Viability Assessment Total System Performance Assessment - Summary of Results and Sensitivity Analyses

Presented to:
Nuclear Waste Technical Review Board

Presented by:
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Outline

- TSPA-VA Model Components
- TSPA-VA Elements of Reference Design
- TSPA-VA Base Case
  - Conceptual Models
  - Model Component Results
- TSPA-VA Base Case Results
- TSPA-VA Comparative Sensitivity Analyses
- TSPA-VA Uncertainty Analyses
- Significance of Principal Factors for VA Reference Design
- Design Option Sensitivity Analyses
- Summary and Conclusions

Acknowledgments

- **TSPA-VA Core Team:**
  - Holly Dockery, Jack Gauthier, Jerry McNeish, Dave Sevougian, Mike Wilson
- **TSPA-VA Abstraction Team:**
  - Bill Arnold, Rally Barnard, Nick Francis, Bill Halsey, Cliff Ho, Jim Houseworth, Joon Lee, Dave Sassani, Tony Smith, Christine Stockman
- **TSPA-VA Analysts:**
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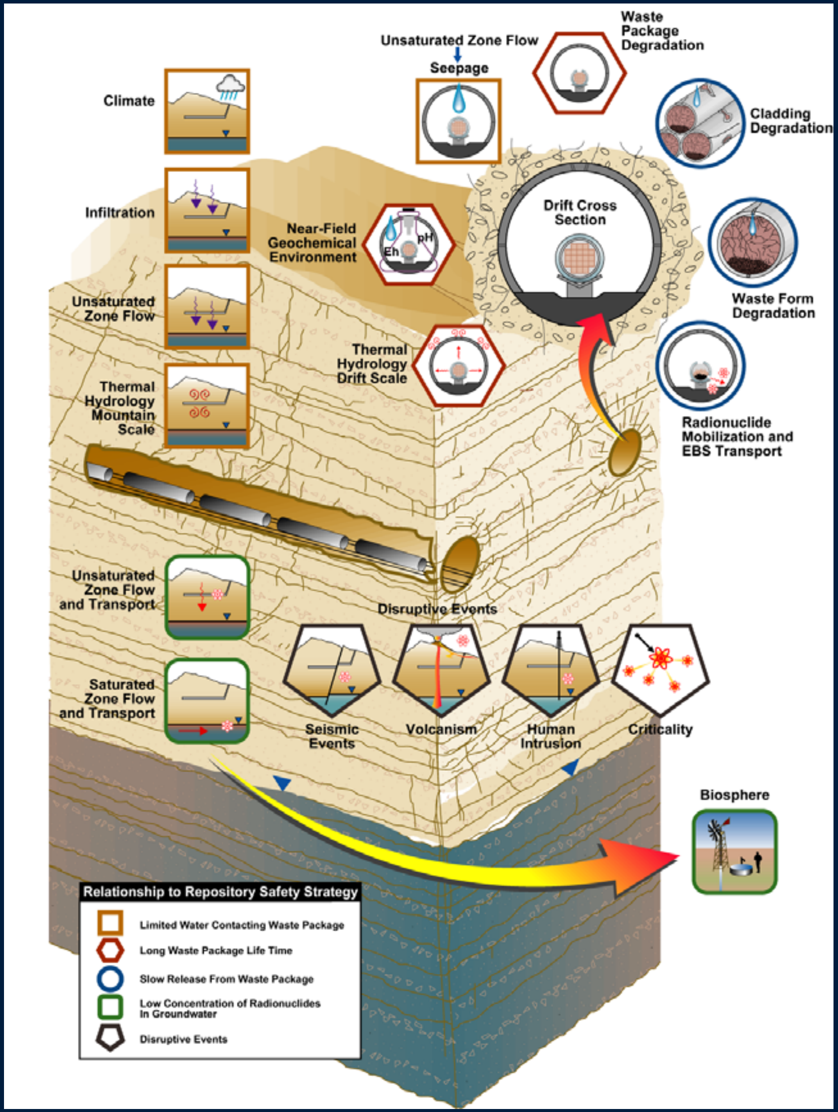
- **TSPA-VA Graphics:**
  - Kathy Gaither, Lori Long, Ivana Stepkovic

TSPA-VA Model Components

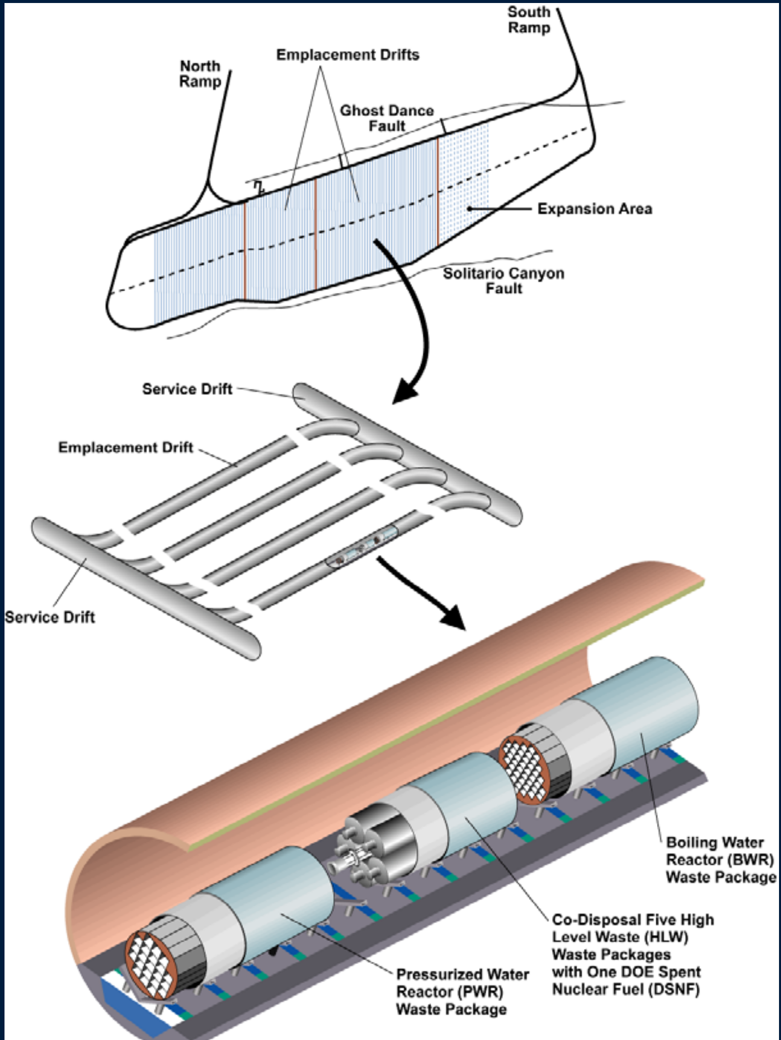


- Major model components are related to the attributes of the repository safety strategy and NRC's key technical issues
- Natural and engineered barriers comprise the total system
- Each major component requires an explicit model to represent the relevant processes

TSPA-VA Model Components

Attributes of the Repository Safety Strategy	Principal Factors	TSPA Model Components	NRC Key Technical Issue
Limited water contacting waste packages	Precipitation and infiltration of water into the mountain	Climate	Unsaturated and saturated flow under isothermal conditions
		Infiltration	
	Percolation to depth	Unsaturated Zone Flow	
	Seepage into drifts	Seepage	
	Effects of heat and excavation on flow	Thermal Hydrology	Repository design and thermal-mechanical effects
	Dripping onto waste package		Thermal effects on flow
	Humidity and temperature at waste package		
Long waste package lifetime	Chemistry on waste package barrier	Near Field Geochemical Environment	Evolution of Near Field Environment
	Integrity of outer waste package barrier	Waste Package Degradation	Container life and source term
	Integrity of inner waste package barrier		
Slow release from waste packages	Seepage into water package		
	Integrity of spent fuel cladding	Cladding Degradation	
	Dissolution of UO_2 and glass waste-form	Waste Form Degradation	
	Solubility of Np-237	Radionuclide Mobilization and EBS Transport	
	Formation of radionuclide-bearing colloids		
	Transport within and out of waste package		
Radionuclide concentration reduction during transport	Transport through unsaturated zone	Unsaturated Zone Transport	Unsaturated and saturated flow under isothermal conditions and Radionuclide transport
	Transport in saturated zone	Saturated Zone Transport	
	Dilution from pumping		
	Biosphere dilution	Biosphere Transport	

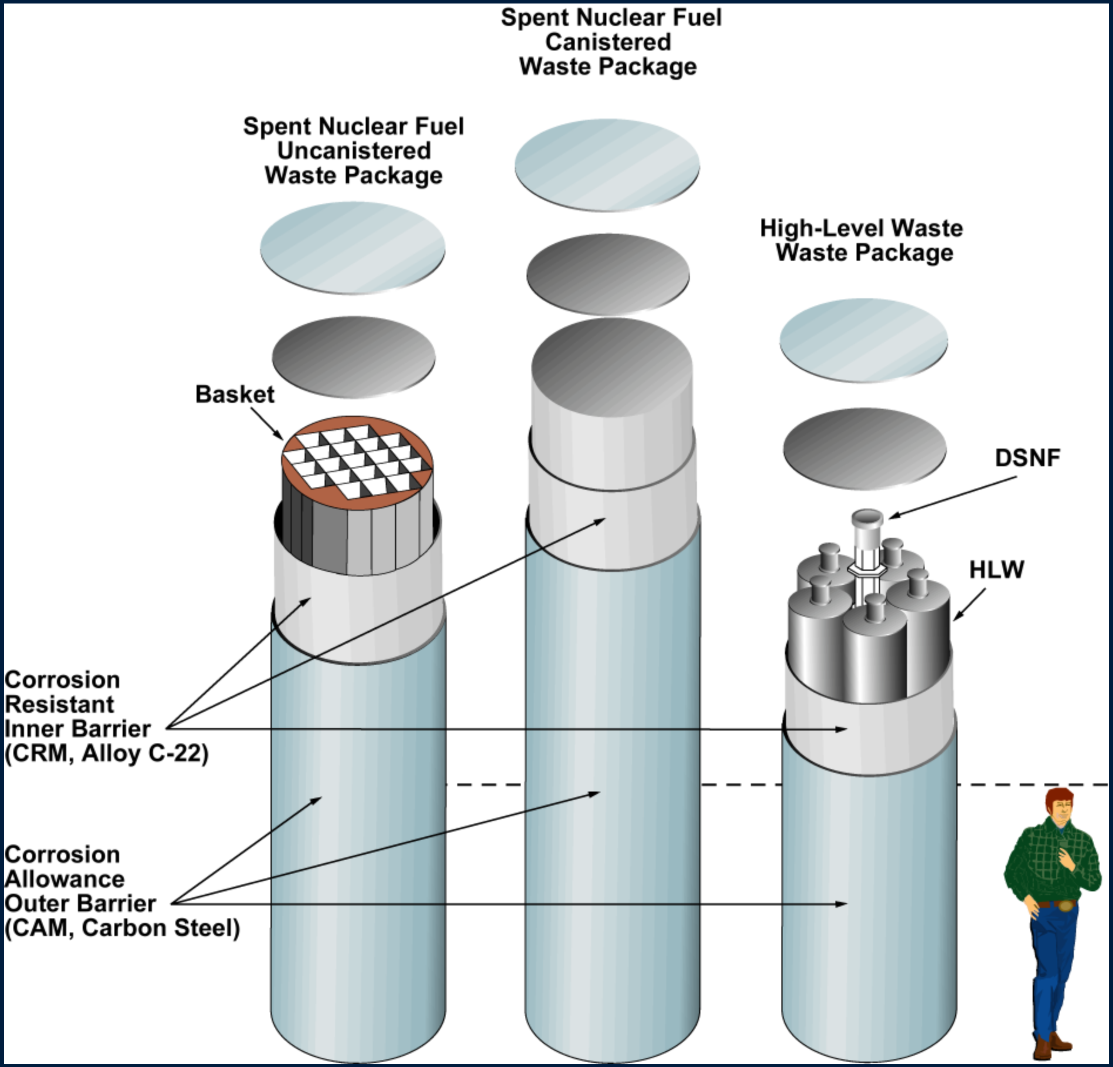
TSPA-VA - Basic Elements of the Reference Repository Design



Cutaway of a Drift with Three Representative Waste Package Types

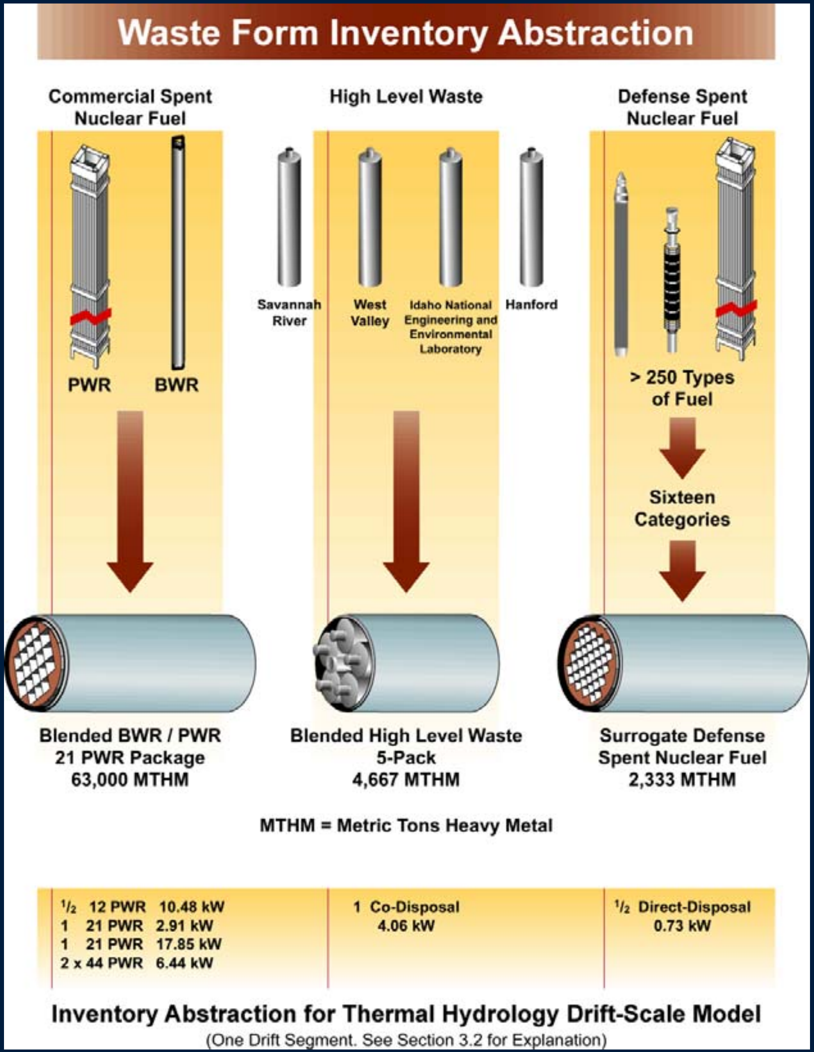
- 70,000 MTHM
- 85 MTHM/acre
- 5.5-m drifts with 0.2-m concrete liner
- No backfill or drip shields

TSPA-VA - Basic Elements of the Reference Waste Package Design



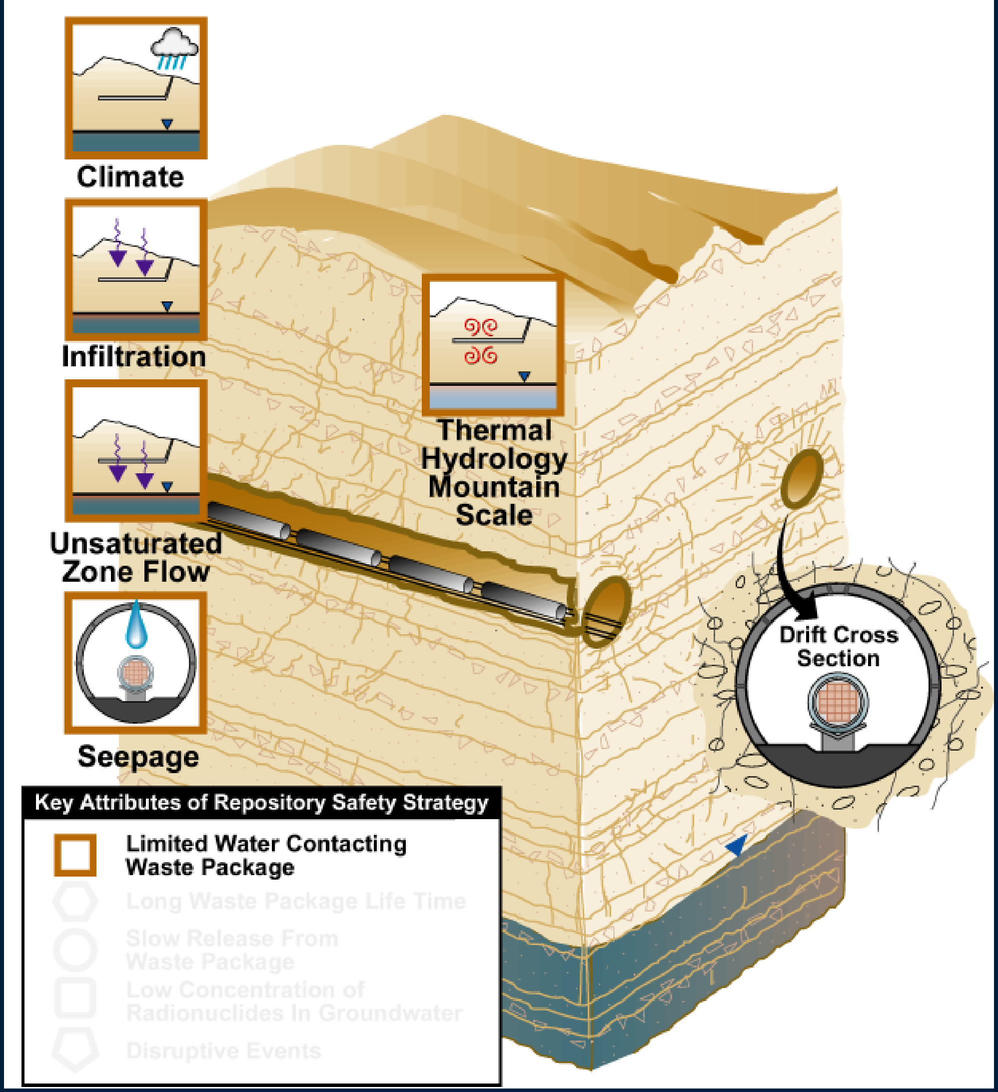
- 21-PWR, 44-BWR, 5 HLW canisters with DOE SNF
- 10-cm carbon steel
- 2-cm C-22 inner barrier (corrosion resistant material)

TSPA-VA - Basic Elements of the Reference Waste Form Designs



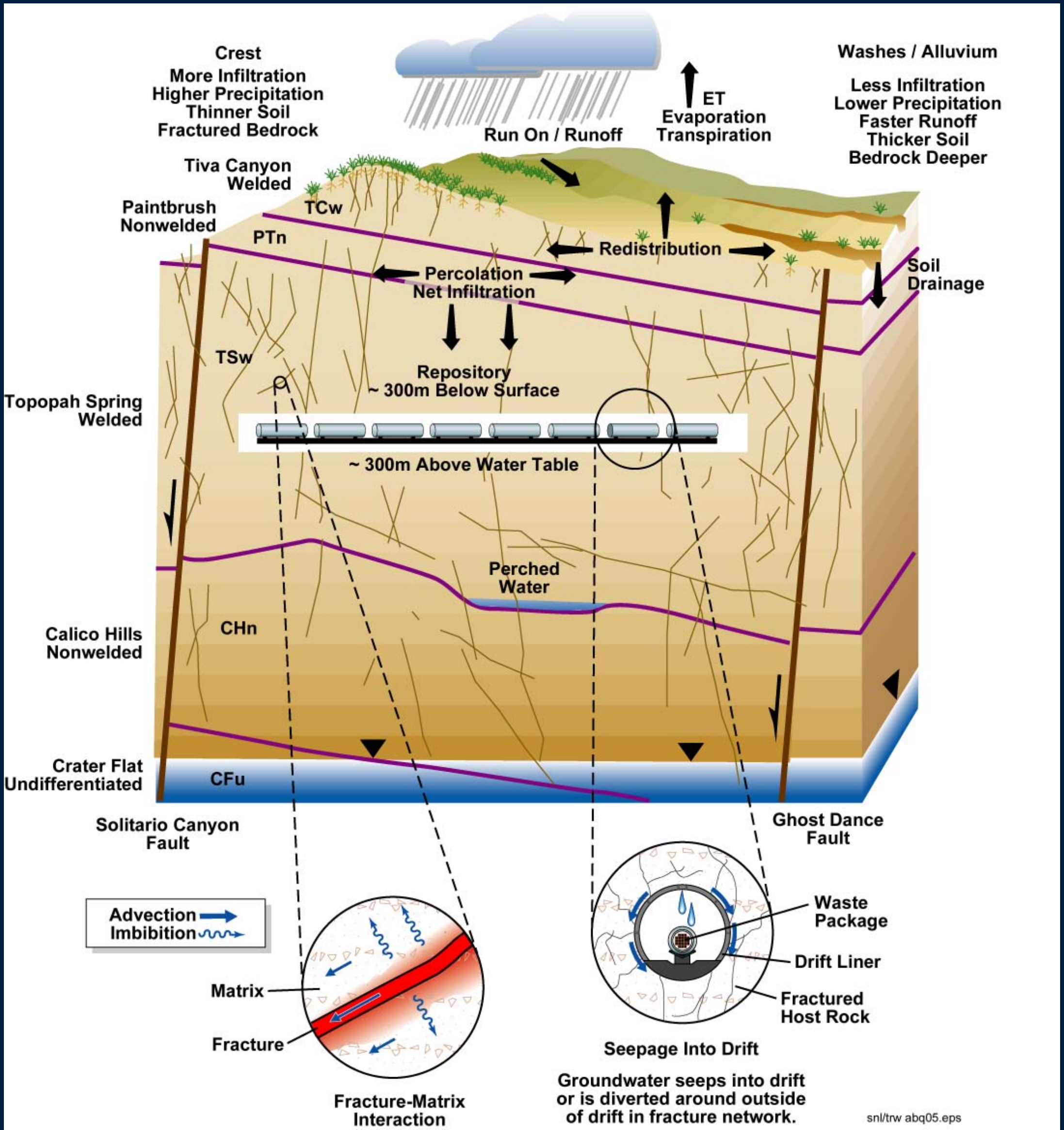
- 63,000 MTHM CSNF
  - 99% with Zircaloy Clad
- 4,667 MTHM HLW
- 2,333 MTHM DOE SNF
  - 2,100 MTHM N-reactor
  - 65 MTHM Navy fuel
- 50 MTHM Pu - MOX and/or ceramic

TSPA-VA Model Components - Limited Water Contacting Waste Package



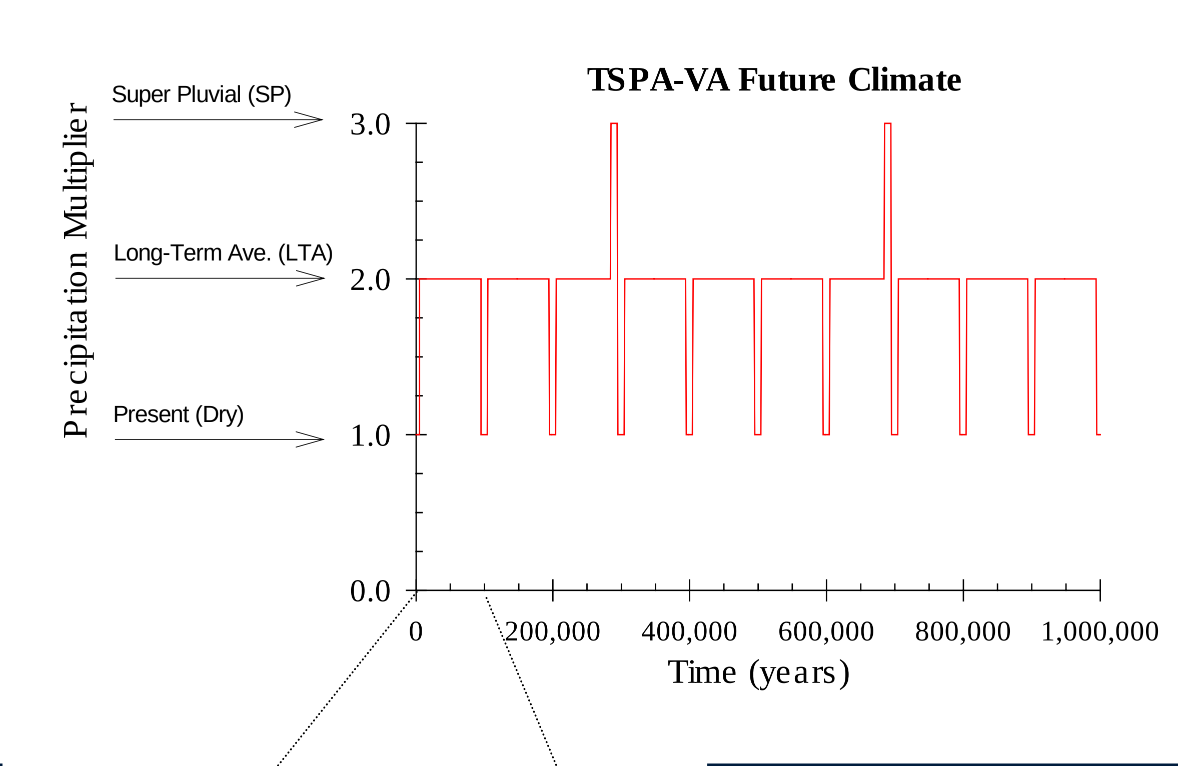
- Components that affect the availability and timing of water flow into drifts
- All natural hydrologic processes are spatially and temporally variable

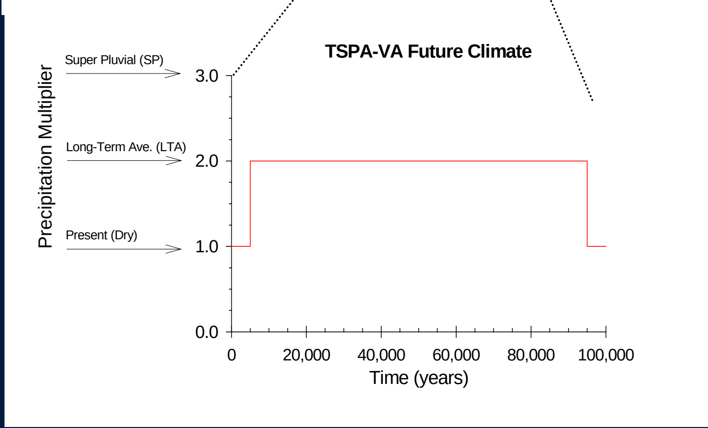
Conceptual Model of Unsaturated Zone Flow



- Precipitation at surface has short (annual) and long (geologic) transients
- Precipitation and infiltration are greater at higher elevations
- Infiltration is greatest with thin soil cover
- Percolation is predominantly gravity driven and in fractures
- Seepage is a function of percolation and fracture permeability and capillarity

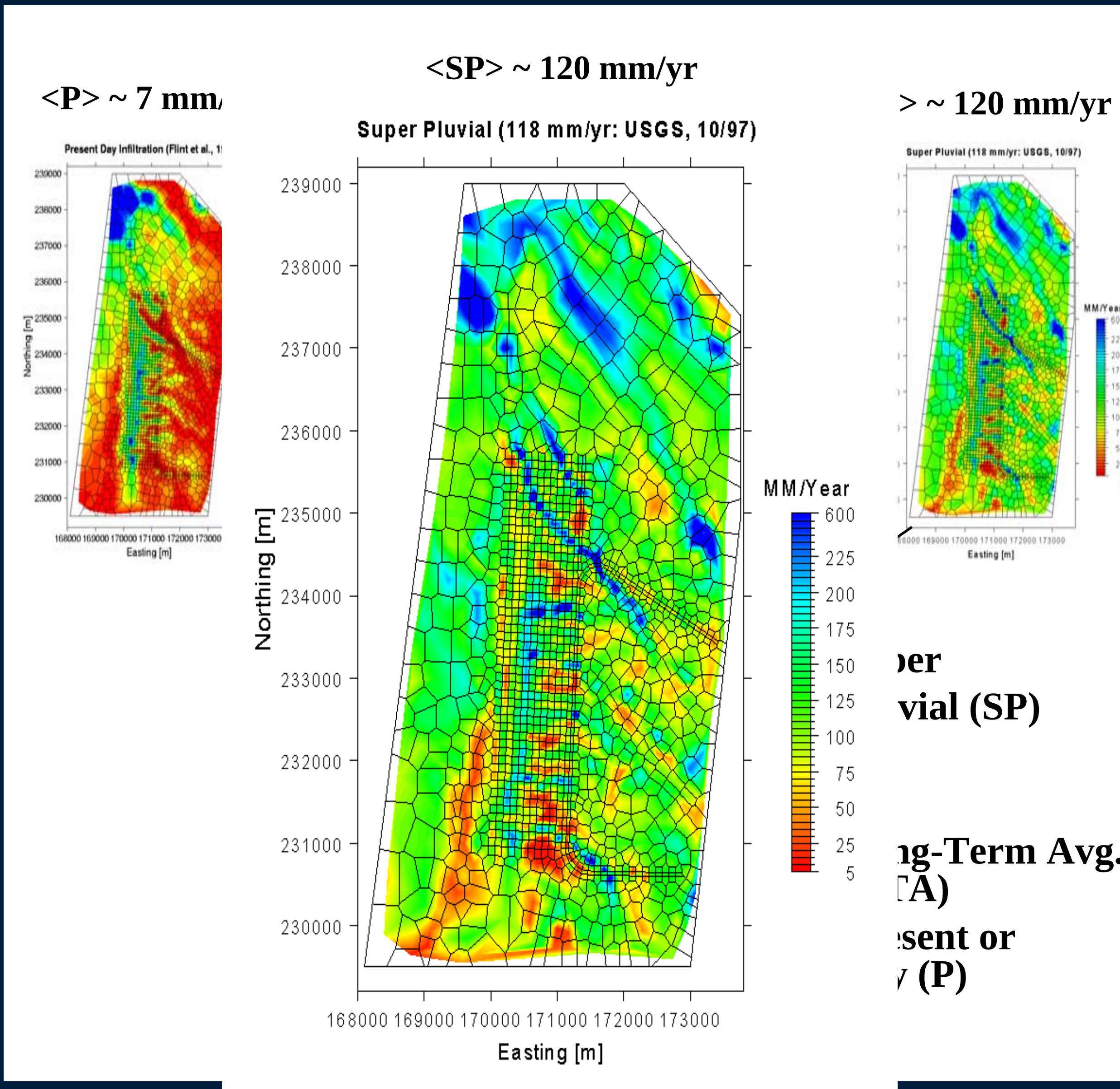
TSPA-VA Base Case Climate History





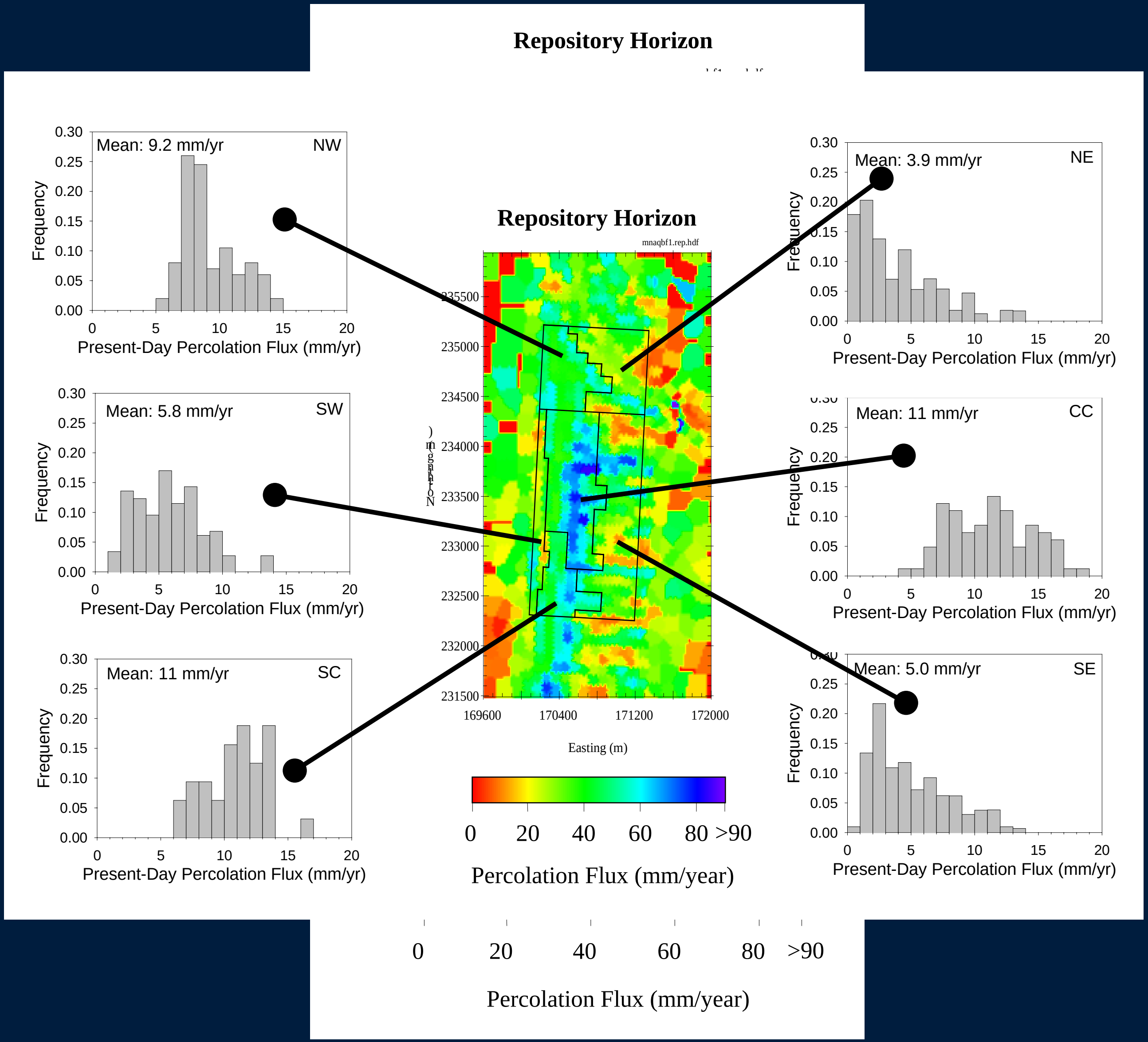
- Present-day climate is dry compared to the long-term average climate at Yucca Mountain
- Long-term average climate about a factor of 2 times wetter and Super-pluvial climate about a factor of 3 times more precipitation
- Timing of change to long-term average climate is very uncertain - assumed to be random in next 10,000 years

TSPA-VA Base Case Infiltration History



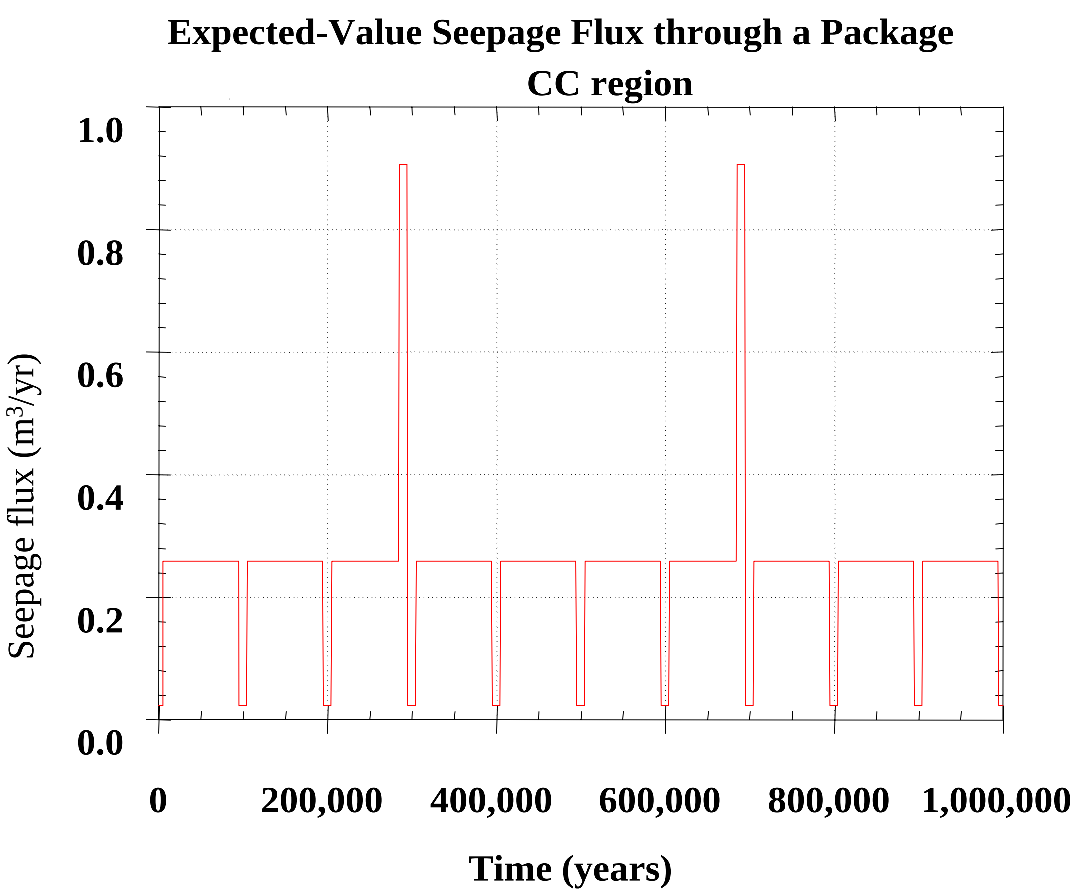
- Present-day infiltration derived from observations at neutron holes and extrapolated using correlations with soil thickness (Flint et al.)
- Infiltration higher at ridge crests (more precipitation and less soil cover)
- Long-term average and super pluvial infiltrations derived from same extrapolation as used for present-day infiltration map
- Infiltration is a non-linear function of precipitation

TSPA-VA Base Case Percolation Flux



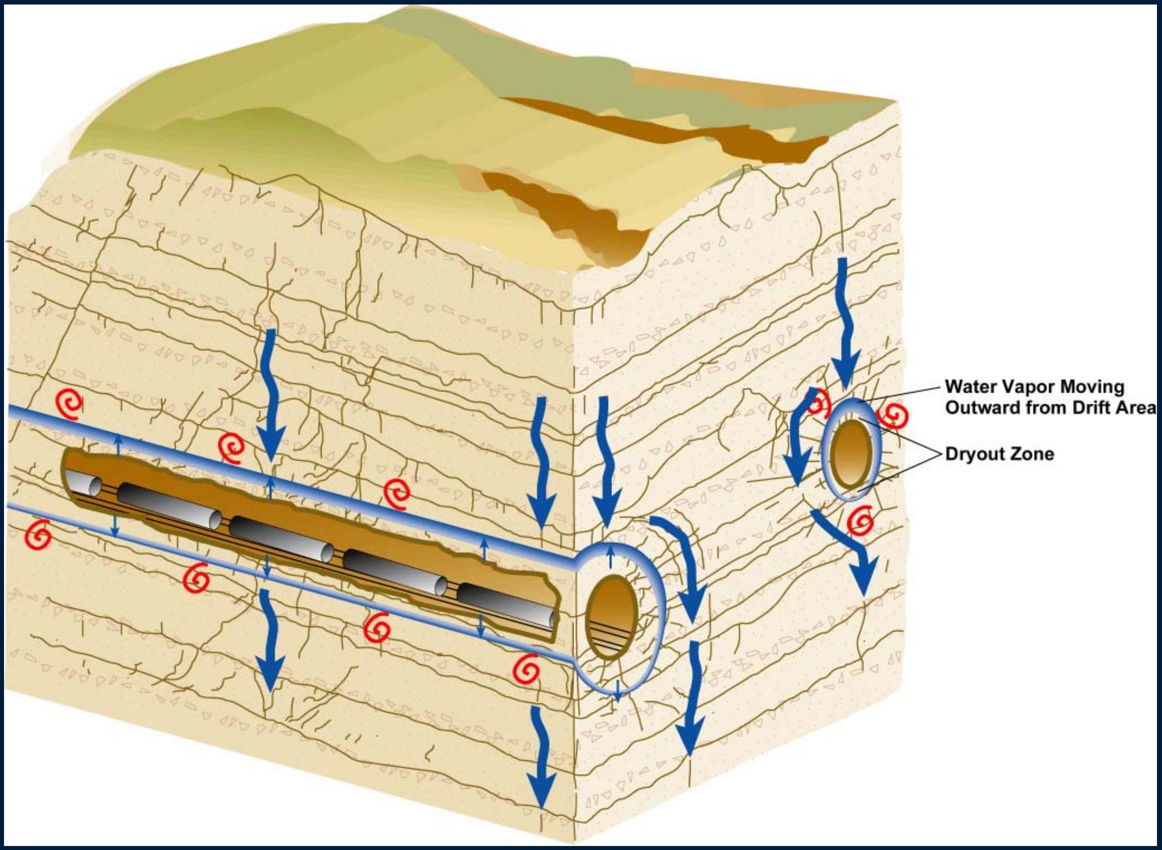
- Present-day percolation flux is illustrated
- Repository block has been discretized into 6 regions to capture thermal-hydrologic variability
- Percolation is dominantly vertical above repository (minimal lateral diversion)
- Percolation has been bounded with a number of independent observations

TSPA-VA Base Case Seepage



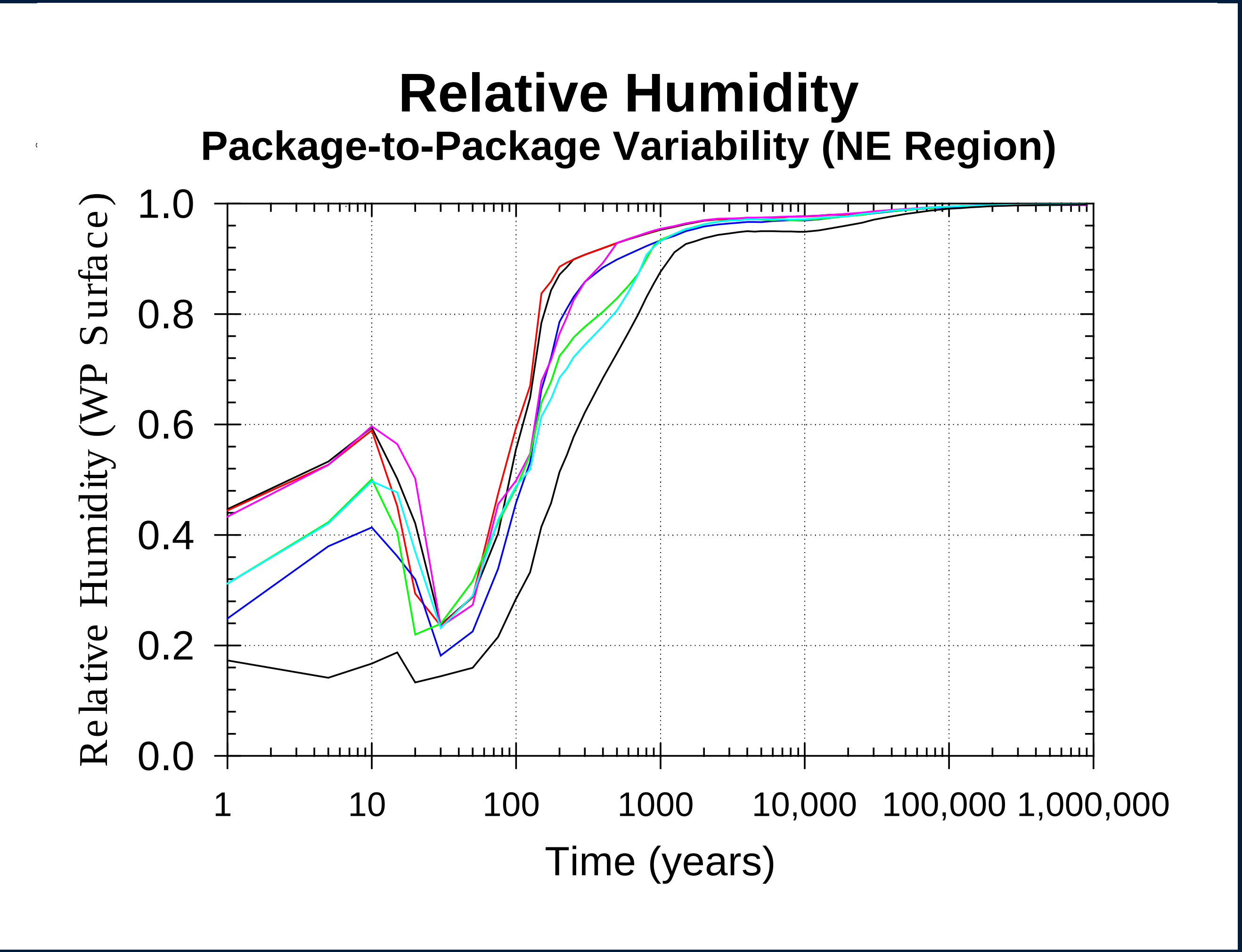
- Seepage fraction (=fraction of packages likely to encounter seeps) and seepage amount are a function of percolation flux and fracture properties
- For long term average climate, about 30% of the waste packages are assumed to encounter seeps, with an average flow rate per seep of about 300 l/yr
- Both seepage fraction and seepage amount are very uncertain

Conceptual Model of Thermal Hydrology



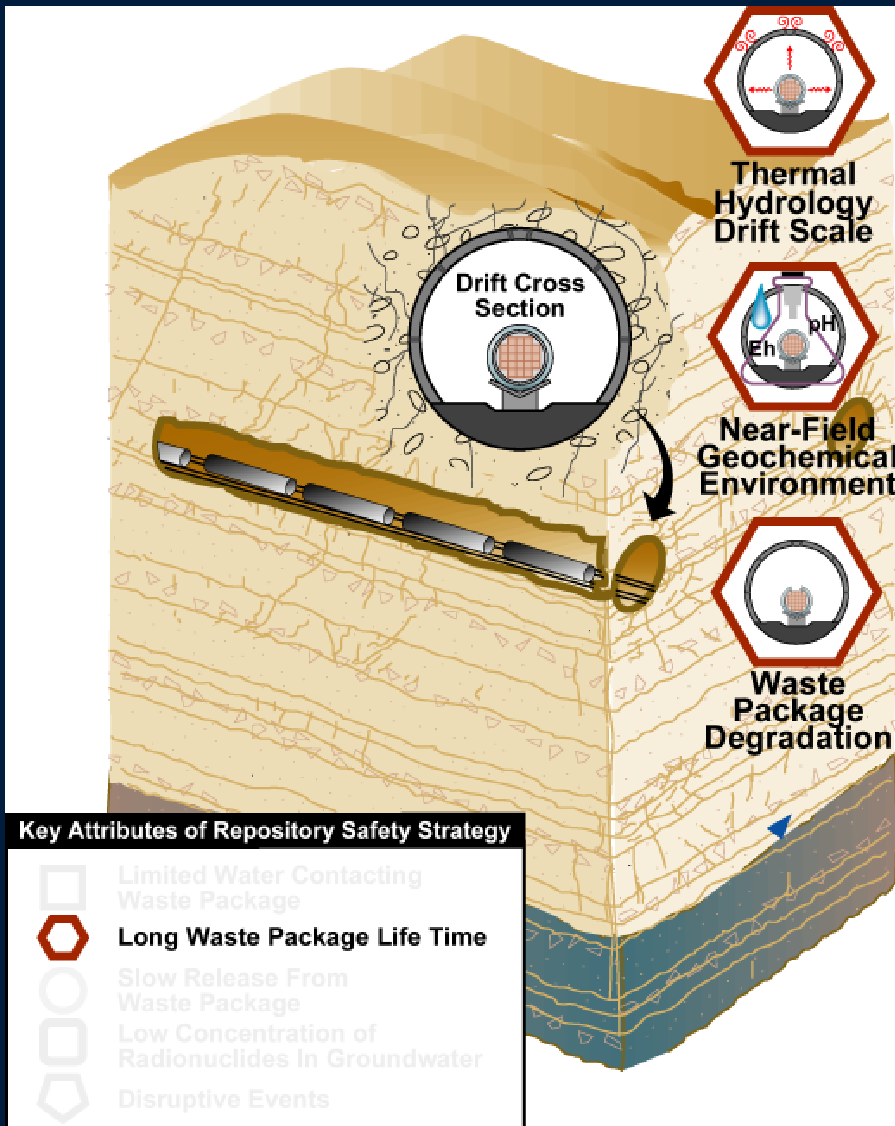
- **Initially water boils and is driven away from drifts as vapor in fractures**
- **Water can condense above and between drifts**
- **Water is pulled back into matrix by matrix imbibition**
- **Size and duration of "dry-out" zone depends on design, rock properties and ambient percolation flux**

TSPA-VA Base Case Thermal Hydrology



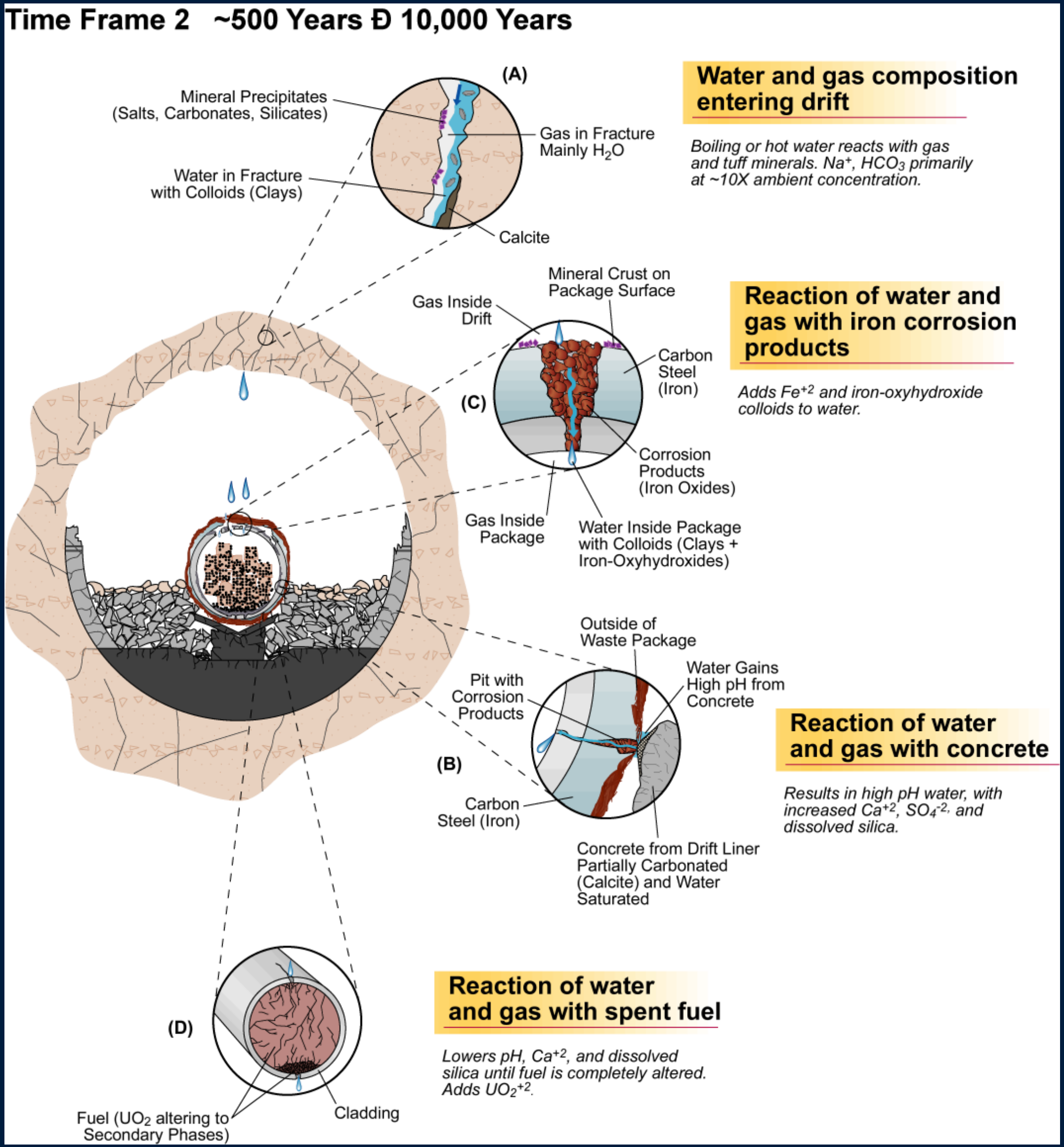
- Thermal hydrologic response varies for different packages with different thermal output
- Thermal hydrologic response varies with space due to different percolation fluxes
- Responses match observed responses in single-heater test
- Relative humidity exceeds threshold for humid air corrosion of mild steel after a few 100 years

TSPA-VA Model Components - Long Waste Package Life Time



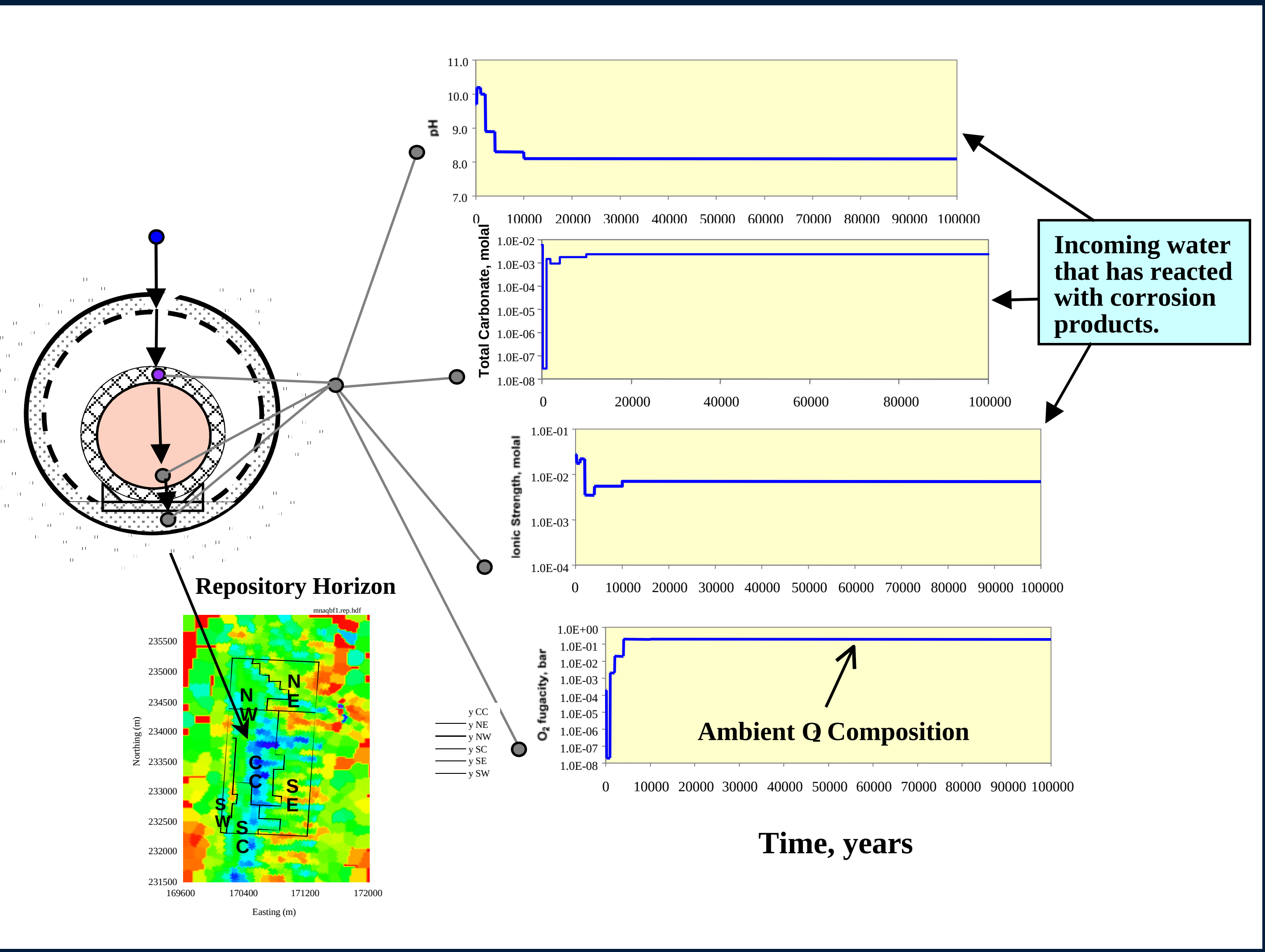
- Thermal, hydrologic, and chemical environments affect waste package degradation
- These environments change with time (especially over the first 1,000 - 10,000 years) and space

Conceptual Model of Near Field Geochemical Environment



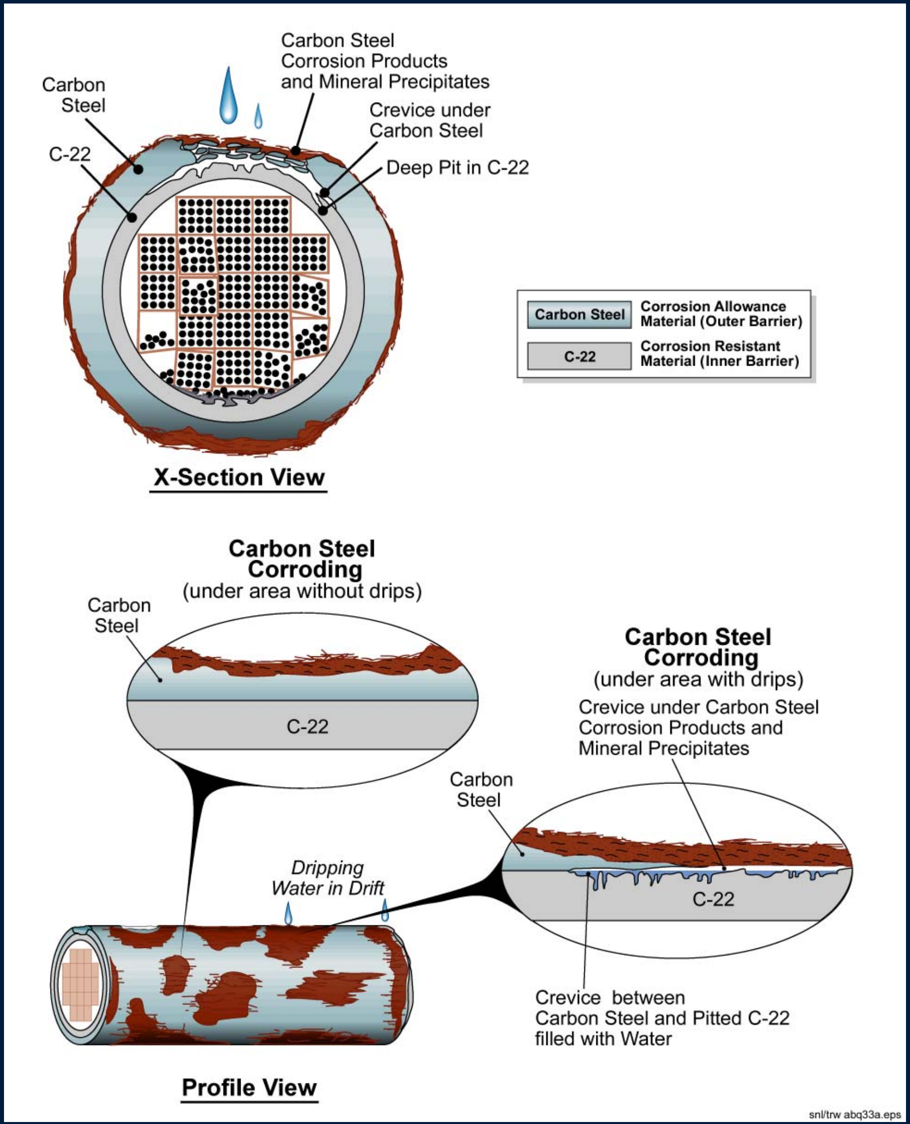
- Temporal evolution of geochemical environment depends on series of reactions of water with rock and emplaced materials
- pH of water entering drift depends on degradation of concrete liner

TSPA-VA Base Case Near Field Geochemical Environment



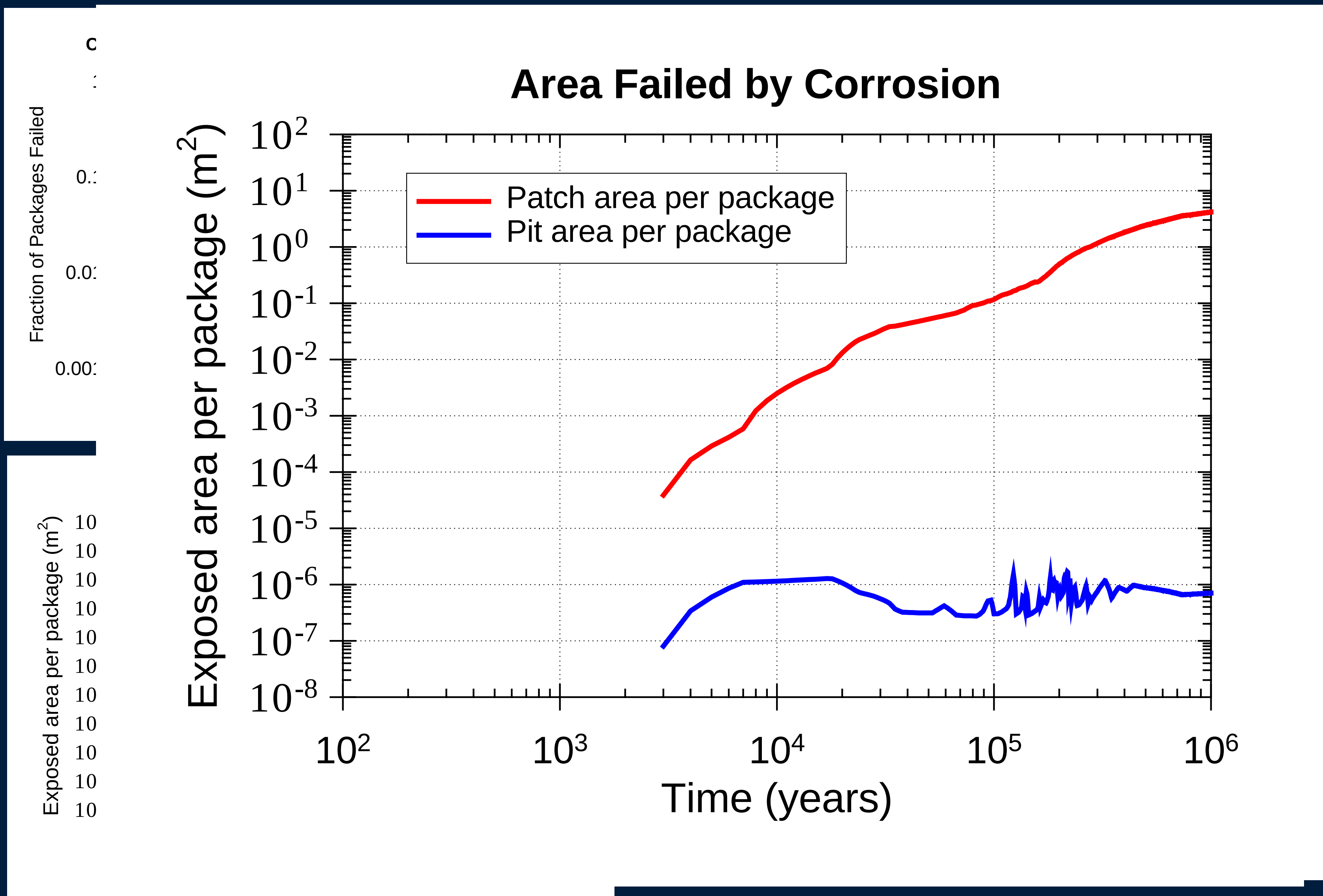
- Geochemistry in drift controlled by air mass fraction
- Water reacts with concrete, steel and waste forms
- Key geochemical parameters which affect waste package and waste form degradation, radionuclide solubility and colloid stability
  - pH
  - CO_3
  - Ionic strength

Conceptual Model of Waste Package Degradation



- Mild steel outer layer corrodes by humid air or aqueous corrosion
- Mild steel corrosion rate derived from analog materials and literature data
- C-22 inner layer is very corrosion resistant and generally requires liquid water to corrode
- C-22 corrosion rate is dependent on chemistry of water in crevice between mild steel and C-22
- C-22 corrosion rate derived form expert elicitation based on laboratory data

TSPA-VA Base Case Waste Package Degradation



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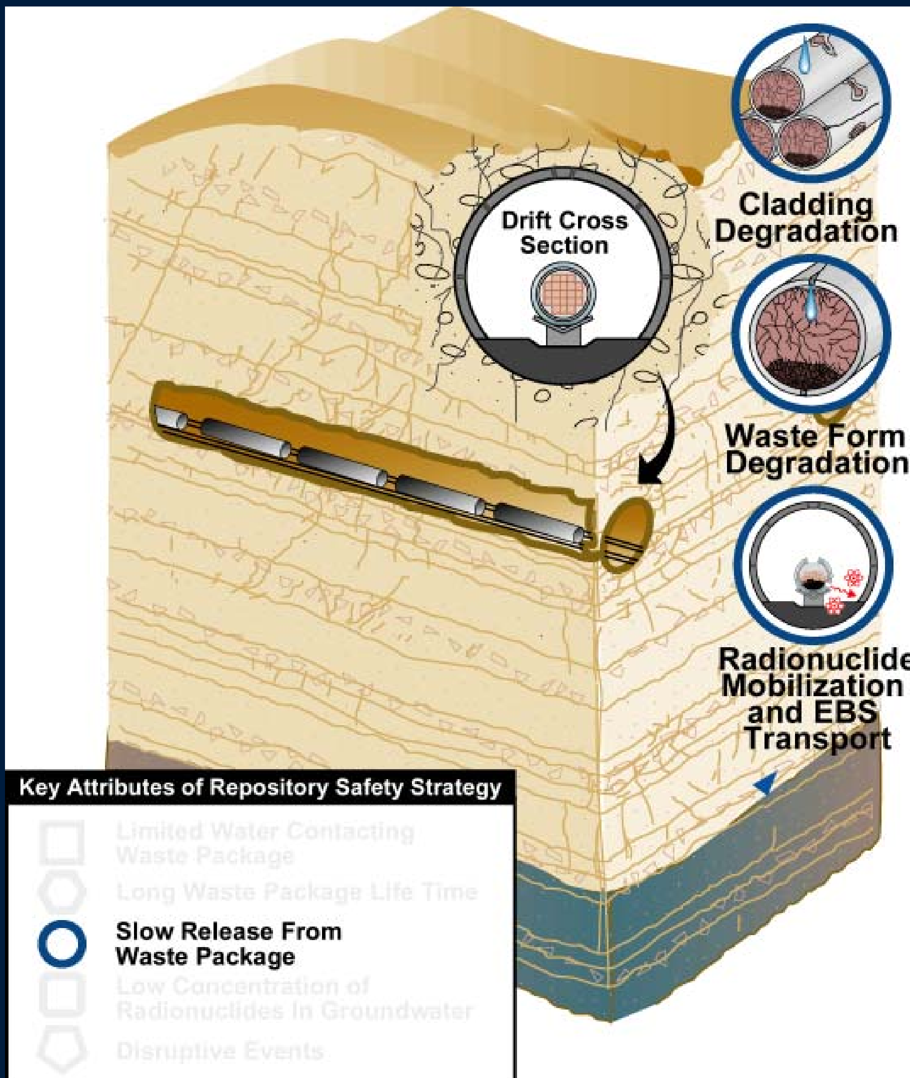
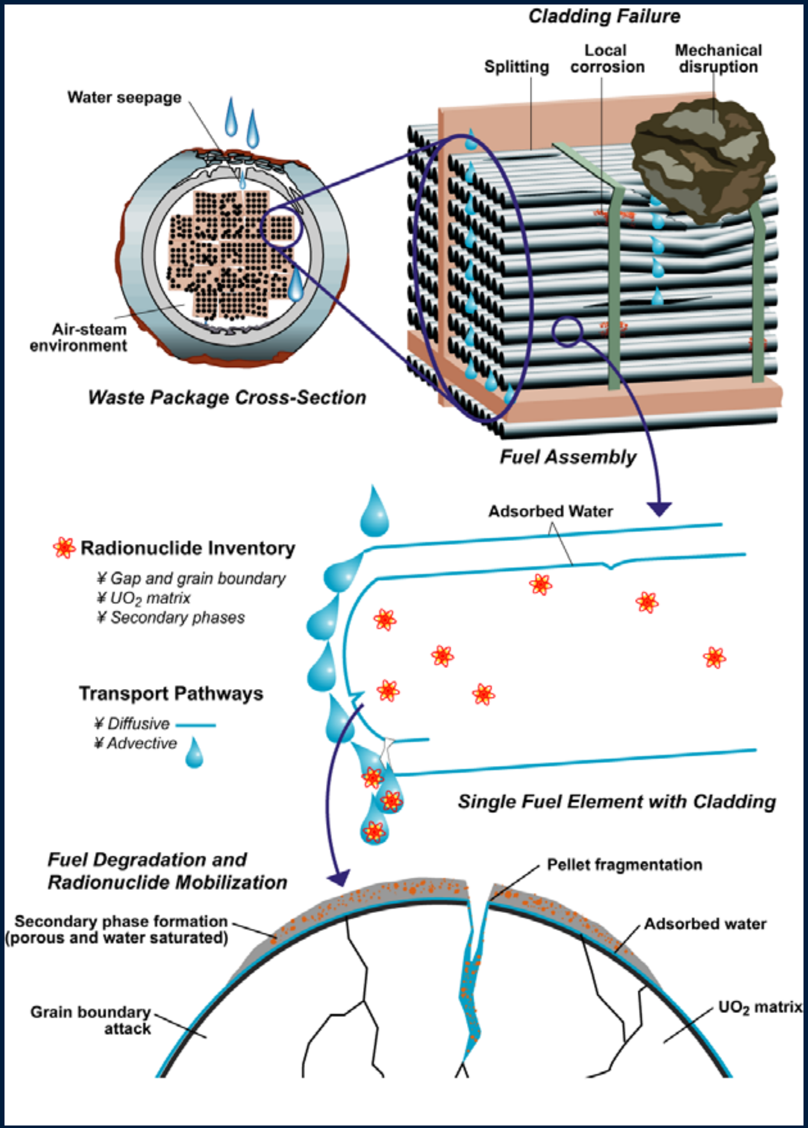
TSPA-VA Model Components - Slow Release From Waste Package



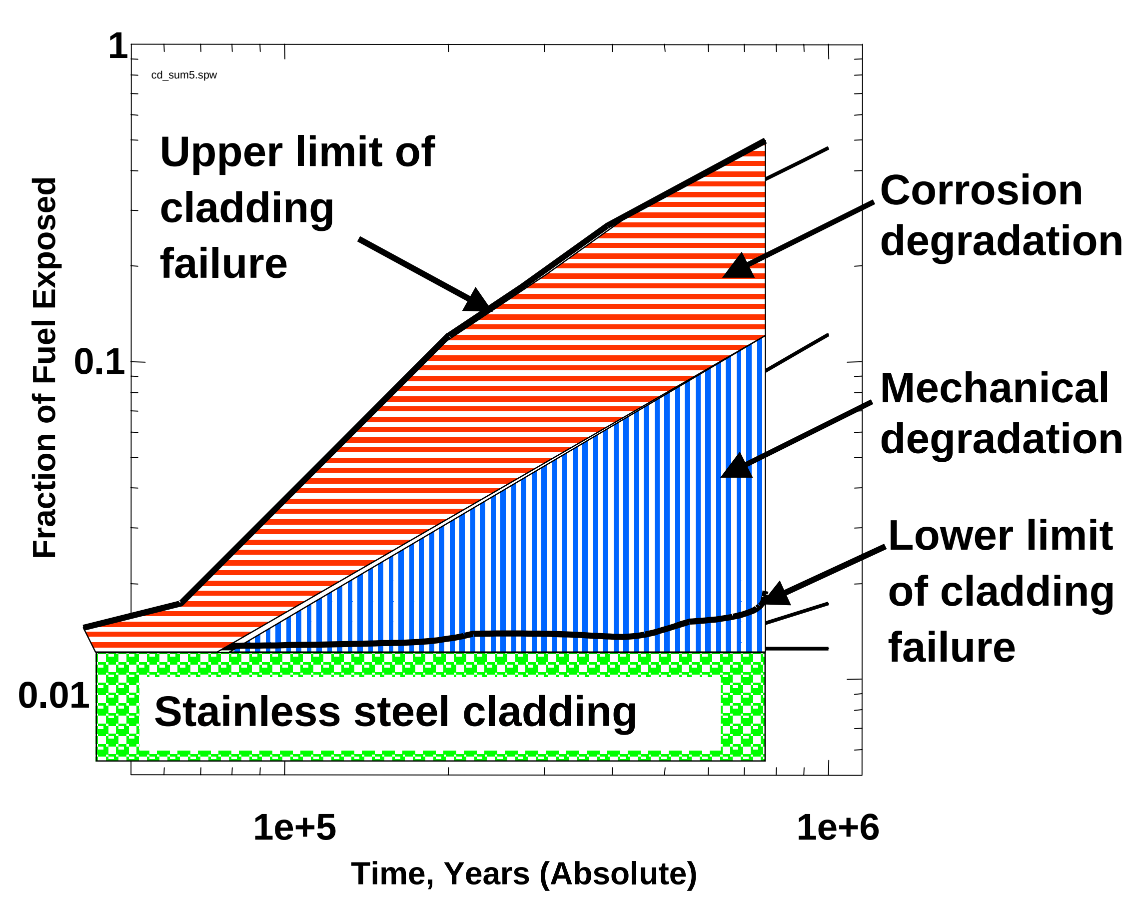
- **Thermal, hydrologic and chemical environment affect:**
  - **Cladding degradation**
  - **Waste form degradation**
  - **Radionuclide mobilization**
  - **EBS transport**
- **Release is spatially and temporally variable and uncertain**

Conceptual Model of Waste Form Degradation



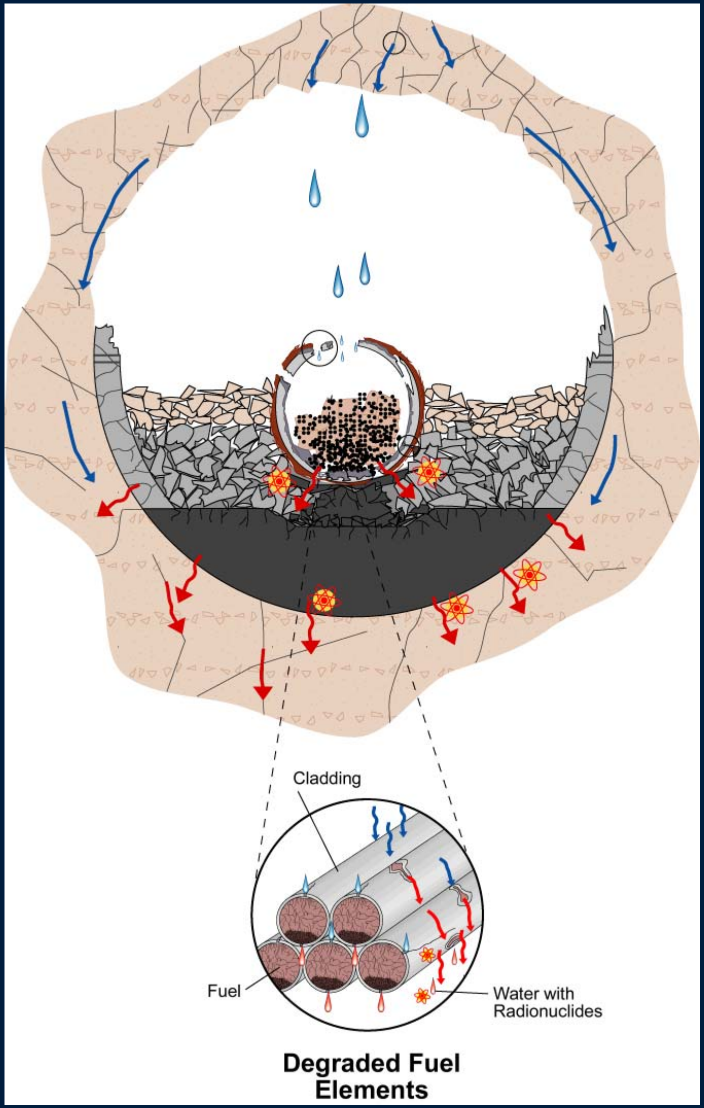
- Cladding provides the next barrier minimizing the contact of water with the spent fuel
- Some cladding is degraded at emplacement or rapidly when water contacts the cladding
- Most of the Zircaloy cladding is intact for long periods of time
- The exposed waste form degrades in a few 1000 years, although it can be altered to a number of secondary phases, immobilizing most actinides

TSPA-VA Base Case
Cladding Degradation



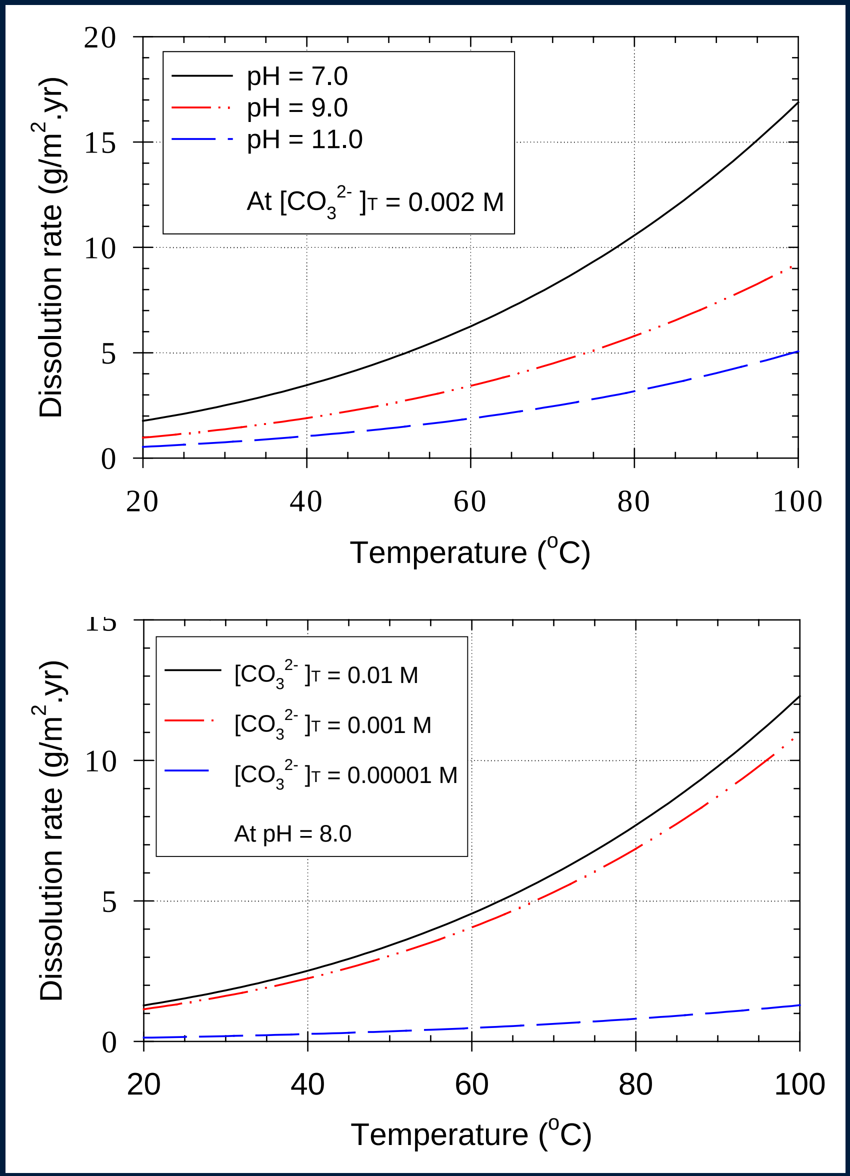
- Cladding degrades by creep rupture if exposed to high enough temperature
- Cladding can undergo mechanical degradation once the waste package has failed
- Cladding can corrode but at a rate lower than C-22
- Cladding degradation rate is uncertain

Conceptual Model of Mobilization and Transport Through the Engineered Barriers



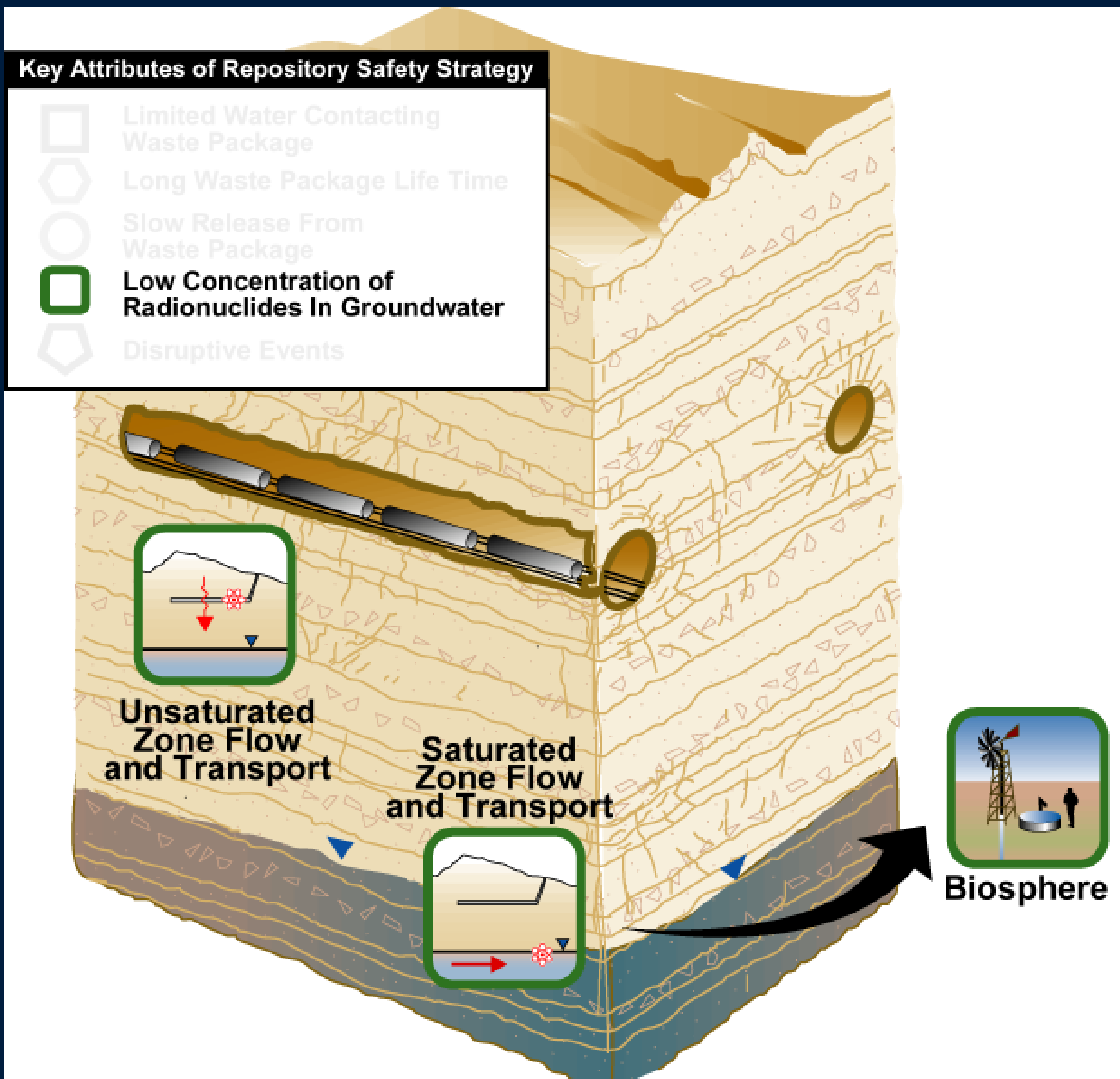
- Release of mobile (high solubility) radionuclides (e.g., Tc-99 and I-129) requires only continuous water film
- Release of solubility-limited radionuclides (e.g., Np-237) and colloids (e.g., Pu-242) requires advective flux of water through waste package
- Release rate of mobile radionuclides controlled by the rate at which waste forms are exposed and available for release
- Release rate of less mobile radionuclides controlled by cumulative amount of inventory exposed and available for release

TSPA-VA Base Case
Waste Form Degradation



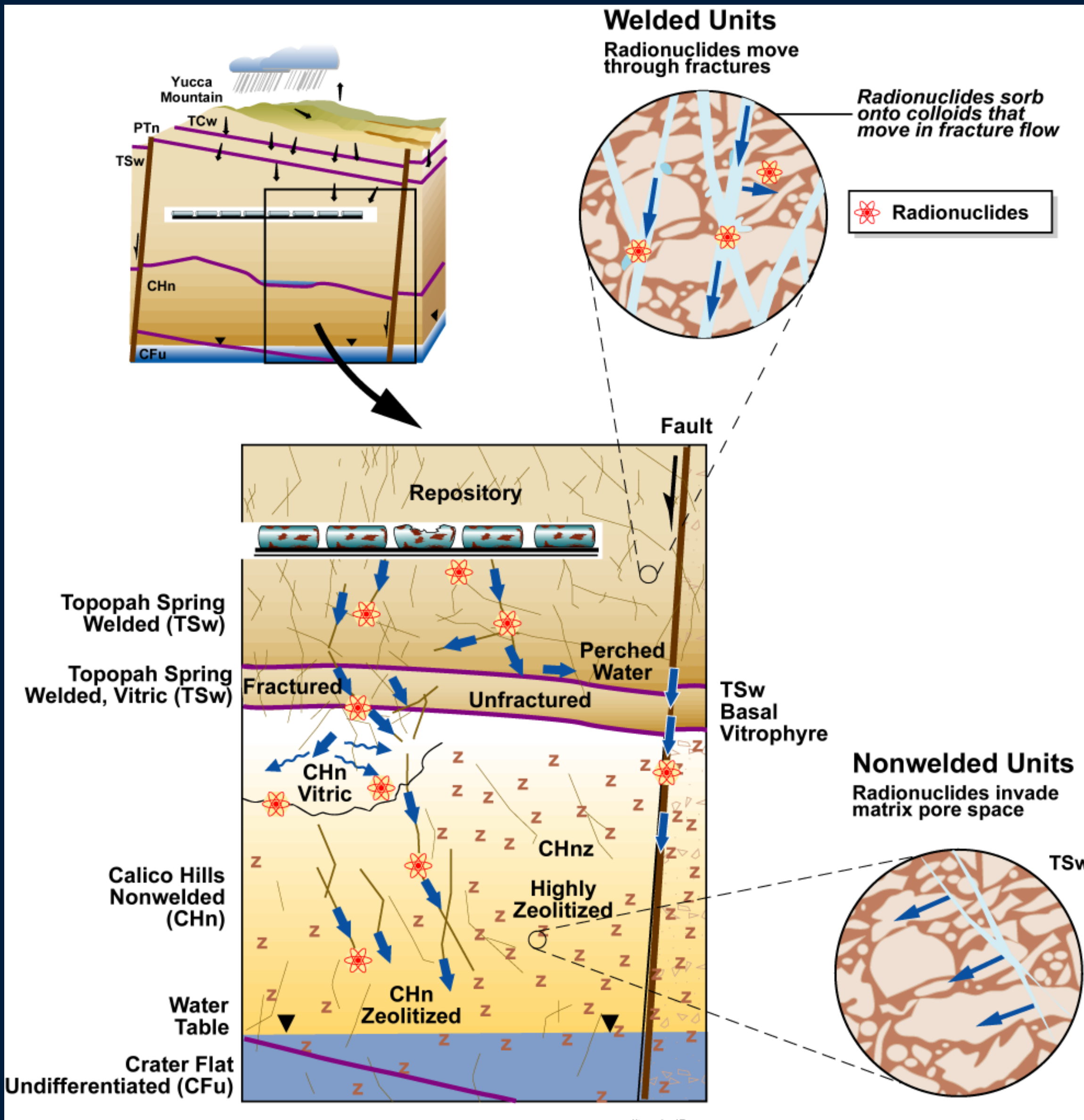
- **Each waste form has a different degradation rate**
- **Degradation rates based on laboratory observations**
- **For CSNF area of ~10^{-4} m^2/g, degradation occurs in ~1,000 years**
- **Actual concentration depends on radionuclide solubility**

TSPA-VA Model Components - Low Concentration of Radionuclides in Groundwater



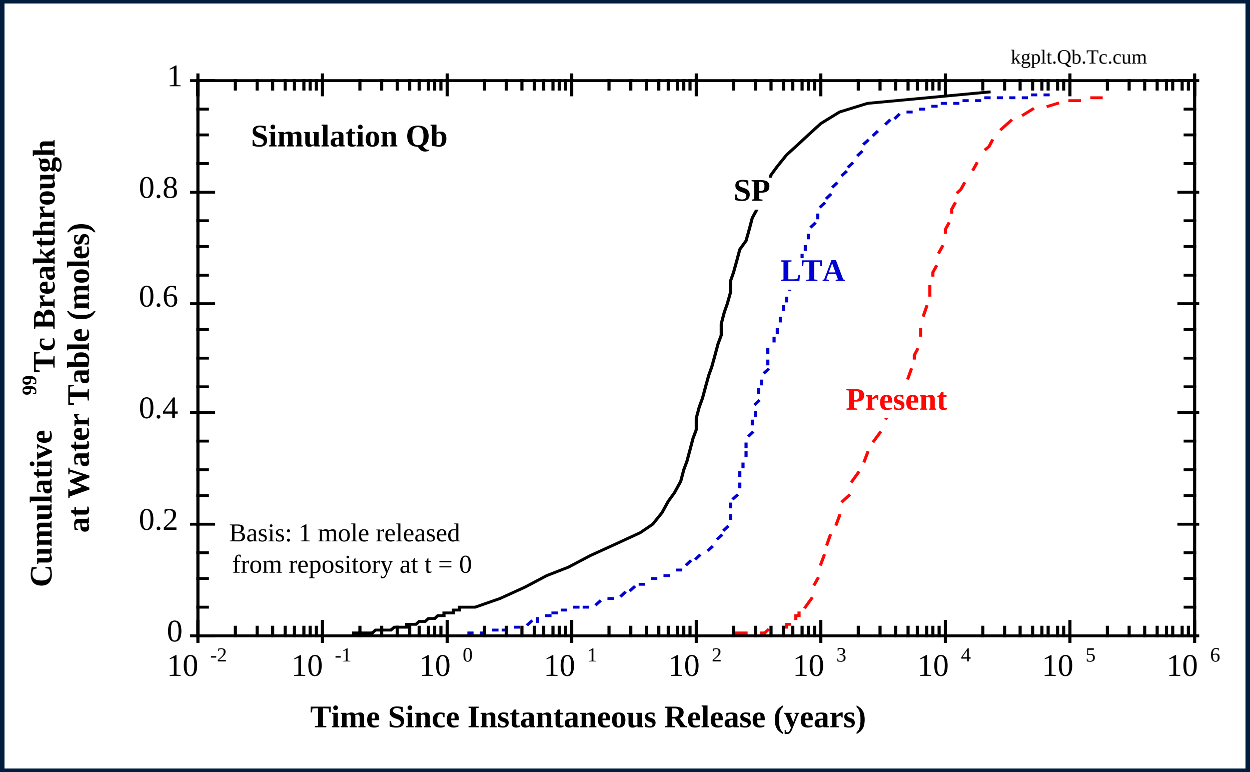
- **Mass of radionuclides released from engineered barriers mixes with water in unsaturated zone**
- **Radionuclides travel through the unsaturated tuffs about 300 m to the water table and then 20 km downgradient to a hypothetical well**

Conceptual Model of Unsaturated Zone Transport



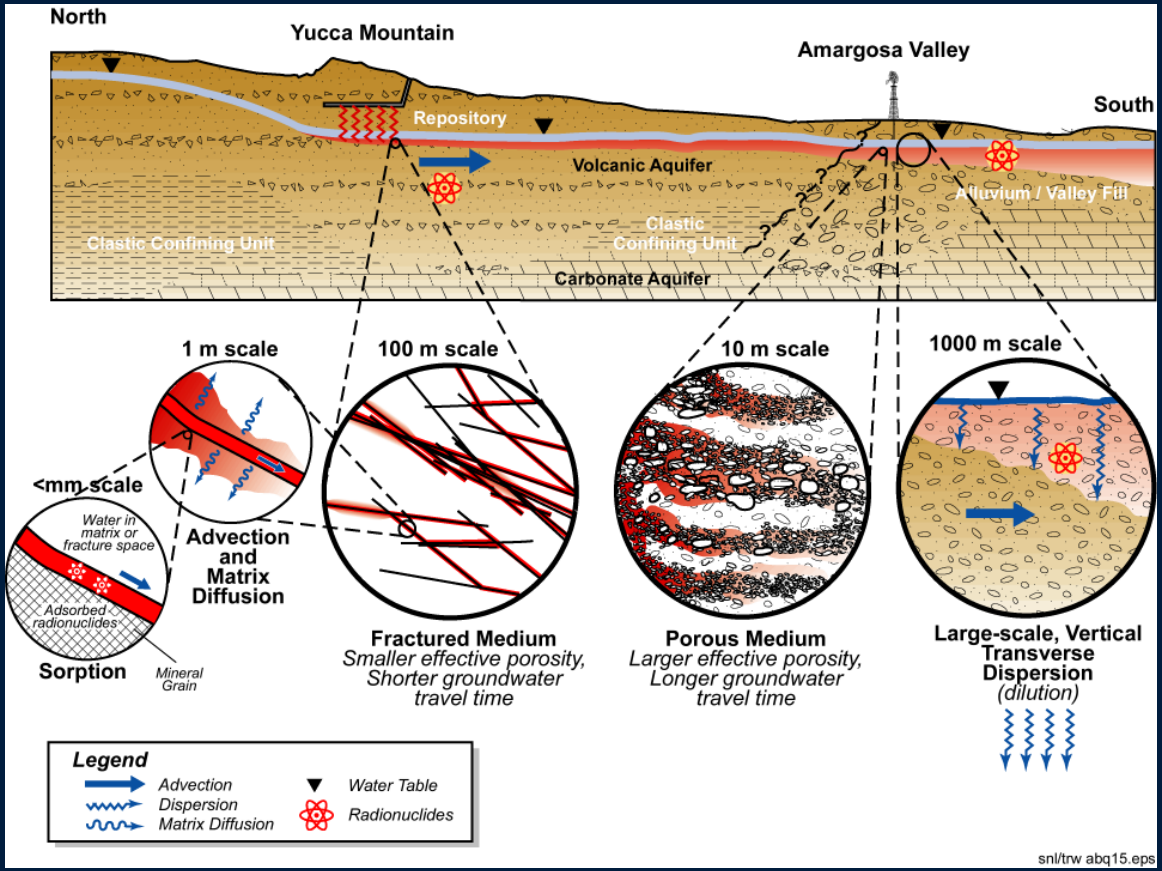
- Flow and transport in welded units is dominated by fractures
- Flow and transport in non-welded units is dominated by matrix
- Sorption of some radionuclides is increased in zeolites
- Vertical downward flux can be diverted in presence of perched water zones

TSPA-VA Base Case
Unsaturated Zone Transport



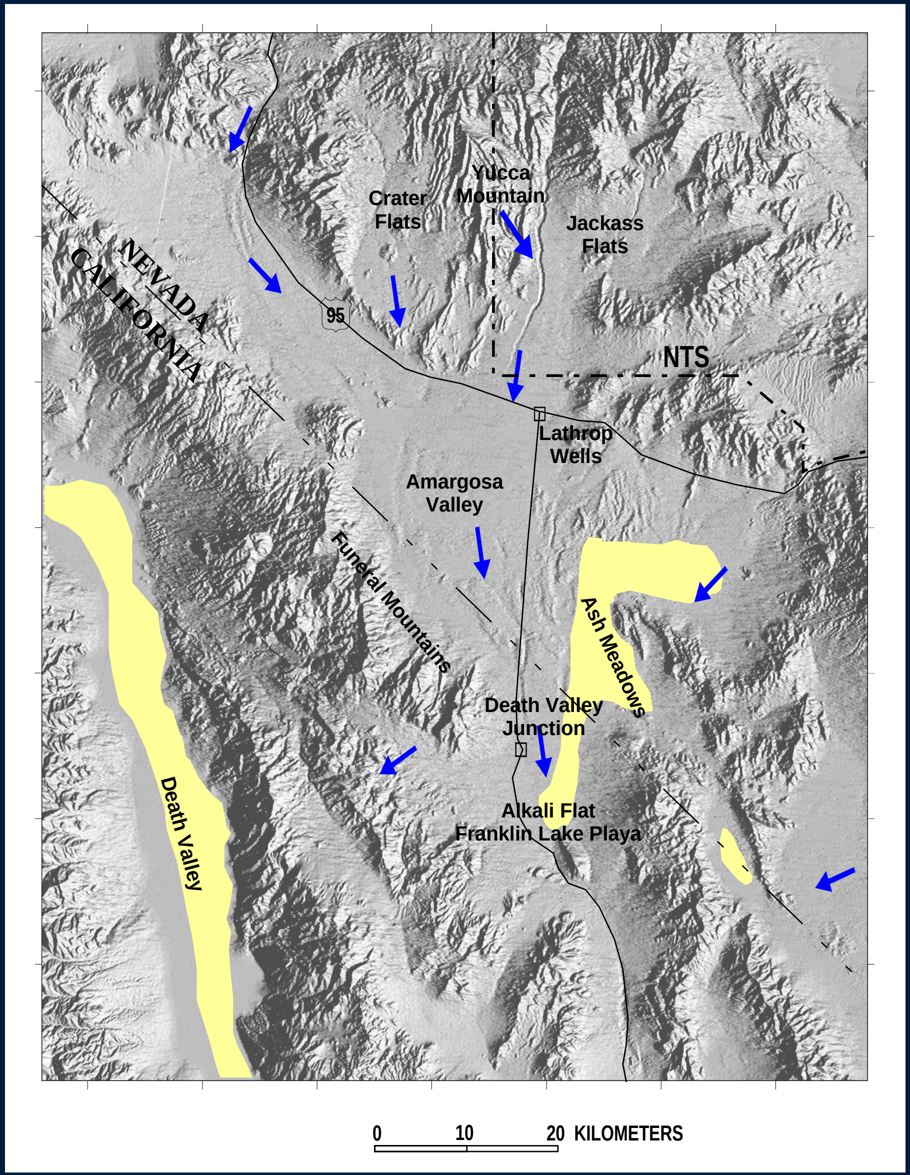
- Present day climate advective travel time for unretarded species (e.g., Tc-99 and I-129) is a few 1000 years
- Present day climate advective travel time for slightly retarded species (e.g., Np-237) is about 10,000 years
- Long-term average climate travel time for unretarded species is a few 100 years and for retarded species is a few 1000 years

Conceptual Model of Saturated Zone Transport



- **Advective dispersive mixing in saturated zone assumed minimal**
- **Degree of effective dilution to 20 km derived from expert elicitation for non-coalescing plumes**
- **Simulated transport in 6 representative stream tubes**
- **Transport in alluvium can delay some radionuclides due to adsorption**

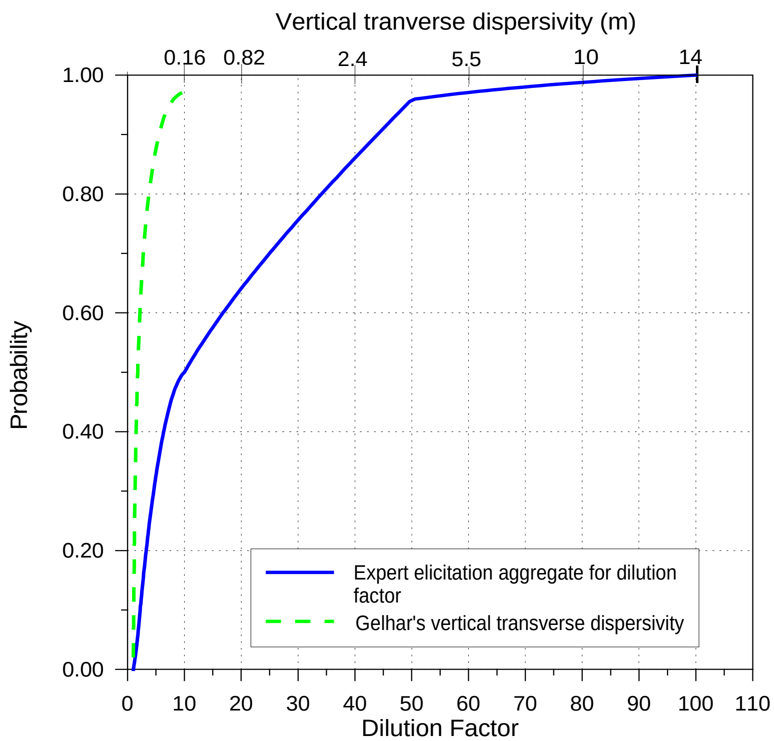
Regional Groundwater Flow Regime in the Vicinity of Yucca Mountain



- Flow is to southeast and then south
- 20 km well approximately at NTS fence line or Lathrop Wells
- Ultimate groundwater discharge at Franklin Lake Playa or Death Valley

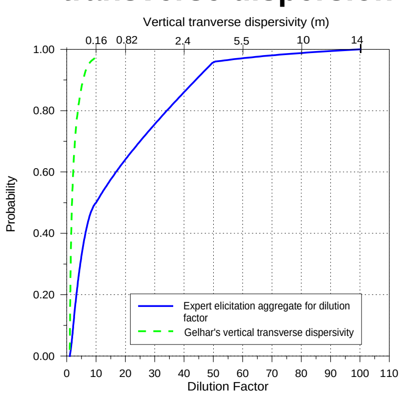
TSPA-VA Base Case
Saturated Zone Transport

Dilution from transverse dispersion

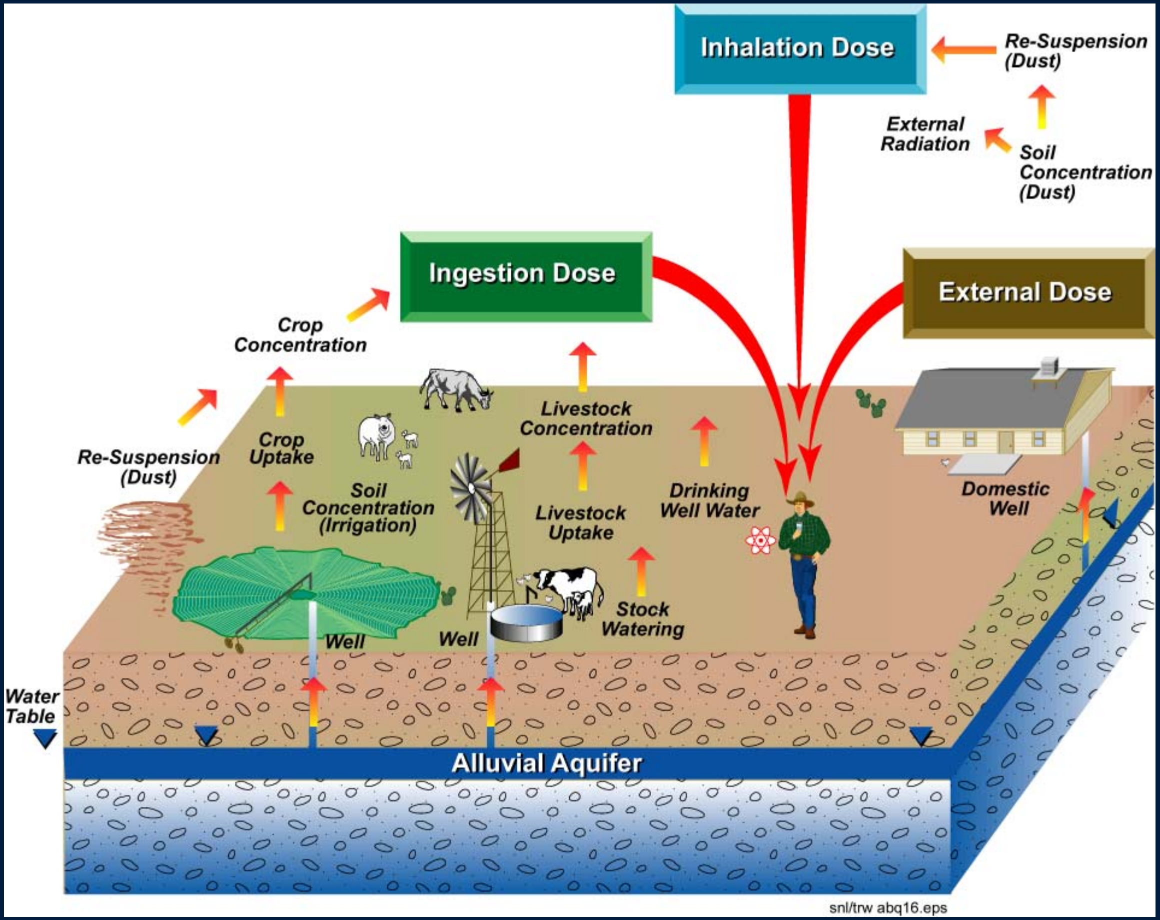


- Used 6 streamtubes in the saturated zone to develop convolution integrals of expected arrival of mass released from unsaturated zone to 20 km
- Dilution in saturated zone determined from expert elicitation with conservative assumption of mixing between individual stream tubes

Dilution from transverse dispersion



Conceptual Model of Biosphere



- Consider all potential biosphere pathways
- Use ICRP-30 for dose calculation
- Use demographic site survey for water use and food consumption

TSPA-VA Base Case Results

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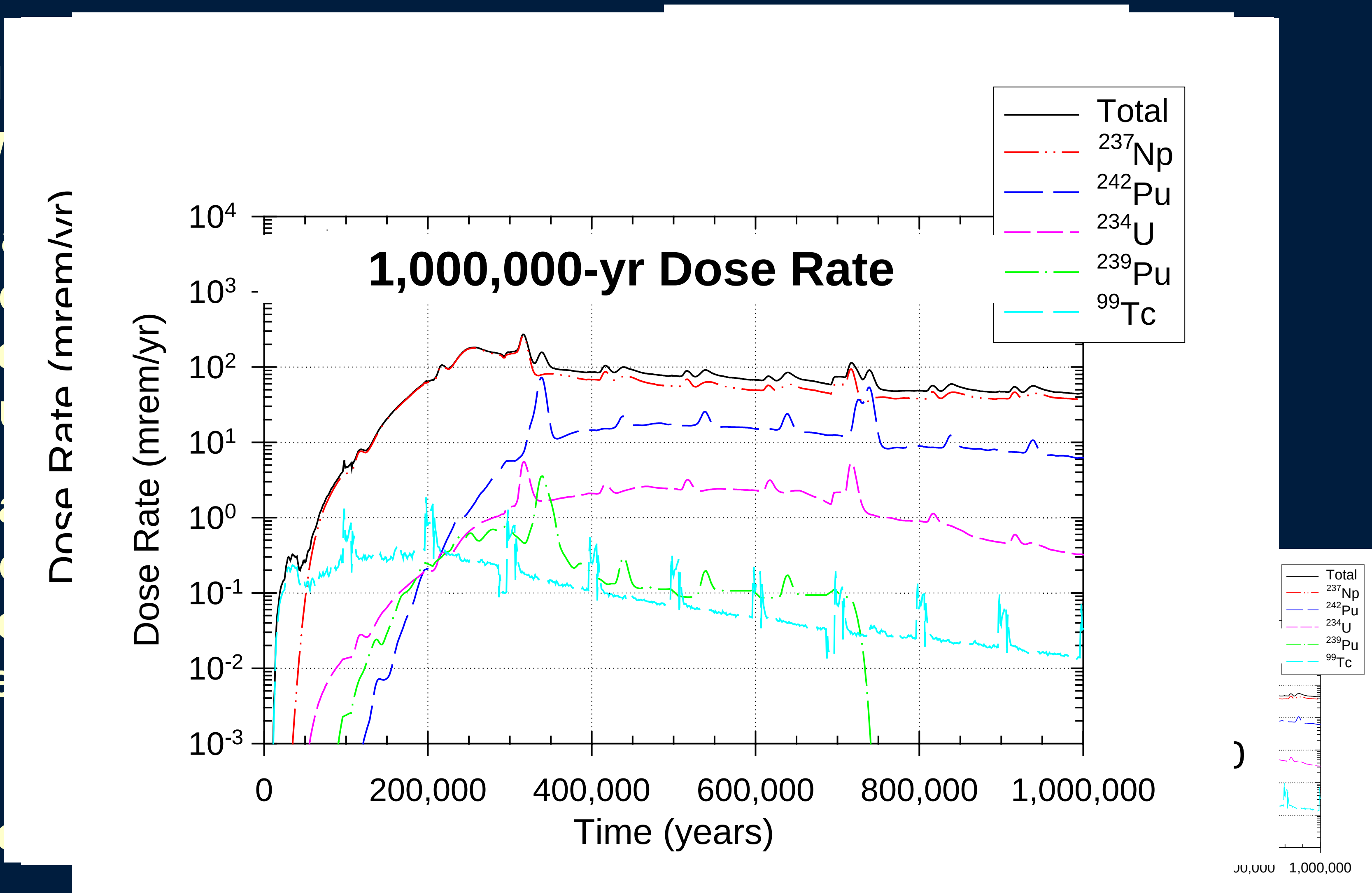
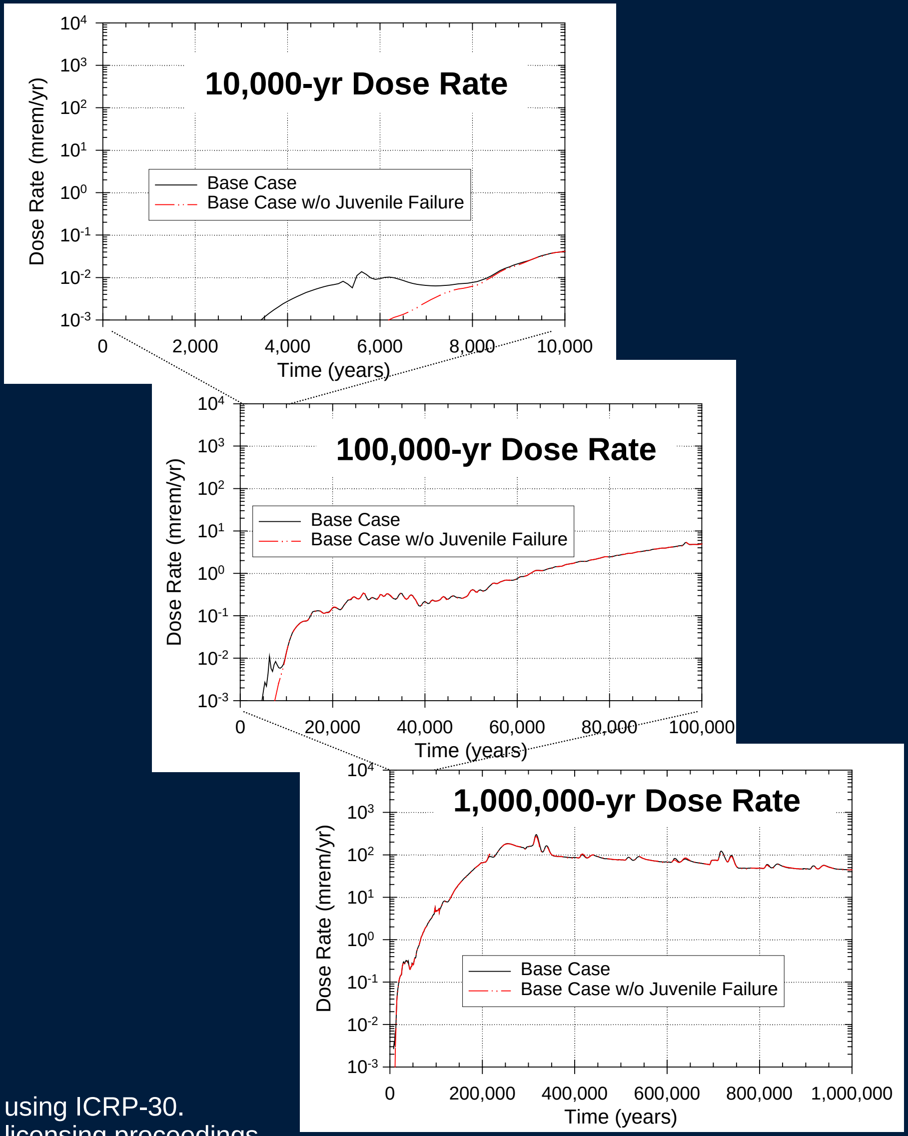


These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
These results are model-specific and may be insufficient for future adjudicatory licensing proceedings.

TSPA-VA Base Case Results - Assumed Premature Waste Package Failure

- **Assumed premature failure at 1,000 years due to**
  - **Unexpected large rock fall**
  - **Undetected weld defect**
  - **Unexpected chemical environment**
- **After about 8,000 years, the "expected" doses dominate the doses due to the assumed premature failure**



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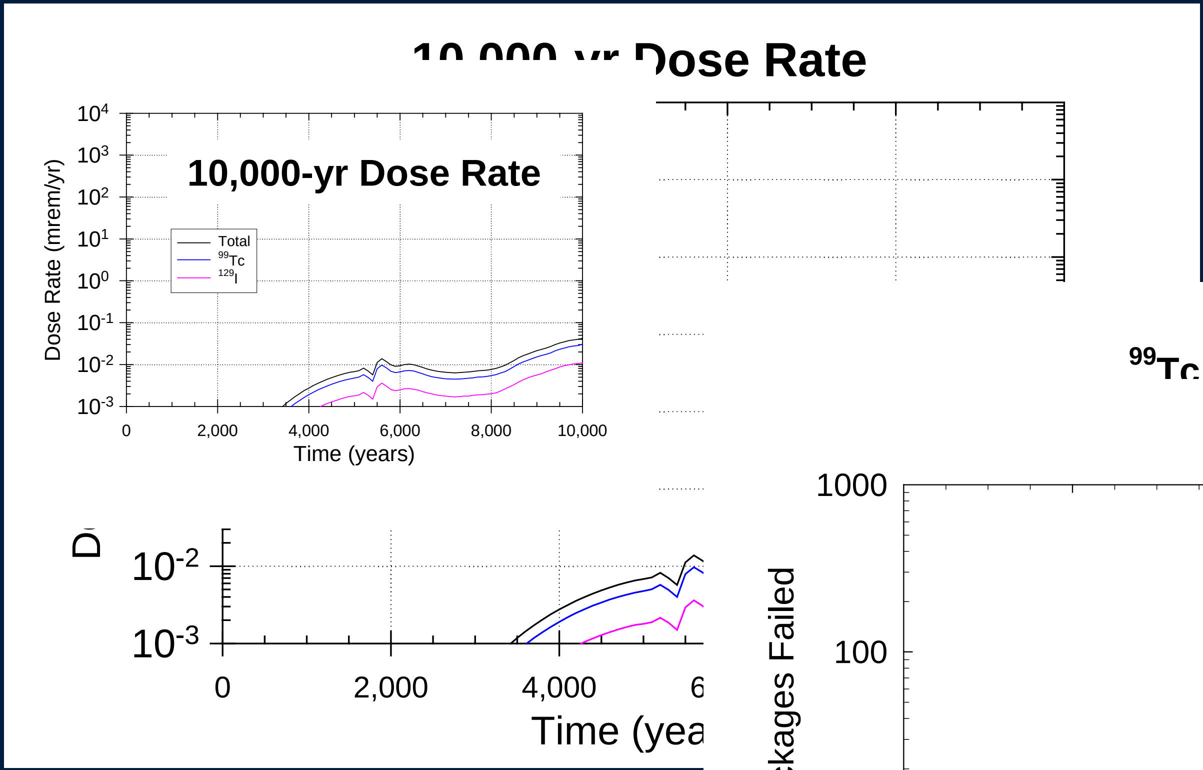
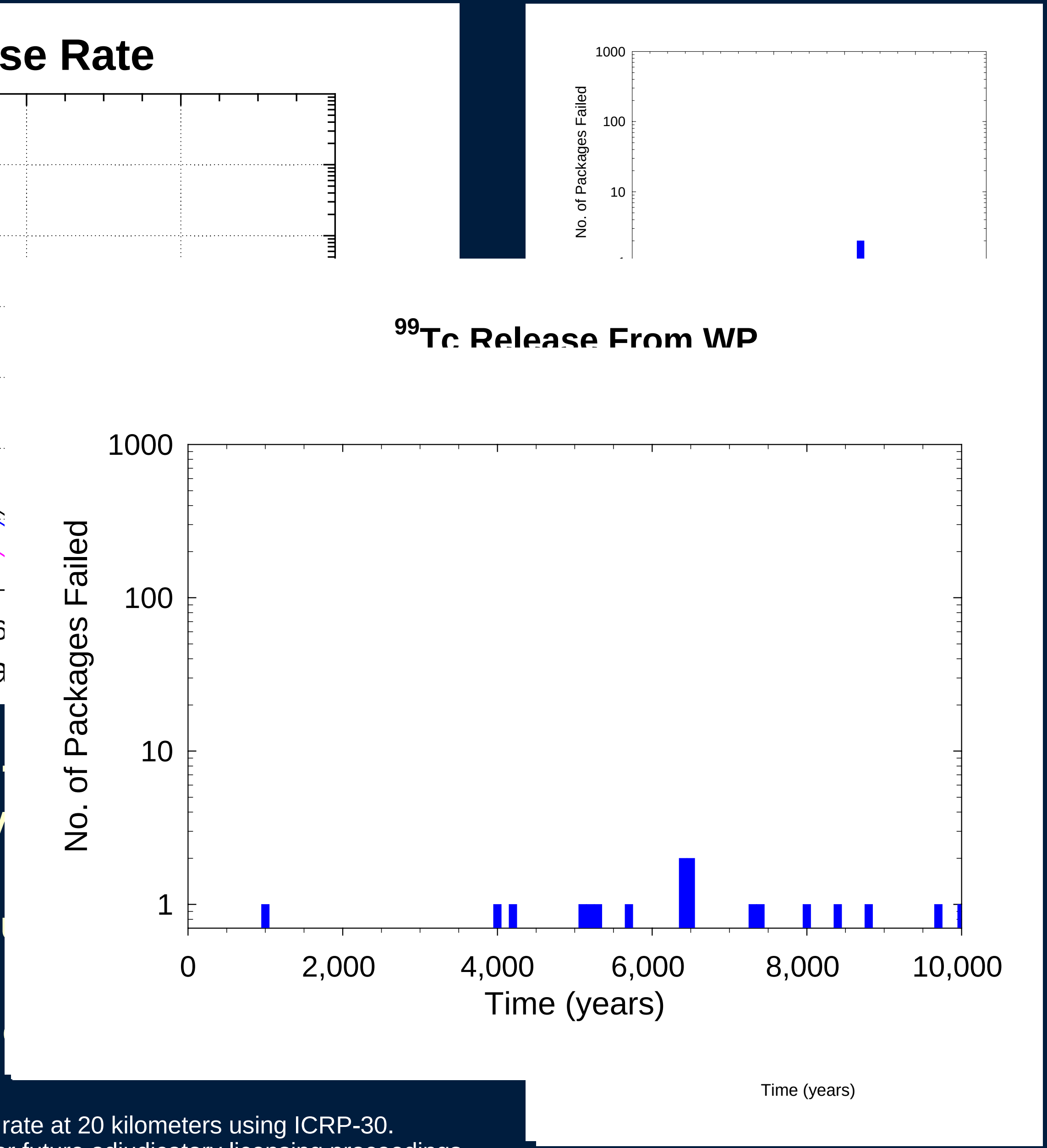
TSPA-VA Base Case Results - 10,000 Years

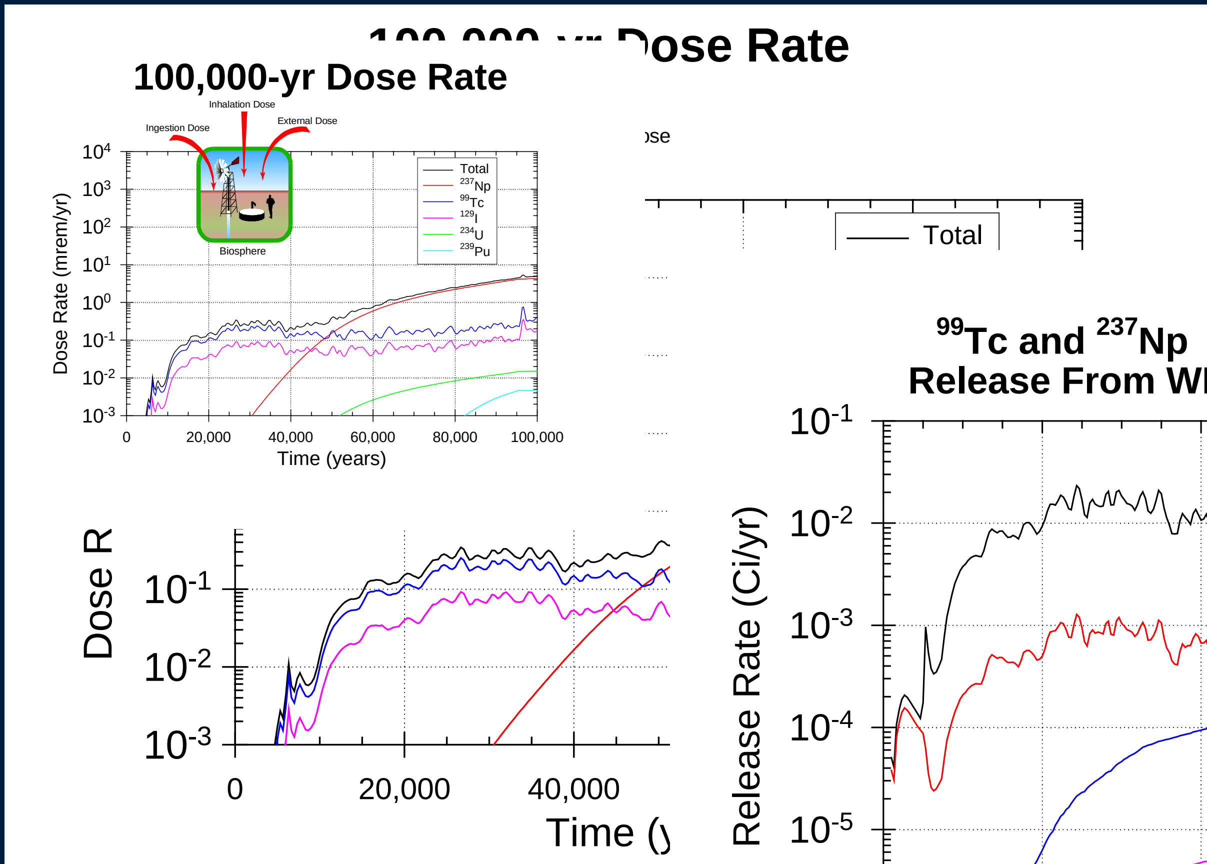


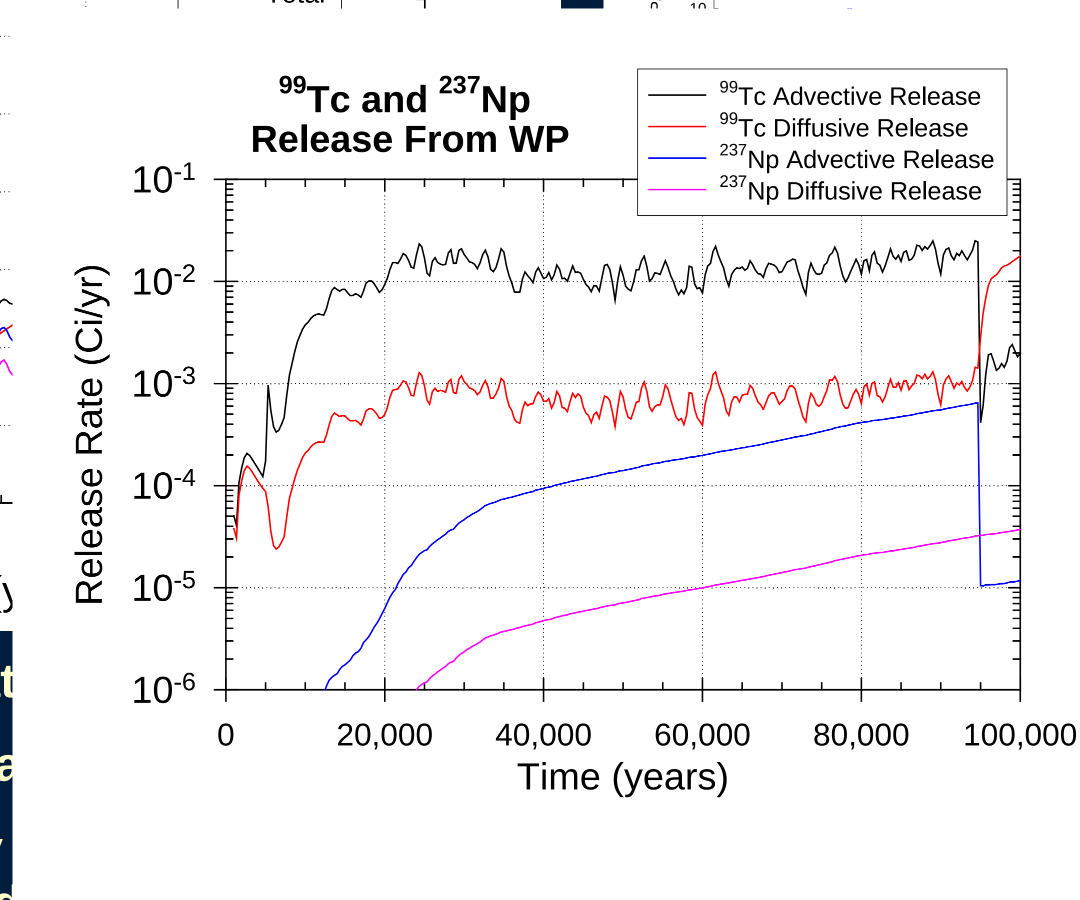


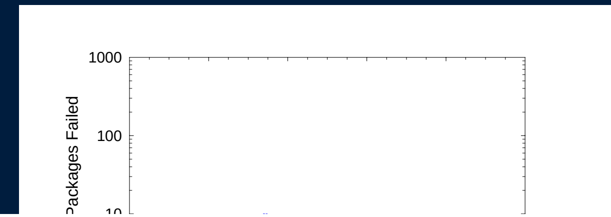
- "Expected" value dose rate <0.
- Tc and I releases controlled by failure
- Initially, seepage into pits throu
- Climate change at 5,000 years (dilution) and raises water tabl

These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
These results are model-specific and may be insufficient for future adjudicatory licensing proceedings.

TSPA-VA Base Case Results - 100,000 Years



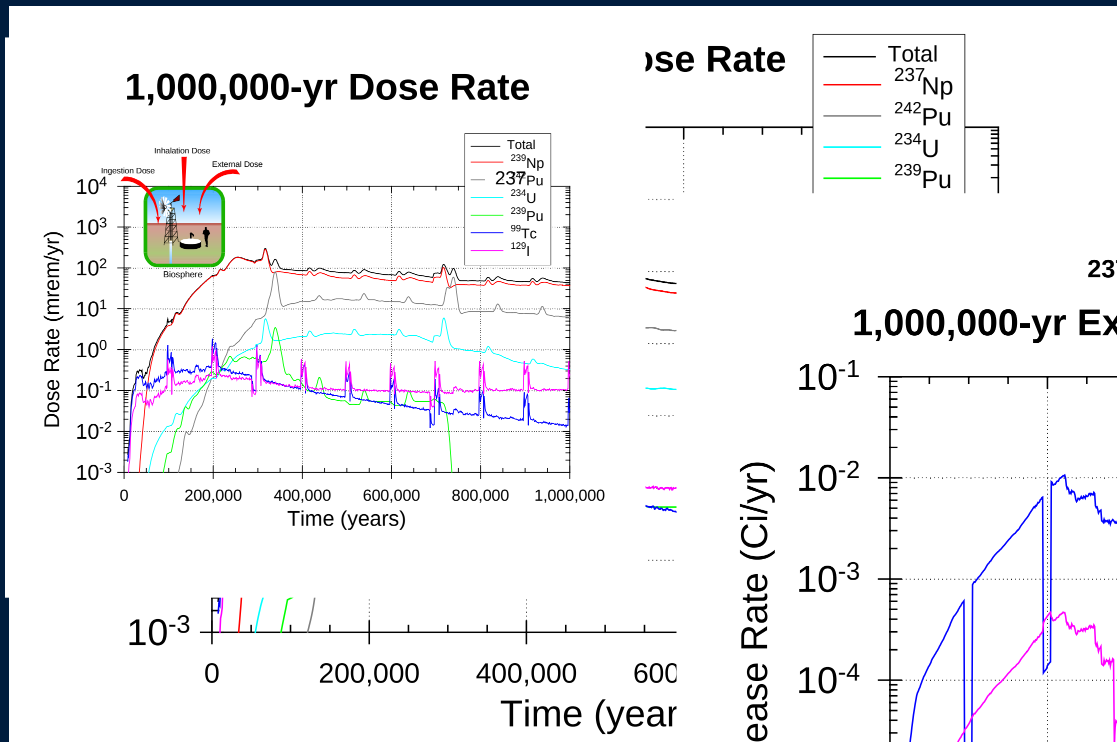


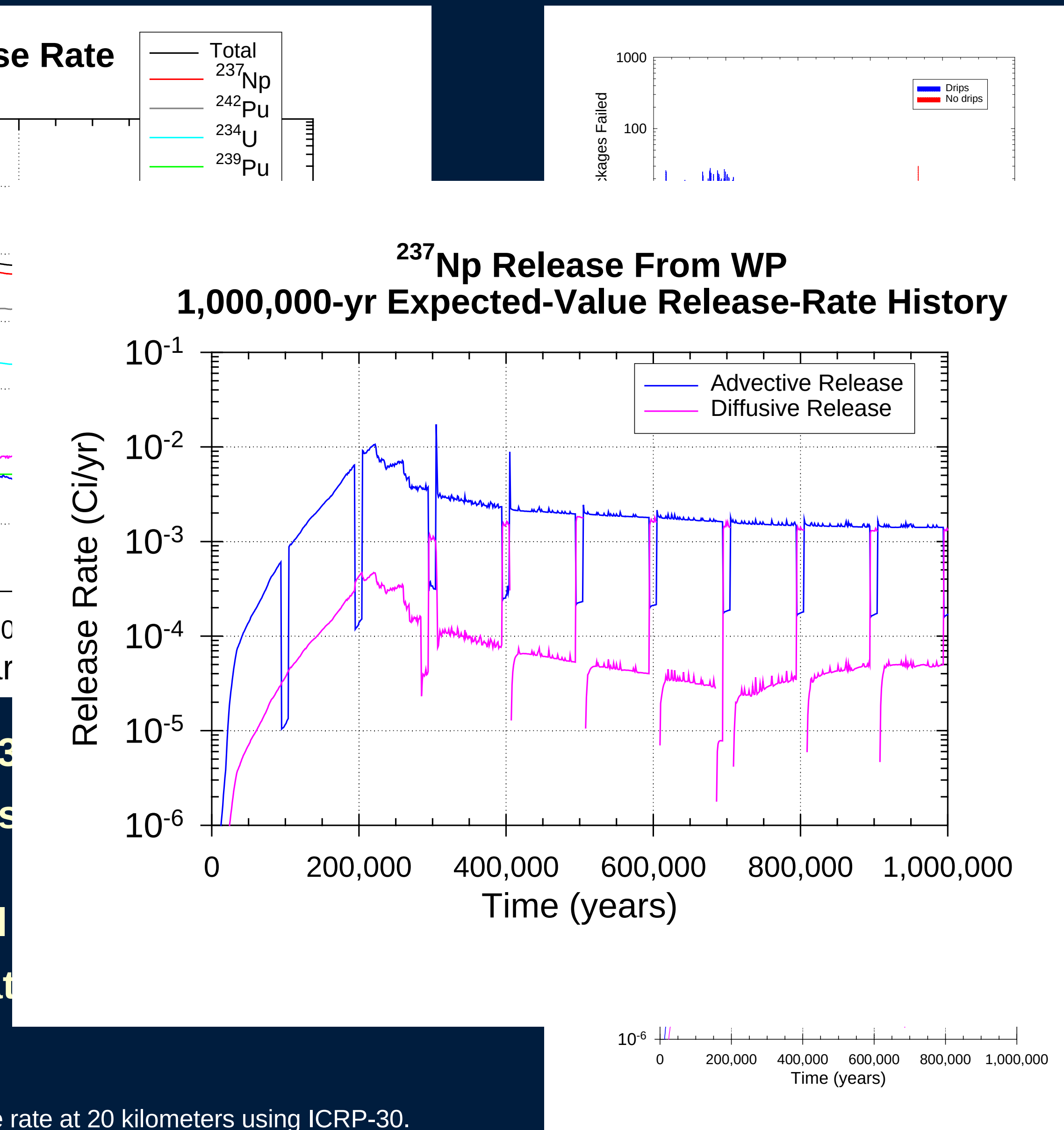


- "Expected" value dose rat
- Np dose rate exceeds Tc a
- Np releases controlled by waste packages failed and seepage flux

These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
These results are model-specific and may be insufficient for future adjudicatory licensing proceedings.

TSPA-VA Base Case Results - 1,000,000 Years





- "Expected" value dose rate ~ 3
- Peak occurs at ~ 300,000 years
  climate state
- Some contribution of colloidal
- Np dose controlled by cumulat
  and seepage flux

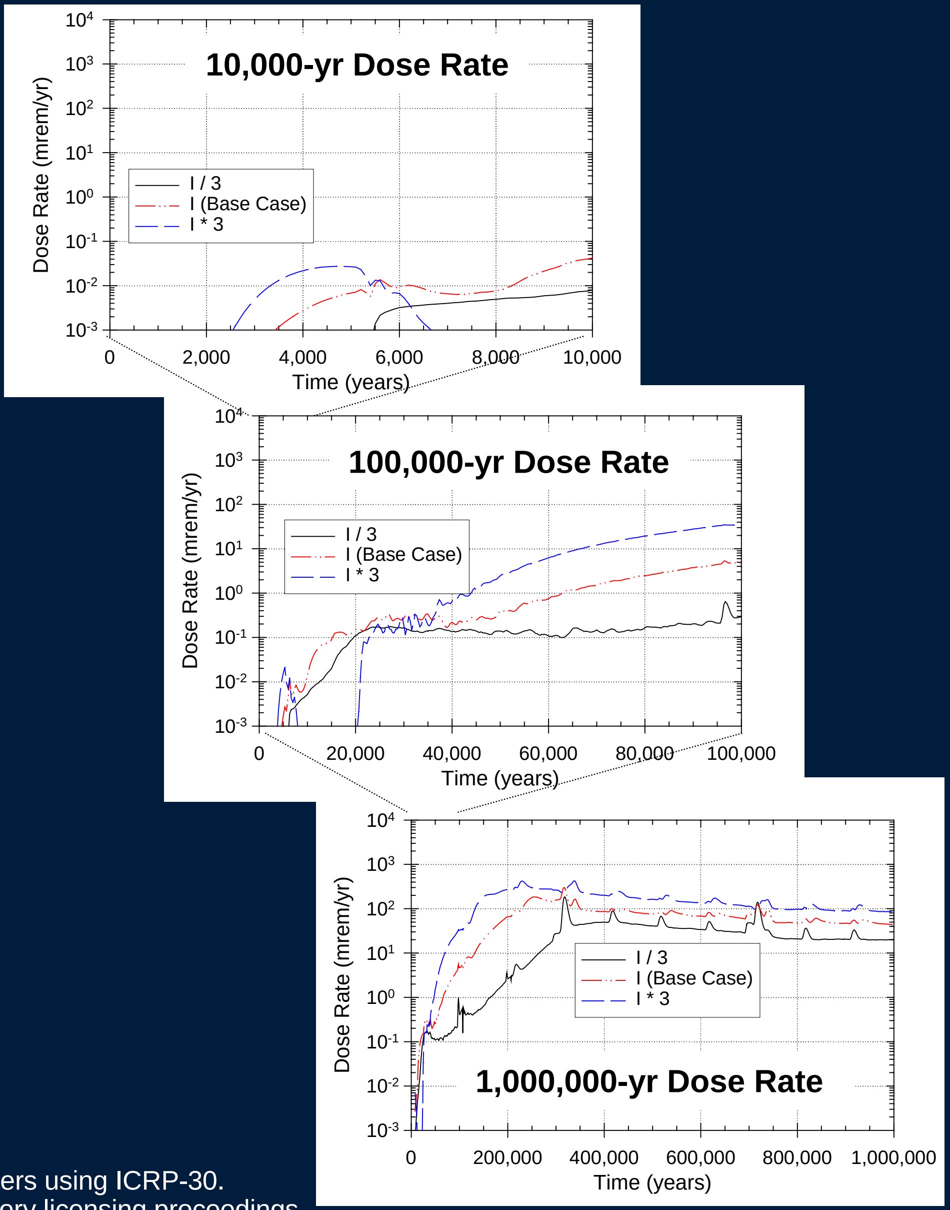
These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
These results are model-specific and may be insufficient for future adjudicatory licensing proceedings.

Sensitivity and Uncertainty Analyses for TSPA-VA

Attributes of the Repository Safety Strategy	Principal Factors	Heterogeneity/ Variability in Base Case	Uncertainty Addressed in Base Case (Chapter 4.3)	Uncertainty Addressed in Comparative Analyses (Chapter 5)
Limited water contacting waste packages	Precipitation and infiltration of water into the mountain	✓	✓	✓
	Percolation to depth	✓	✓	✓
	Seepage into drifts	✓	✓	✓
	Effects of heat and excavation on flow			✓
	Dripping onto waste package	✓		
	Humidity and temperature at waste package	✓		
Long waste package lifetime	Chemistry on waste package			✓
	Integrity of outer waste package barrier	✓	✓	
	Integrity of inner waste package barrier	✓	✓	✓
Low rate of release of radionuclides from breached waste packages	Seepage into waste package		✓	✓
	Integrity of spent fuel cladding		✓	✓
	Dissolution of UO_2 and glass waste-form		✓	✓
	Solubility of Np-237		✓	✓
	Formation of radionuclide-bearing colloids		✓	✓
	Transport within and out of waste package			✓
Radionuclide concentration reduction during transport from the waste packages	Transport through unsaturated zone	✓	✓	
	Transport in saturated zone	✓	✓	
	Dilution from pumping			✓
	Biosphere transport uptake		✓	✓

TSPA-VA Sensitivity Analyses - Infiltration Rate

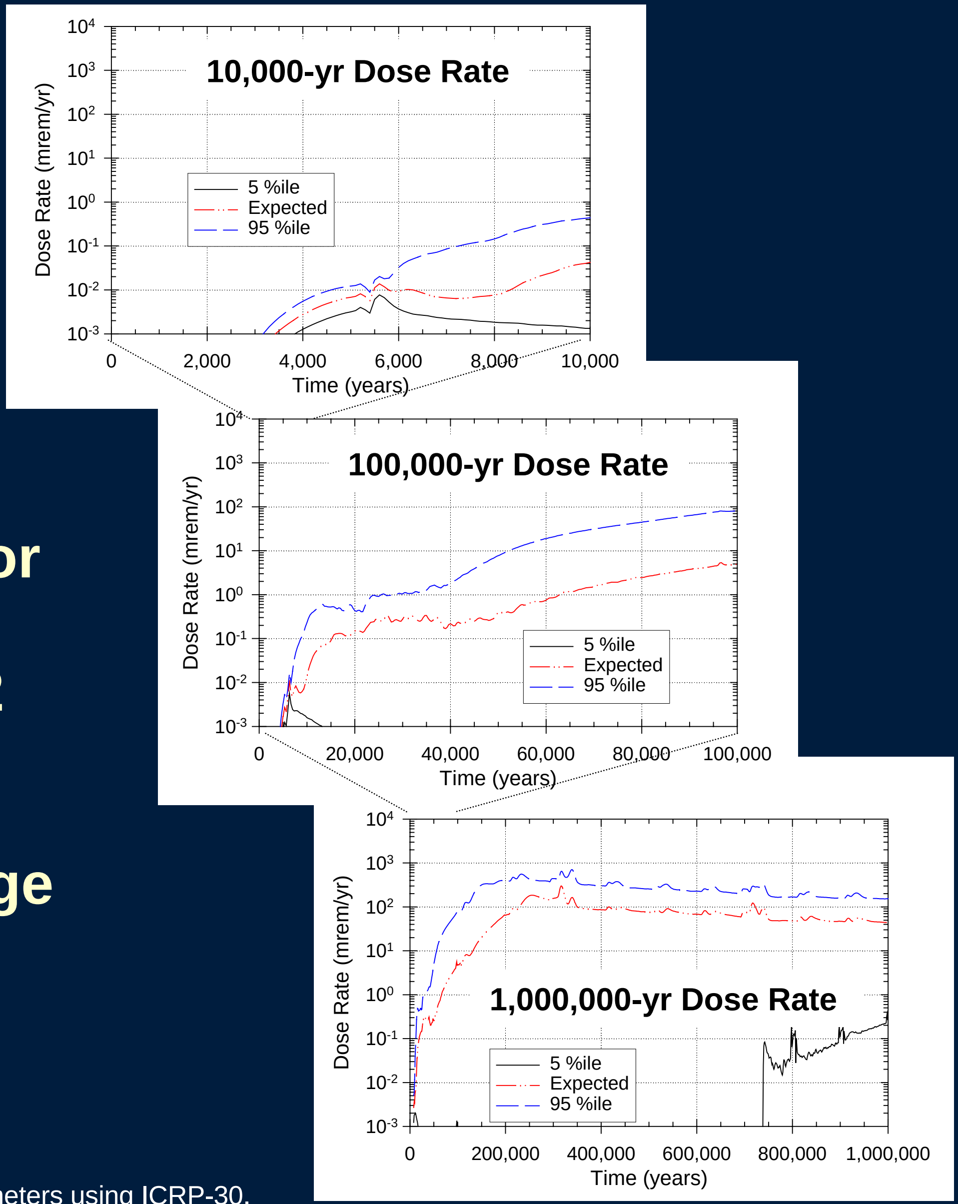
- Infiltration rates could be ~ 3 times higher or lower than base case
- Increased infiltration causes increased percolation, increased seepage, increased number of packages contacted by water
- Causes ~ 10 x greater or less dose over 100,000 years



These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
These results are model-specific and may be insufficient for future adjudicatory licensing proceedings.

TSPA-VA Sensitivity Analyses - Seepage

- Seepage fraction and seepage amount are uncertain functions of percolation
- Causes several orders of magnitude effect on dose for 95% ile. No seepage yields very slow corrosion of C-22
- Only assumed premature failure in absence of seepage

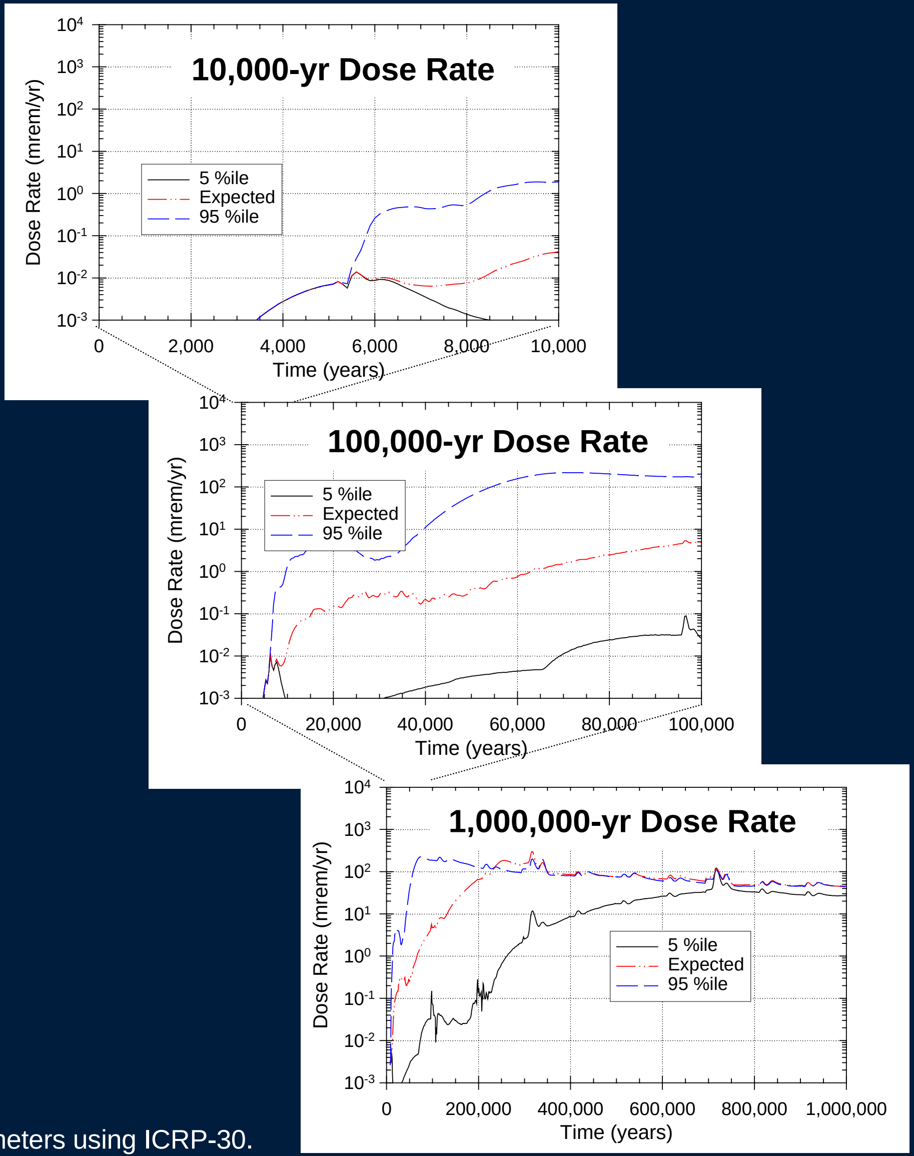


These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
These results are model-specific and may be insufficient for future adjudicatory licensing proceedings.

TSPA-VA Sensitivity Analyses - C-22 Degradation Rate

- **Both mean C-22 degradation rate and variability are uncertain**

- **Wide range of doses (several orders of magnitude) due to number of waste packages failed and fraction of waste package surface degraded**



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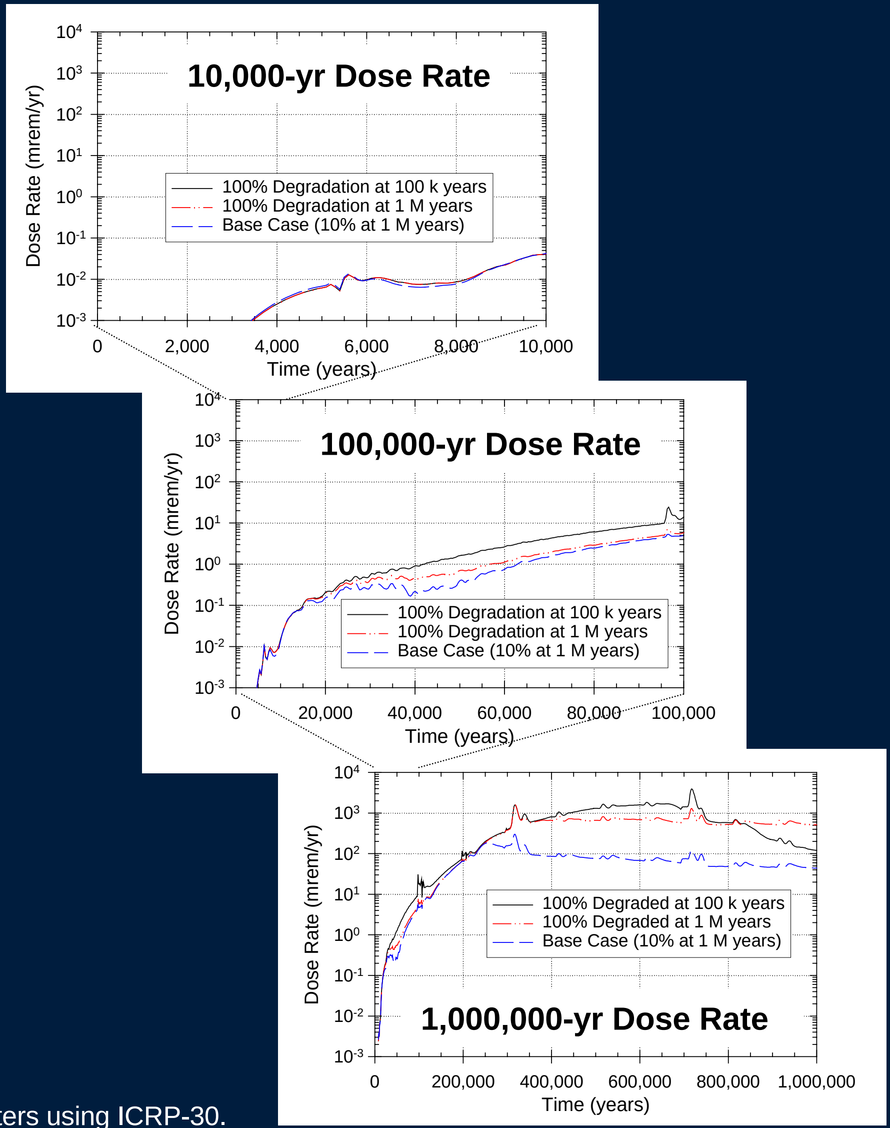
TSPA-VA Sensitivity Analyses - Cladding Degradation

- **Cladding degradation is uncertain**
- **Bounding assumption of all cladding failed increases early doses by ~ 50**
- **At late time, Np doses controlled by cumulative inventory exposed and advective flux**



These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
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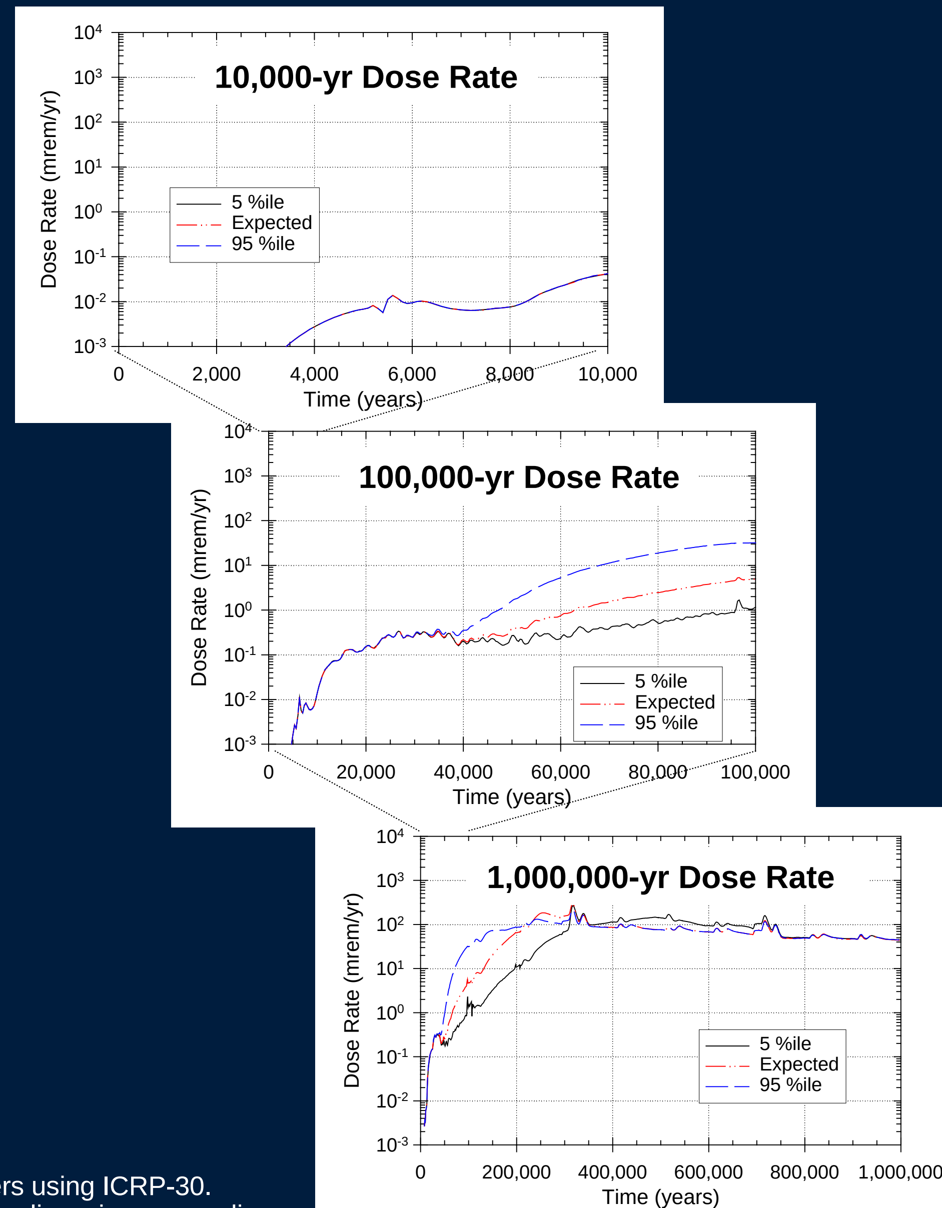
TSPA-VA Sensitivity Analyses - Np Solubility

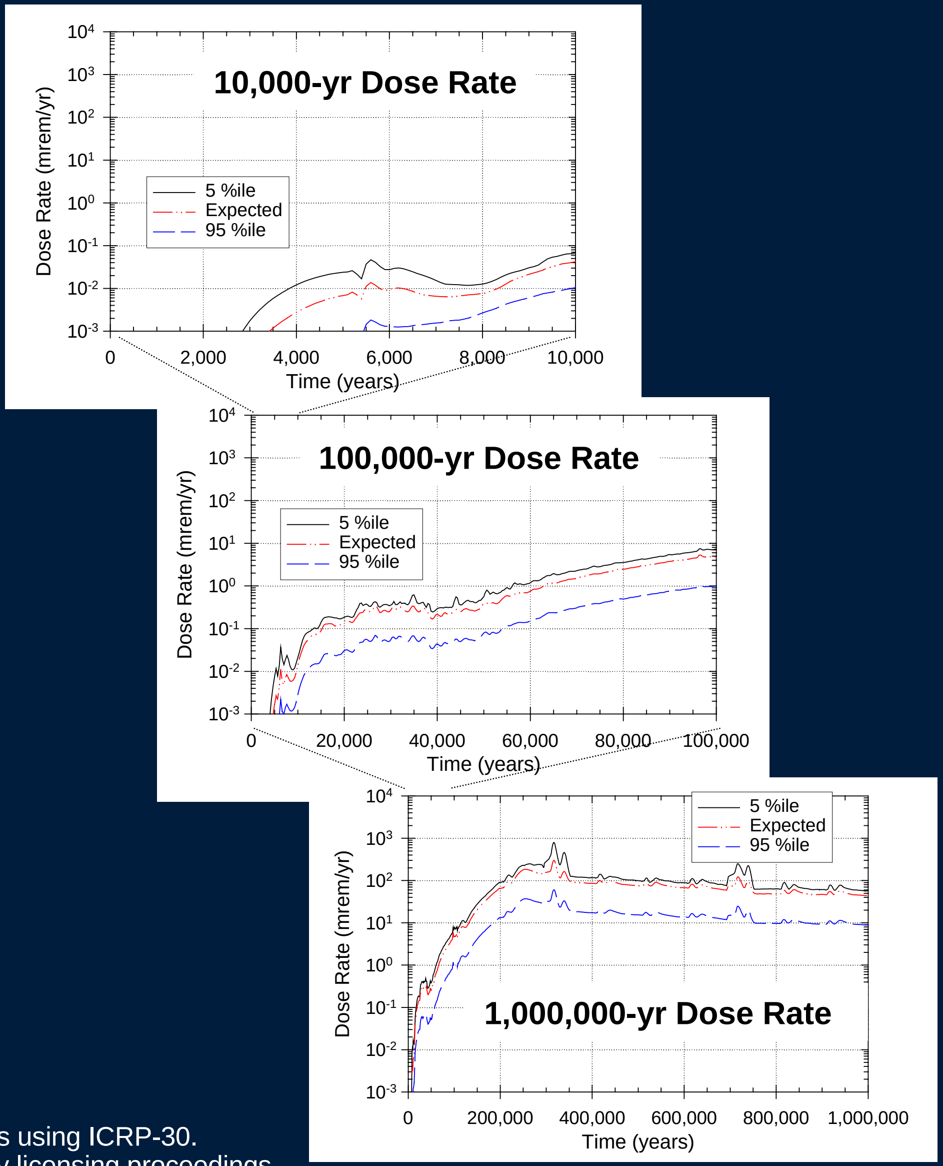
- Np solubility spans several orders of magnitude
- At times < 50,000 years, Tc doses dominate
- Causes ~ 10 x greater or less dose over 100,000 years
- At late time Np doses controlled by cumulative inventory exposed and advective flux



These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
These results are model-specific and may be insufficient for future adjudicatory licensing proceedings.

TSPA-VA Sensitivity Analyses - Saturated Zone Dilution

- **Saturated zone dilution varies from 1-20**
- **"Expected" value ~ 2**
- **Effect is linear**



These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
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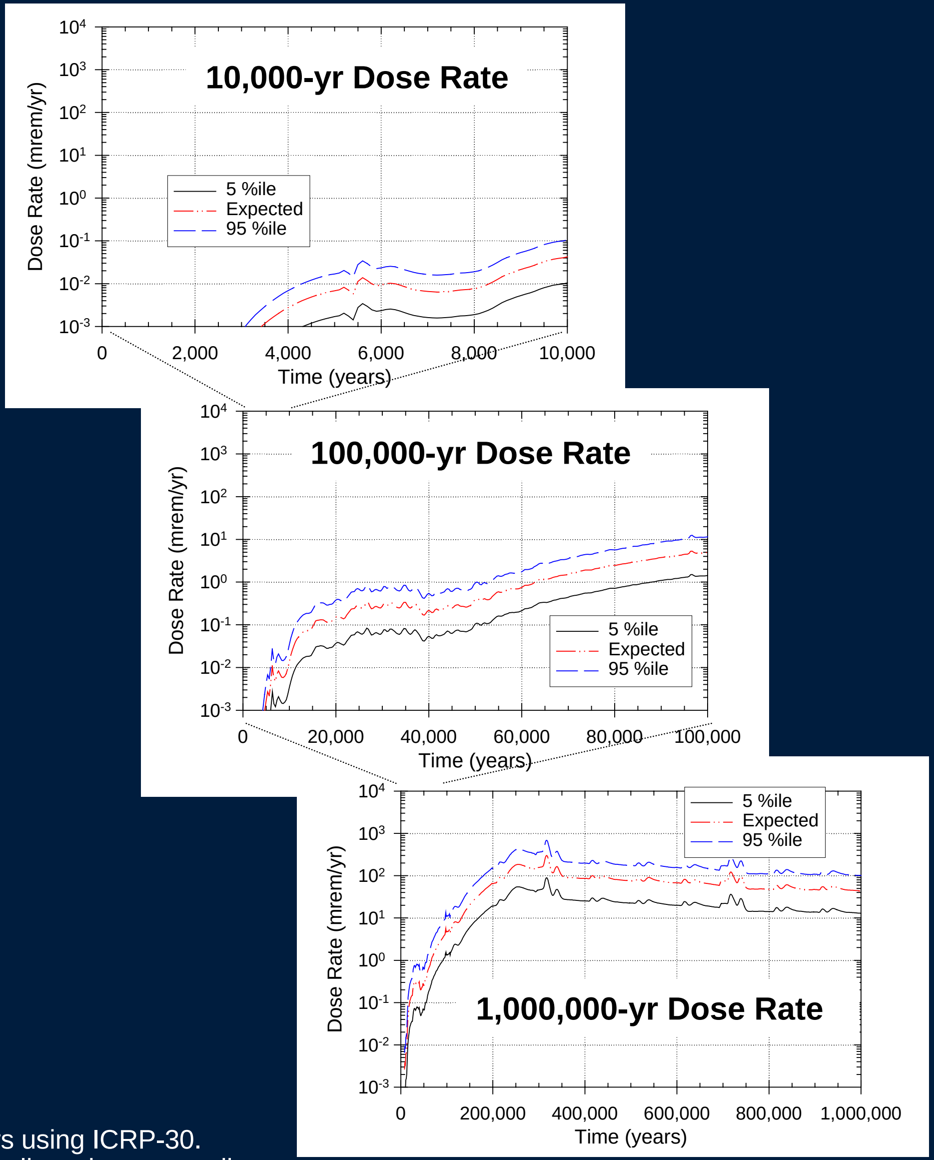
TSPA-VA Sensitivity Analyses - Dose Conversion Factor

- **Dose conversion factor ~ factor of 10 from 5th to 95th % ile**
- **Effect is linear**



These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
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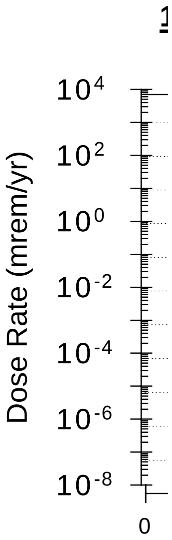
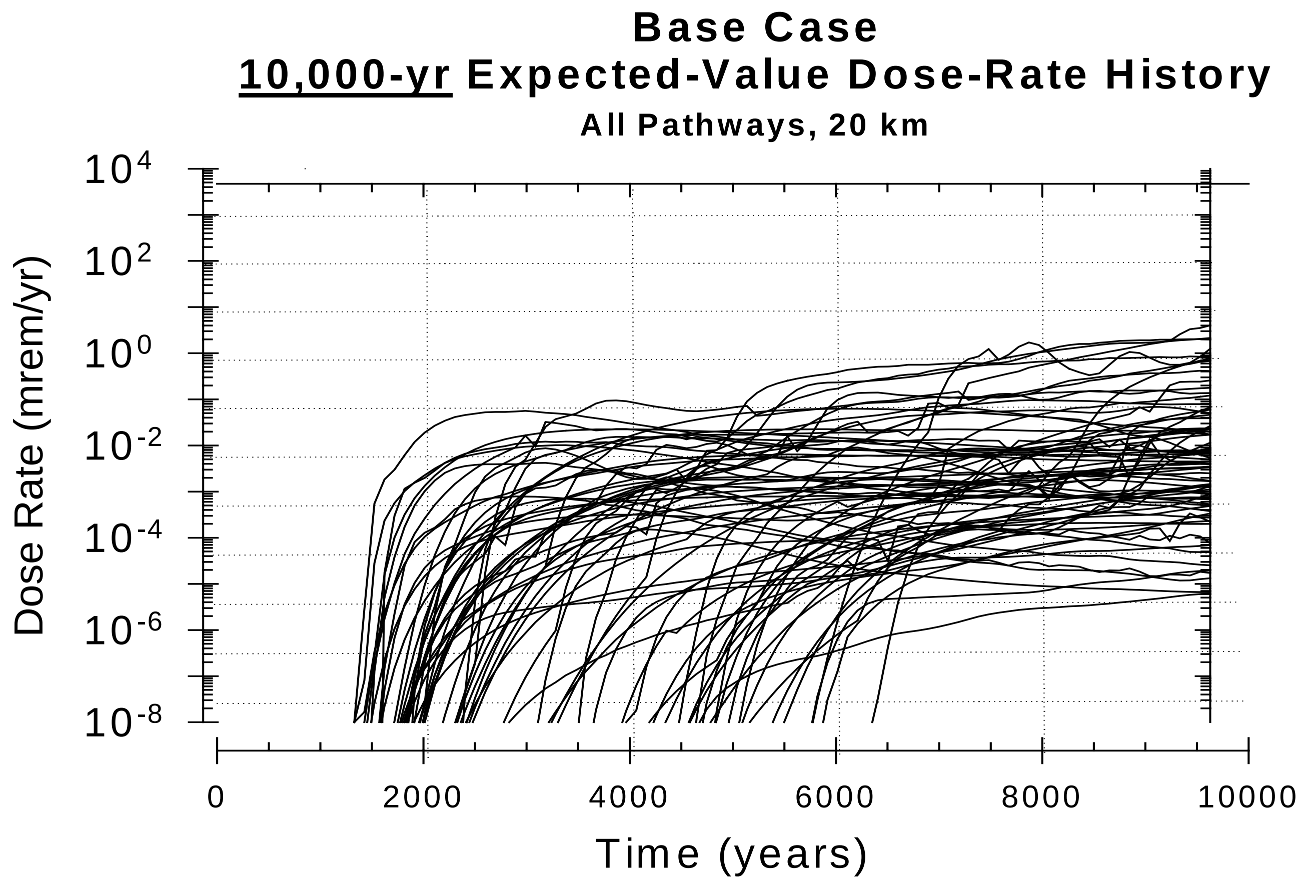
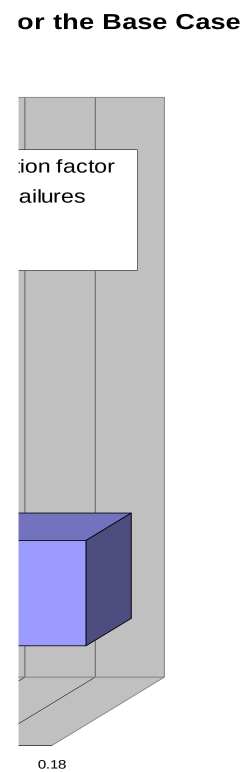
TSPA-VA Uncertainty Analysis

- Run TSPA-VA base case model in a Monte-Carlo fashion, sampling from all uncertain parameters simultaneously
  - Conduct analyses over 10,000; 100,000; 1,000,000 years
- Examine suite of results
  - Scatter plots
  - Regression analyses
  - Contributors to variance
- Assist in identifying significance of principal factors in repository safety strategy

TSPA-VA Uncertainty Analysis and Principal Factors - 10,000 Years







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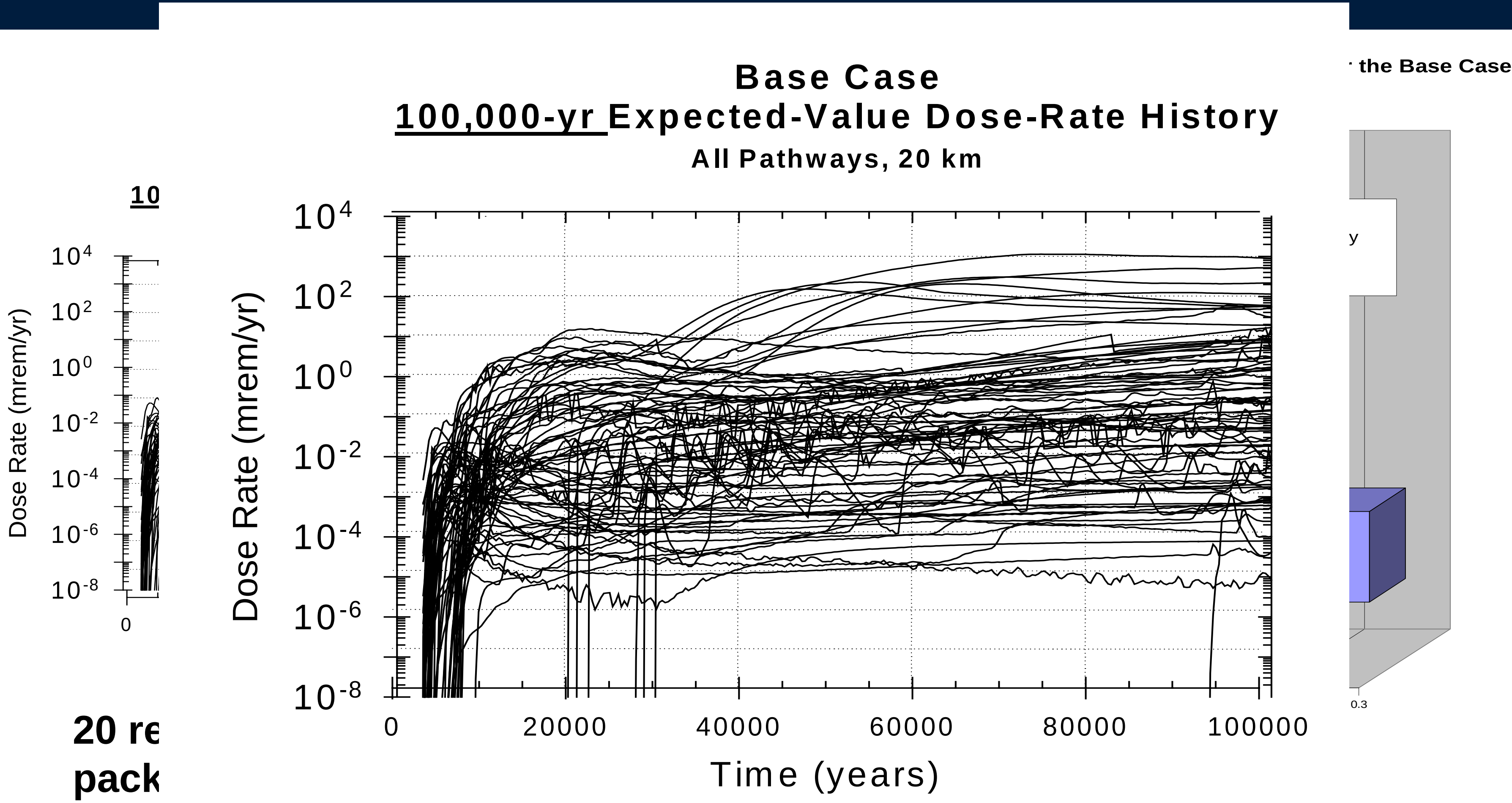
These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
These results are model-specific and may be insufficient for future adjudicatory licensing proceedings.

TSPA-VA Uncertainty Analysis and Principal Factors - 100,000 Years



These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
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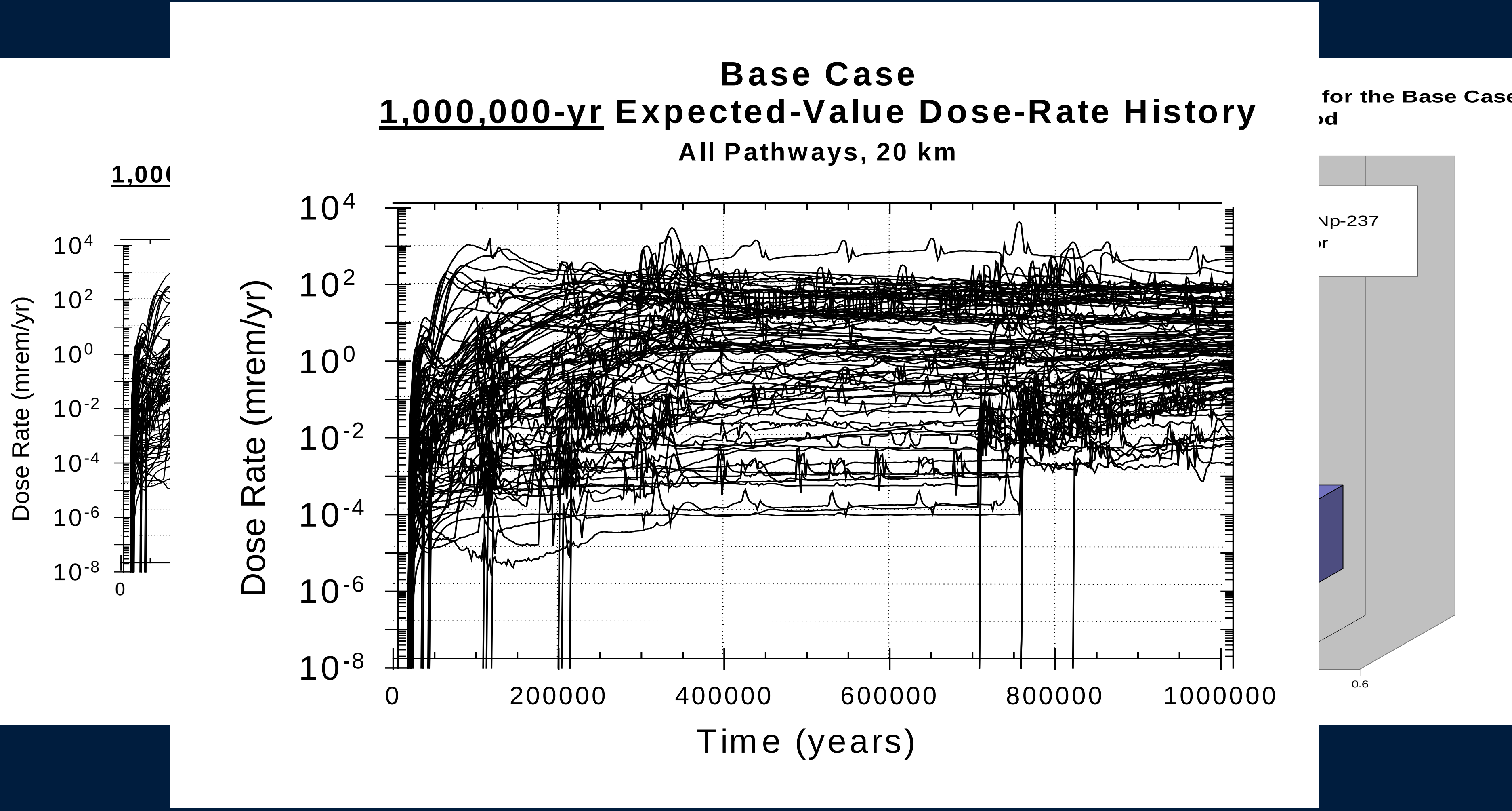
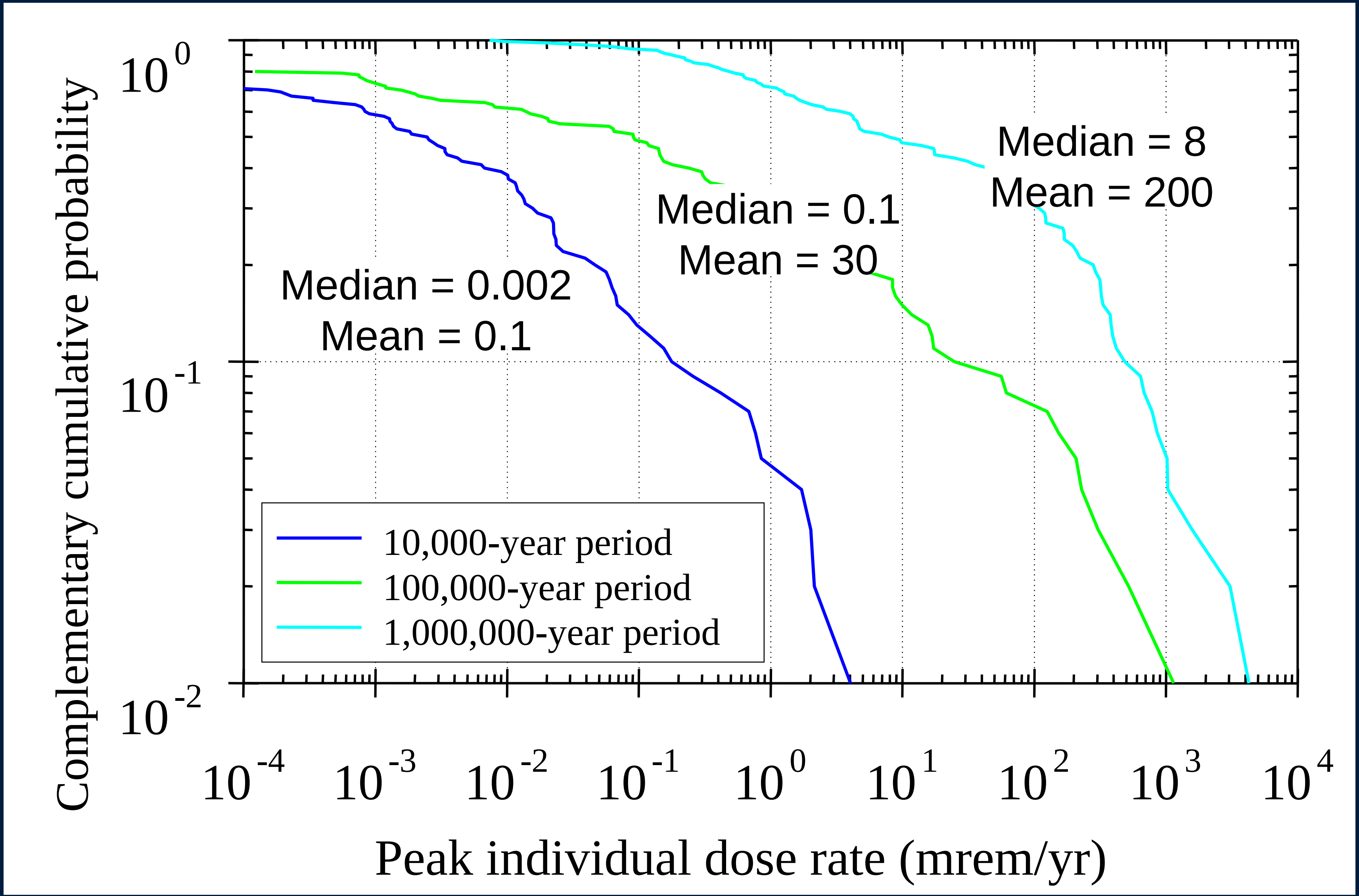
TSPA-VA Uncertainty Analysis and Principal Factors - 1,000,000 Years



These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
These results are model-specific and may be insufficient for future adjudicatory licensing proceedings.

Base Case CCDFs of Peak Dose Rate



These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
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Significance of Uncertainty in Principal Factors on Post Closure System Performance

Attributes of the Repository Safety Strategy	Principal Factors	Significance to 10,000 Years	Significance from 10,000 to 100,000 Years	Significance from 100,000 to 1,000,000 Years
Limited Water contacting waste packages	Precipitation and infiltration of water into the mountain	M	M	M
	Percolation to depth	M	M	M
	Seepage into drifts	H	H	M
	Effects of heat and excavation on flow	L	M	M
	Dripping onto waste package	L	M	M
	Humidity and temperature at waste package	M	L	L
Long waste package lifetime	Chemistry on waste package	M	M	M
	Integrity of outer waste package barrier	M	L	L
	Integrity of inner waste package barrier	H	H	H
Low rate of release of radionuclides from breached waste packages	Seepage into waste package	M	M	M
	Integrity of spent fuel cladding	H	H	M
	Dissolution of UO_2 and glass waste-form	L	M	M
	Solubility of Np-237	L	M	M
	Formation of radionuclide-bearing colloids	L	M	M
	Transport within and out of waste package	M	M	M
Radionuclide concentration reduction during transportation from the waste packages	Transport through unsaturated zone	M	M	L
	Transport in saturated zone	M	M	M
	Dilution from pumping	M	M	M
	Biosphere transport uptake	M	M	M

Significance of Uncertainty in Principal Factors on Post Closure Performance - Legend

Significance defined by using sensitivity/uncertianty analyses

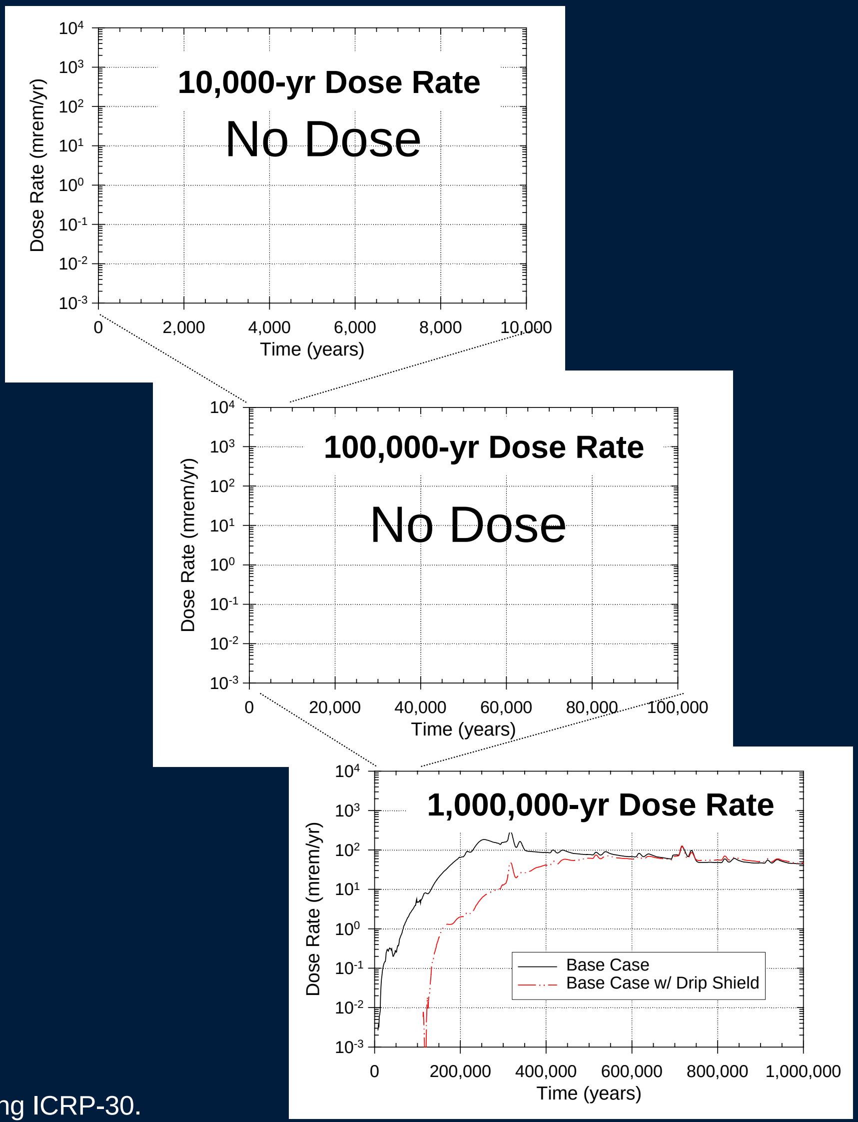
- **H = High significance = Uncertainty in principal factor can lead to > 100 time increase or decrease in peak dose rate from mean value**
- **M = Medium significance = Uncertainty in principal factor can lead to 10 to 100 time increase or decrease in peak dose rate from mean value**
- **L = Low significance = Uncertainty in principal factor can lead to < 10 time increase or decrease in peak dose rate from mean value**

TSPA-VA Design Option Sensitivity Analyses

- Uncertainty in performance assessments can be reduced by conducting additional scientific investigations or adding features to enhance design
- Two design options have been investigated in VA
  - Drip shield placed over waste package
  - Ceramic coating on waste package
- Additional design alternatives have been investigated in the draft EIS (Dixon/Morton briefings)
- Additional design enhancements have been identified and qualitatively evaluated in VA (Baily/Voegele briefings)

TSPA-VA Design Option Analyses - C-22 Drip Shield

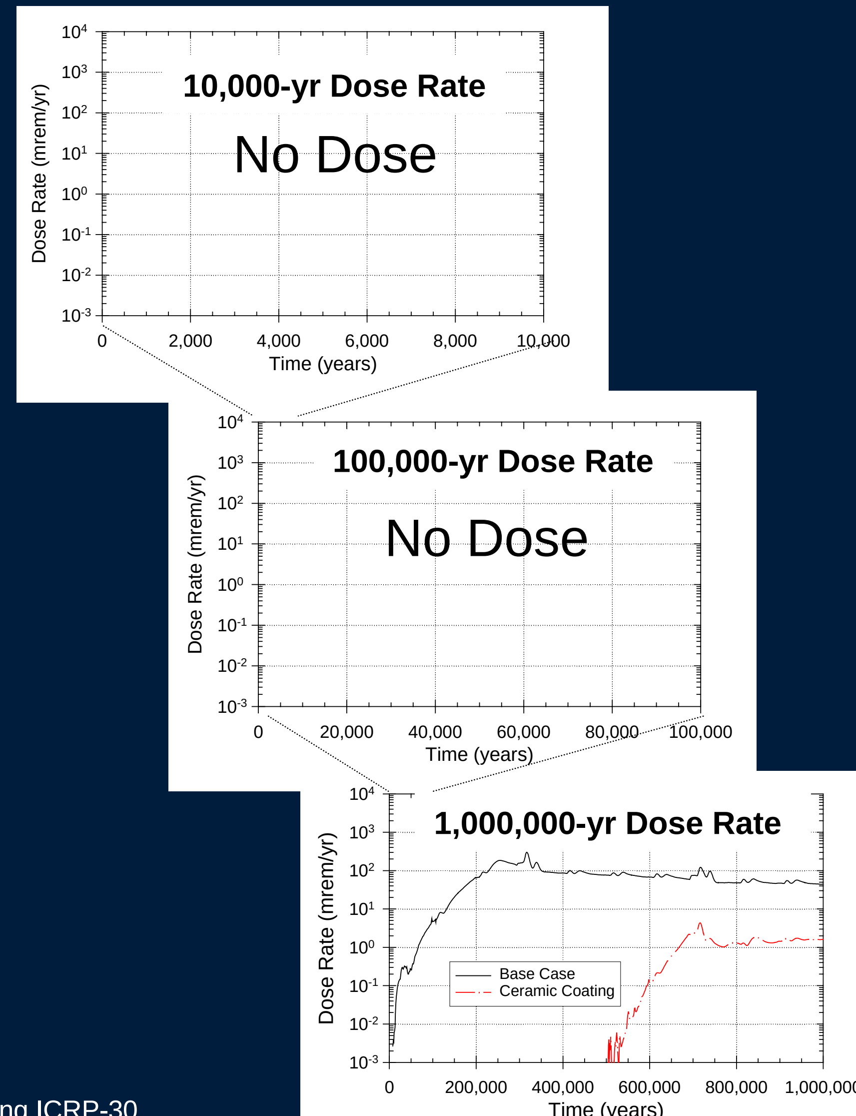
- 2-cm C-22 drip shield degrades analogously to C-22 inner waste package
- Mild steel degrades under drip shield by humid air corrosion
- C-22 drip shield must develop holes before seepage can encounter waste package
- C-22 waste package will “fail” at same location as C-22 drip shield
- No waste package failures for ~100,000 years



These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
These results are model-specific and may be insufficient for future adjudicatory licensing proceedings.

TSPA-VA Design Option Analyses - Ceramic Coating

- Ceramic coating protects underlying mild steel from humid air or aqueous corrosion
- Ceramic coating protected by back fill
- Ceramic coating reduces degradation of mild steel
- Ceramic coating may fail by “blisters” at several 100,000 years
- Mild steel and C-22 under the ceramic coating continue to provide protection



These analyses represent an all pathways individual dose rate at 20 kilometers using ICRP-30.
These results are model-specific and may be insufficient for future adjudicatory licensing proceedings.

Summary and Conclusions

- "Expected" behavior of Yucca Mountain VA Reference Design
  - < 0.1 mrem/yr to 10,000 years
  - < 10 mrem/yr to 100,000 years
  - < 300 mrem/yr to 1,000,000 years
- Uncertainty in "expected" behavior
  - ~ 0 to 10 mrem/yr to 10,000 years
  - ~ 0 to 1,000 mrem/yr to 100,000 years
  - ~ 0.01 to 3,000 mrem/yr to 1,000,000 years
- Significant factors affecting performance include
  - degradation rate of waste package
  - seepage into drifts

Performance Allocation for Principal Factors and Design Options

Repository System Attributes	Principal Factors and Design Options	Potential Importance to Postclosure Performance[1]
Limited Water contacting waste packages	Precipitation and infiltration of water into the mountain	M
	Percolation to depth	M
	Seepage into drifts	H
	Effects of heat and excavation on flow	M
	Dripping onto waste package	M
	Humidity and temperature at waste package	M
	Water diversion by drip shield + backfill	H
Long waste package lifetime	Chemistry of water on waste package	M
	Integrity of outer carbon steel waste package barrier	M
	Integrity of inner corrosion-resistant waste package barrier	H
	Ceramic waste package coating	H
Low rate of release of radionuclides from breached waste packages	Seepage into waste package	M
	Integrity of spent fuel cladding	H
	Dissolution of uranium oxide and glass waste forms	M
	Neptunium solubility	M
	Formation of radionuclide-bearing colloids	M
	Transport through and out of waste package	M
Radionuclide concentration reduction during transport from the waste packages	Transport through unsaturated zone	M
	Transport in saturated zone	M
	Dilution from pumping	M
	Biosphere dilution	M