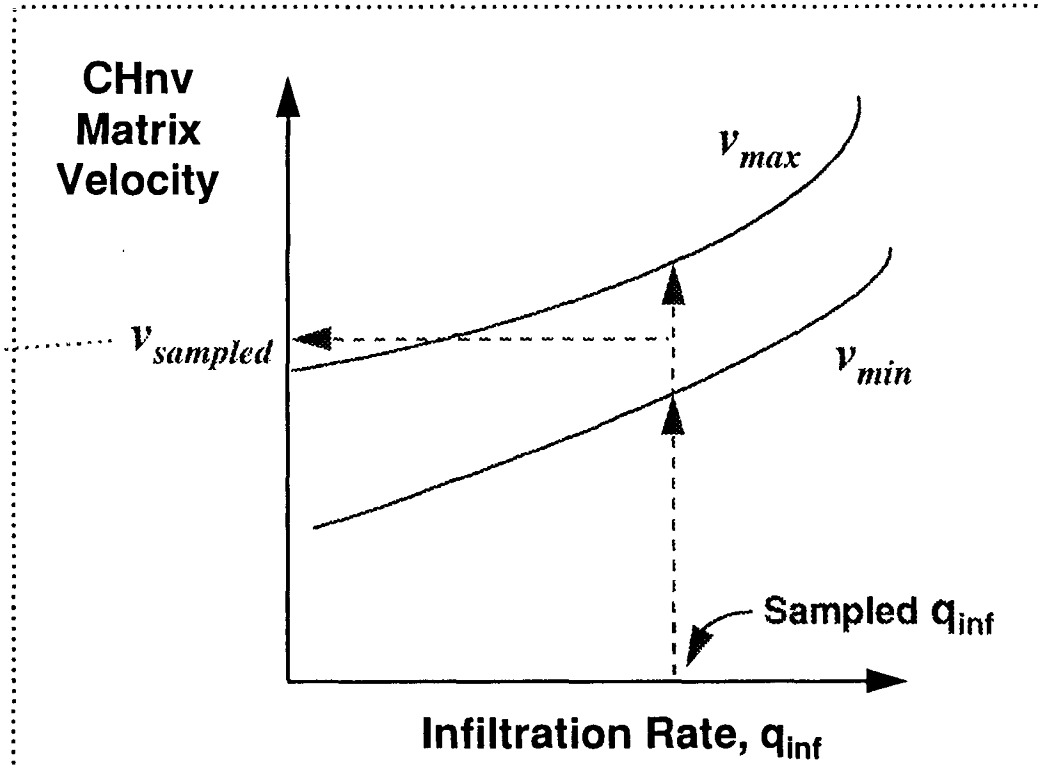
(Fractional-Fracture-Flow: Process-Level Abstractions)



$$\frac{f_{sampled} - f_{min}}{f_{max} - f_{min}} = U(0,1)$$

How Fast?
(Matrix-Velocity-Field: Process-Level Abstractions)





$$\frac{\log_{10} v_{sampled} - \log_{10} v_{min}}{\log_{10} v_{max} - \log_{10} v_{min}} = 1 - U(0,1)$$

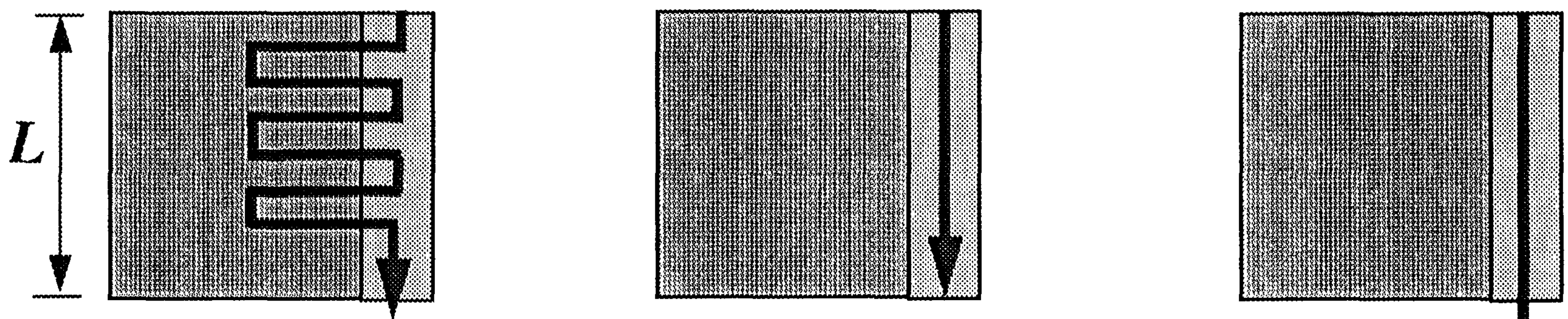
UZ Aqueous Transport Model

- TSPA stochastic model: RIP (Golder)
- Transport-pathway geometry
- Dual-continua representation: fracture - matrix
- How much nuclide mass in each continuum:
  - » Fracture flow fraction (from process-level model abstractions)
  - » Fracture connectivity (TSPA model): intra-unit and inter-unit
- How fast nuclide mass travels through each continuum:
  - » Unretarded matrix-velocity abstractions (from process-level models)

How Much?

(<u>Intra</u>-unit Fracture Connectivity: TSPA Abstraction)

- Average path length in fracture or in matrix before transitioning is equal $1/\lambda$, where λ is the Markovian-process transition rate:



$$\lambda = \frac{1}{(0.1)L} \qquad \lambda = \frac{1}{L} \qquad \lambda = \frac{1}{(100)L}$$

- random travel length in fracture, $l = -\frac{1}{\lambda}\ln[U(0,1)]$

UZ Aqueous Transport Model

- TSPA stochastic model: RIP (Golder)
- Transport-pathway geometry
- Dual-continua representation: fracture - matrix
- How much nuclide mass in each continuum:
  - » Fracture flow fraction (from process-level model abstractions)
  - » Fracture connectivity (TSPA model): intra-unit and inter-unit
- How fast nuclide mass travels through each continuum:
  - » Unretarded matrix-velocity abstractions (from process-level models)
  - » Chemical/physical retardation of fracture/matrix velocities (TSPA model)

How Fast?

(Aqueous-phase retardation: TSPA Abstraction)

- Chemical retardation in matrix: K_d model (equilibrium, infinite capacity)
  - » $R_d = 1 + \frac{\rho_{bd}}{\phi_m S_w} K_d$
  - » Whole-rock (tuff) K_d's from LANL experiments (Meijer and Triay, 1995): stochastic distributions
  - » Includes many effects: e.g., sorption, ion-exchange, precipitation/dissolution
- Physical retardation in fractures (for some sensitivity cases)
  - » Equilibrium matrix diffusion model, $R_{md} = 1 + \frac{\phi_m S_m}{\phi_f S_f} R_d$

Climate Change Model

- **Two scenarios for initial infiltration flux, q_{inf}, (at closure):**
  - » "high" q_{inf} = U(0.5,2.0) mm/yr
  - » "low" q_{inf} = U(0.01,0.05) mm/yr
- **Periodic variation in q_{inf} (Long and Childs, 1993):**
  - » No dryer than present day; wettest conditions during glaciation
  - » Triangular Period of 100,000 years, with peak at 50,000 years
  - » Peak infiltration is a random multiple of initial q_{inf}, uniformly sampled between 1 and 5. Thus, maximum q_{inf} for "high" scenario is 10 mm/yr and maximum q_{inf} for "low" scenario is 0.25 mm/yr.
- **Simultaneous rise of water table assumed in some sensitivity analyses (Marshall et al., 1993):**
  - » Maximum rise at 50,000 years
  - » Peak rise uniformly sampled between 20 - 80 m, using same random multiplier as for q_{inf}

Saturated Zone Transport Model

- Composite permeability/flux model (i.e., average of fractures and matrix)
- SZ flux distribution: log-normal with mean of 2.0 m/yr and S.D. of 0.49 (Barr, 1993)
- AE boundary at 5 km from the base of all UZ columns
- K_d's for devitrified rock, but higher than UZ devitrified (Meijer, 1995)
- Longitudinal dispersion, but no lateral dispersion
- If considered, lateral dispersion plus sub-basin mixing could reduce doses significantly

Biosphere/Dose Model

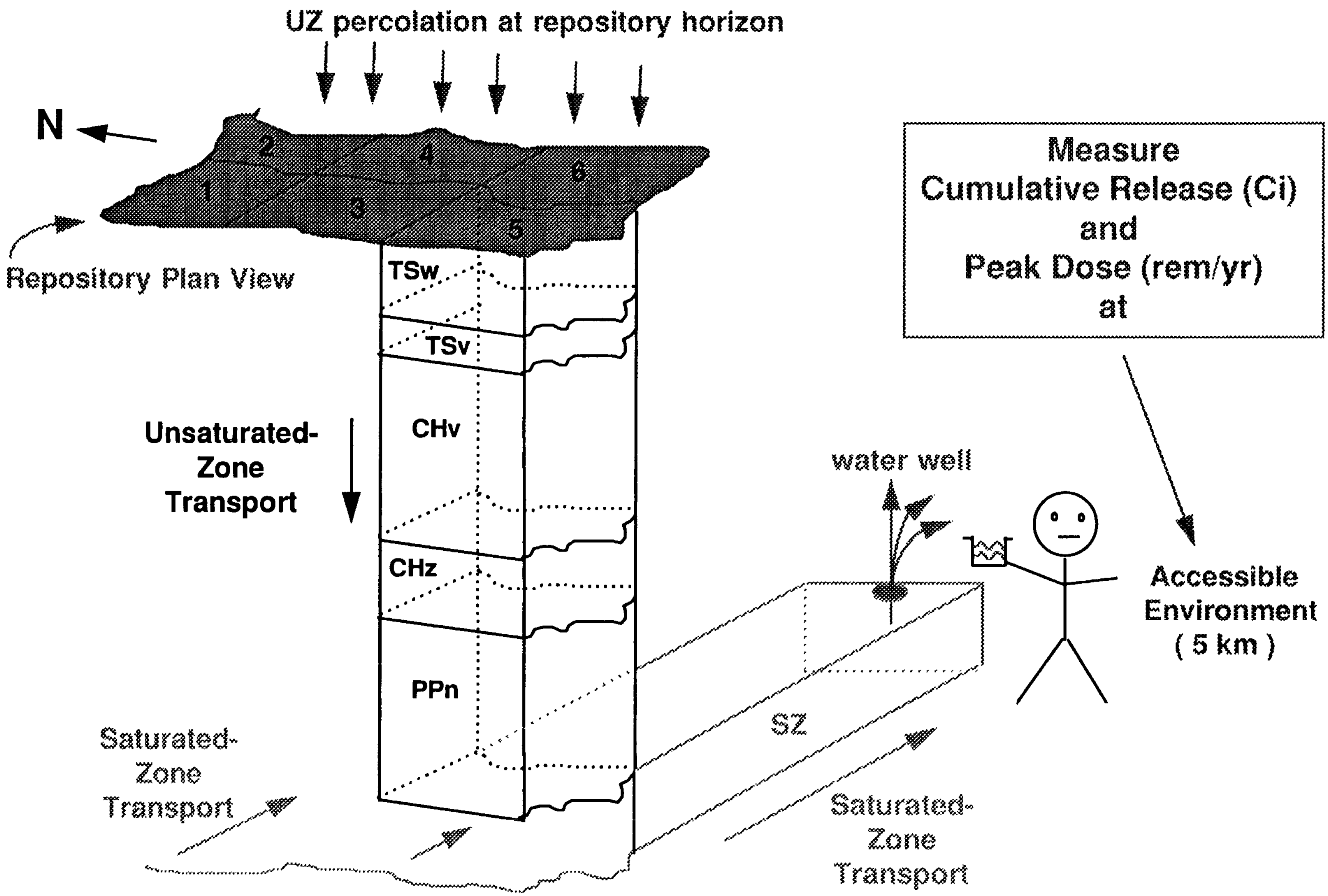
- Predicted peak dose to maximally exposed individual
- EPA (1988) dose conversion factors for ingestion only, 2 liters/day of drinking water
- Dilution volumetric flow equal to repository width times 50-m well-depth times saturated-zone flux

RESULTS: Predicted Repository Performance

- Releases and doses at accessible environment boundary, 5 km down-gradient from the repository.
  - » Performance over two time periods: 10,000 years and 1,000,000 years
  - » Sensitivity analyses for
    - – alternate conceptual models of geosphere transport
    - – alternate conceptual models for near-field (WP/EBS) environment
    - – alternate repository designs

- Subsystem Performance: EBS vs. geosphere

Schematic of Natural Barriers



10,000-year Predicted Performance

- Complementary cumulative distribution functions (CCDF) of total release, normalized to Table 1 of 40 CFR Part 191

- CCDFs of Total Peak Dose (rem/yr)

- 10,000-year, expected-value, release-rate (Ci/yr) and dose (rem/yr) histories at AE for various radionuclides: ^{99}Tc, ^{129}I, ^{14}C

Sensitivity Analyses

- UZ Infiltration rate: "high" (0.5 - 2.0 mm/yr) vs. "low" (0.01 - 0.05 mm/yr)
- Repository thermal loading: (25 vs. 83 MTU/acre)
- Thermohydrologic model for near-field performance
- Fracture/matrix interaction
  - » Intra-unit fracture continuity
  - » Matrix diffusion
- Backfill (air, gravel, capillary barrier)
- Waste-package degradation model

<u>Zero-Release</u> Cases at 10,000 Years

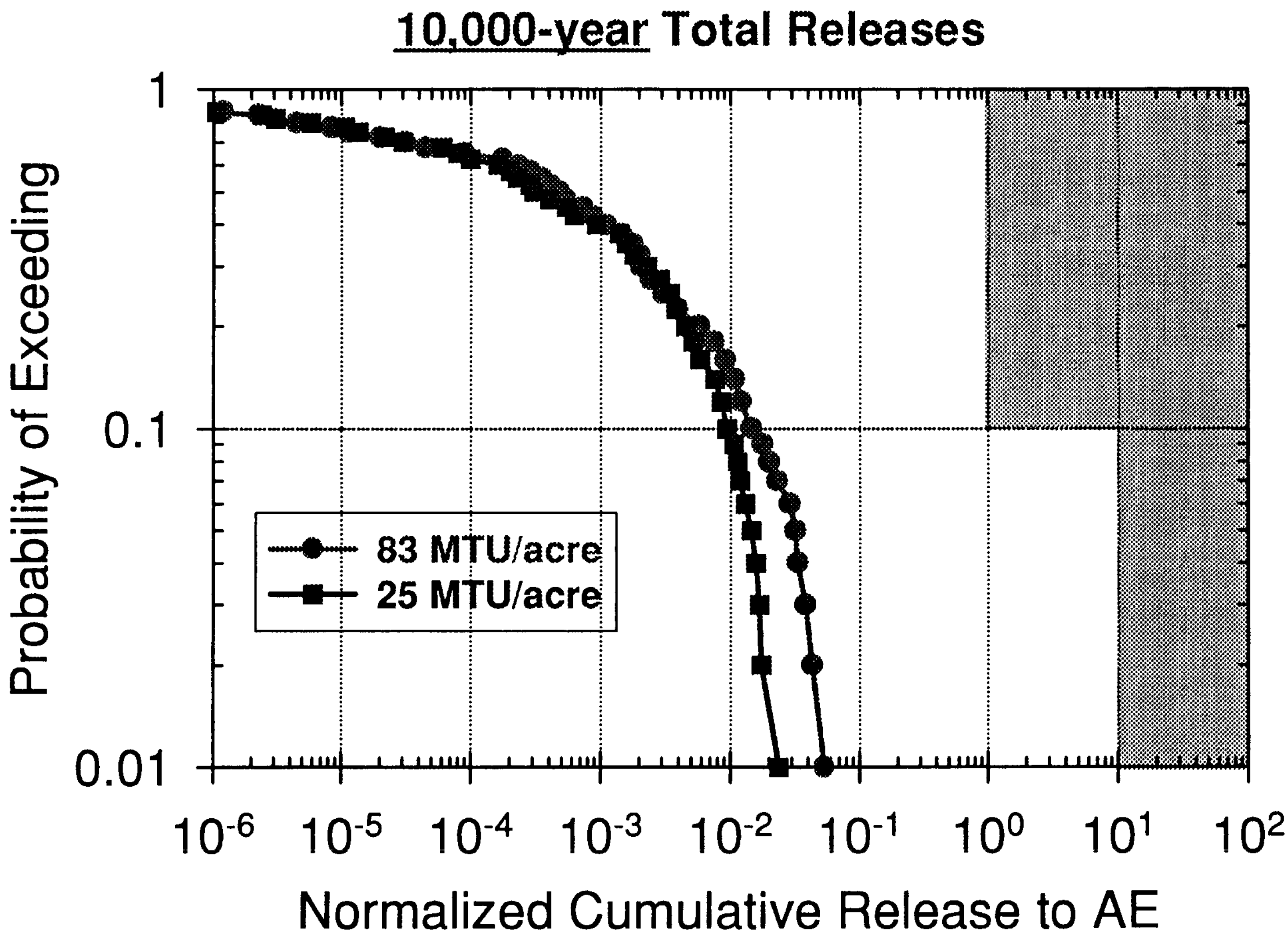
- No releases at AE for low-infiltration-rate range (0.01 - 0.05 mm/yr)
- No releases at AE for Buscheck 80 MTU/acre
- No releases at AE for UZ equilibrium matrix diffusion
- No releases at AE for cathodic protection of waste packages

Sensitivity Analyses

- Repository thermal loading: (25 vs. 83 MTU/acre)
- Fracture/matrix interaction
  - » Intra-unit fracture continuity
- Backfill (air, gravel, capillary barrier)

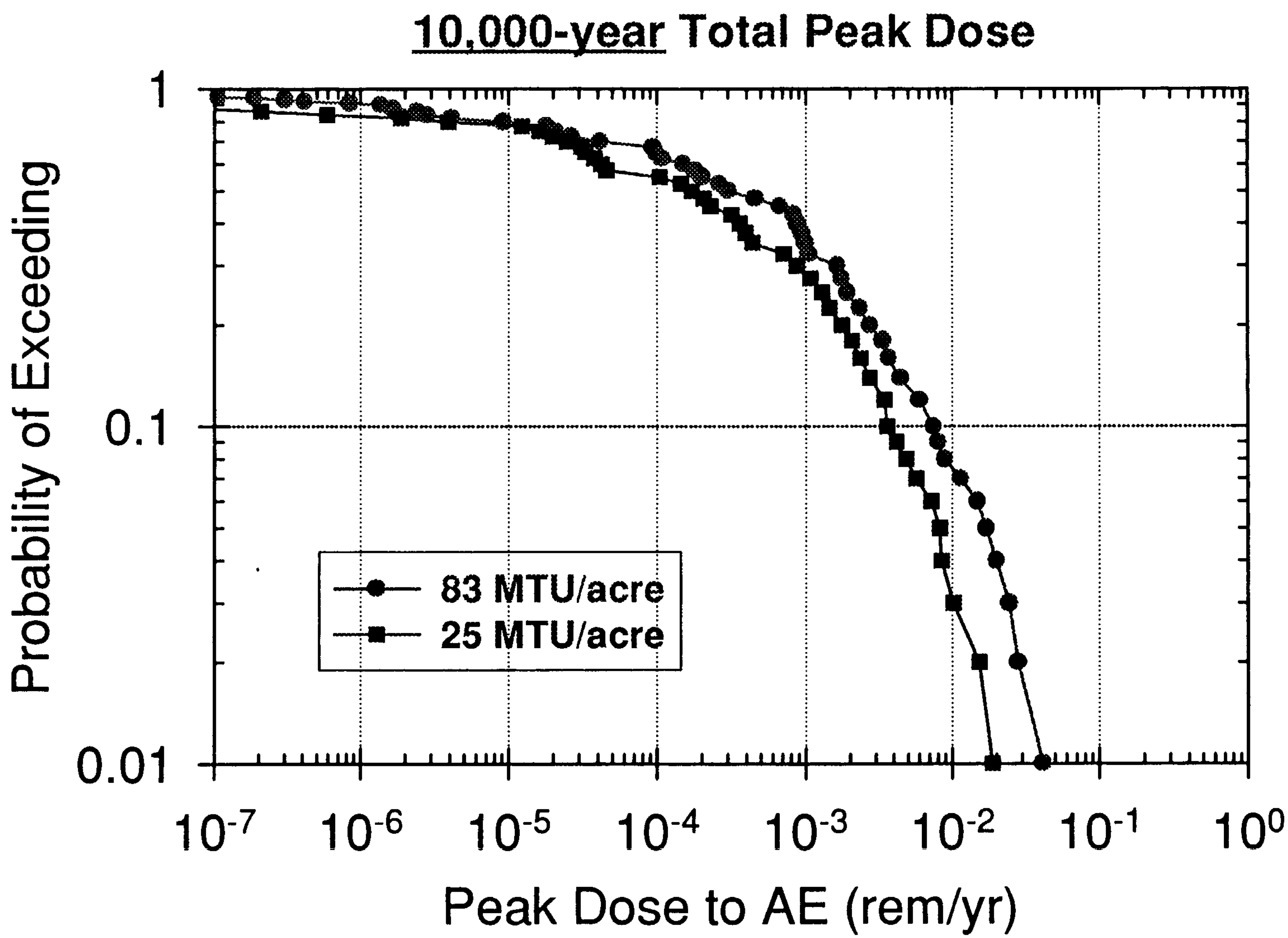
<u>Cumulative Release</u> for Alternate Thermal Loads

(no backfill, high q_{inf} range)

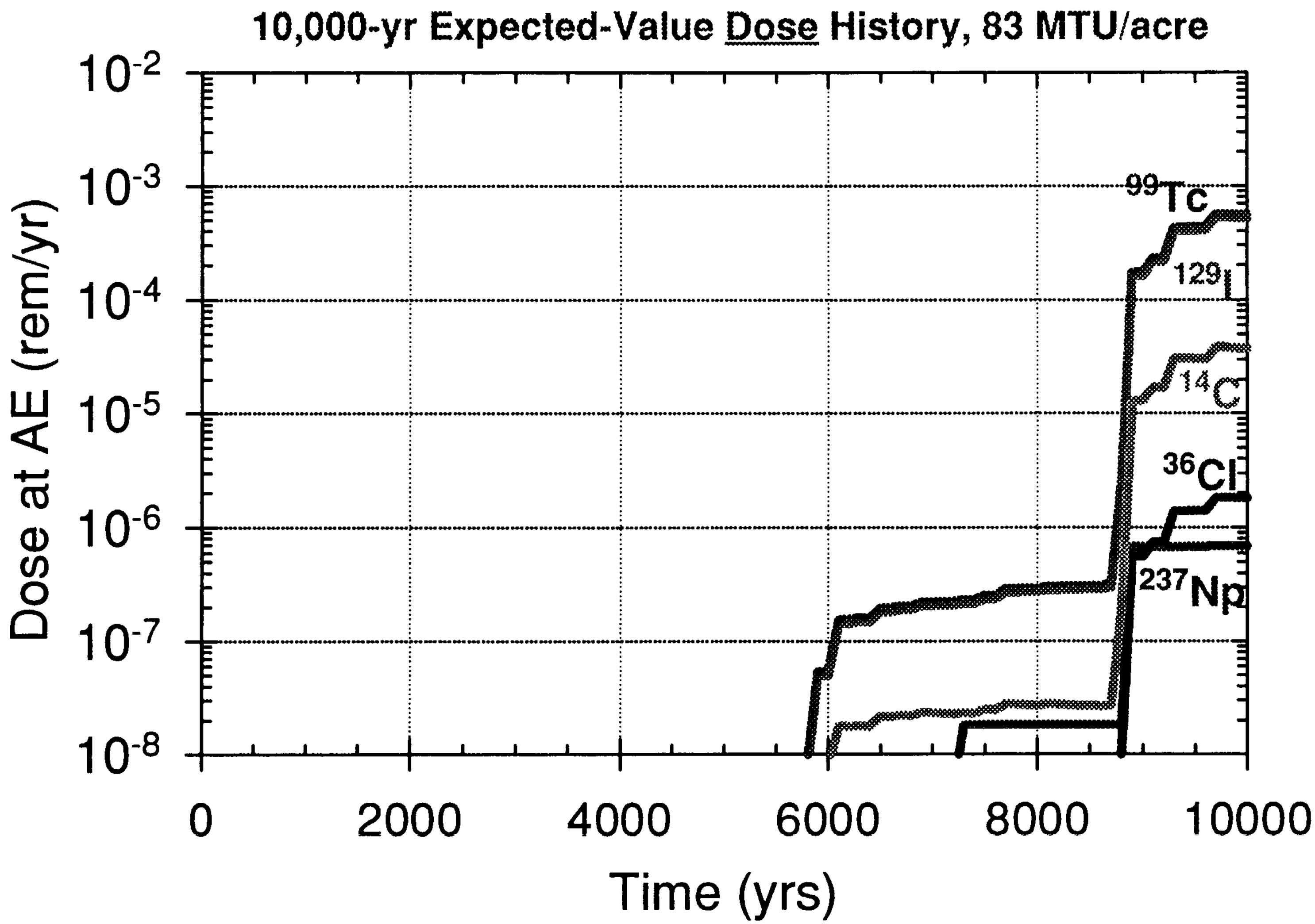


Peak Dose for Alternate Thermal Loads

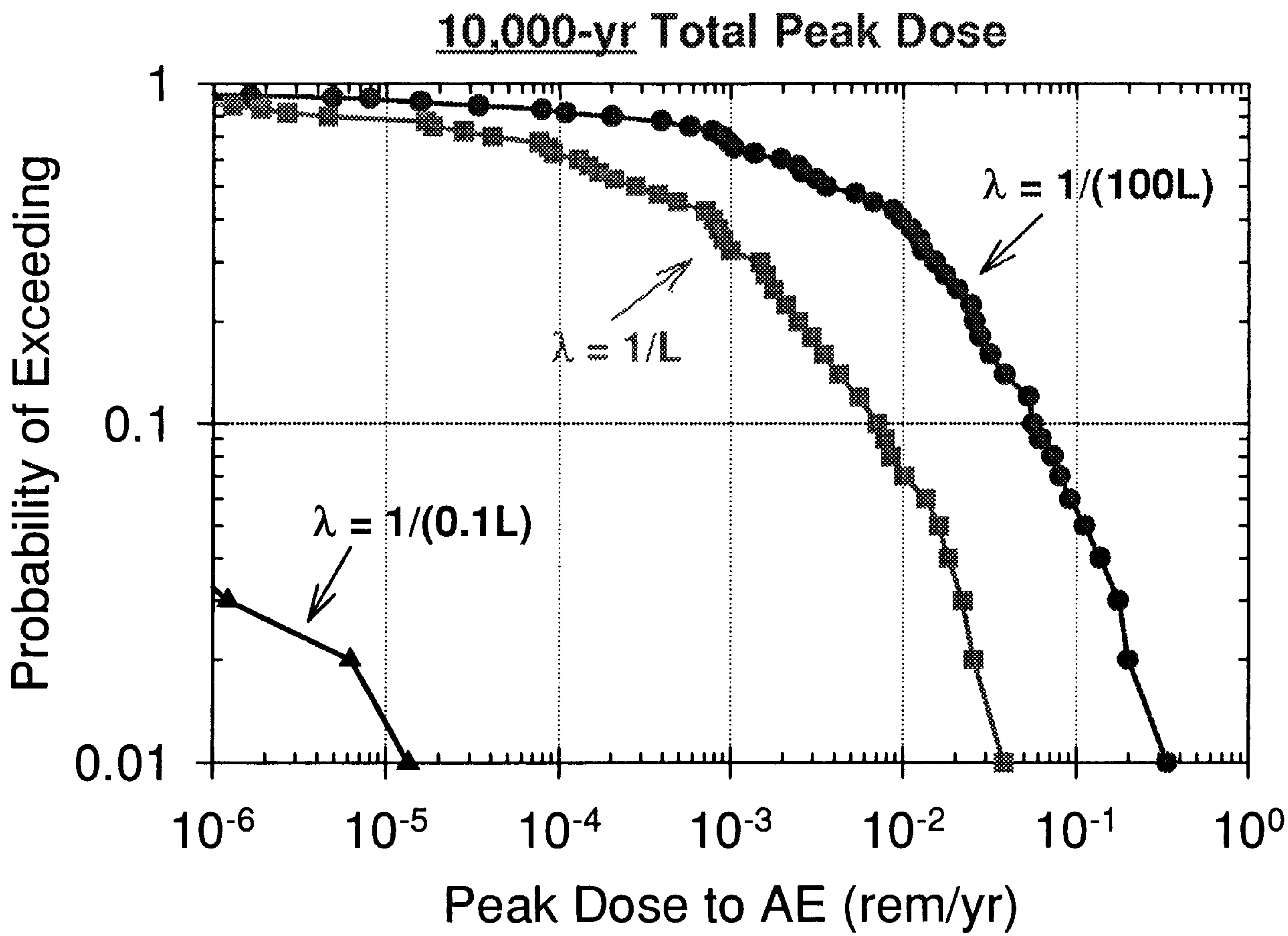
(no backfill, high q_{inf} range)



Expected-Value Dose History: 83 MTU/acre
(no backfill, high q_{inf} range)

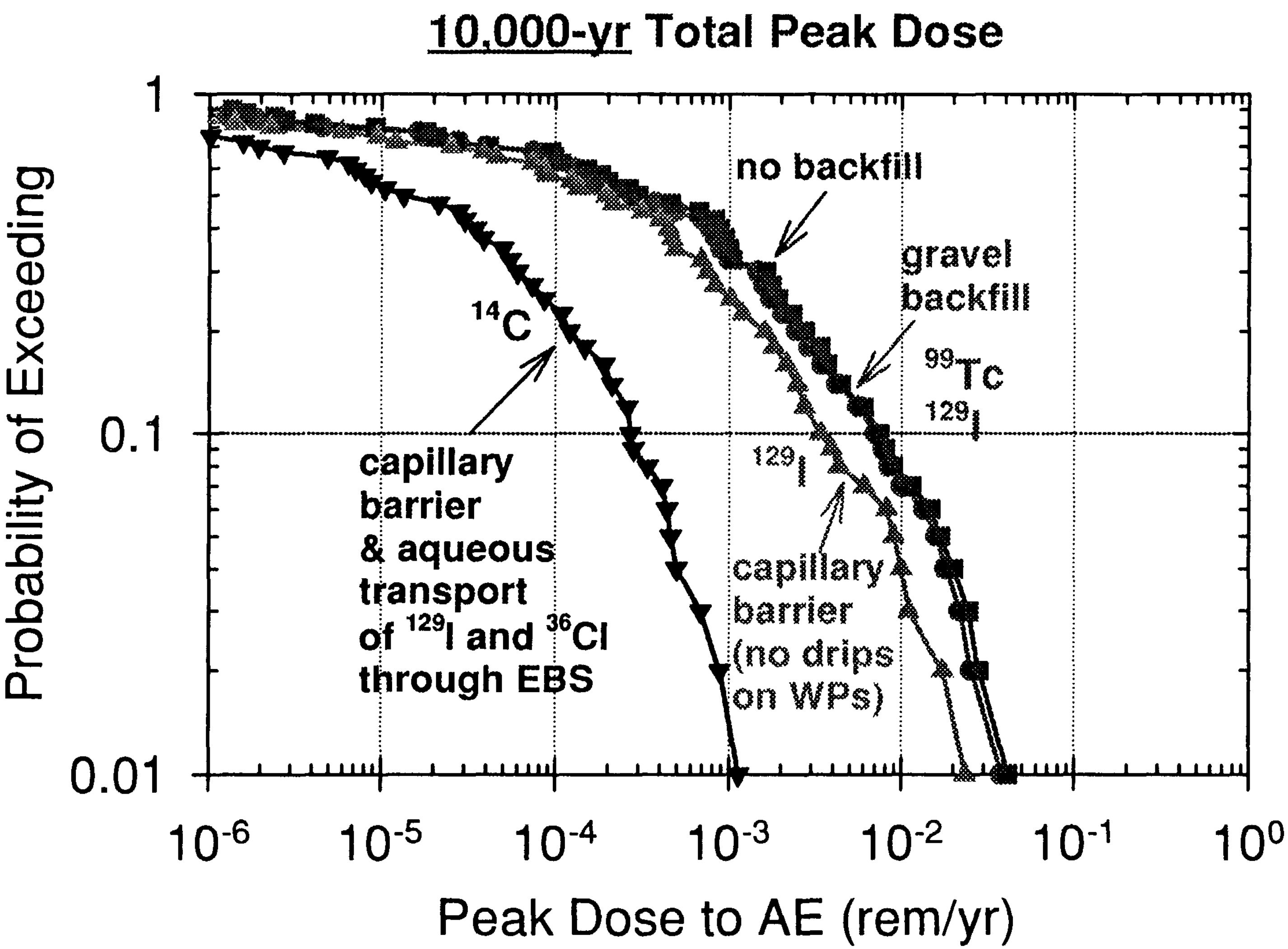


Intra-unit Fracture Connectivity



Alternate Backfill/Barriers in Near Field

(83 MTU/acre, high q_{inf}=0.5-2.0 mm/yr)



1,000,000-year Predicted Performance

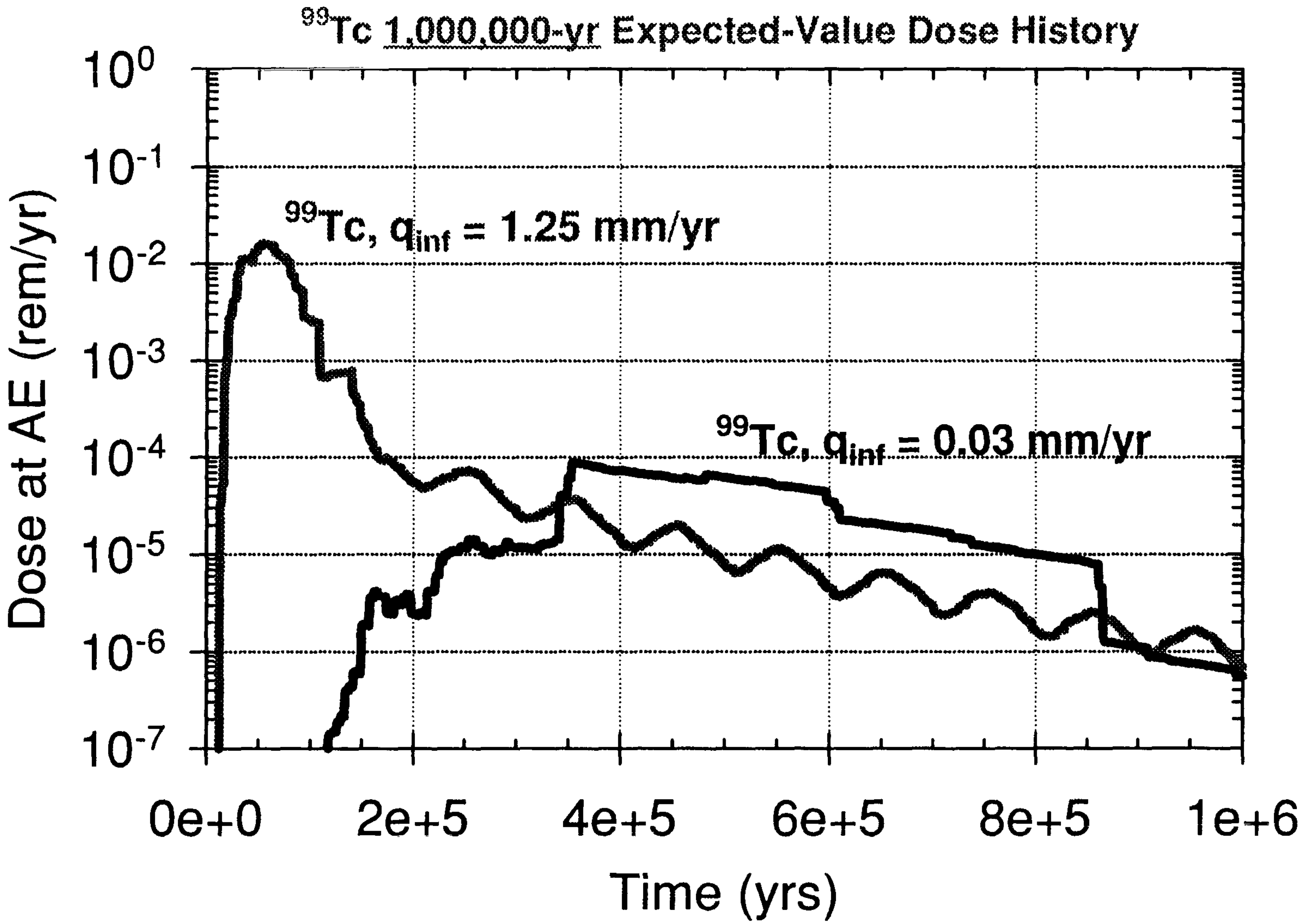
- CCDFs of Total Peak Dose (rem/yr)
- 1,000,000-year, expected-value, dose histories (rem/yr) at AE for various radionuclides, especially ^{99}Tc, ^{237}Np, ^{129}I
- Linear regression statistics for most important parameters

Sensitivity Analyses

- UZ Infiltration rate: "high" (0.5 - 2.0 mm/yr) vs. "low" (0.01 - 0.05 mm/yr)
- Repository thermal loading: (25 vs. 83 MTU/acre)
- Thermohydrologic model for near-field performance
- Fracture/matrix interaction
  - » Intra-unit fracture continuity
  - » Matrix diffusion
- Waste-package degradation model
- Backfill (air, gravel, capillary barrier)

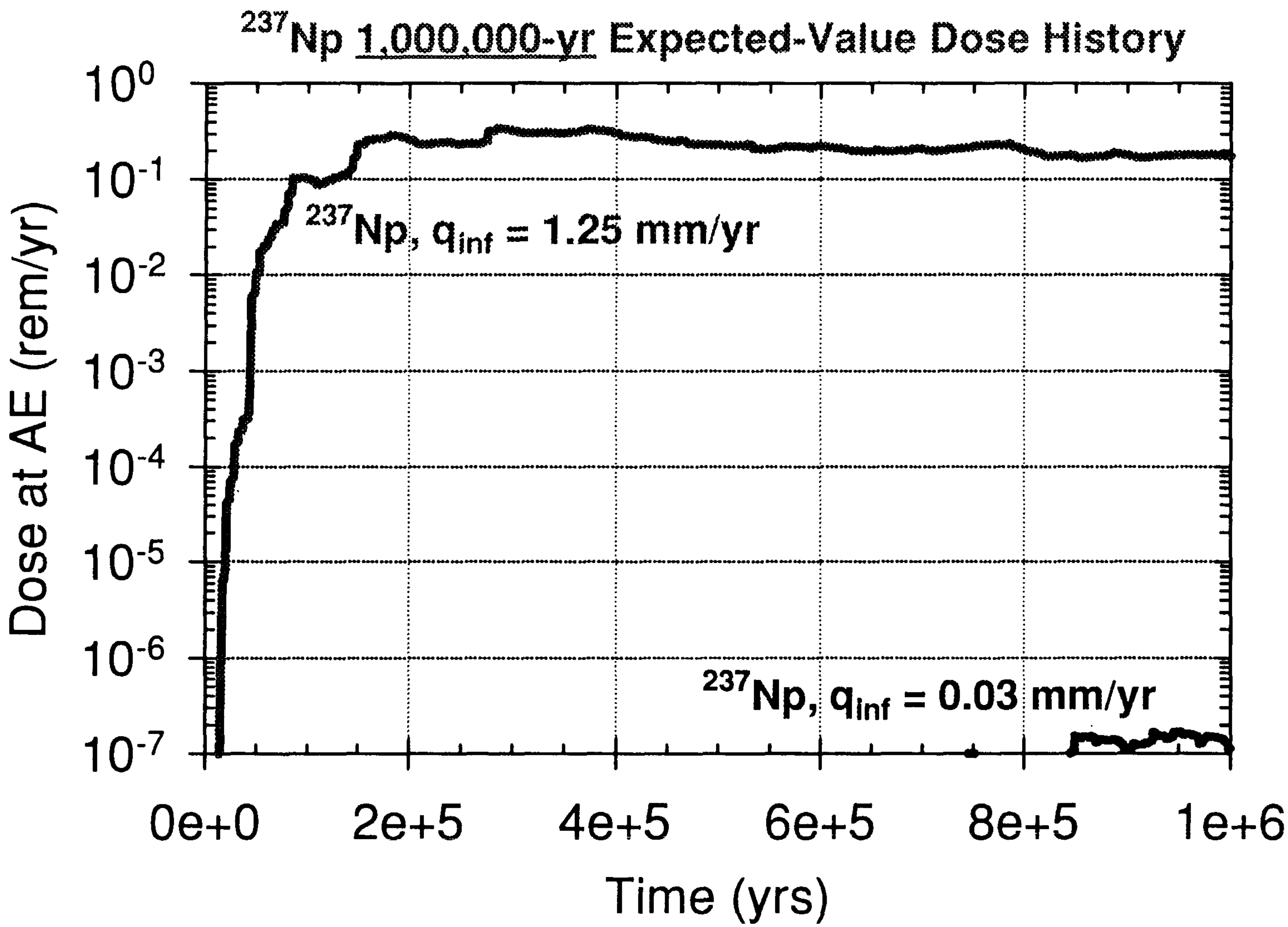
Alternate Infiltration Rates (0.03 vs. 1.25 mm/yr)

(83 MTU/acre, gravel backfill, climatic variation of q_{inf})



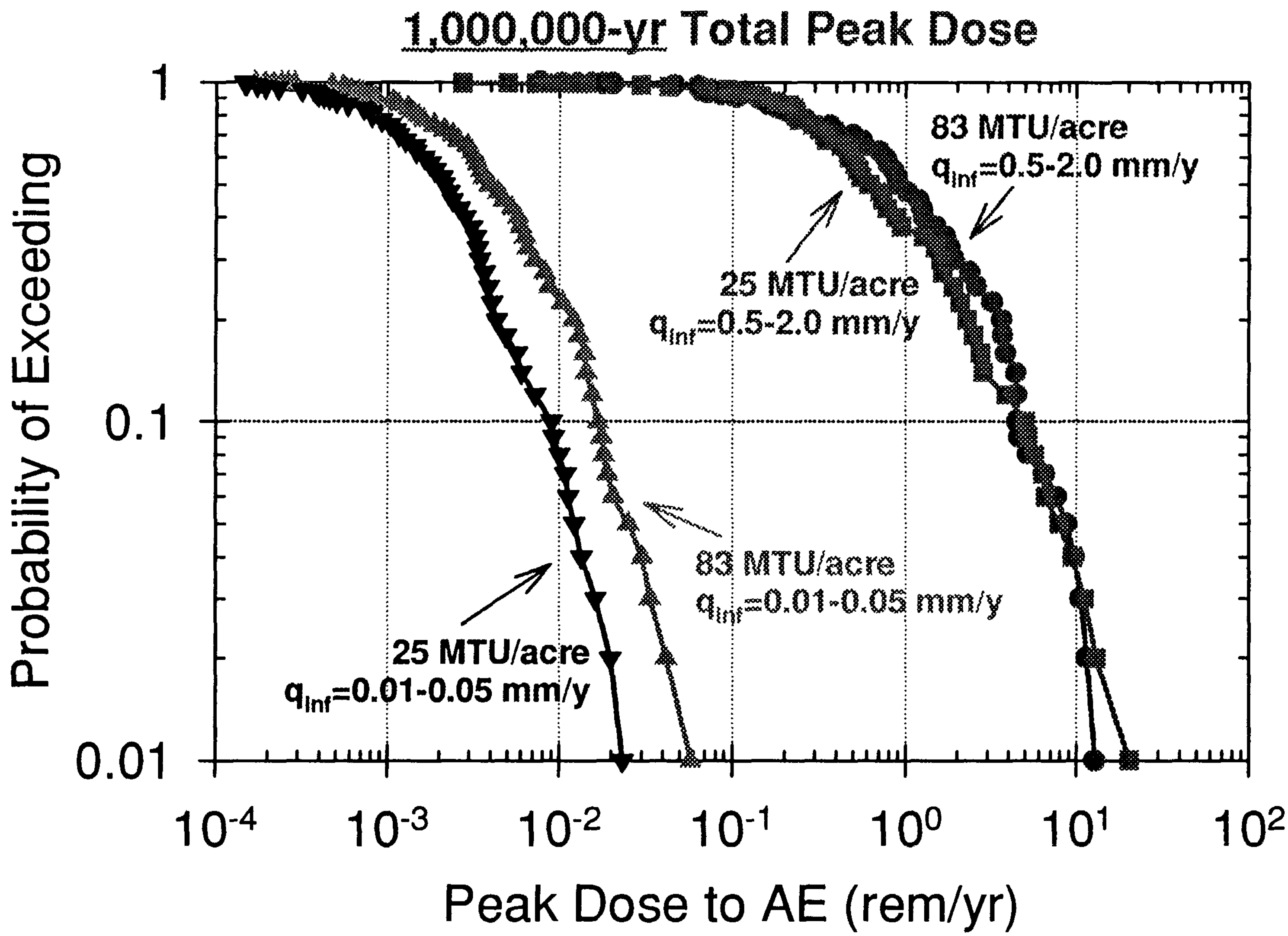
Alternate Infiltration Rates (0.03 vs. 1.25 mm/yr)

(83 MTU/acre, gravel backfill, climatic variation of q_{inf})



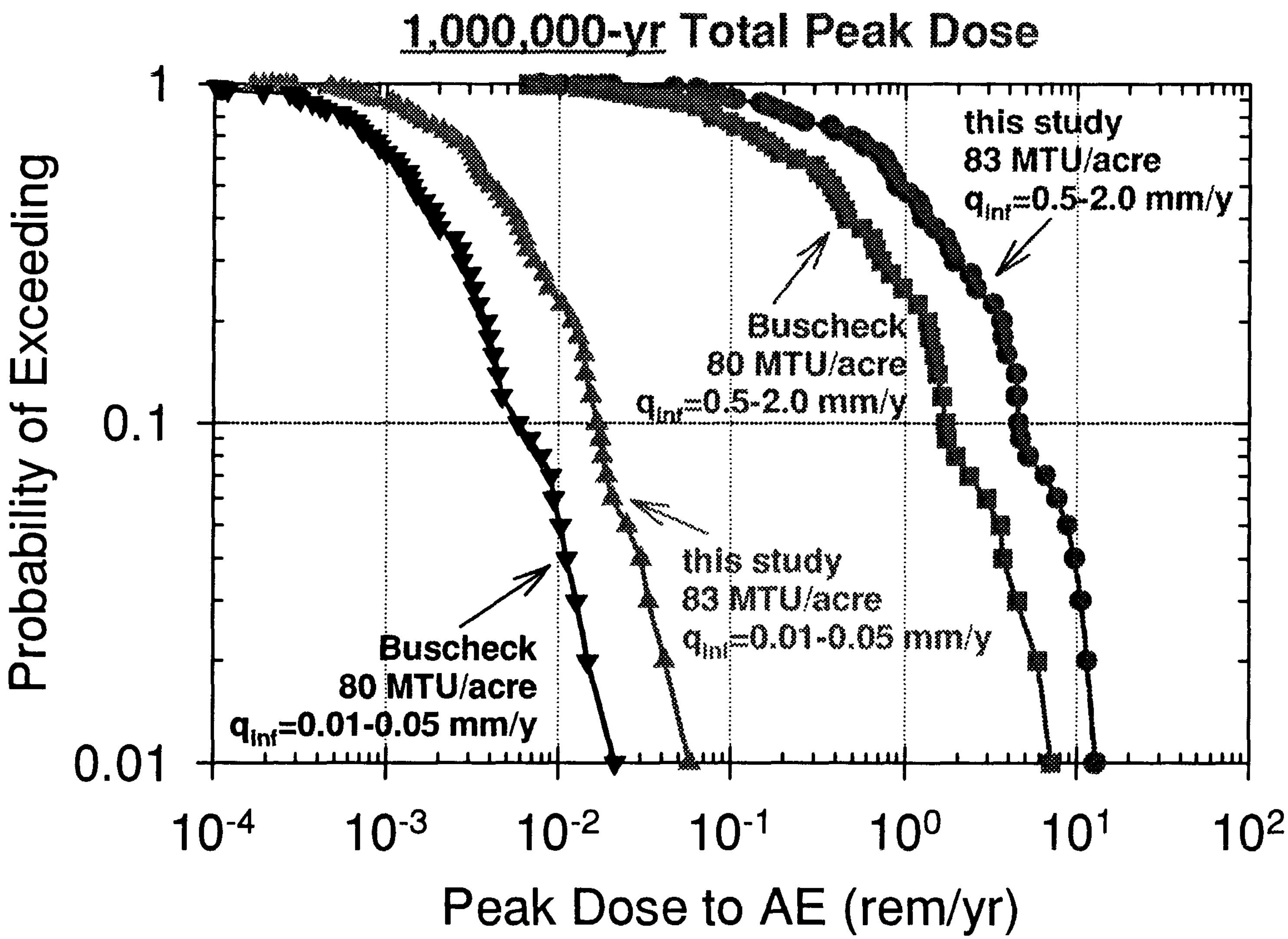
Alternate Thermal Loads and Infiltration-Rate Ranges

(gravel backfill, climatic variation of q_{inf})



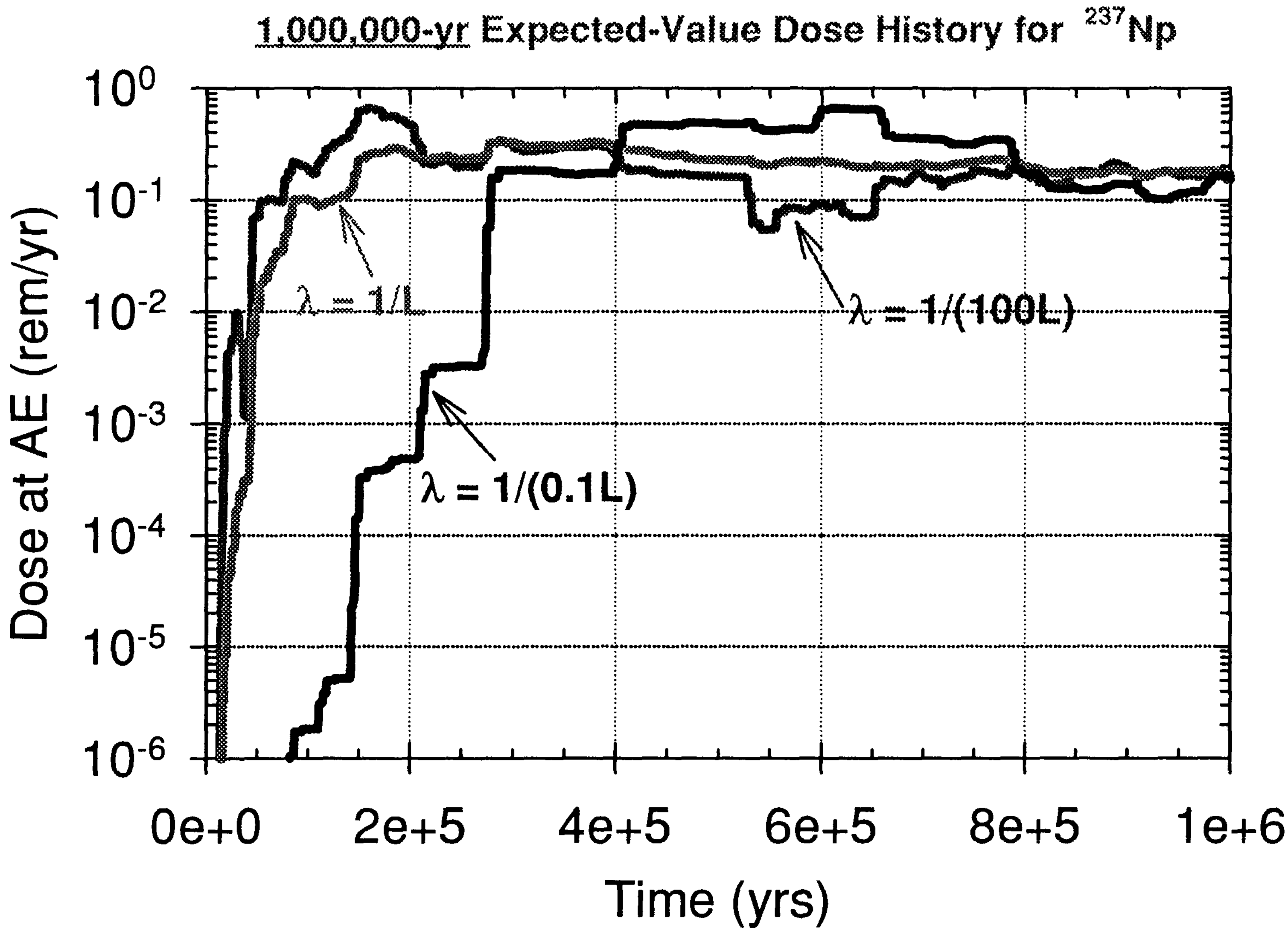
Alternate Near-Field Thermal-Hydrologic Models

(no backfill, climatic variation of q_{inf})



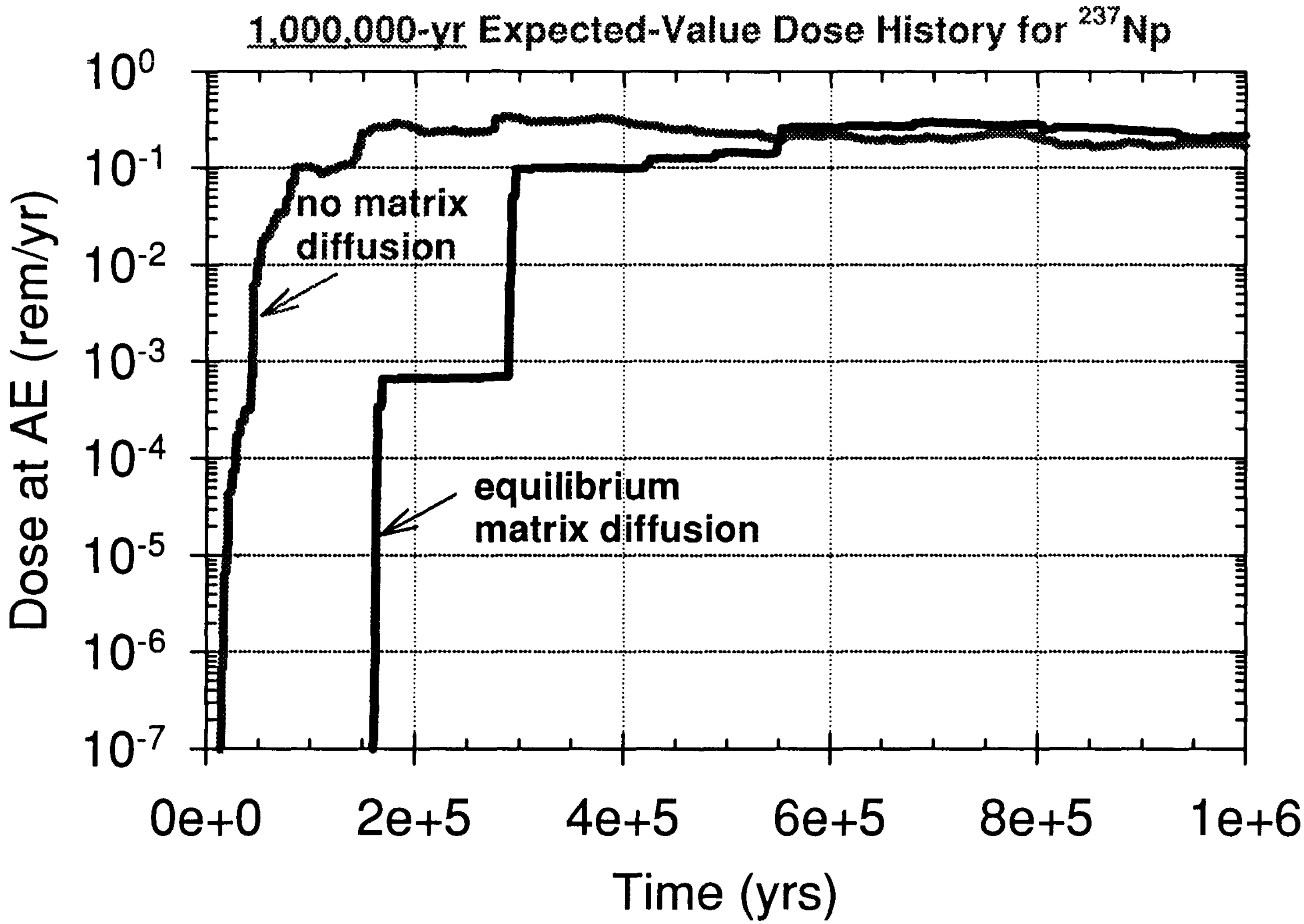
Intra-unit Fracture Connectivity: Effect on ^{237}Np

(83 MTU/acre, gravel backfill, q_{inf} = 1.25 mm/yr)



<u>Matrix Diffusion</u>: Effect on ^{237}Np

(83 MTU/acre, gravel backfill, q_{inf} = 1.25 mm/yr)

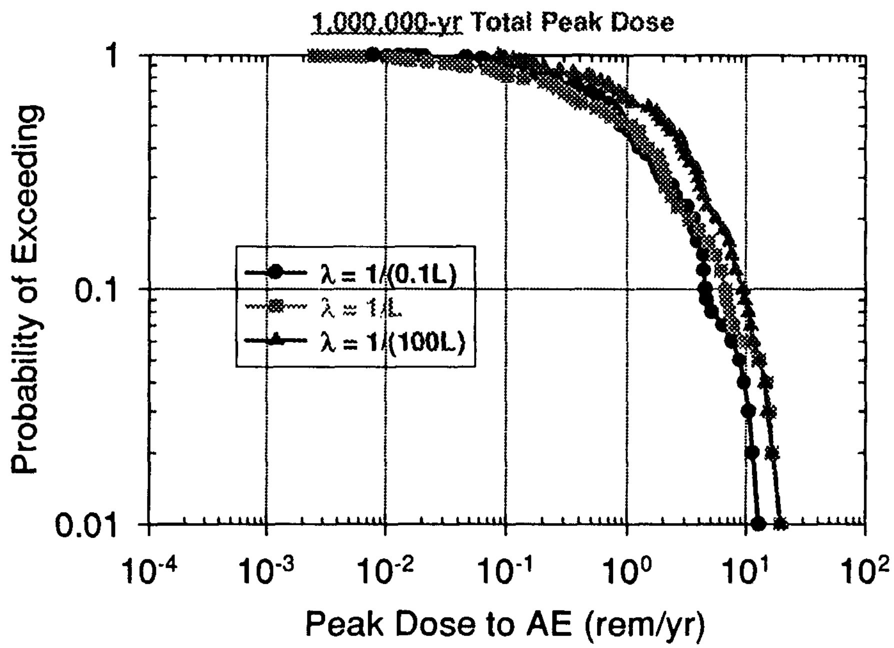


Effect of Fracture/Matrix Interaction in Geosphere

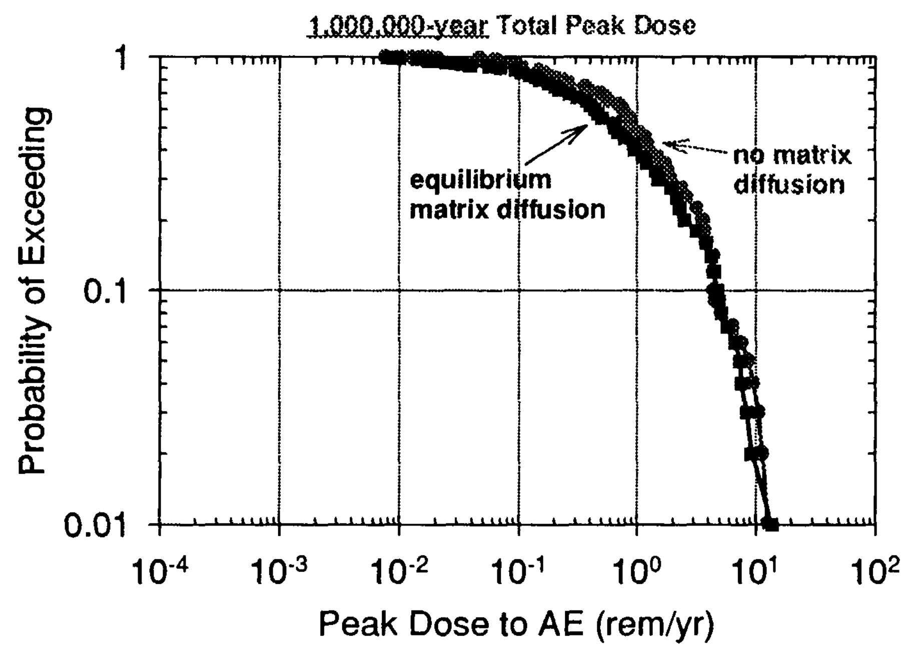
1,000,000-year Total Peak Dose

(83 MTU/acre, gravel backfill, climatic variation of q_{inf})

Intra-unit Fracture Connectivity

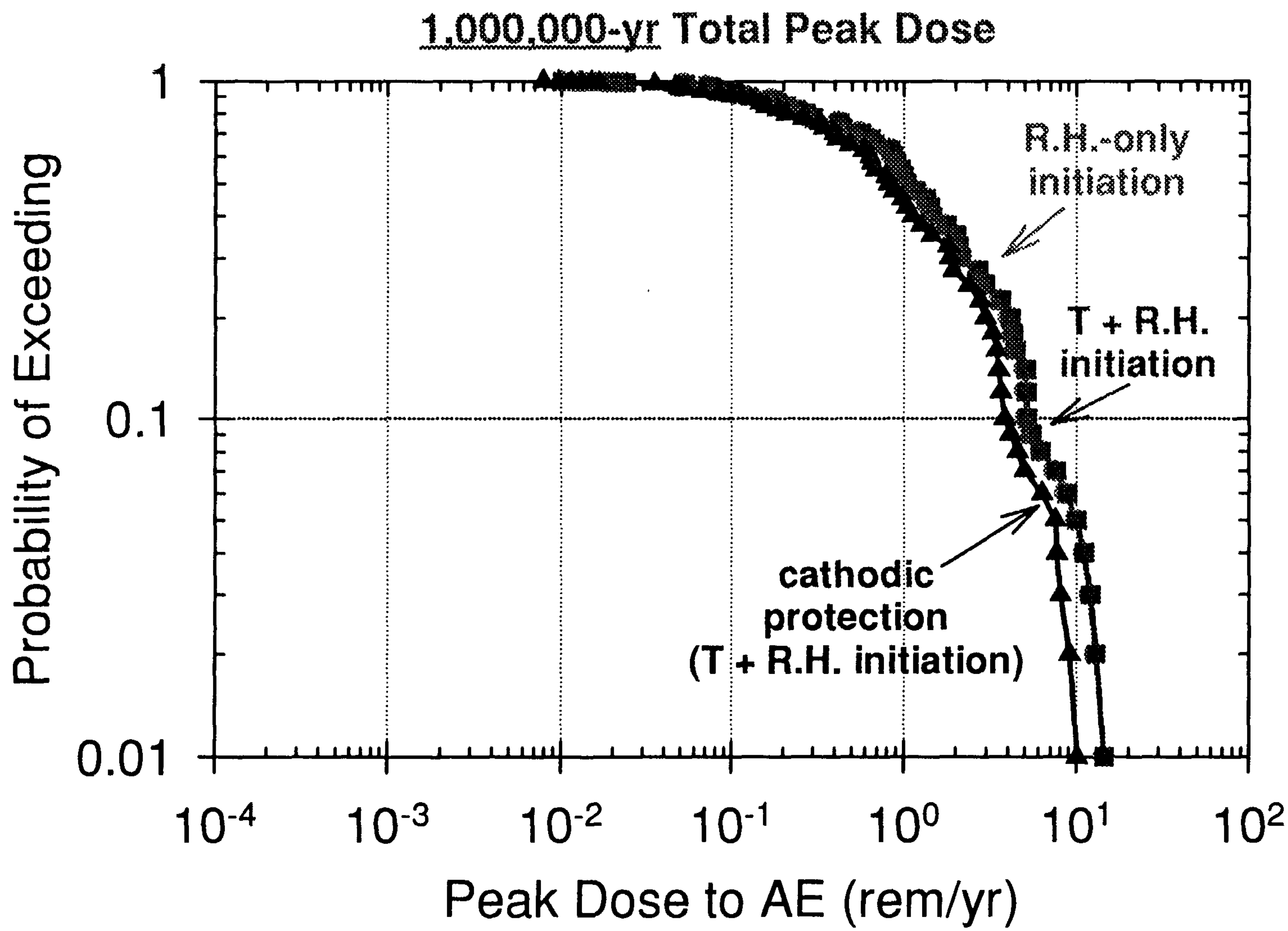


Matrix Diffusion



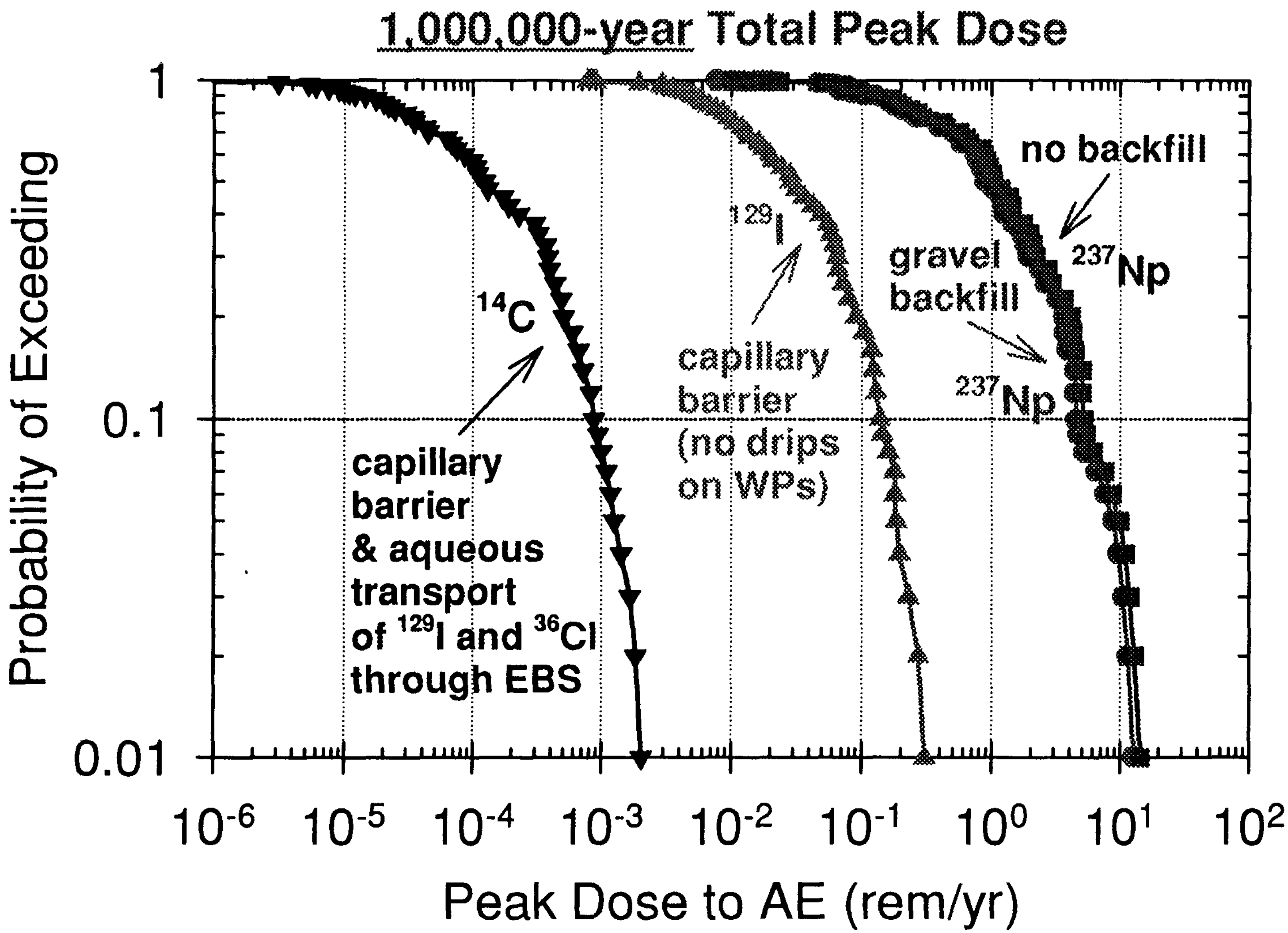
Alternate Waste-Package Degradation Models

(83 MTU/acre, no backfill, <u>high</u> q_{inf}=0.5-2.0 mm/yr, climatic variation of q_{inf})



Alternate Backfill/Barriers in Near Field

(83 MTU/acre, high q_{inf}=0.5-2.0 mm/yr, climatic variation of q_{inf})



Performance Sensitivity to Model Parameters

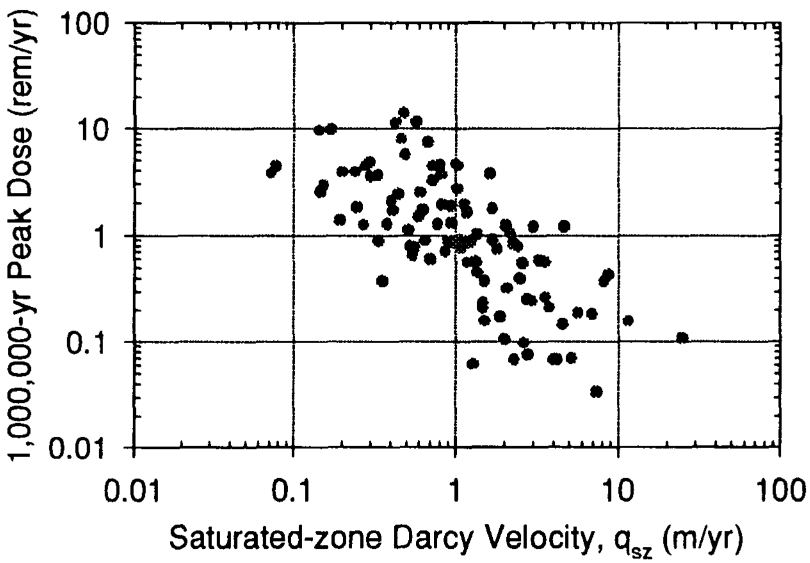
- Scatter plots of performance measures (i.e., 1,000,000-year total peak dose) versus most important model parameters; 100 realizations

- Stepwise linear regression to determine most important groups of model parameters and the percent variance explained

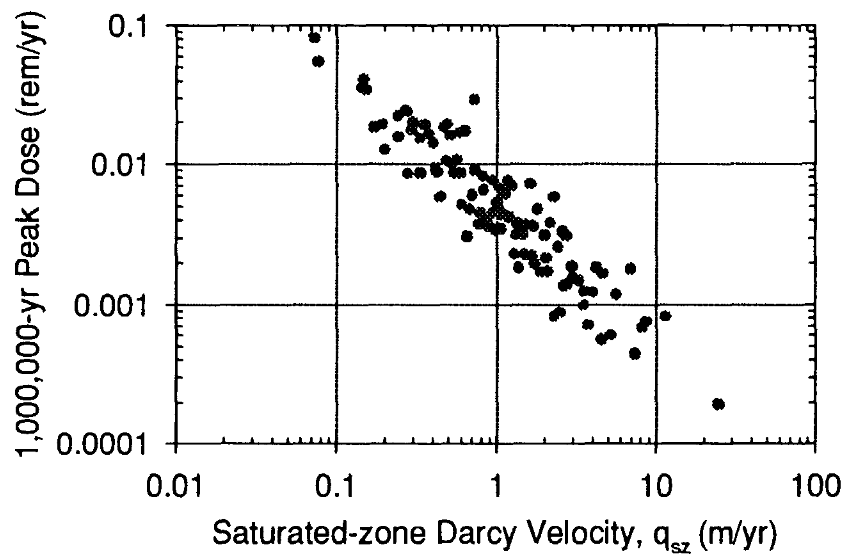
Sensitivity of 1,000,000-year Total Peak Dose to SZ flux distribution, q_{SZ}

(83 MTU/acre, gravel backfill, climatic variation of q_{inf})

high q_{inf} range (0.5 - 2.0 mm/yr)



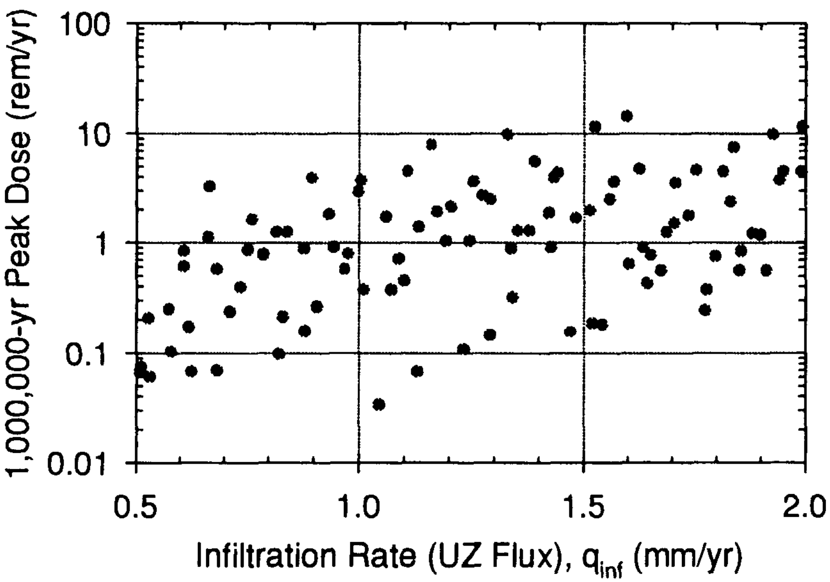
low q_{inf} range (0.01 - 0.05 mm/yr)



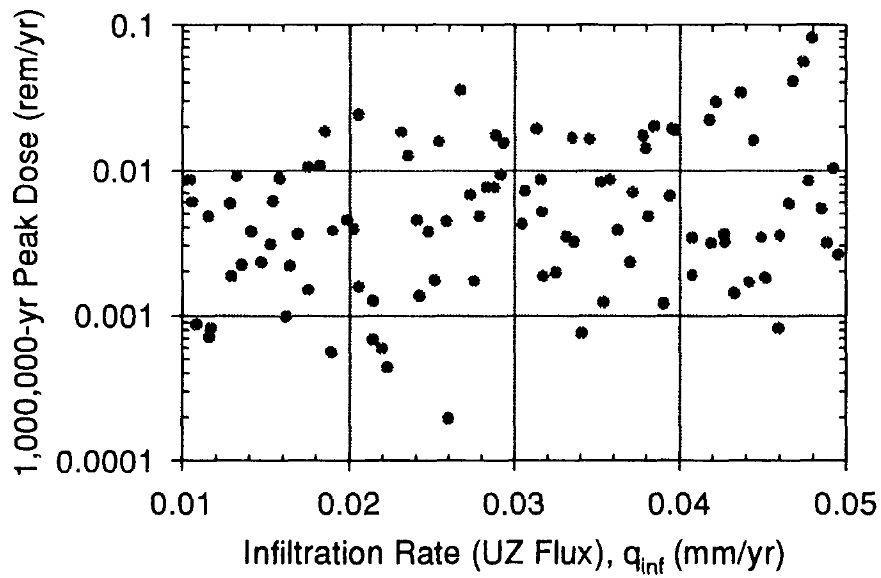
Sensitivity of 1,000,000-year Total Peak Dose to Infiltration-rate distribution, q_{inf}

(83 MTU/acre, gravel backfill, climatic variation of q_{inf})

high q_{inf} **range (0.5 - 2.0 mm/yr)**



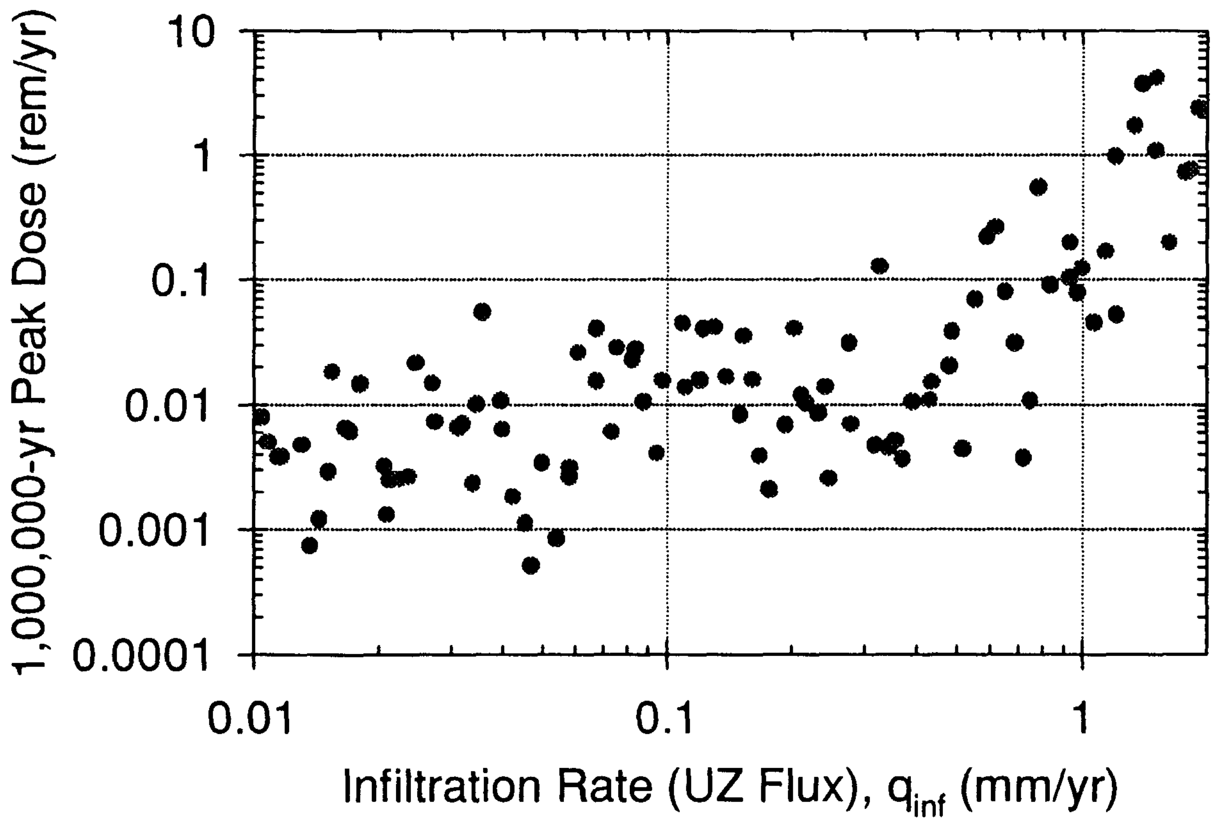
low q_{inf} **range (0.01 - 0.05 mm/yr)**



Sensitivity of 1,000,000-year Total Peak Dose to <u>Infiltration-rate distribution,</u> q_{inf}

(83 MTU/acre, gravel backfill, climatic variation of q_{inf})

<u>Entire</u> q_{inf} range (0.01 - 2.0 mm/yr)



Stepwise Linear Regression for 1,000,000-year Total Peak Dose

(83 MTU/acre, gravel backfill, climatic variation of q_{inf})

<u>high</u> q_{inf} range (0.5 - 2.0 mm/yr)

Performance Measure	ln (P.M.) vs. x		ln (P.M.) vs. ln (x)	
	Rank Importance	% of variance explained	Rank Importance	% of variance explained
U_{cli}(1,3)	3	53	4	81
Np K_d (TSv, CHnv)				
q_{sz}	1	23	1	48
f_{frac} CHnz				
v_{mat} CHnz				
q_{inf} (UZ)	2	45	2	65
f_{frac} TSv	5	62		
v_{mat} TSv			5	85
f_{frac} TSw			3	75
v_{mat} TSw	4	60		

Stepwise Linear Regression for 1,000,000-year Total Peak Dose

(83 MTU/acre, gravel backfill, climatic variation of q_{inf})

low q_{inf} range (0.01 - 0.05 mm/yr)

Performance Measure	ln (P.M.) vs. x		ln (P.M.) vs. ln (x)	
	Rank Importance	% of variance explained	Rank Importance	% of variance explained
$U_{cli}(1,3)$	3	57		
Np K_d (TSv, CHnv)				
q_{SZ}	1	49	1	89
f_{frac} CHnz				
v_{mat} CHnz			2	97
q_{inf} (UZ)	2	55		
f_{frac} TSv				
v_{mat} TSv				
f_{frac} TSw				
v_{mat} TSw			3	98

Stepwise Linear Regression for 1,000,000-year Total Peak Dose

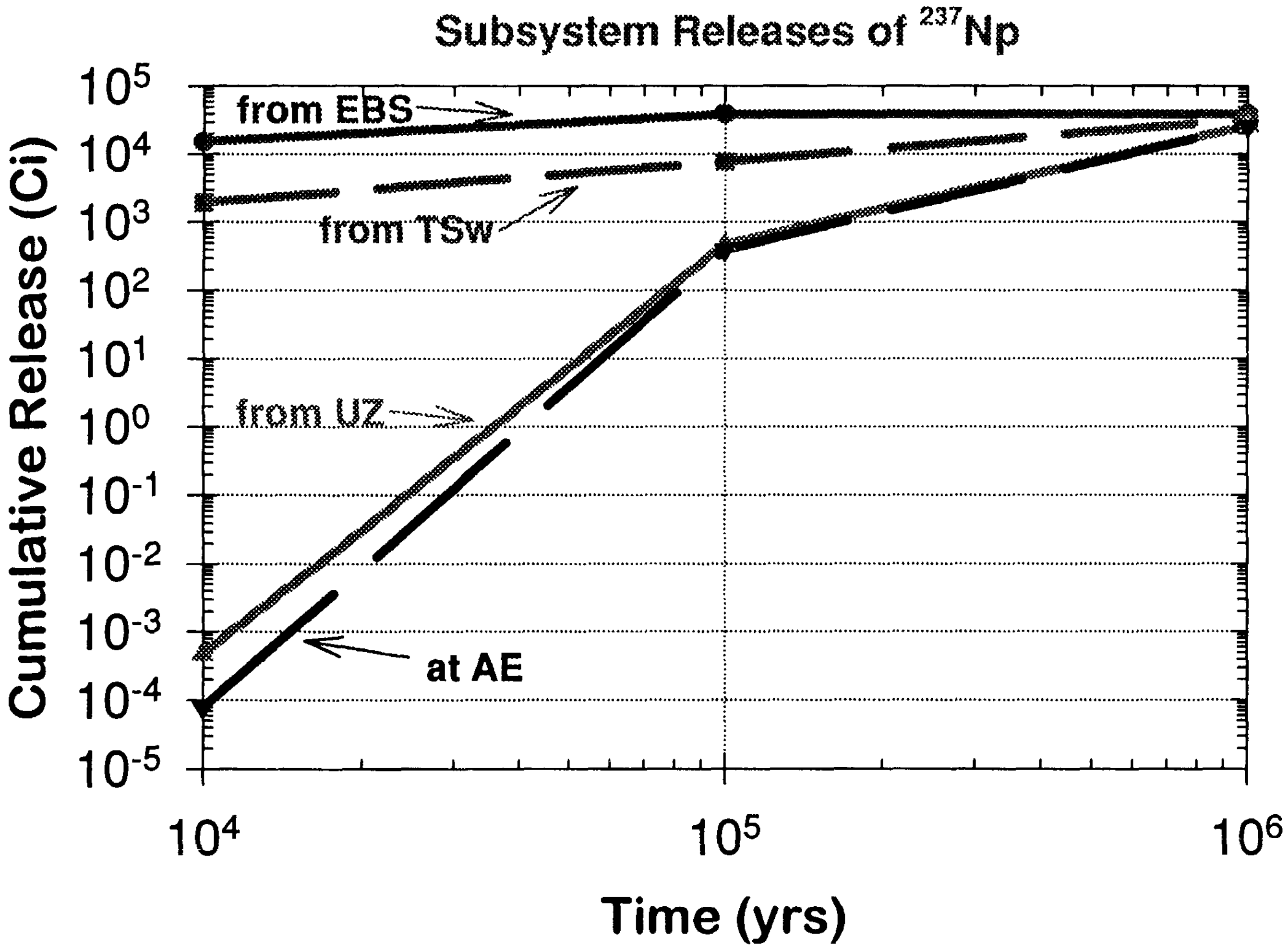
(83 MTU/acre, gravel backfill, climatic variation of q_{inf})

<u>Entire</u> q_{inf} range (0.01 - 2.0 mm/yr)

Performance Measure	ln (P.M.) vs. x		ln (P.M.) vs. ln (x)	
	Rank Importance	% of variance explained	Rank Importance	% of variance explained
U_{cli}(1,3)	3	78	5	88
Np K_d (TSv, CHnv)	4	80		
q_{sz}	2	75	2	74
f_{frac} CHnz				
v_{mat} CHnz				
q_{inf} (UZ)	1	64	1	50
f_{frac} TSv				
v_{mat} TSv				
f_{frac} TSw	5	81		
v_{mat} TSw			4	86
WP f_{drip}			3	83

Subsystem Performance: Expected-Value Releases for ^{237}Np

(83 MTU/acre, gravel backfill, climatic variation of q_{inf})



Conclusions: 10,000-year Performance

- 10,000-year normalized cumulative releases are below Table 1 limits and are controlled mainly by ^{14}C releases
- There are no releases for "low" infiltration, Buscheck 80 MTU/acre, waste-package cathodic protection, and UZ matrix diffusion
- Depending on the conceptual model, fracture/matrix interaction in the UZ can significantly affect peak dose and cumulative release
- 10,000-year peak dose (mainly ^{99}Tc and ^{129}I) is most sensitive to
  - » Matrix velocity in the CHnv
  - » Percolation flux in the unsaturated zone

Conclusions: 1,000,000-year Performance

- 1,000,000-year peak dose is most sensitive to
  - » Dilution in the saturated zone
  - » Percolation flux in the unsaturated zone
- 1,000,000-year peak dose may be greatly reduced by a barrier that intercepts dripping water on the packages, i.e., diffusive releases alone through the WP/EBS produce very low doses at the AE
- Fracture/matrix interaction in the UZ can delay peak doses significantly (by 100,000 years or more), but can only slightly reduce the peak over a 1,000,000-year time frame
- Alternate thermal loading, alternate thermohydrologic models for the near field, and alternate corrosion-initiation models do not have a large effect on 1,000,000-year peak doses