YUCCA MOUNTAIN PROJECT

Studies

Basic Structure, Conceptual Model, and Results of the TSPA-VA

Presented to:
Nuclear Waste Technical Review Board
Performance Assessment Panel

Presented by:
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U.S. Department of Energy
Office of Civilian Radioactive Waste Management

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Acknowledgements

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Outline

- **Summary of Key Components in Natural and Engineered Systems**
- **Summary of Key Features of VA Reference Design**
- **Description of Significant Processes and Results of Key Components used in TSPA-VA Base Case**
- **Simplified Hand Calculation of Total System Performance**

Methods to Present a Traceable and Transparent TSPA

- Identify all relevant processes for each key component that could impact long term performance
- Identify all the models that correspond to the key components and how these models are interconnected
- Identify the data in each model which forms the basis for each model
- Identify how the information flows from one component to the next in generating the total system behavior
- Explain all the results of each component and the total system in physical terms
- Produce a simple calculation of the system performance that elucidates the key aspects in the analyses

Postclosure Safety Strategy Attributes	TSPA Model Components
Water Contacting Waste Package	Climate Infiltration Unsaturated Zone Flow-Percolation Seepage Drips onto Waste Package Thermal Hydrology
Waste Package Lifetime	Near-Field Geochemical Environment Waste Package Degradation
Mobilization Rate of Radionuclides	Cladding Degradation Waste Form Degradation Seepage into Waste Package Colloid Formation and Stability Radionuclide Solubility Transport within Waste Package
Concentration of Radionuclides in ground water	EBS Transport Unsaturated Zone Transport Saturated Zone Transport Dilution from Pumping Biosphere

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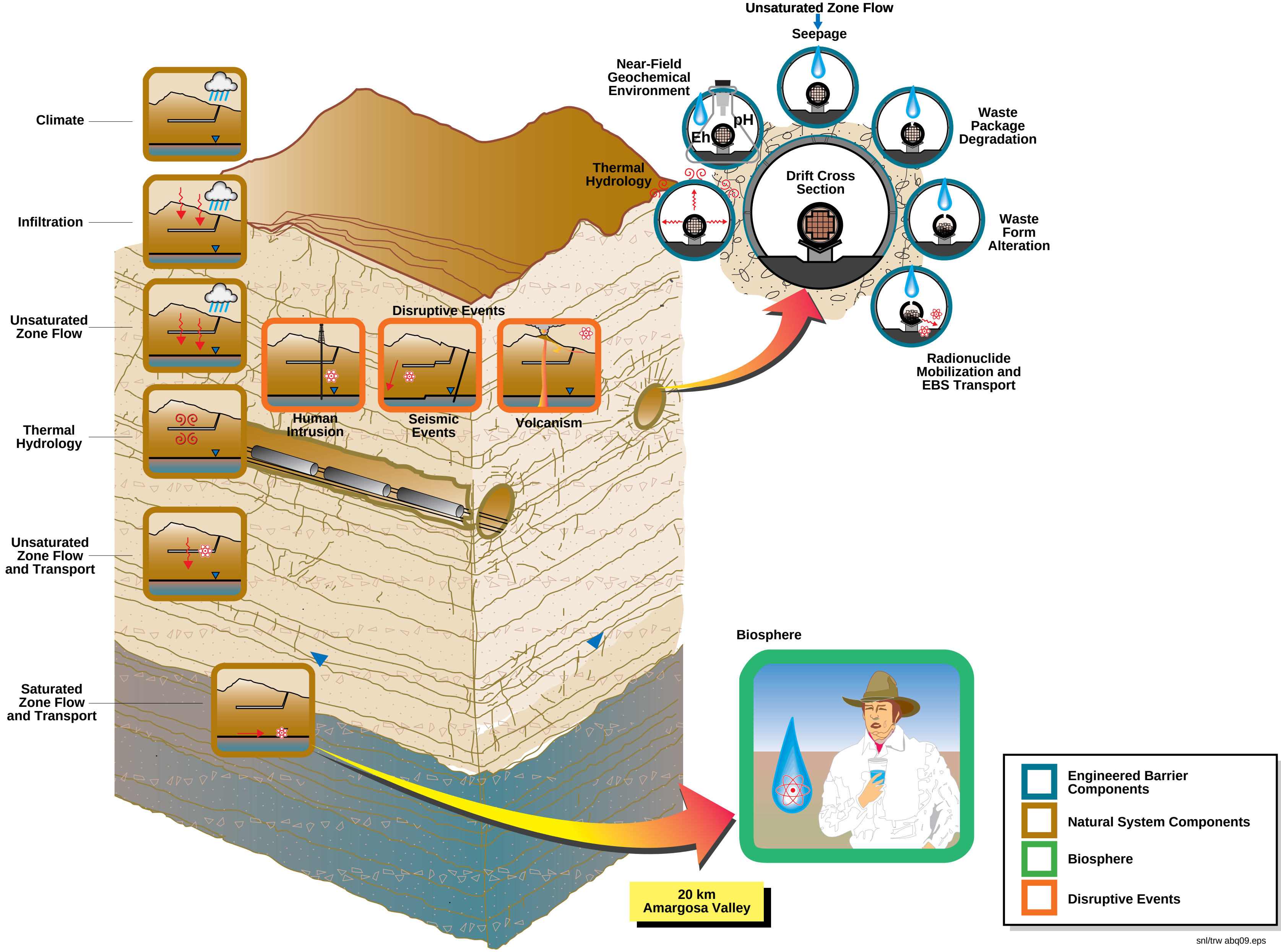
TSPA Model Components

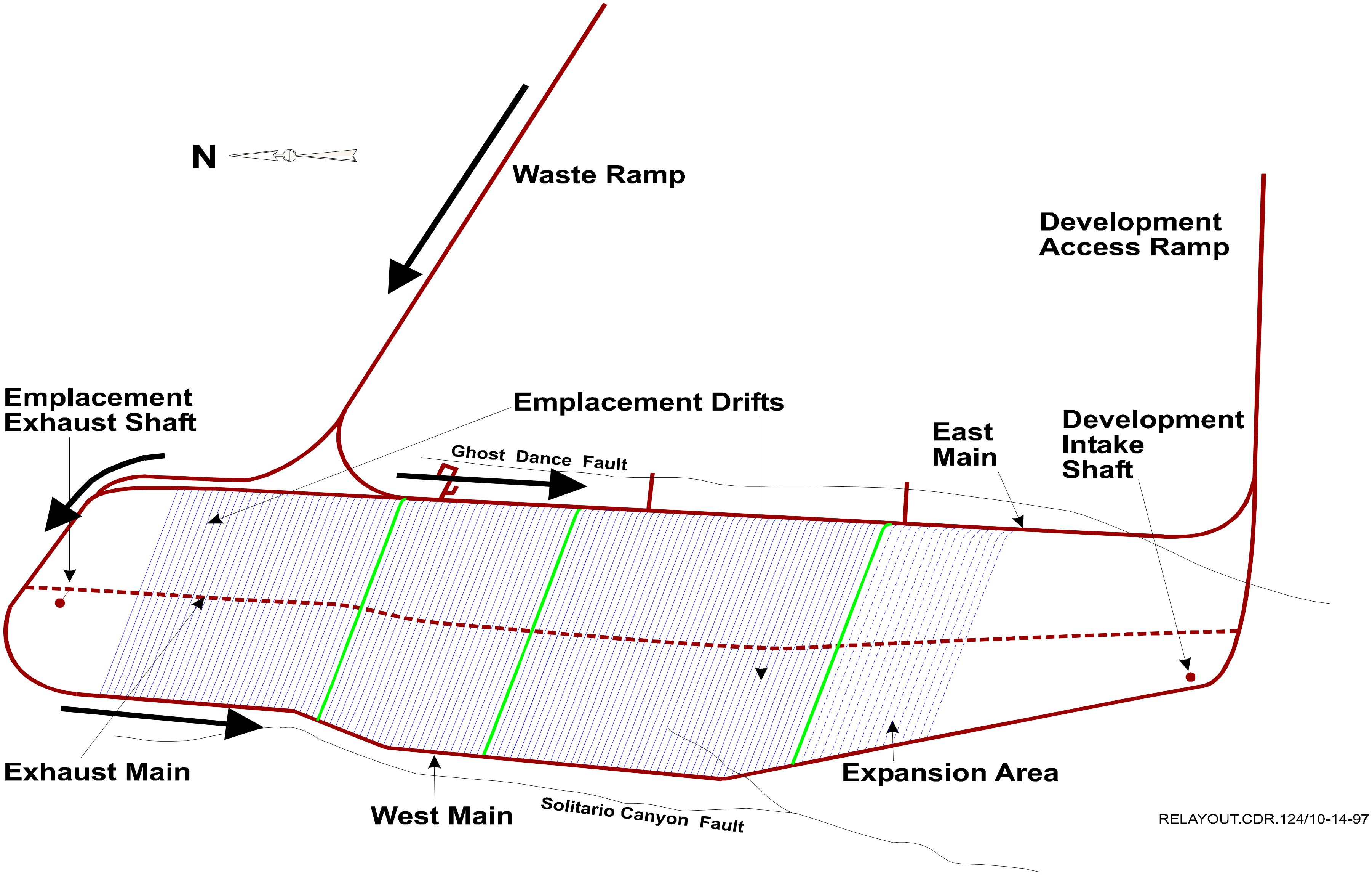


Key Features of Reference Design for Viability Assessment: Repository

- ~300m depth; ~300m above water table
- Topopah Spring welded units
  - 34 - Middle nonlithophysal
  - 35 - Lower lithophysal
  - 36 - Lower nonlithophysal

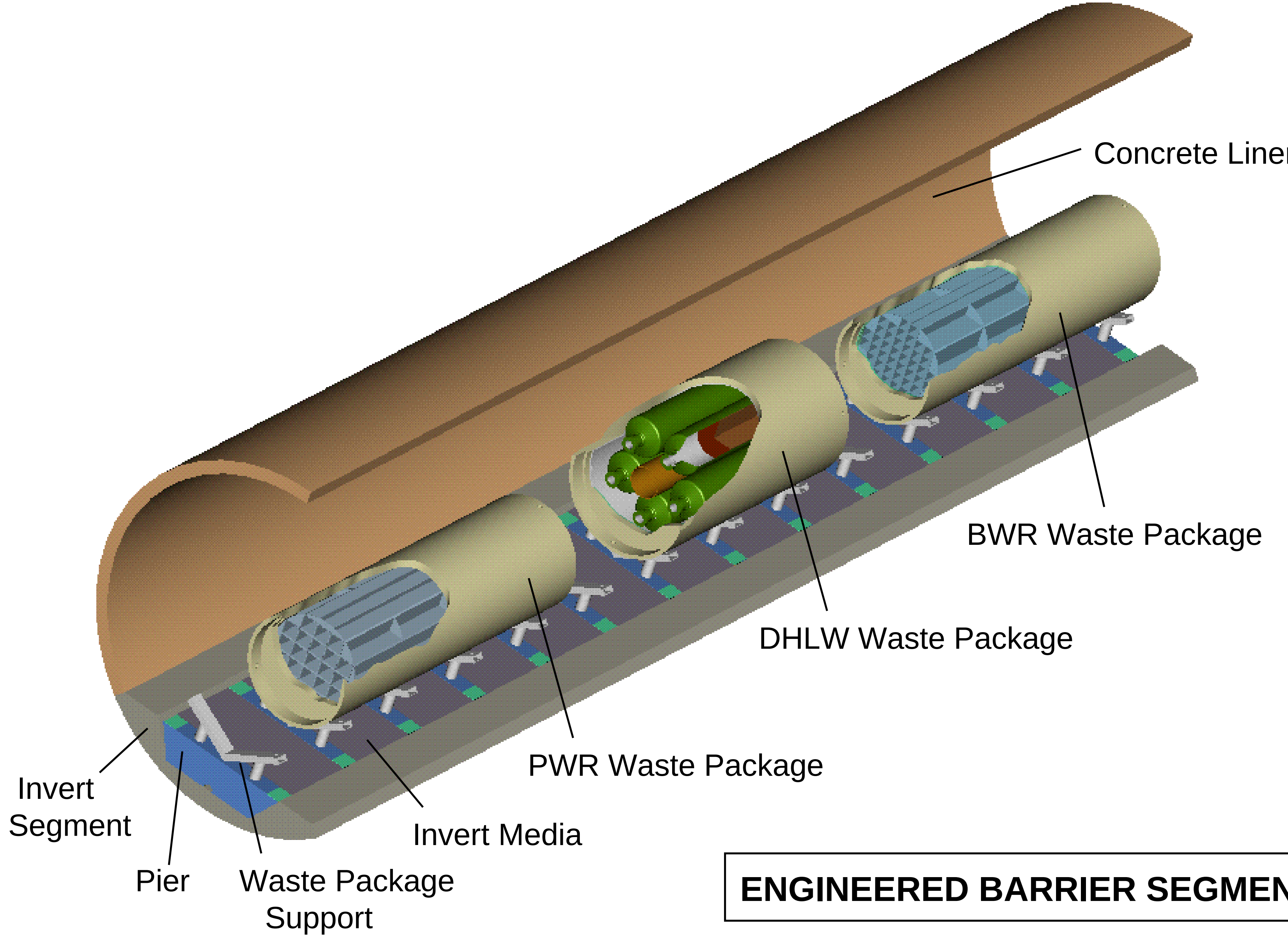
- 85 MTHM/Acre
- 70,000 MTHM
  - 63,000 MTHM CSNF
  - 2,333 MTHM DOE-SNF
  - 4,667 MTHM HLW
  - 65 MTHM Navy Fuel
  - 50 MTHM Pu-MOX

Preliminary Repository Layout



Key Features of Reference Design for Viability Assessment: Engineered Barrier/Emplacement Drift

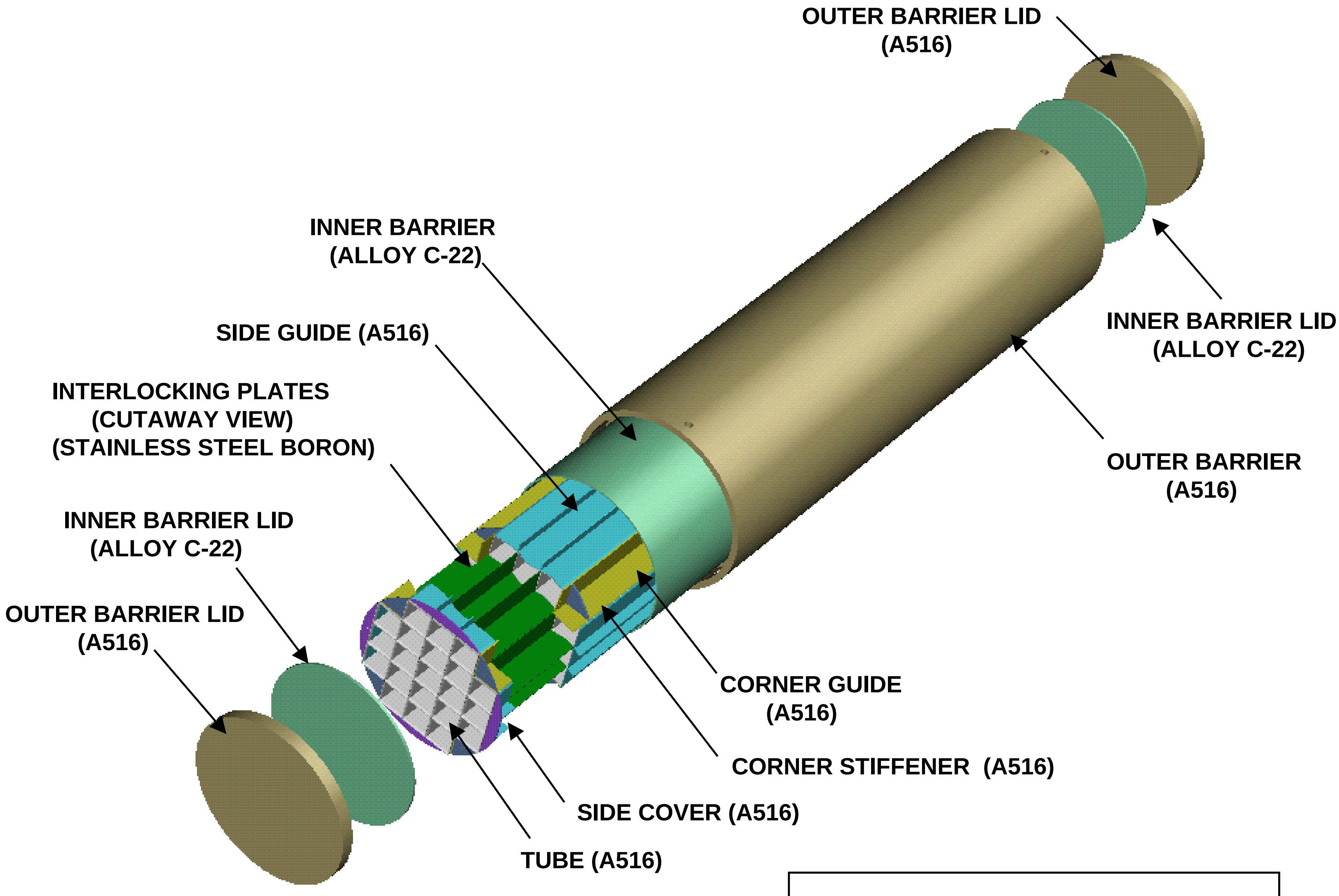
- **5.5m - diameter drift**
- **20cm concrete liner**
- **Waste Packages placed on mild steel supports on concrete invert**
- **Waste Package spacing ~5m (point load)**
- **No backfill or drip shields**



ENGINEERED BARRIER SEGMENT

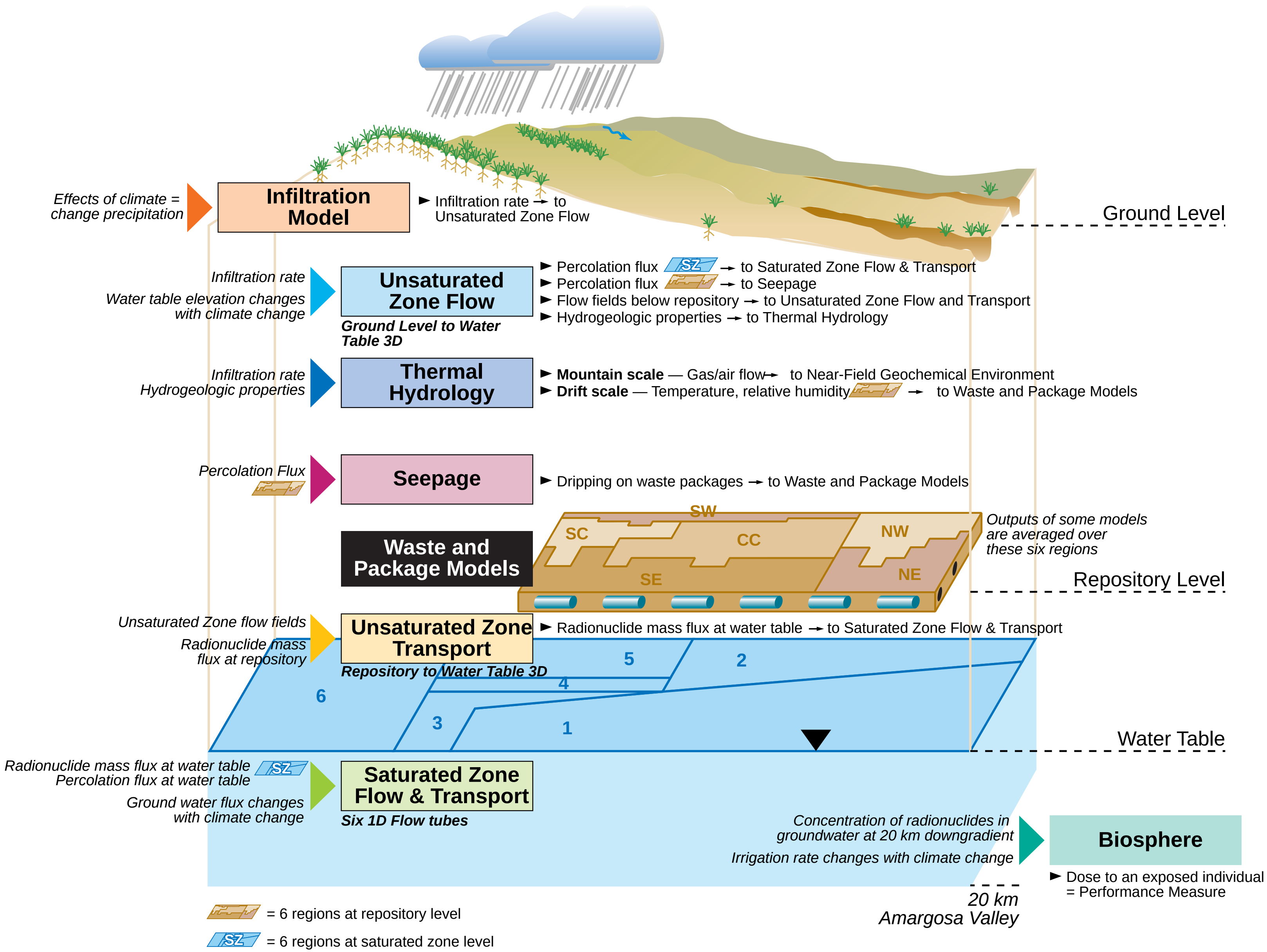
Key Features of Reference Design for Viability Assessment: Waste Package

- **21-PWR or 44-BWR CSNF**
- **5-HLW canisters co-disposed with DOE SNF**
- **10cm mild steel outer barrier**
- **2cm C-22 inner barrier**



21-PWR UCF
WASTE PACKAGE ASSEMBLY

Information Flow for TSPA-VA



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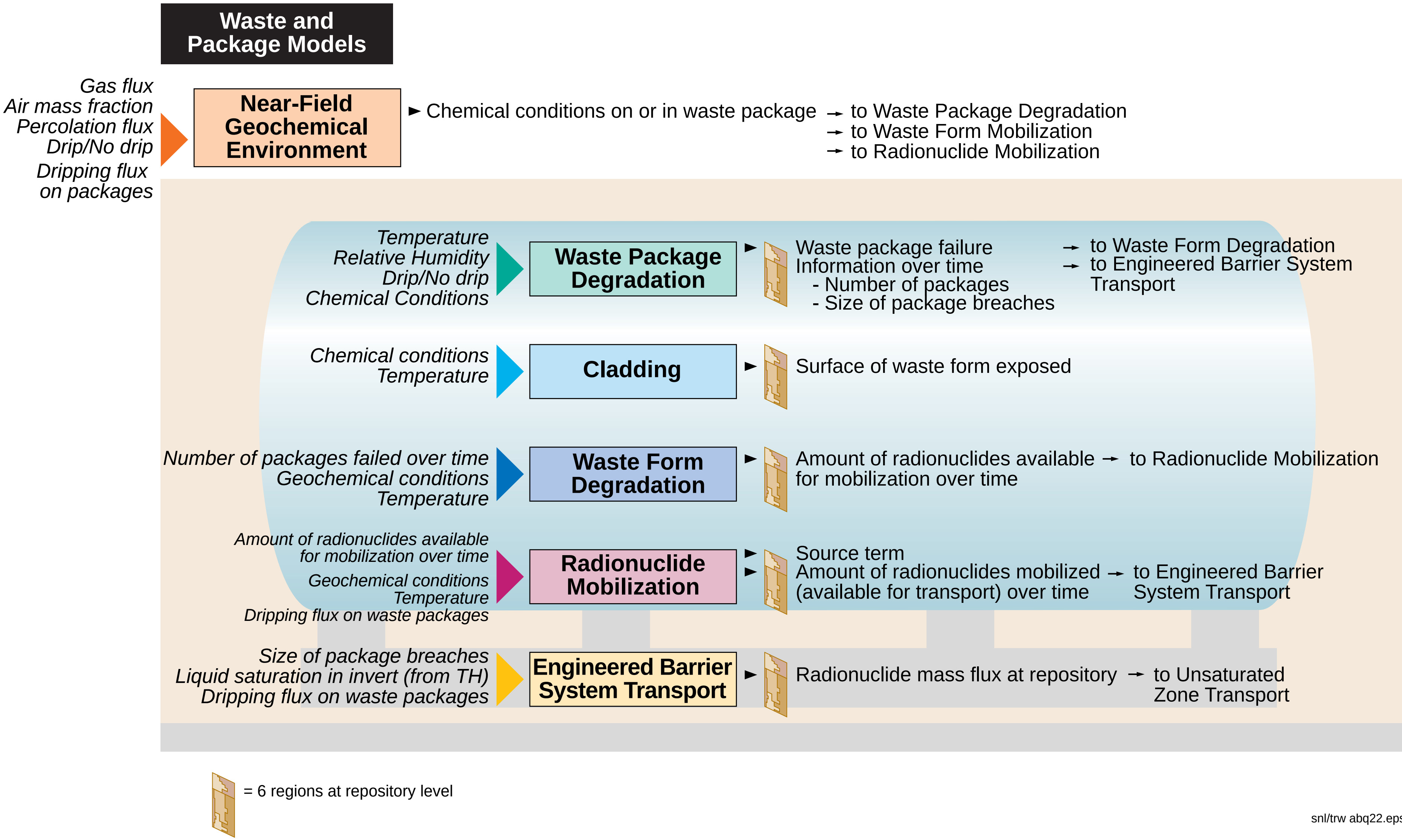
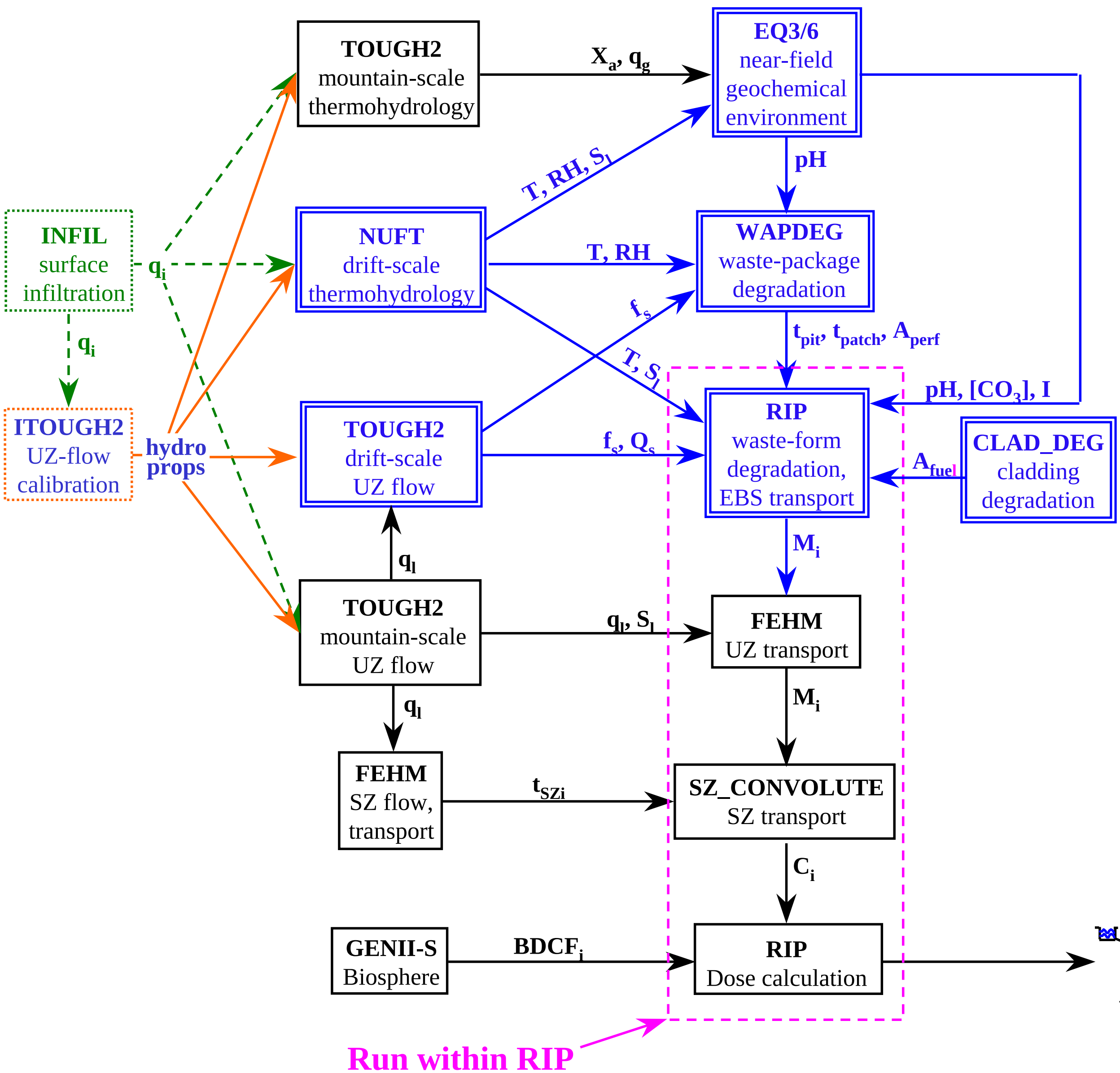
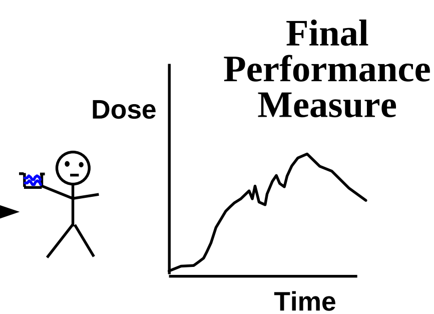
Information Flow for TSPA-VA



TSPA-VA Code Configuration

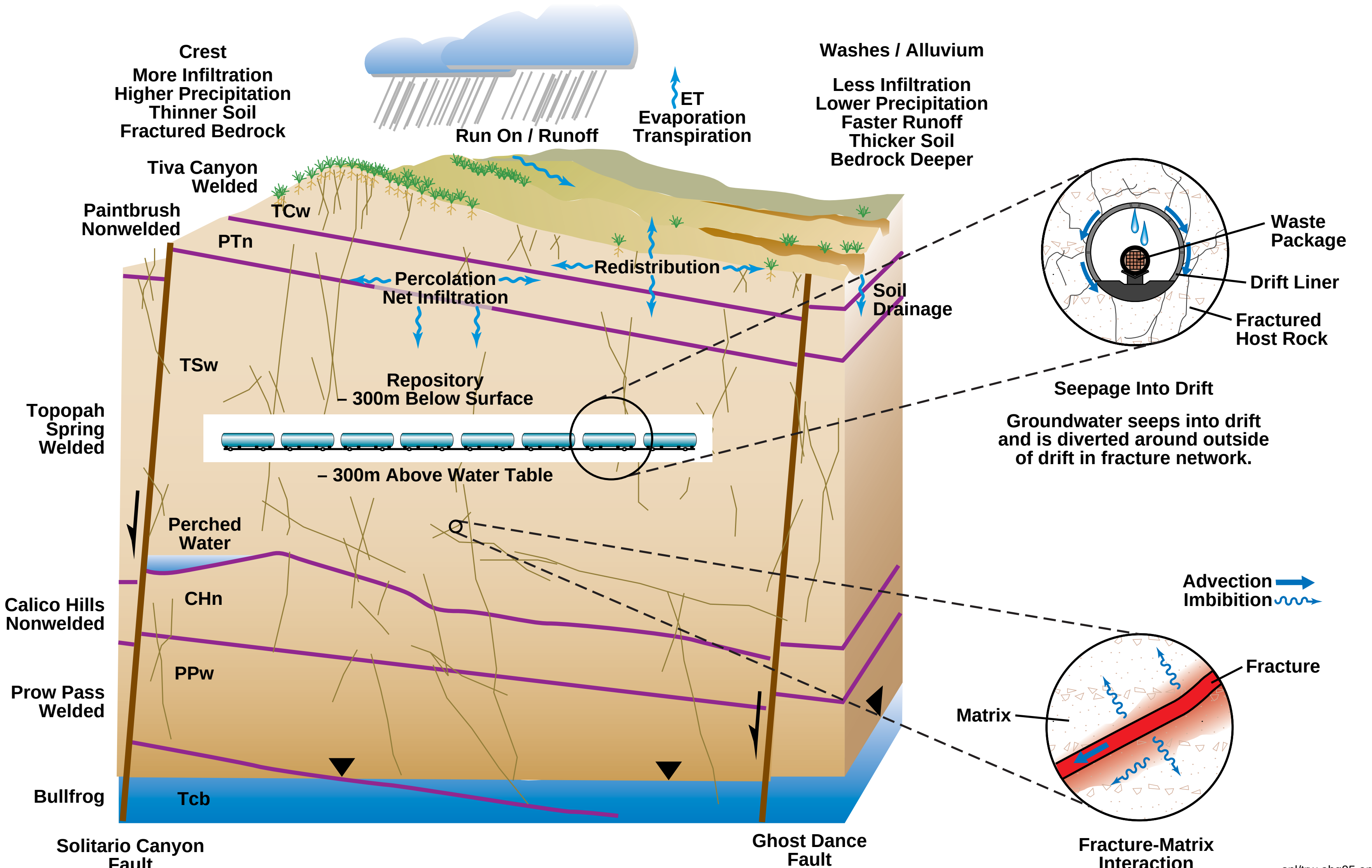


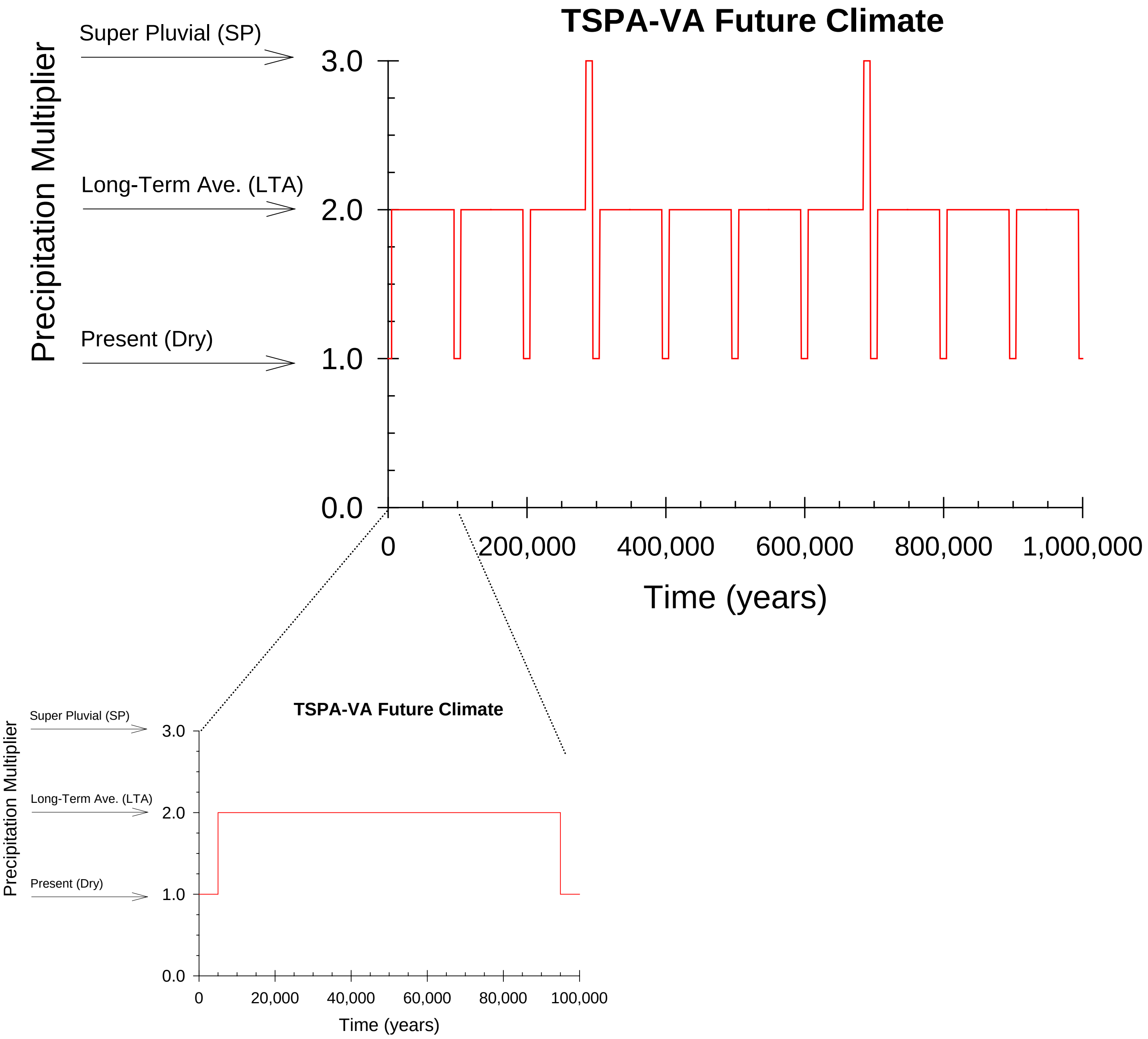


OUTPUT Parameters

T	Temperature
RH	Relative humidity
S_l	Liquid saturation
X_a	Air mass fraction
q_g	Gas flux
q_l	Liquid flux
q_i	Infiltration flux
f_s	Fraction of WPs with seeps
Q_s	Seep flow rate
pH	pH
$[CO_3]$	Carbonate concentration
I	Ionic strength
t_{pit}	Initial-pit-penetration time
t_{patch}	Initial-patch-penetration time
A_{perf}	Perforated container area
A_{fuel}	Exposed fuel area
M_i	Radionuclide mass flux
C_i	Radionuclide concentration
t_{SZi}	SZ transport time
$BDCF_i$	Biosphere dose conversion factor

Conceptual Models of Hydrologic Processes



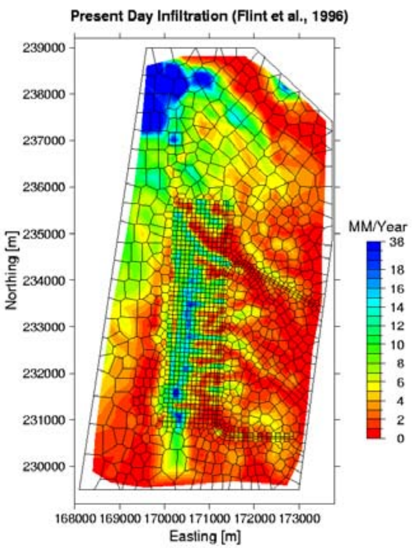

TSPA-VA Future Climate
Super Pluvial (SP)
Long-Term Ave. (LTA)
Present (Dry)
Precipitation Multiplier
3.0
2.0
1.0
0.0
0
200,000
400,000
600,000
800,000
1,000,000
Time (years)
TSPA-VA Future Climate
Super Pluvial (SP)
Long-Term Ave. (LTA)
Present (Dry)
Precipitation Multiplier
3.0
2.0
1.0
0.0
0
20,000
40,000
60,000
80,000
100,000
Time (years)

TSPA Base Case Climate History (Precipitation)

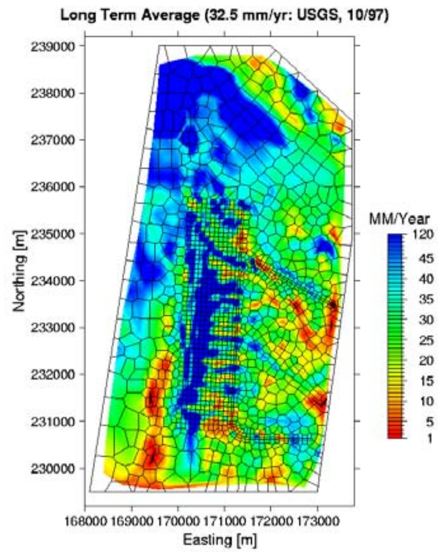
- Use 3 climate states
  - Present (dry)
  - Long-Term Average
  - Super Pluvial
- Assume instantaneous change between climate states
- Durations
  - Present (5,000 yrs.)
  - Long-Term Average (90,000 yrs.)
  - Super Pluvial (10,000 yrs.)
- Timing
  - Present (~ every 100,000 yrs.)
  - Long-Term Average (~ 80% of time)
  - Super Pluvial (~ every 300,000 yrs.)
- Magnitude
  - Long-Term Average (2x Present Precipitation)
  - Super Pluvial (3x Present Precipitation)

TSPA-VA Base Case Infiltration History

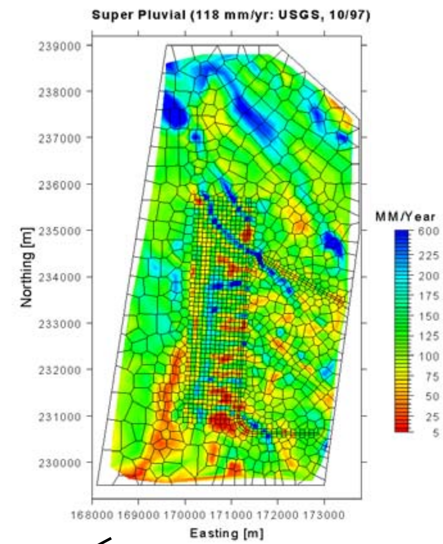
<P> ~ 7 mm/yr

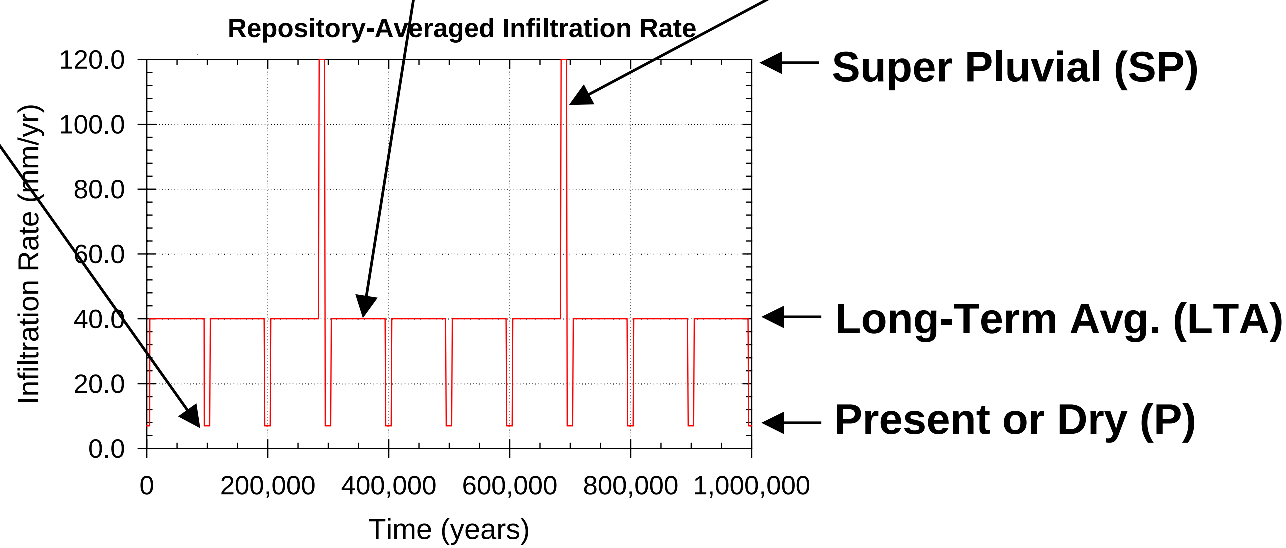


<LTA> ~ 40 mm/yr



<SP> ~ 120 mm/yr

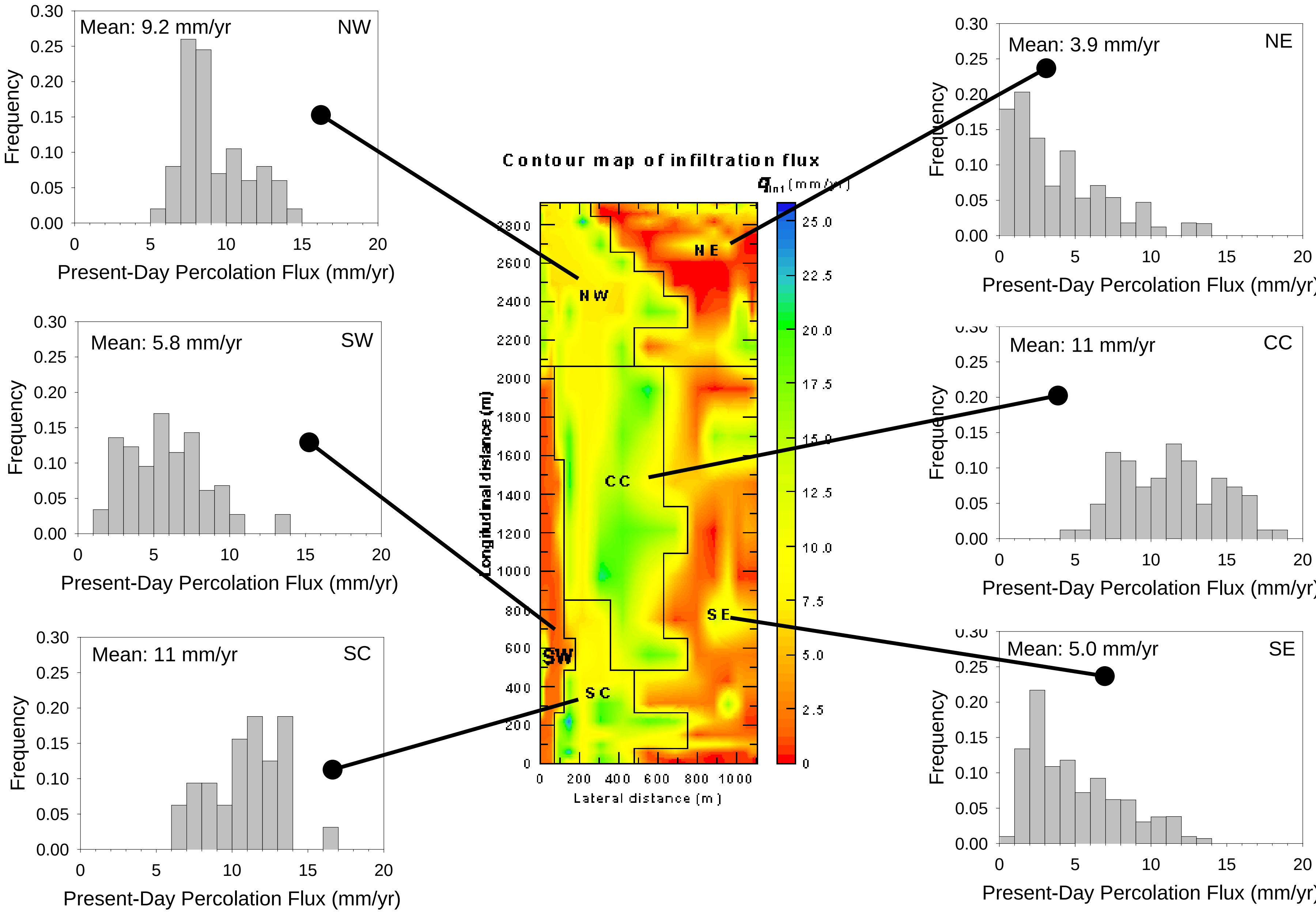




TSPA-VA Base Case Infiltration History

- **Present infiltration model (Flint and Hevesi) calibrated to shallow neutron holes**
- **Infiltration model used to extrapolate the effects of precipitation changes**
- **Infiltration changes non-linearly with precipitation due to duration, intensity and timing of precipitation**
- **Three discrete infiltration rates used as input to UZ Flow Model**

TSPA-VA Base Case Unsaturated Zone Flow: Percolation Flux

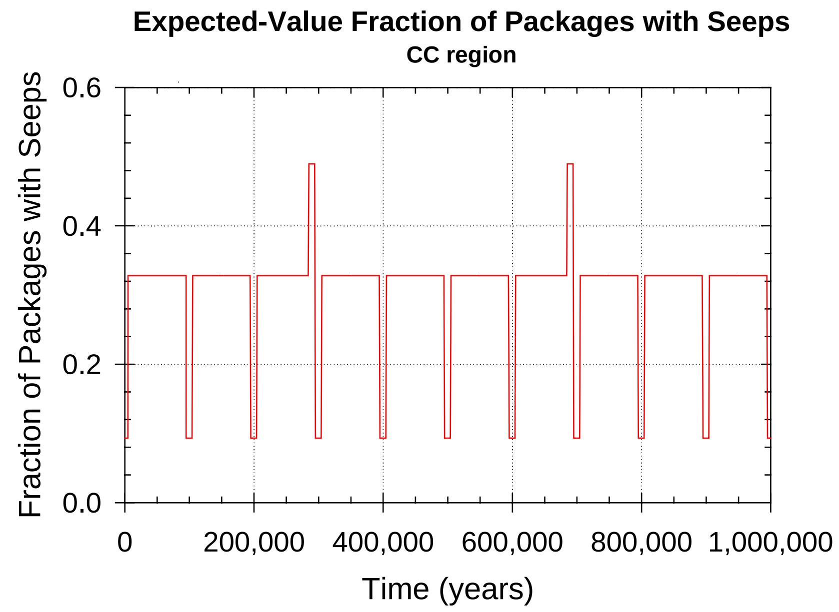


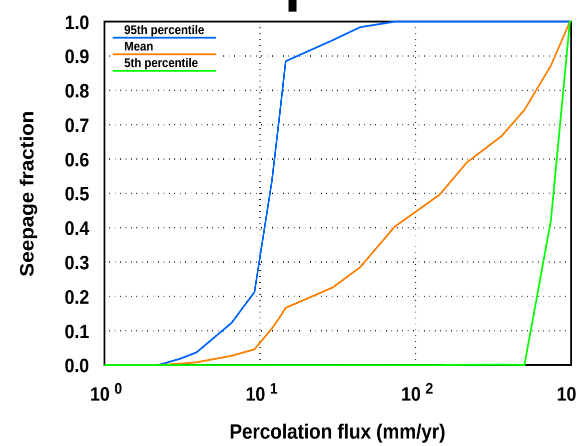
TSPA-VA Base Case
Unsaturated Zone Flow Model

- **UZ Flow Model calibrated with matric potential, temperature, chloride, Cl-36, perched zones, pneumatics**
- **Percolation flux varies spatially, but is subdued reflection of infiltration**
- **Percolation at repository discretized into six regions, ranging from**
  - **4 to 11 mm/yr (present-day climate);**
  - **31 to 55 mm/yr (long-term average);**
  - **81 to 140 mm/yr (super pluvial)**

TSPA-VA Base Case Seepage: Fraction of Waste Package with Seeps

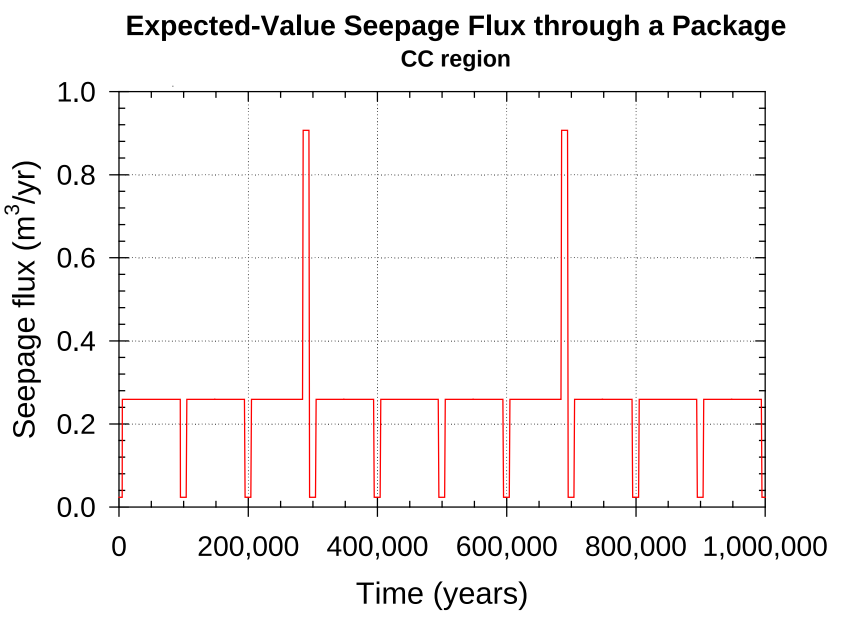
- **Seepage fraction defines the probability of a seep intersecting a waste package**
- **Seepage model considers heterogeneous fracture network**
- **Conservatively assume all seeps above spring line can intersect waste package**
- **Long-Term Average mean fraction of packages with seeps is ~0.3 (varies between six discrete regions)**
- **Uncertainty in seepage fraction due to uncertainty in fracture permeability and capillarity**

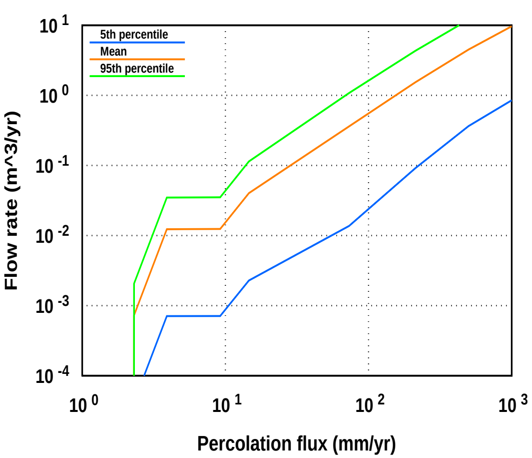




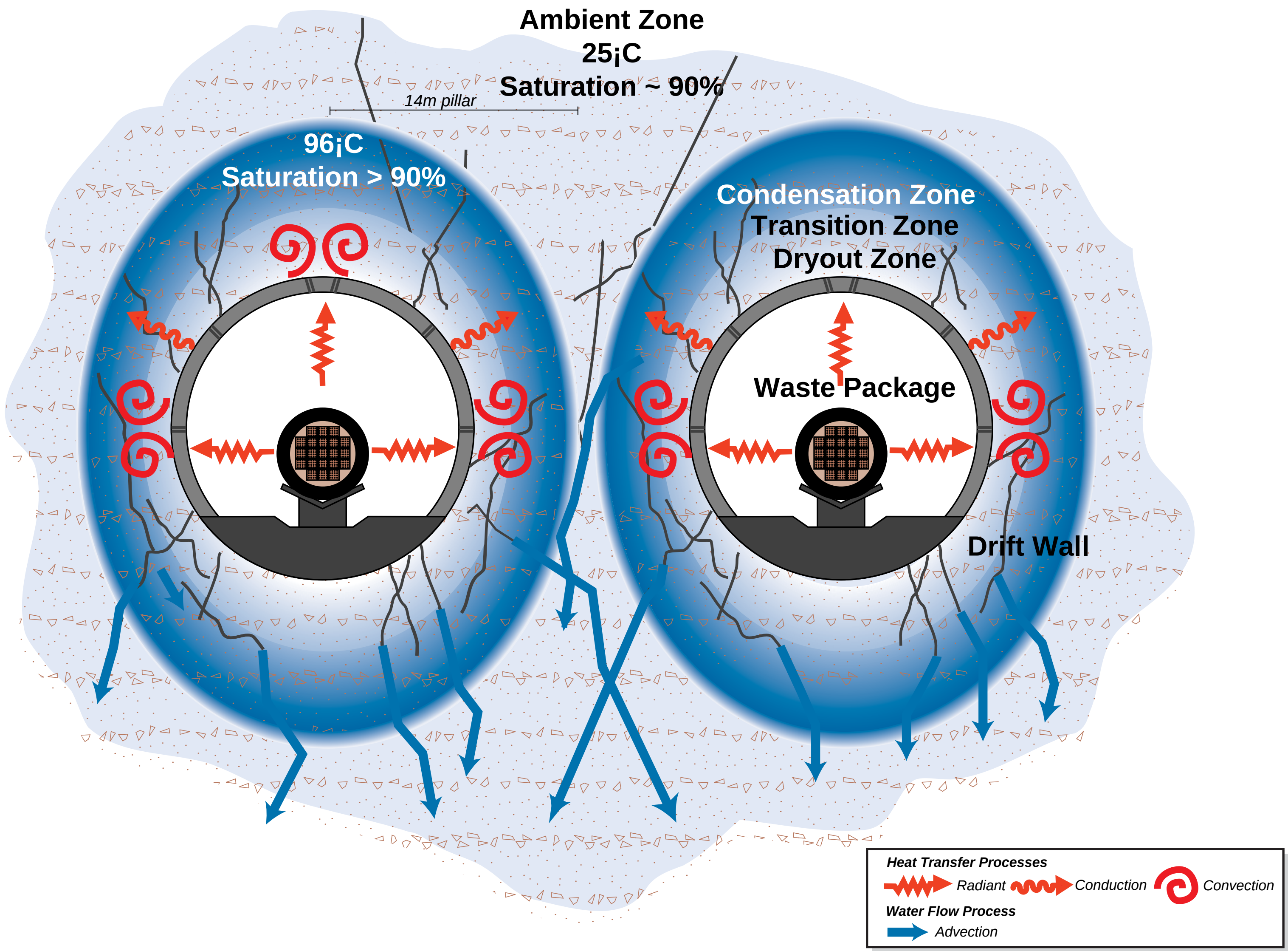
TSPA-VA Base Case Seepage: Seepage Flux

- **Seepage model fluxes compare with ESF niche tests (about 1,000 - 10,000 x ambient flux)**
- **Seepage flux determined by adding fluxes from each individual modeled seep which intersects a waste package**
- **Long-Term Average mean seepage flux is ~ 0.2 m³/yr (varies between six discrete regions)**
- **Given ~ 30% of packages see seeps (LTA) and average seepage flux is ~0.2 m3/yr; ~ 1,000 m3/yr seeps into drifts, which is ~ 1/200 or 0.5% of total percolation flux across repository footprint**





Thermal Hydrology in TSPA-VA



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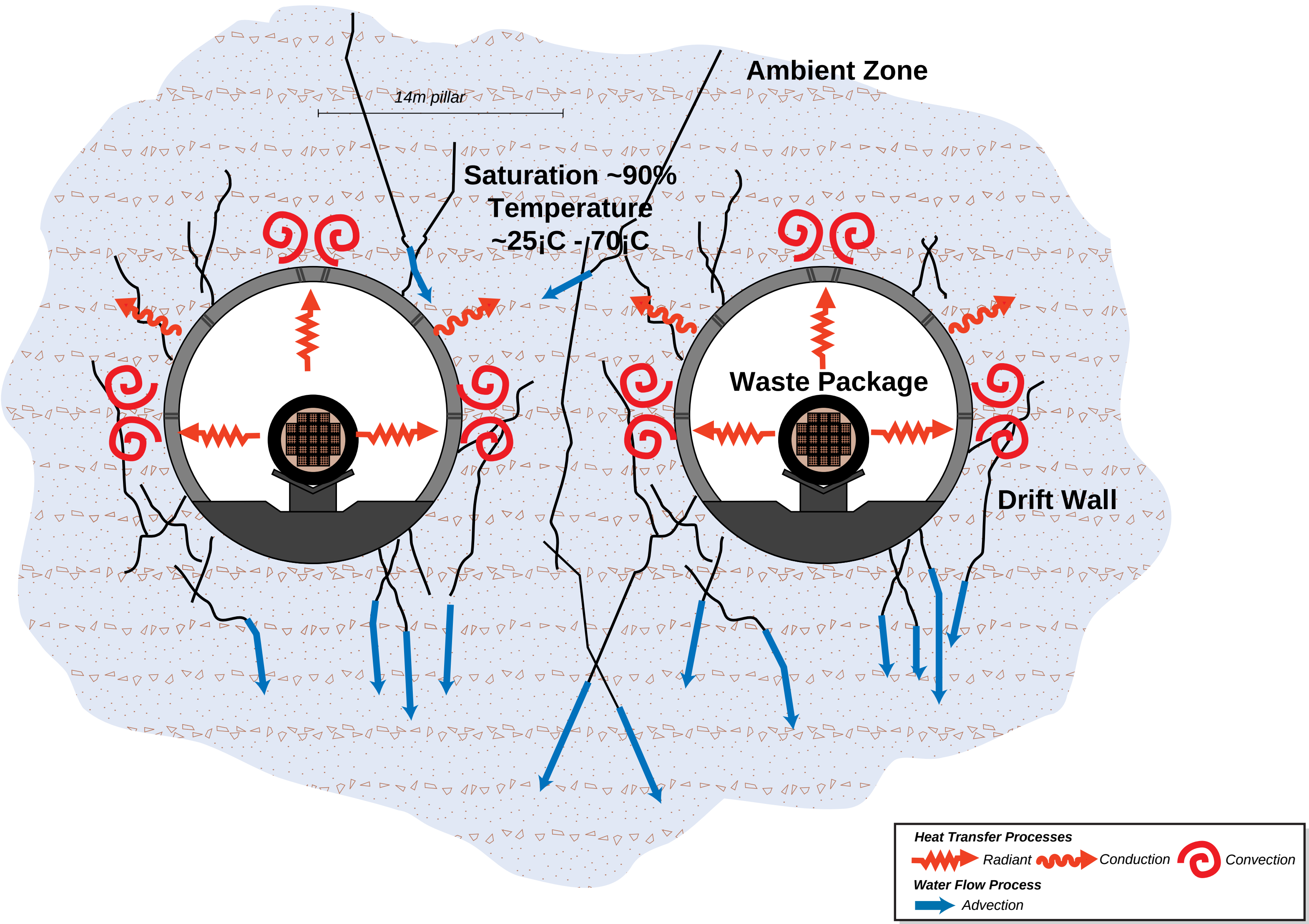
Thermal Hydrology in TSPA-VA



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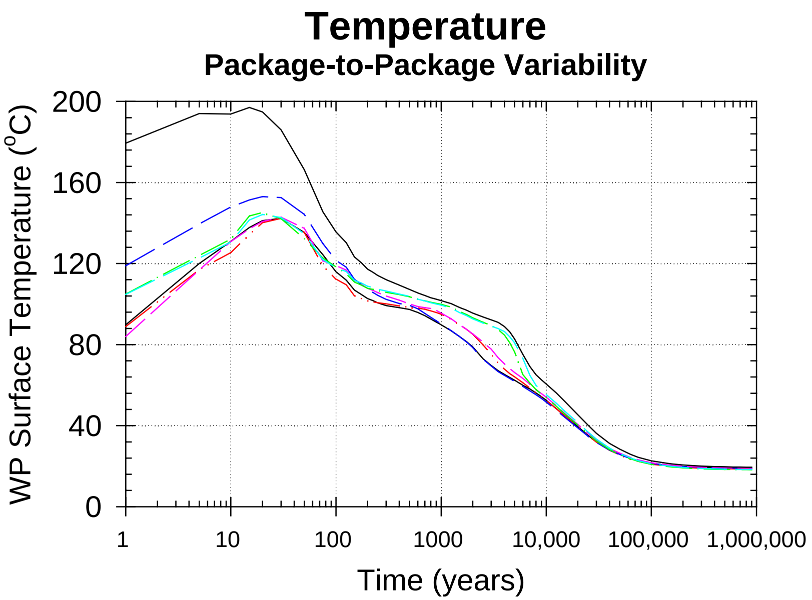
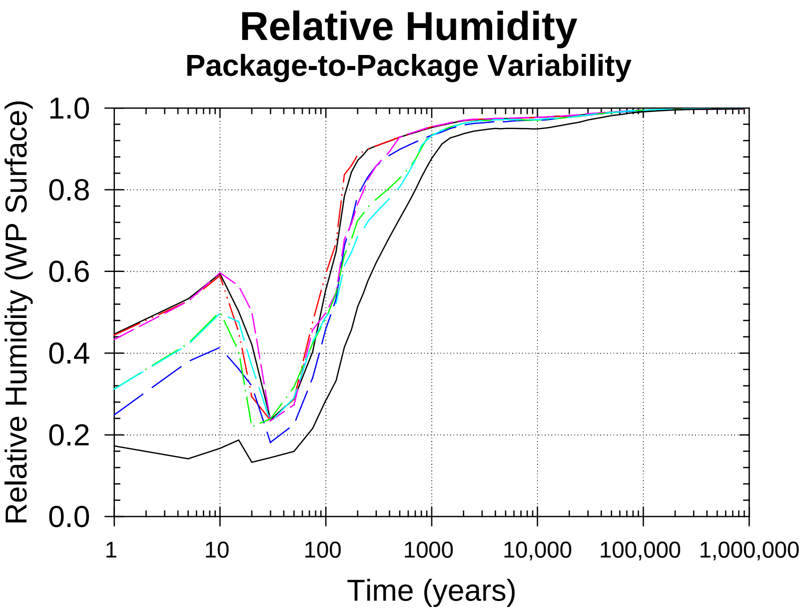
TSPA-VA Base Case Thermal Hydrology

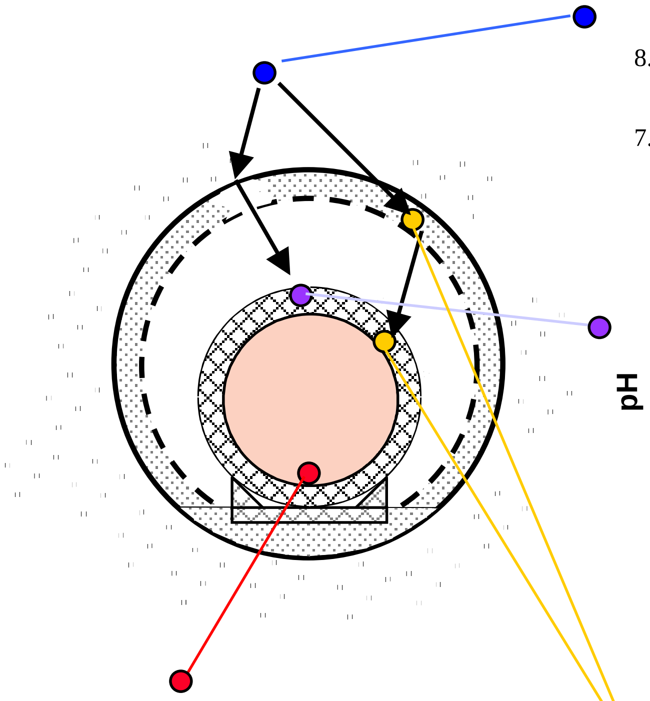
- Thermal hydrology model used to predict single heater test and drift-scale test results
- Principal results used are temperature and relative humidity on waste package surface and saturation in invert
- Redistribution of moisture (modified fluxes) analogous to assuming Long-Term Average percolation fluxes occur at 2,000 - 3,000 years after emplacement
- Variability in T/RH response in six regions and for different waste packages – variability is minimal after ~ 1,000 years

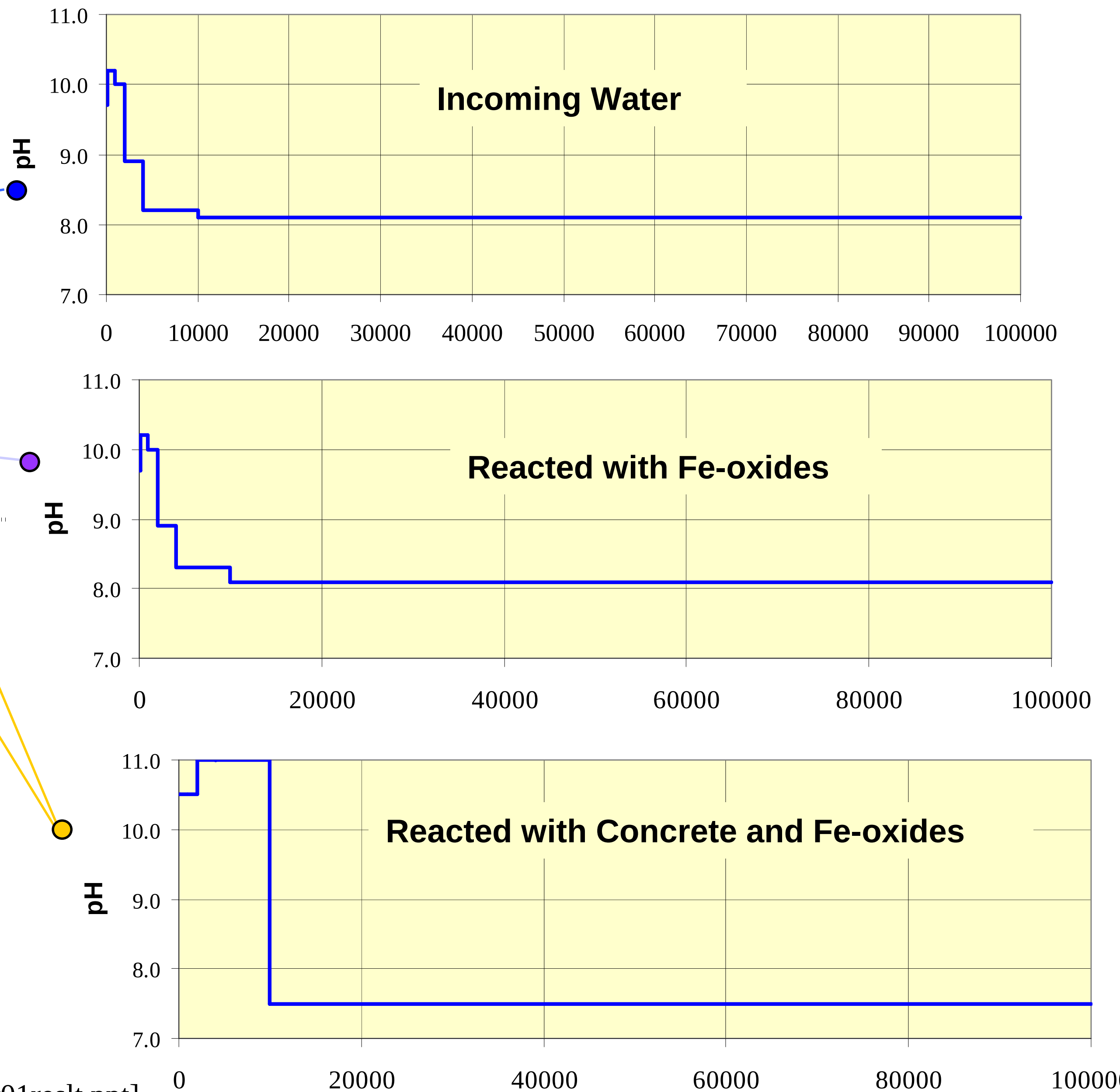




TSPA-VA Base-Case Near-Field Geochemical Environment

[Schematic, not design drawing]





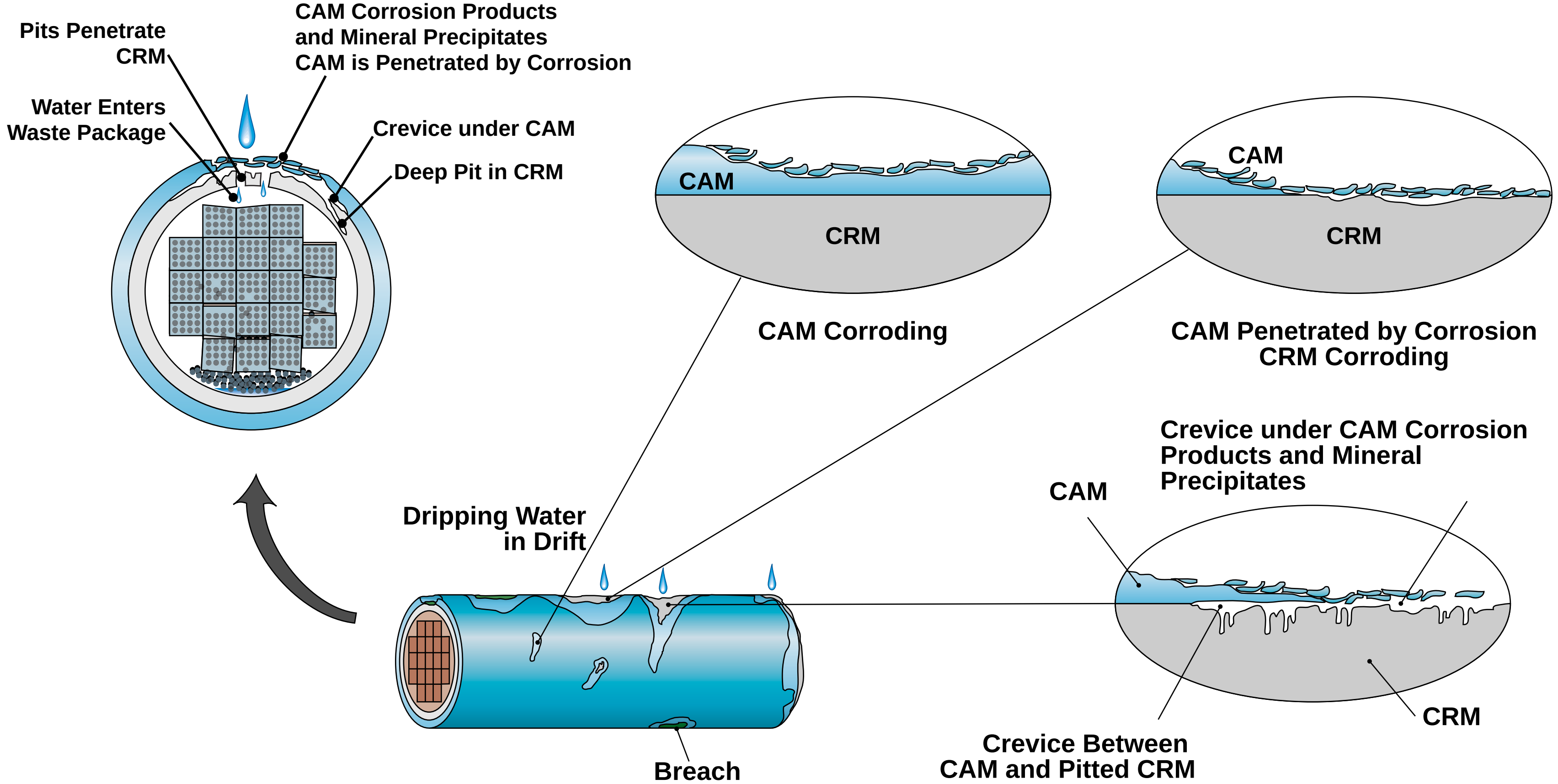
Note: Water reacted with spent fuel has perturbed pH only during active alteration of original UO_2. This is approximately 500-1000 years.

[Revised 20-Apr-98, NFGErev01reslt.ppt]

TSPA-VA Base Case Near Field Geochemical Environment

- Geochemistry in drift controlled by air mass fraction determined from mountain-scale thermal hydrology
- Discrete time windows used to evaluate batch chemical equilibrium
- Chemistry altered by presence of
  - Concrete liner
  - Steel
  - Glass or spent fuel waste forms
- Key geochemical parameters are
  - pH (WP degradation, WF degradation, solubility
  - CO_3 (WF degradation, solubility)
  - I (colloid stability)

Waste Package Degradation



CAM = Corrosion Allowance Material Outer Barrier

CRM = Corrosion Resistant Material Inner Barrier

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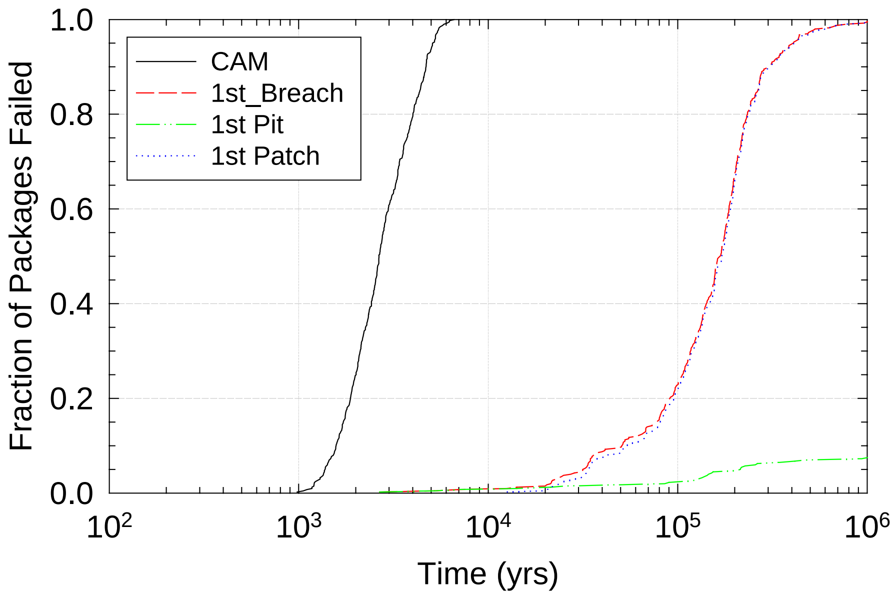
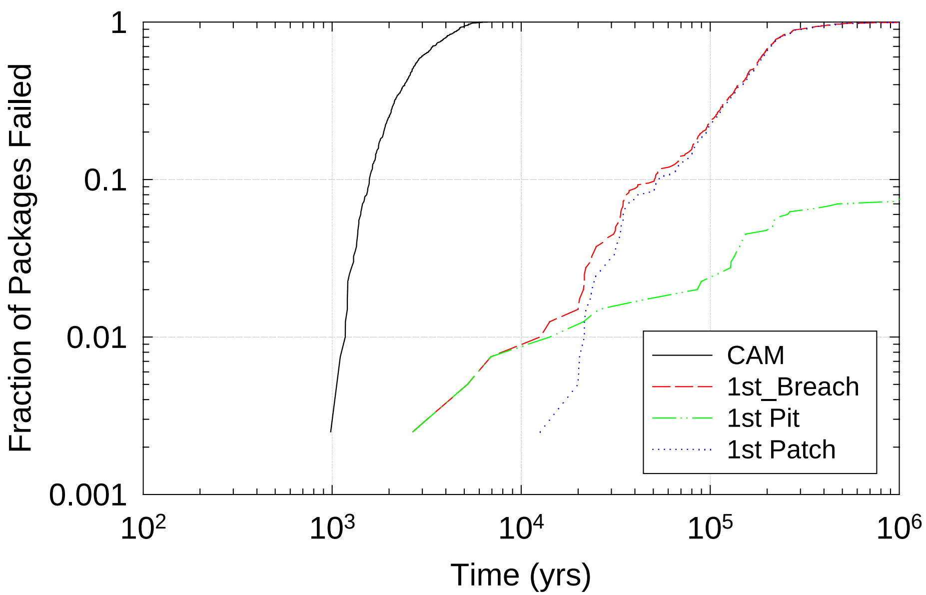
TSPA-VA Base Case Waste Package Degradation: Initial “Failure”

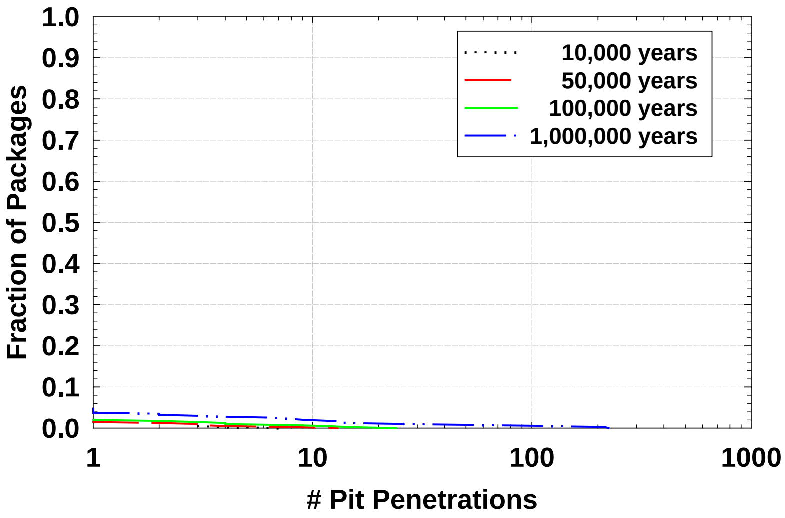
- “Failure” defined by initial pits (mm^2) or patch (100’s cm^2) opening through corrosion resistant material
- Primary degradation method is corrosion
- Possible early failures considered - one waste package at 1,000 years in base case
- Rate of “failure” of waste packages with seeps is ~2% / 10,000 years
- Earliest corrosion “failures” are by pits at ~ 3,000 years and by patches at ~ 10,000 years
- Waste packages without seeps do not “fail” until several 100,000 years

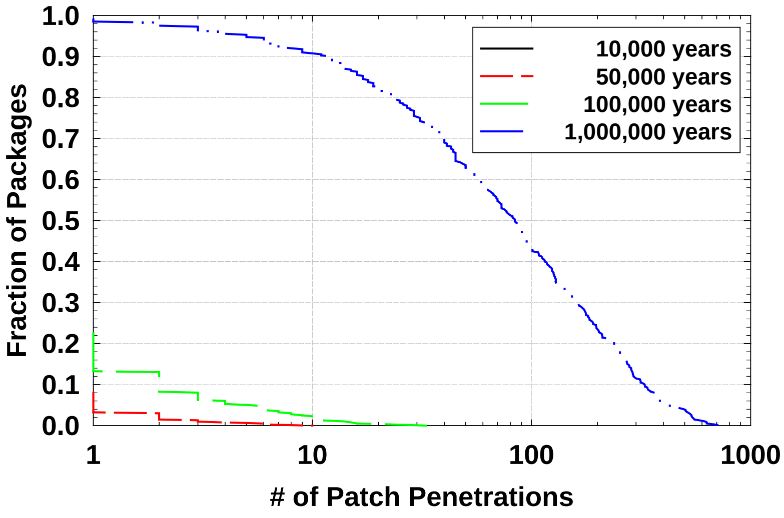




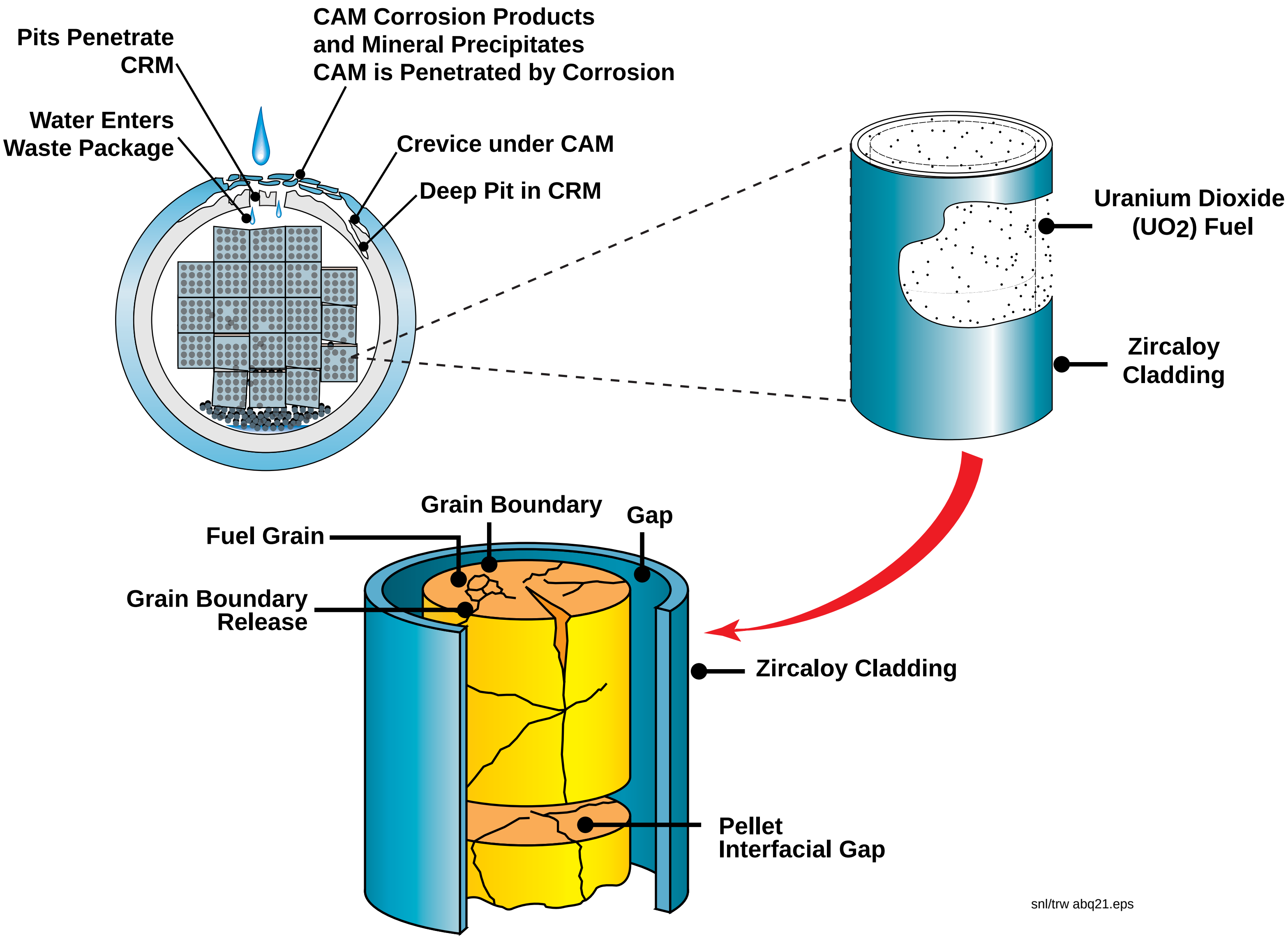
TSPA-VA Base Case Waste Package Degradation: Surface Area "Failed"

- **Percent of waste package surface exposed used to define percent of seepage flux which can enter waste package**
- **Regardless of where the first breach occurs, seeps are assumed to intersect the exposed openings**
- **Seeps are allowed to infiltrate package even if openings are pit size and filled with corrosion product**
- **Due to larger area, patches are more significant for EBS releases of solubility – limited radionuclides**



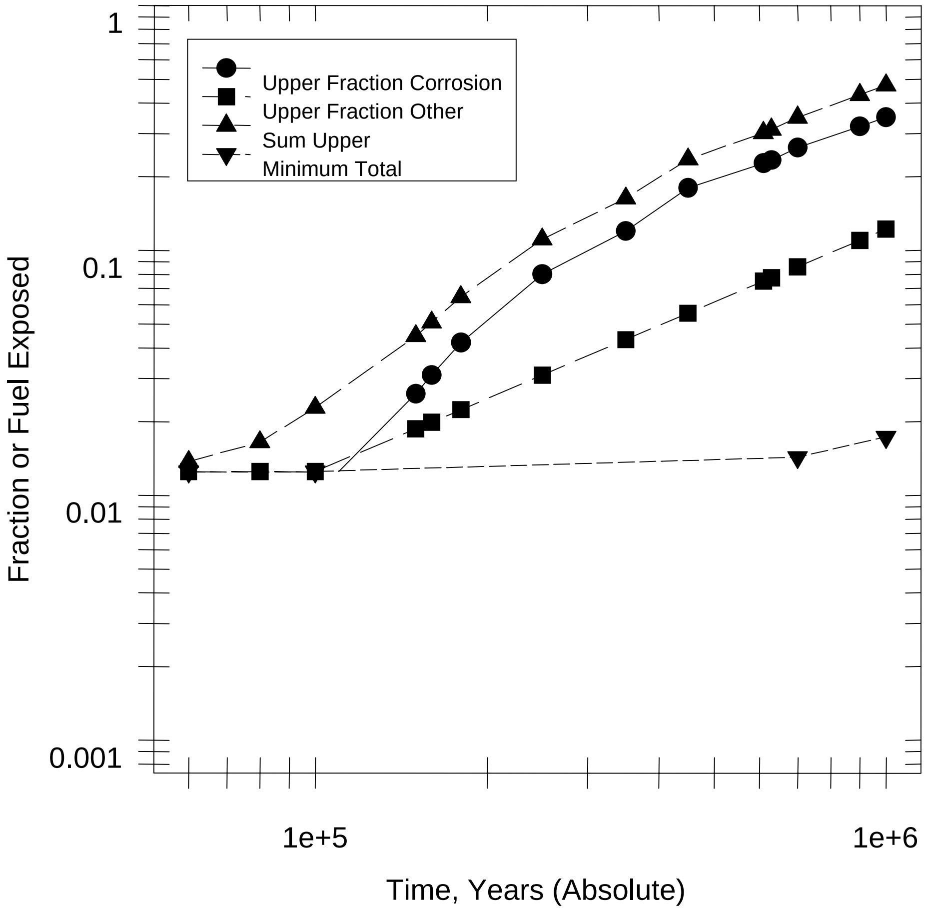


Waste Form Degradation



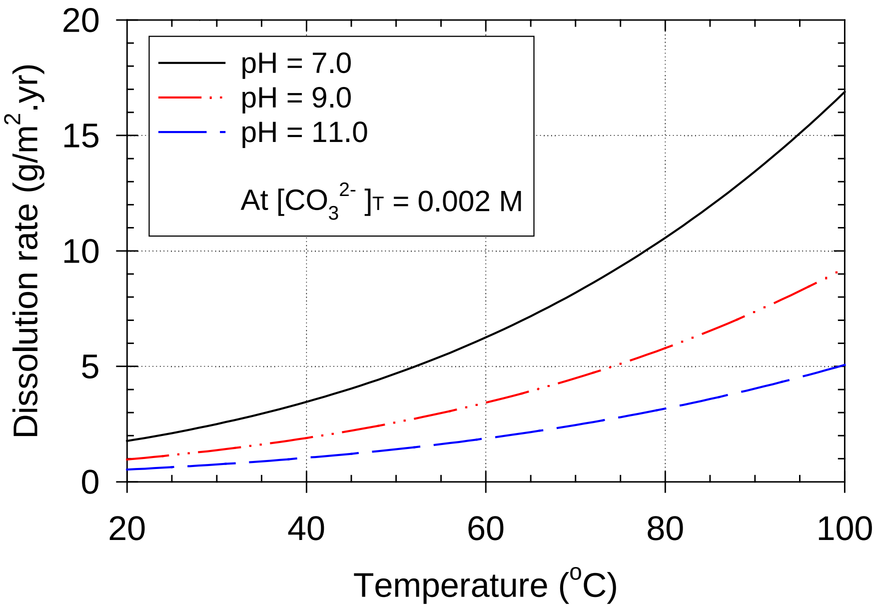
TSPA-VA Base Case Cladding Degradation

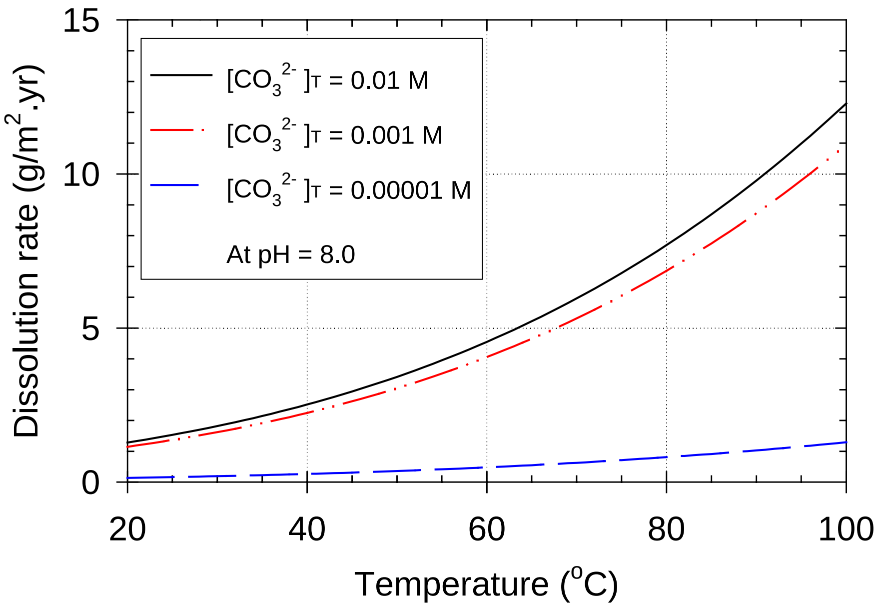
- **Cladding degradation defines fraction of fuel exposed which could potentially be contacted by water**
- **Early degradation defined by seep, premature failures and stainless steel fraction (<2%)**
- **Late degradation defined by corrosion and mechanical failure (mean ~10% @ 1,000,000 years)**
- **Corrosion determined by scaling Zircaloy corrosion to C-22 corrosion under similar conditions (~100 x more corrosion resistant)**
- **As cladding degrades with time, increased fuel surface area is potentially exposed to water**



TSPA-VA Base Case Waste Form Degradation

- **Each waste type (CSNF, HLW, DOE, SNF, Navy, Pu) has a different degradation rate**
- **Degradation rates based on laboratory observations**
- **For CSNF specific surface area of ~10^{-4} m^2/g, degradation is ~1,000 years**
- **Assume that 100% of exposed surface is contacted by water**





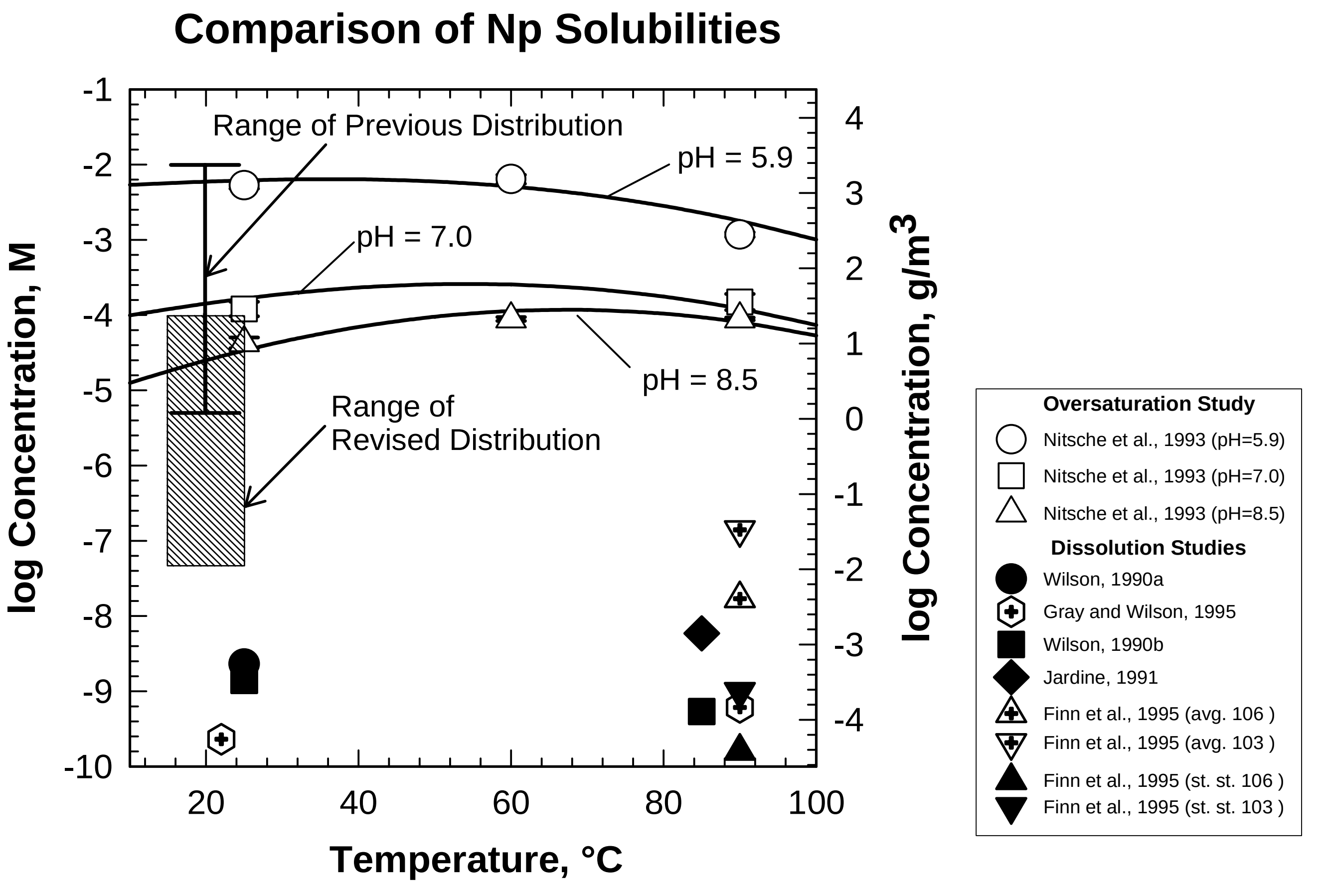
TSPA-VA Base Case Radionuclide Mobilization: Colloids

- Consider natural (clay, iron oxide) and waste form (glass, spent fuel) colloids
- Colloid stability is a function of ionic strength
- Consider Pu Colloids
- Reversible colloids consider sorption / desorption of Pu onto / off of colloids
- Irreversible colloid fraction derived from comparison with observations near Benham shot

TSPA-VA Base Case Radionuclide Mobilization: Solubility

- **Tc, I, C have very high solubilities - their release is limited by the rate of release from the waste form**
- **Np solubility examined in far from equilibrium conditions (either oversaturation in J-13) or in presence of spent fuel**
- **Np solubility range is 100 x lower than used in TSPA-95; consistent with equilibrium geochemistry model**
- **U, Pa and Pu are also solubility limited**

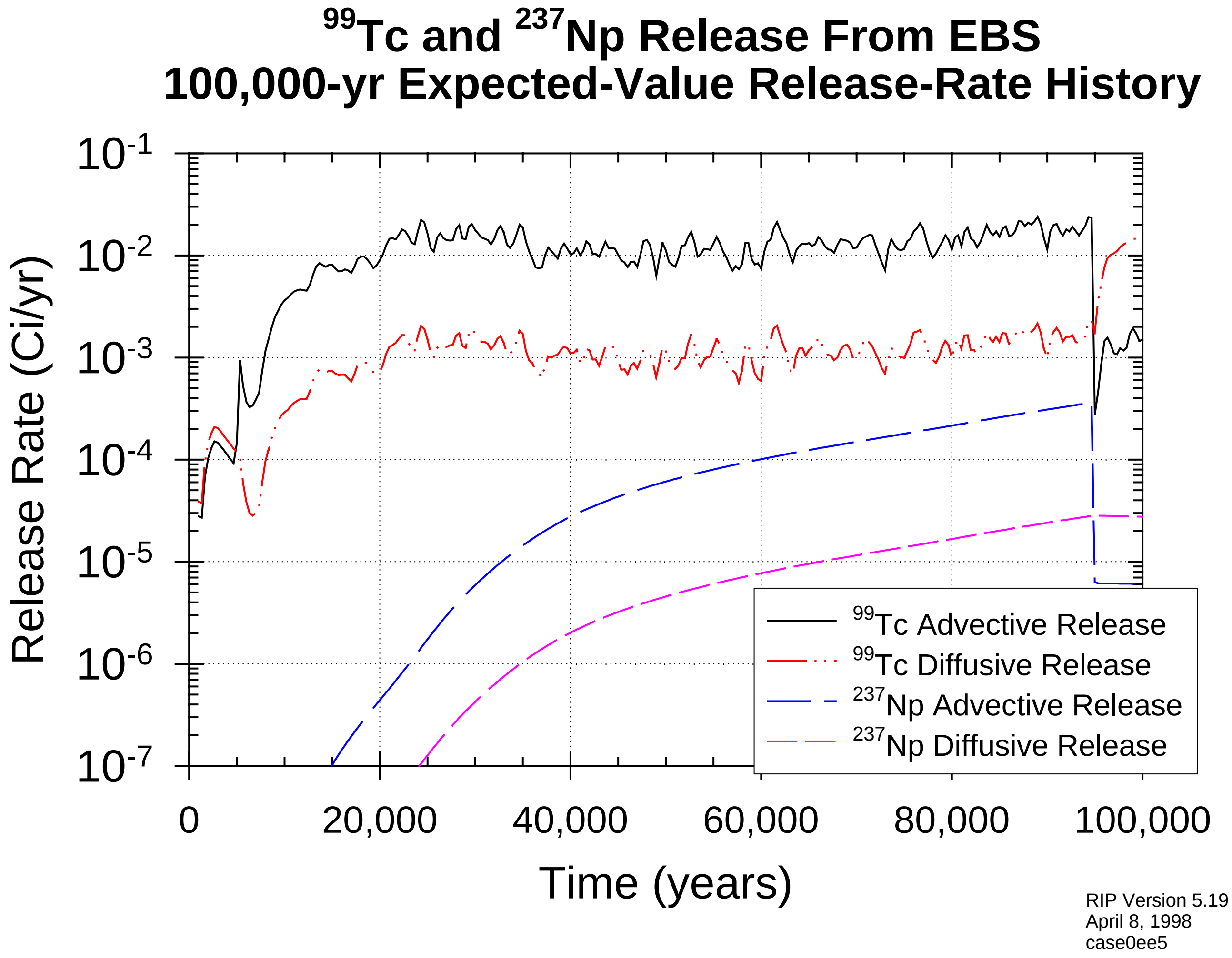
TSPA-VA Base Case Radionuclide Mobilization: Solubility



TSPA-VA Base Case Engineered Barrier System Transport

- Advection out of waste package controlled by the seepage flux which enters the waste package
- Seepage flux into waste package is a function of seepage into drifts and percent of waste package surface exposed and a scaling factor (1-10) to account for uncertainty
- Diffusion through waste package is a function of percent of waste package surface exposed
- Diffusion through invert is a function of liquid saturation in invert which is high for assumed properties of degraded invert
- No retardation considered in degraded waste package or invert materials

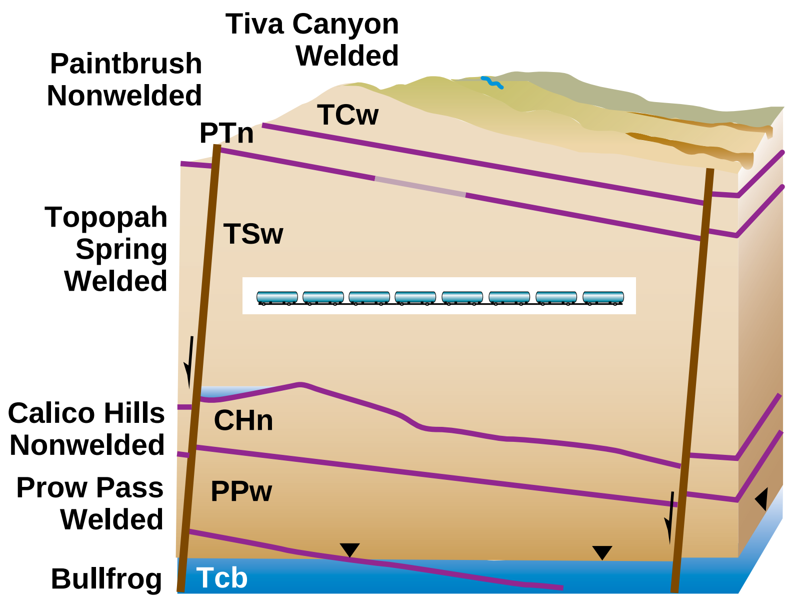
TSPA-VA Base Case Engineered Barrier System Transport: EBS Release Rates

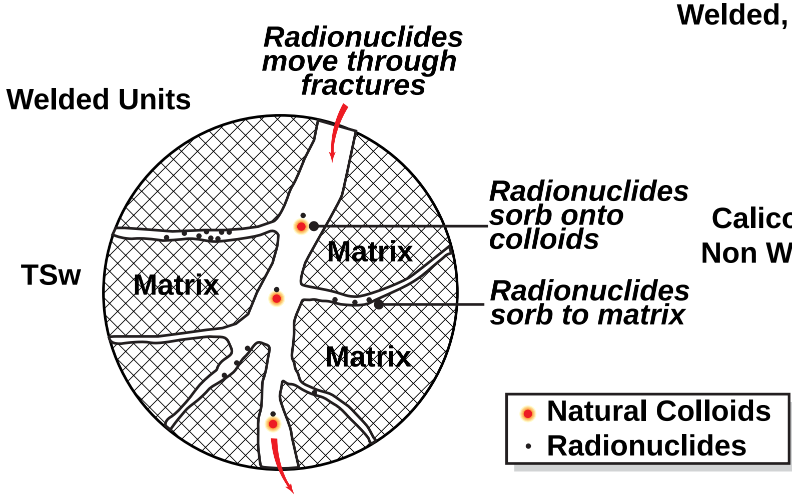


TSPA-VA Base Case Engineered Barrier System Transport: EBS Release Rates

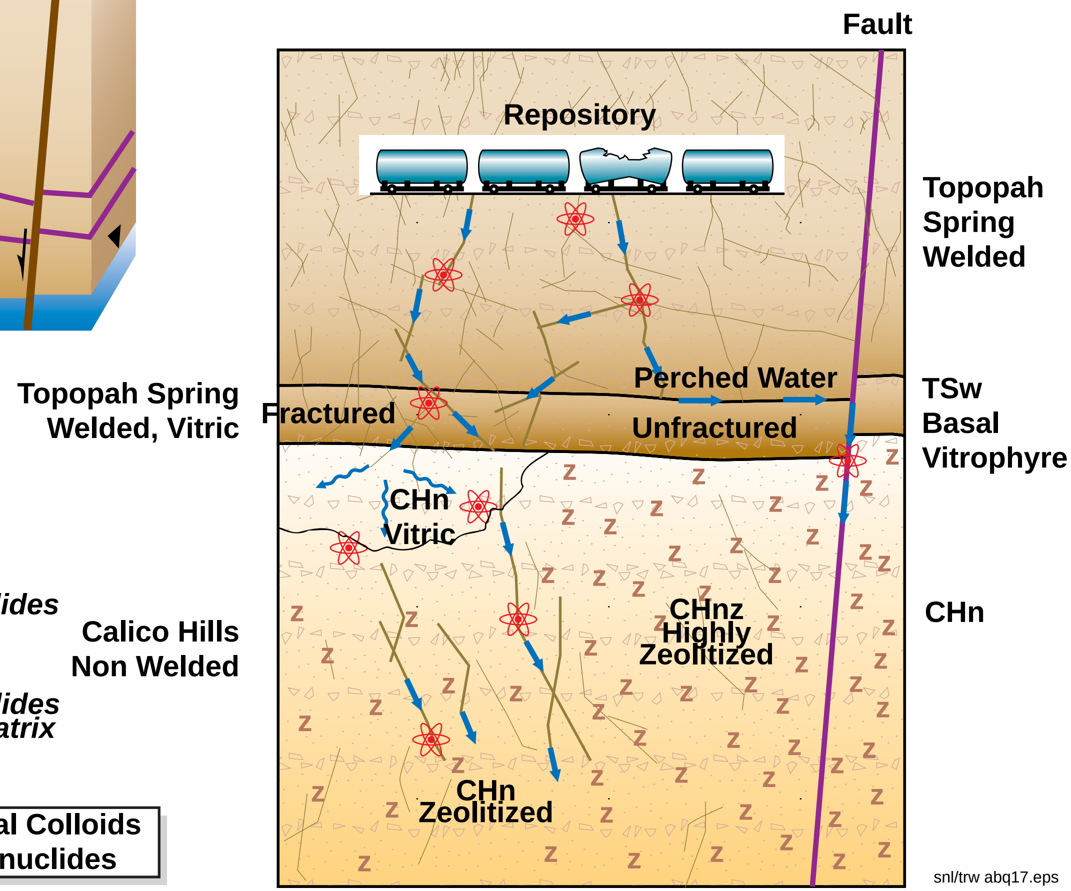
- **Initial release of Tc caused by early waste package failure @ 1,000 years**
- **Tc release reaches a plateau as the rate of waste packages “failing” is ~ linear and the degradation, mobilization and transport are relatively rapid**
- **Tc release is variable reflecting waste package failure distribution**
- **Np release continually increases (until the changes back to a dry climate at ~95,000 years) due to adding the releases from additional waste packages as they “fail”**

Unsaturated Zone Radionuclide Transport

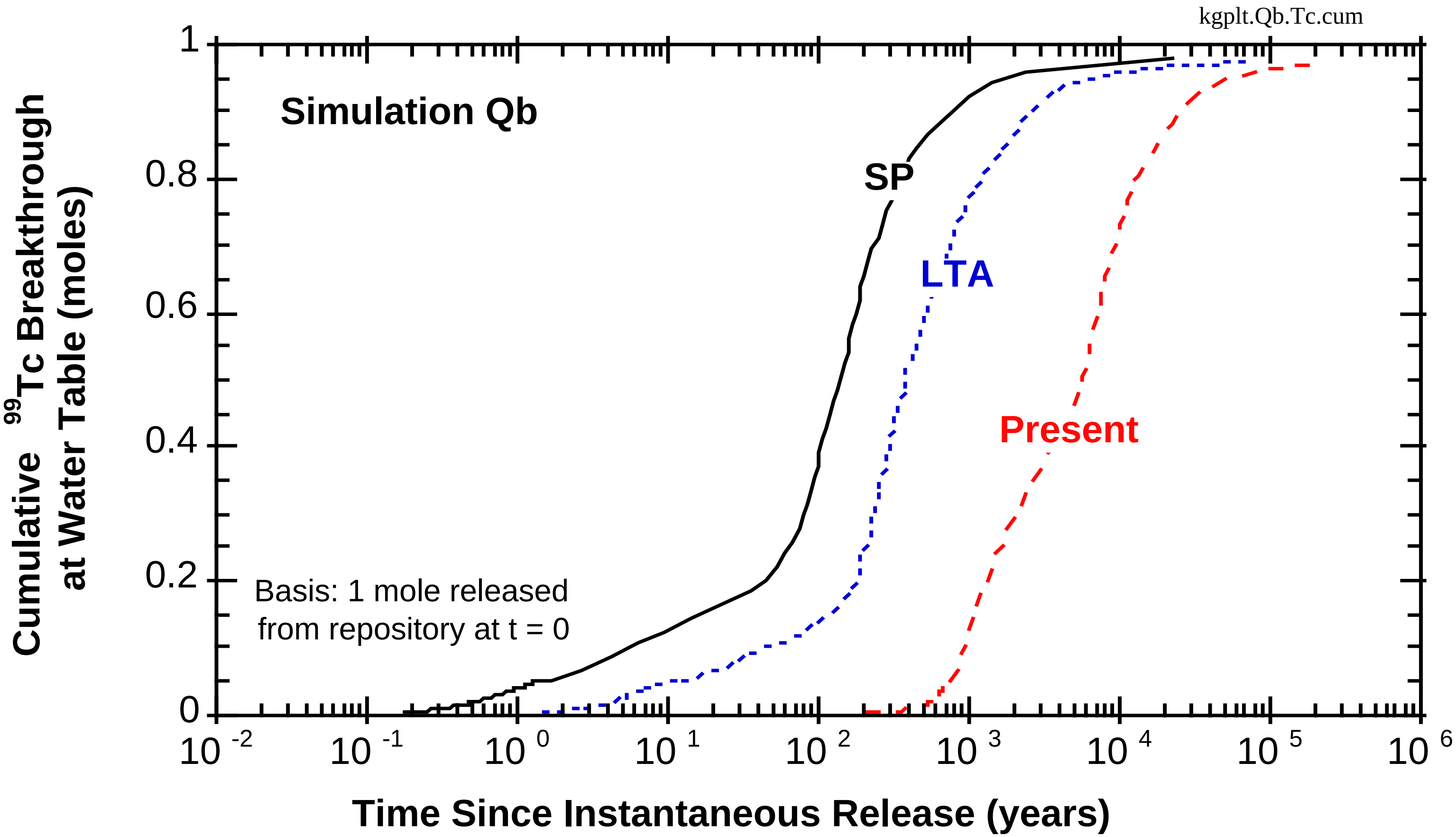




Unsaturated Zone
Radionuclide Transport Mechanisms



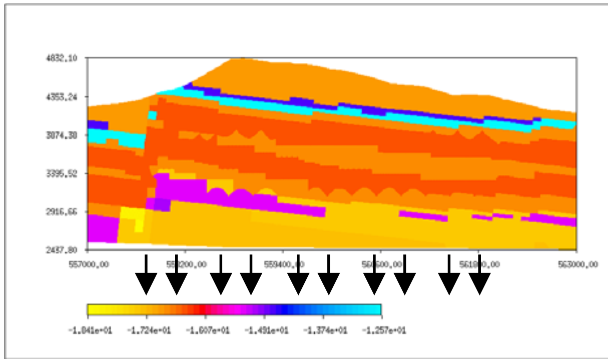
TSPA-VA Base Case
Unsaturated Zone Transport

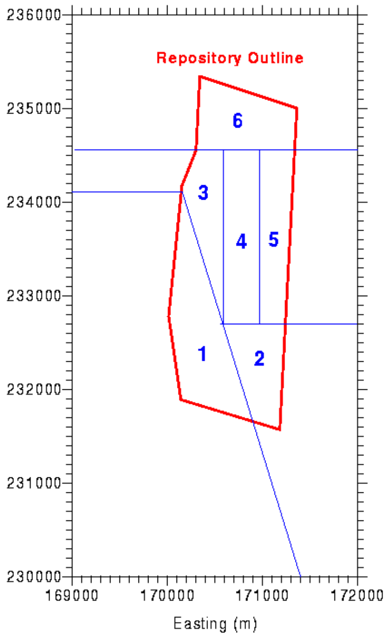


TSPA-VA Base Case
Unsaturated Zone Transport

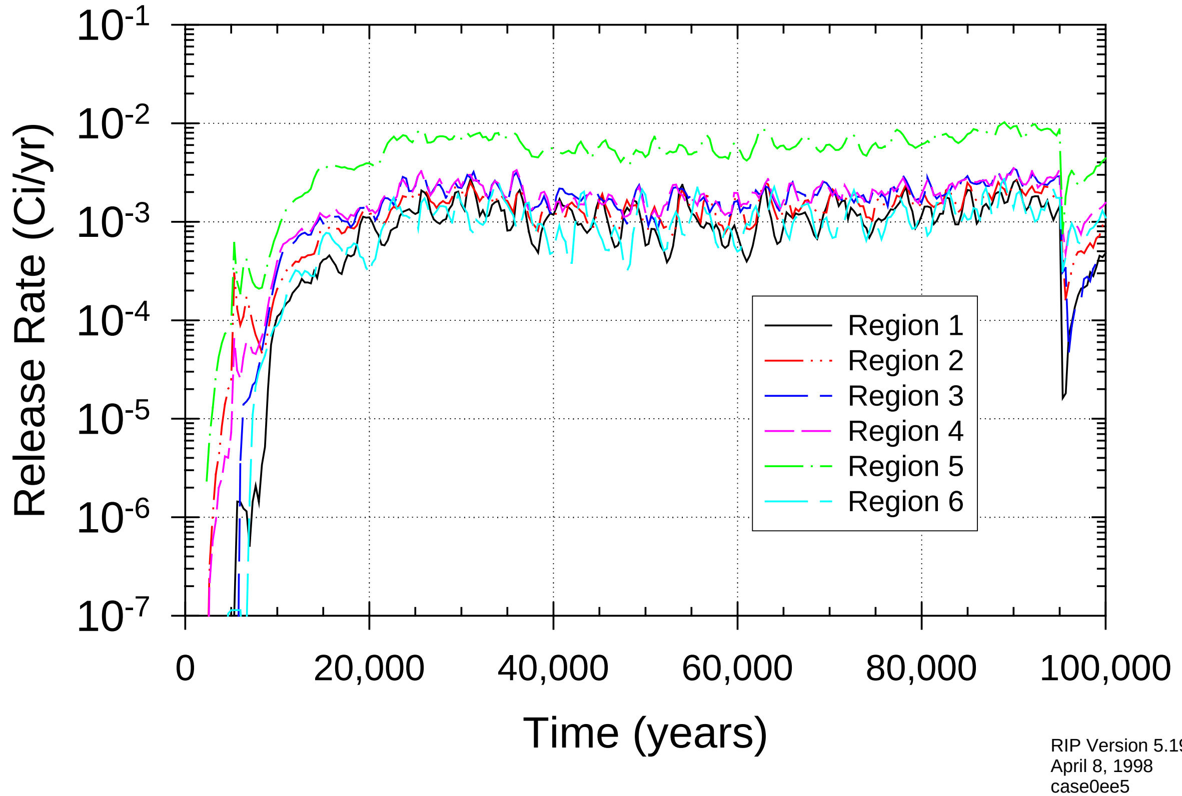
- Present-day travel time of 50% arrival is ~ 10,000 years for unretarded species (Tc)
- Present-day early arrival a result of small fraction of fracture flow in non-welded Calico Hills (or bypassing)
- Long-term average climate travel times are <1,000 years to the water table for unretarded species
- Sorption coefficients derived from laboratory data

100,000-yr ^{99}Tc Release Rate from UZ to SZ by Region





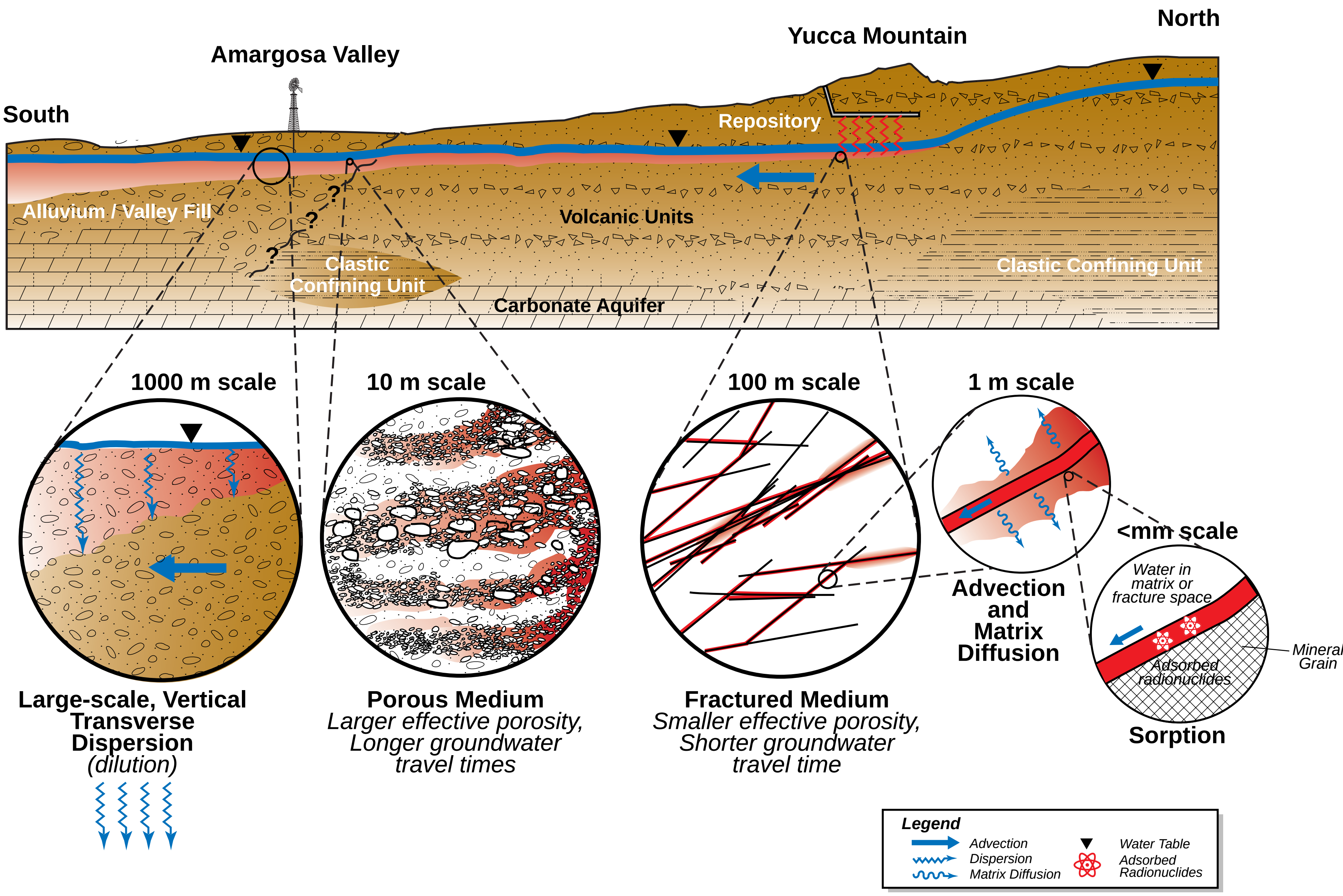
^{99}Tc Release From UZ
100,000-yr Expected-Value Release-Rate History



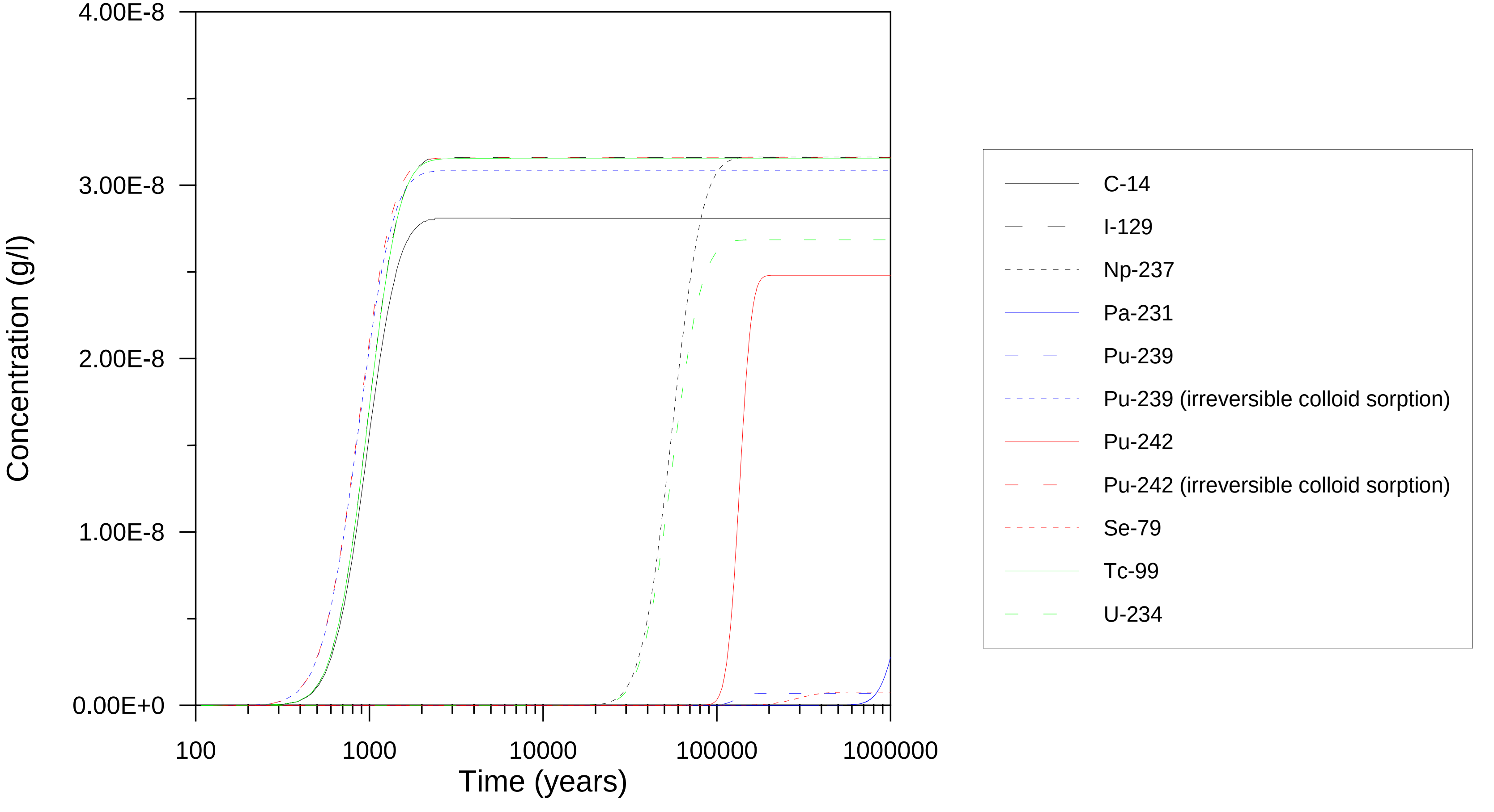
TSPA-VA Base Case Unsaturated Zone Transport: Release Rates from the UZ to the SZ

- Release rates into six regions of the SZ
- Similarity with EBS release rates indicates minimal travel time through UZ for unretarded species
- Irregularities in Tc release rates correlate with discrete waste package “failures”
- Reduction in release rates at 95,000 years caused by change back to dry climate and corresponding water table lowering

Saturated Zone Radionuclide Transport



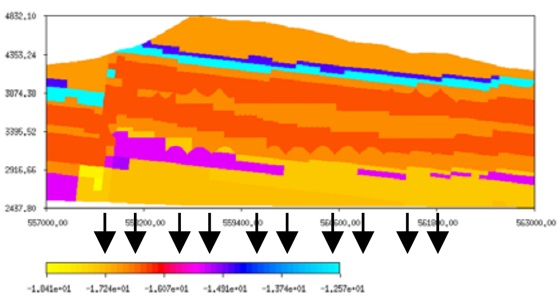
Example TSPA-VA Base Case Saturated Zone Transport

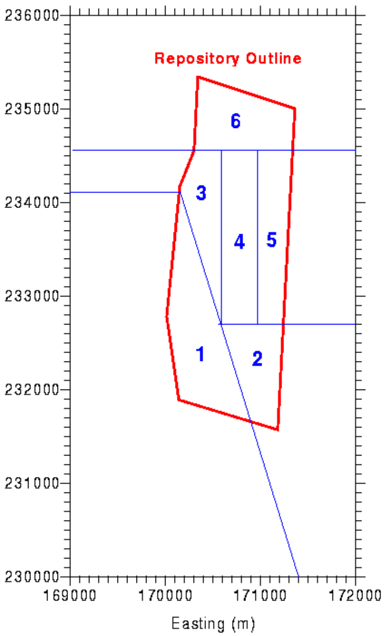


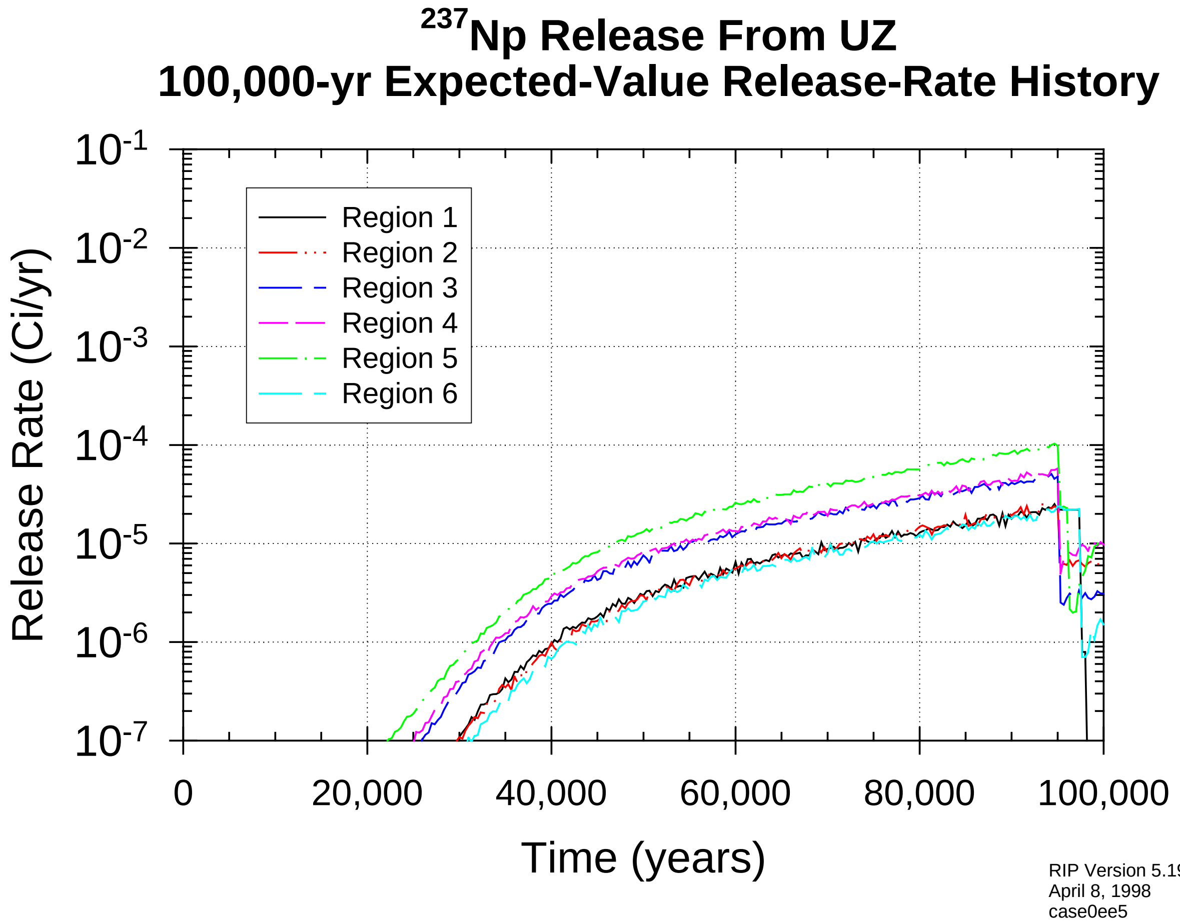
TSPA-VA Base Case
Saturated Zone Transport

- **Use 3-D flow and transport model to define general flow paths and rates and fraction of path in alluvium to 20km**
- **Use six 1-D (stream tubes) model with no transverse dispersivities**
- **Use an effective dilution factor (ranging from 1-100)**
- **Compare results of single stream tubes without dilution to multiple stream tubes with dilution**
- **Travel times in saturated zone range from a few 1,000 years for unretarded species (~Tc) to > 10,000 years for slightly retarded species (~Np)**

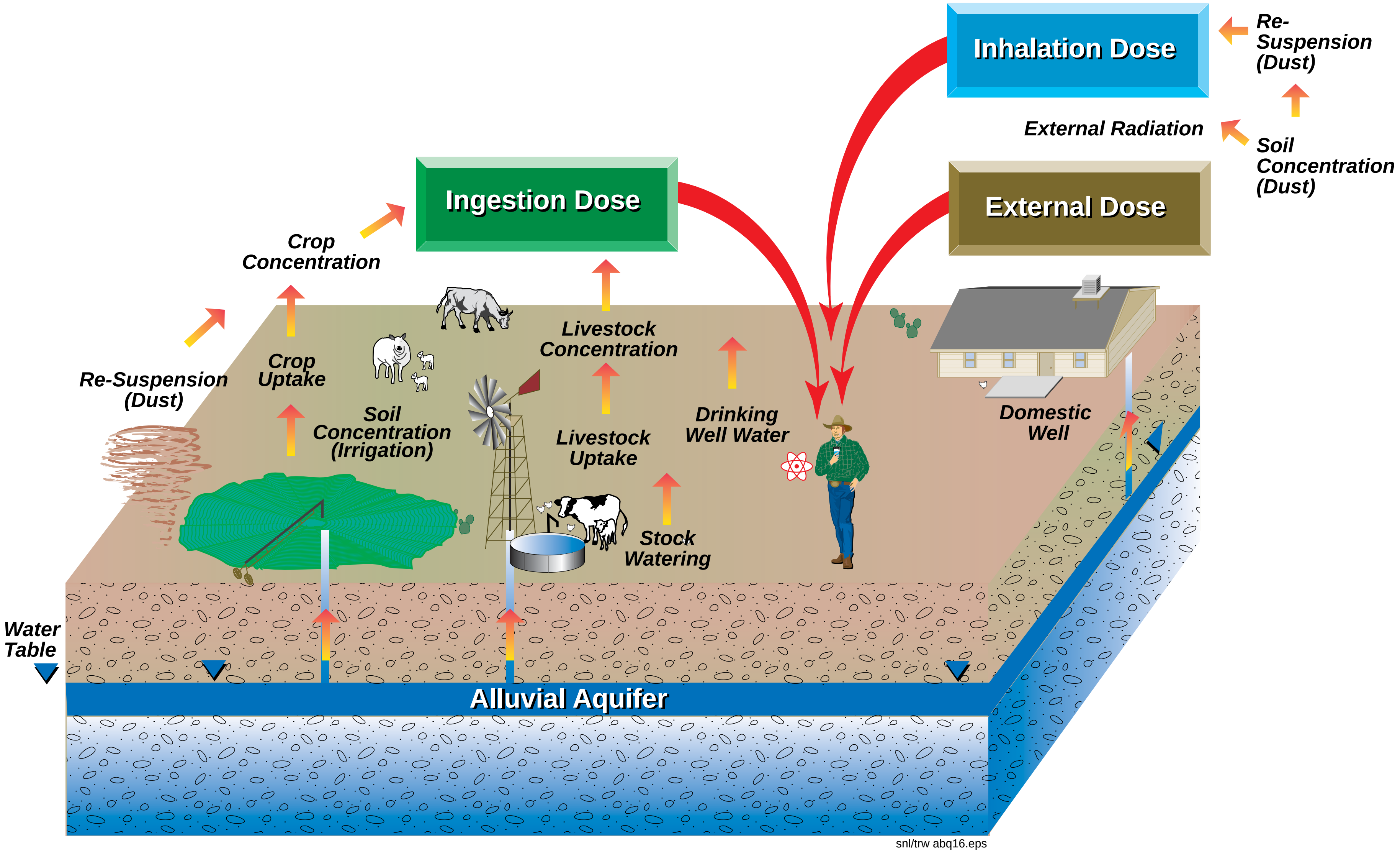
100,000-yr ^{237}Np Release Rate from UZ to SZ by Region



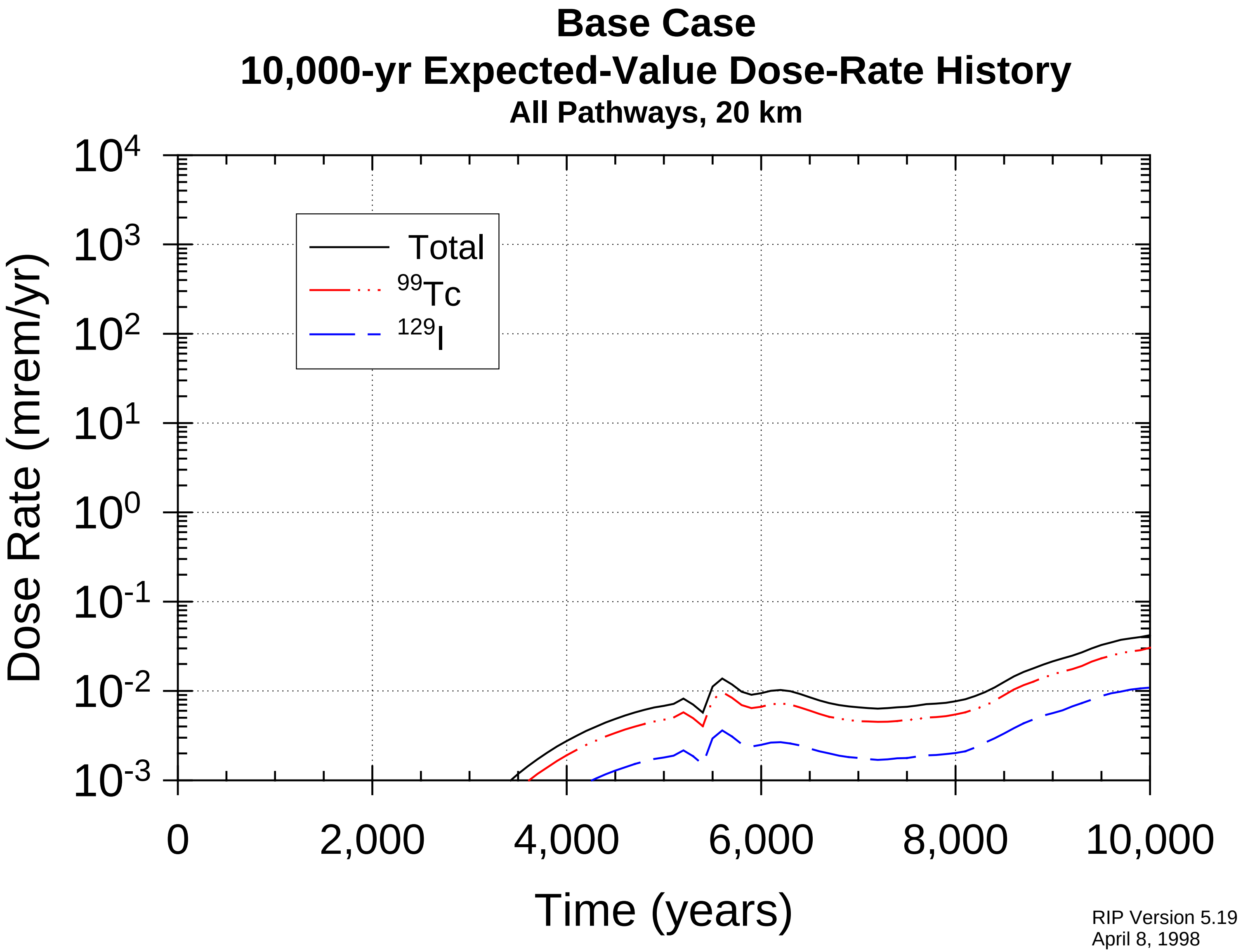




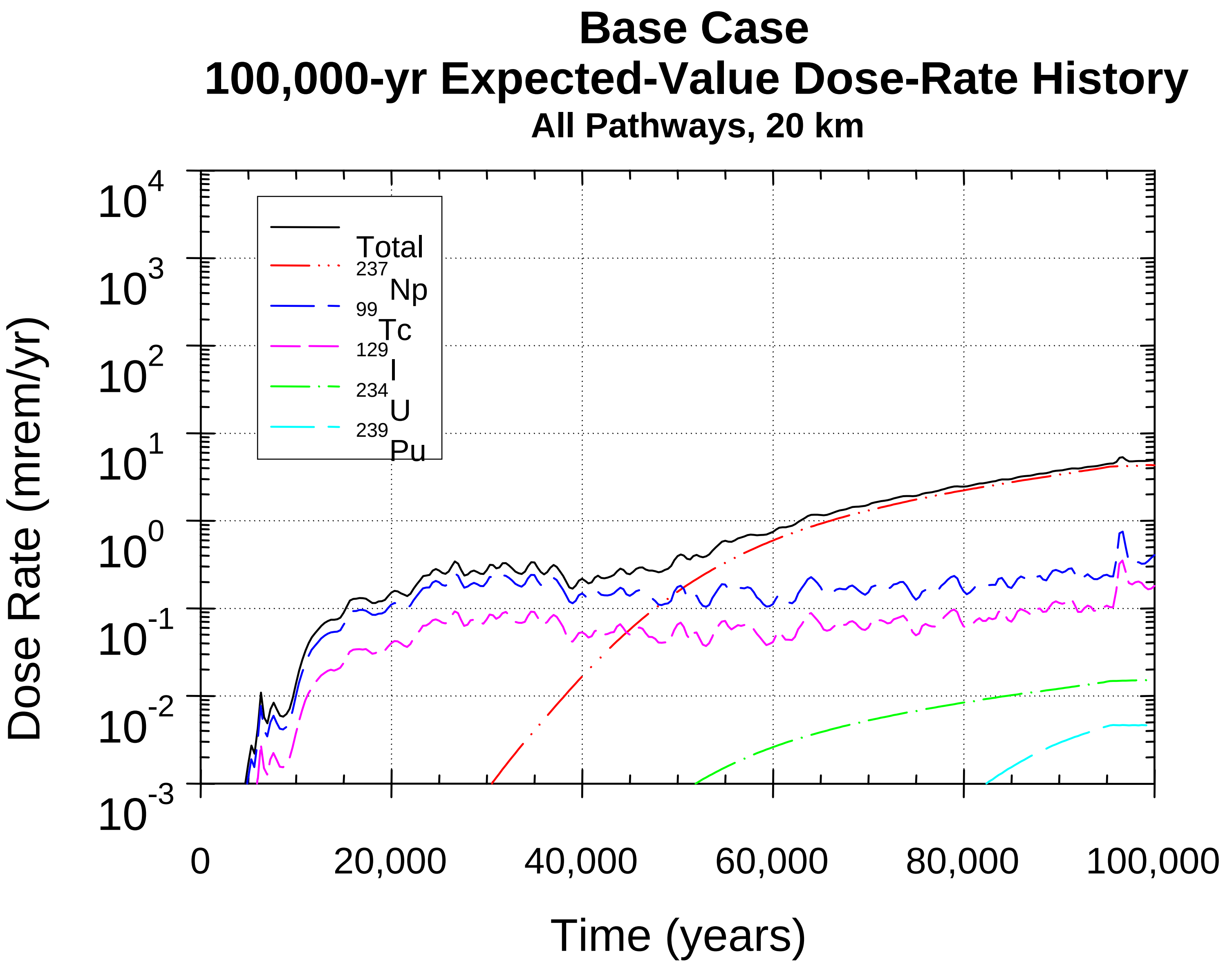
Biosphere Processes in TSPA-VA



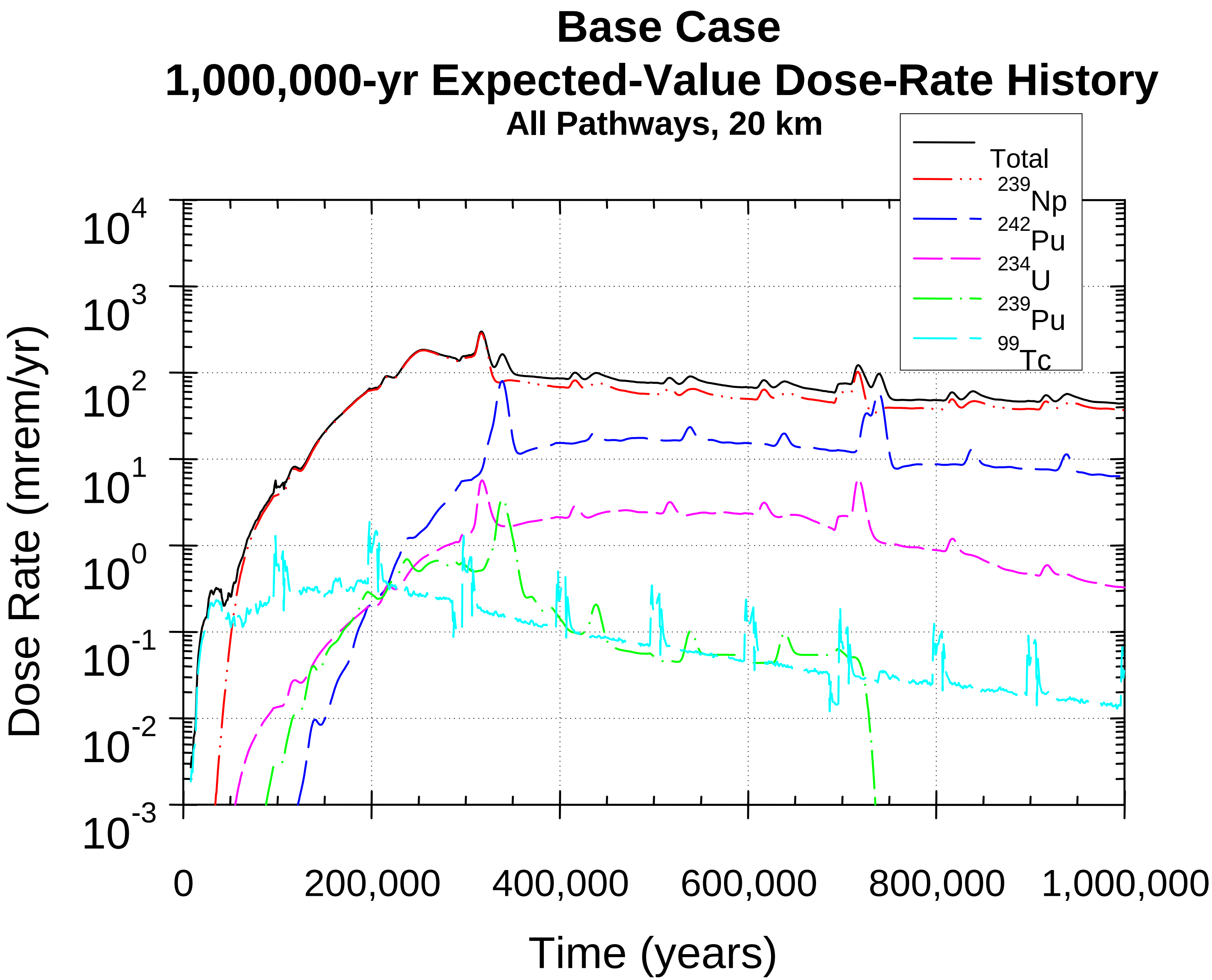
10,000-yr Dose to "Average" Individual at 20 km



100,000-yr Dose to "Average" Individual at 20 km



1,000,000-yr Dose to "Average" Individual at 20 km



TSPA-VA Base Case Results

- Earliest doses (<10,000 years) are controlled by early waste package "failure" (~ 1,000 years)
- From 10,000 to ~50,000 years the doses are controlled by Tc and I and mimic the shape of the EBS release curves
- For times >50,000 years Np controls the doses and they continue to increase as (a) more waste packages "fail" and (b) an increased % of the cladding "fails"
- "Maximum" dose at 10,000 years ~10^{-2} mrem/yr
- "Maximum" dose and 100,000 years ~5 mrem/yr
- Rate down @ ~300,000 years ~300 mrem/yr

Example Hand Calculation of Dose Rate at 100,000 Years: Representative Values

Percolation Flux:	**~ 0.04 m^3/m^2 yr (=40mm/yr)**
	~ $2x10^5$ m^3/yr/repository
Seepage Flux:	**~ 0.2 m^3/yr/WP**
WP "Failures":	**~ 20/1,000 years (dripping)**
	~ 1,000/50,000 years (dripping)
Np Solubility:	**~ 0.3 g/m^3**
WF Surface Exposed:	**~ 2%**
WF Dissolution Rate:	**~ 10^{-3}/yr**
EBS Seepage Flux:	**~ 0.006 m^3/yr/WP (~ 3% of seepage flux)**
SZ "Dilution" Factor:	**~ 10**
Biosphere Dose Conversion Factor:	**~ $5x10^6$ $\frac{\text{mrem/yr}}{\text{g (Np)} /m^3}$**
	~ $5X10^4$ $\frac{\text{mrem/yr}}{\text{g (Tc)}/m^3}$

Example Hand Calculation of Dose Rates at 100,000 Years for a Solubility-Limited Radionuclide -Np

Np Half Life: 2,000,000 yrs

Np Inventory: 10 Ci/WP (~1.5×10^{4} g/WP)

EBS Release Rate: ~ 2×10^{-3} g/yr/WP (0.3 g/m^3 x 0.006 m^3/yr/WP)
~ 2 g/yr/repository (2×10^{-3}g/yr/WP x 1,000 WP)

UZ Concentration: ~ 10^{-5} g/m^3 (2 g/yr/repository ÷ 2×10^{5} m^3/yr/repository)
SZ Concentration: ~ 10^{-6} g/m^3 (10^{-5} g/m^3 ÷10)

Dose Rate: ~ 5 mrem/yr (10^{-6} g/m^3 x 5×10^{6} $\frac{\text{mrem/yr}}{\text{g/m}^3}$)

Postclosure Safety Strategy Attributes	TSPA Model Components	Sensitivity Analyses
Water Contacting Waste Package	Climate	✓
	Infiltration	✓
	Unsaturated Zone Flow-Percolation	✓
	Seepage	✓
	Drips onto Waste Package	
	Thermal Hydrology	
Waste Package Lifetime	Near-Field Geochemical Environment	✓
	Waste Package Degradation	✓
Mobilization Rate of Radionuclides	Cladding Degradation	✓
	Waste Form Degradation	✓
	Seepage into Waste Package	✓
	Colloid Formation and Stability	✓
	Radionuclide Solubility	✓
	Transport within Waste Package	
Concentration of Radionuclides in ground water	EBS Transport	
	Unsaturated Zone Transport	✓
	Saturated Zone Transport	✓
	Dilution from Pumping	
	Biosphere	✓

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Summary

- Presented conceptual models of processes describing the behavior of the Yucca Mountain repository system
- Described the process model abstractions leading to the base case results of TSPA-VA, illustrating the significant components driving the TSPA-VA results
- Conducted a simple back-of-the-envelope analysis that supports the identification of the key components
- Introduced future talks that will address uncertainty analysis of the TSPA-VA and specific sensitivity analyses of individual components

Backup Slides

Description of Significant Processes

Description of Significant Processes: Climate

Amount of precipitation is a function of:

- **Timing and duration of climate change**
- **Global warming**
- **Modifications in global temperature and polar ice caps**
- **Changes in regional and local temperatures and weather patterns**

Description of Significant Processes: Infiltration

Rate of water which infiltrates is a function of:

- **Duration, frequency, timing and magnitude of precipitation events**
- **Soil thickness and properties**
- **Slope angle, roughness and orientation**
- **Vegetation type and amount**
- **Bedrock permeability**

Description of Significant Processes: Unsaturated Zone Hydrology

Rate which water percolates at repository horizon is a function of:

- **Net infiltration**
- **Lithologic heterogeneity of hydrostratigraphic units**
- **Permeability of fractures and matrix**
- **Capillarity of fractures and matrix**
- **Imbibition of matrix**

Description of Significant Processes: Seepage into Drifts

Amount of water which seeps is a function of:

- **Percolation flux in fractures intersecting drifts and permeability**
- **Capillarity and permeability of fractures around drifts**
- **Changes in percolation flux caused by thermal and climate effects**
- **Heterogeneity and continuity of fractures around drifts**
- **Changes in fracture capillarity and permeability caused by thermal mechanical and chemical effects**

Description of Significant Processes: Thermal Hydrology in TSPA-VA

Amount of water in contact with waste packages is a function of:

- **Thermal design of repository and waste packages**
- **Percolation flux in rock**
- **Thermal characteristics of rock**
- **Fracture characteristics of rock**
- **Matrix imbibition of rock mass**
- **Hydrologic characteristics of invert materials**

Description of Significant Processes: Near Field Geochemical Environment

Chemical characteristics of water in contact with waste packages and waste form is a function of:

- **Initial water composition**
- **Gas phase evolution**
- **Water/rock interactions**
- **Water/waste package materials interactions**
- **Water/waste form materials interactions**
- **Water/invert/concrete interactions**

Description of Significant Processes: Waste Package Degradation

Timing and extent of openings through waste package are a function of:

- **Thermal, hydrologic (esp. seeps) and chemical environment on outer surface**
- **Corrosion rates of mild steel**
- **Thermal, hydrologic (esp. seeps) and chemical environment of C-22 surface**
- **Variability in corrosion rates from location to location on waste package**
- **Corrosion rates of C-22**

Description of Significant Processes: Cladding Degradation

Timing and extent of openings through cladding are a function of:

- **Type of cladding (Stainless steel vs Zircaloy)**
- **Thermal environment in waste package**
- **Condition of Zircaloy during handling, transportation, storage**
- **Creep characteristics of Zircaloy**
- **Corrosion of Zircaloy**
- **Mechanical degradation of Zircaloy**

Description of Significant Processes: Waste Form Degradation

Rate of radionuclide release from waste form to water is a function of:

- **Characteristics of waste form**
- **Percent of waste form surface exposed and in contact with water**
- **Chemistry of water in contact with waste form**
- **Presence of secondary phases that form during dissolution**

Description of Significant Processes: Radionuclide Mobilization

Concentration of radionuclides available for release from waste form is a function of:

- **Chemistry and amount of water in contact with waste form**
- **Presence of secondary phases that form during dissolution**
- **Concentration of colloidal particles**
- **Radionuclide solubilities**

Description of Significant Processes: Engineered Barrier System Transport

Concentration of radionuclides released from EBS is a function of:

- **Seepage into drifts, seepage into degraded waste packages and seepage contacting exposed waste form surfaces**
- **Diffusion through waste package openings and partially saturated invert materials**
- **Adsorption onto degraded waste package and invert materials**

Description of Significant Processes: Unsaturated Zone Transport

Concentration of radionuclides released from UZ is a function of:

- **Concentration of radionuclides released from EBS**
- **Percolation flux distribution in fractures and matrix**
- **Adsorption onto fracture surfaces or in matrix**
- **Diffusion between fractures and matrix**
- **Radioactive decay**

Description of Significant Processes: Saturated Zone Transport

Concentration of radionuclides released from SZ is a function of:

- **Concentration of radionuclides released from UZ**
- **Advective velocity of ground water in tuff and alluvial aquifers**
- **Adsorption in tuff matrix and on alluvial sediments**
- **Length of travel path in tuff and alluvial aquifers**
- **Transverse dispersivity in tuff and alluvial aquifers (≈ dilution)**
- **Water extraction scenarios**

Description of Significant Processes: Biosphere

Dose rate for potential receptors is a function of:

- **Concentration of radionuclides released from SZ**
- **Water use and consumption habits of receptors**
- **Principal pathway of radionuclides from water use to receptors**
- **Dose conversion factors**