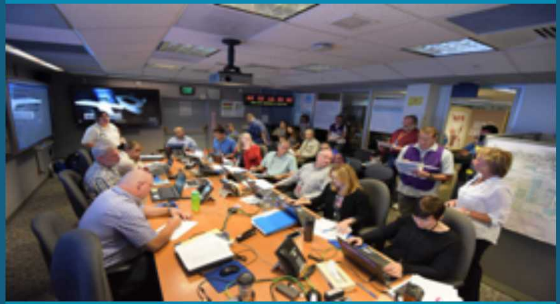
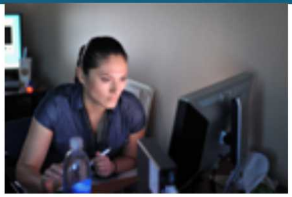
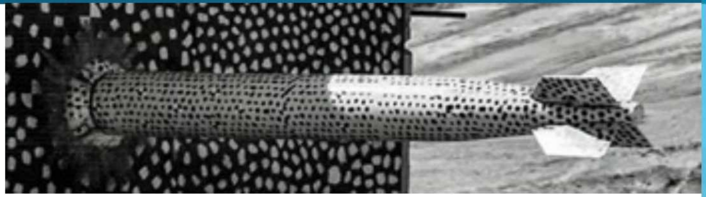
SAND2019-5254PE

L6: Safety Function Approach as Applied to EBS Design







PRESENTED BY

Edward N. Matteo

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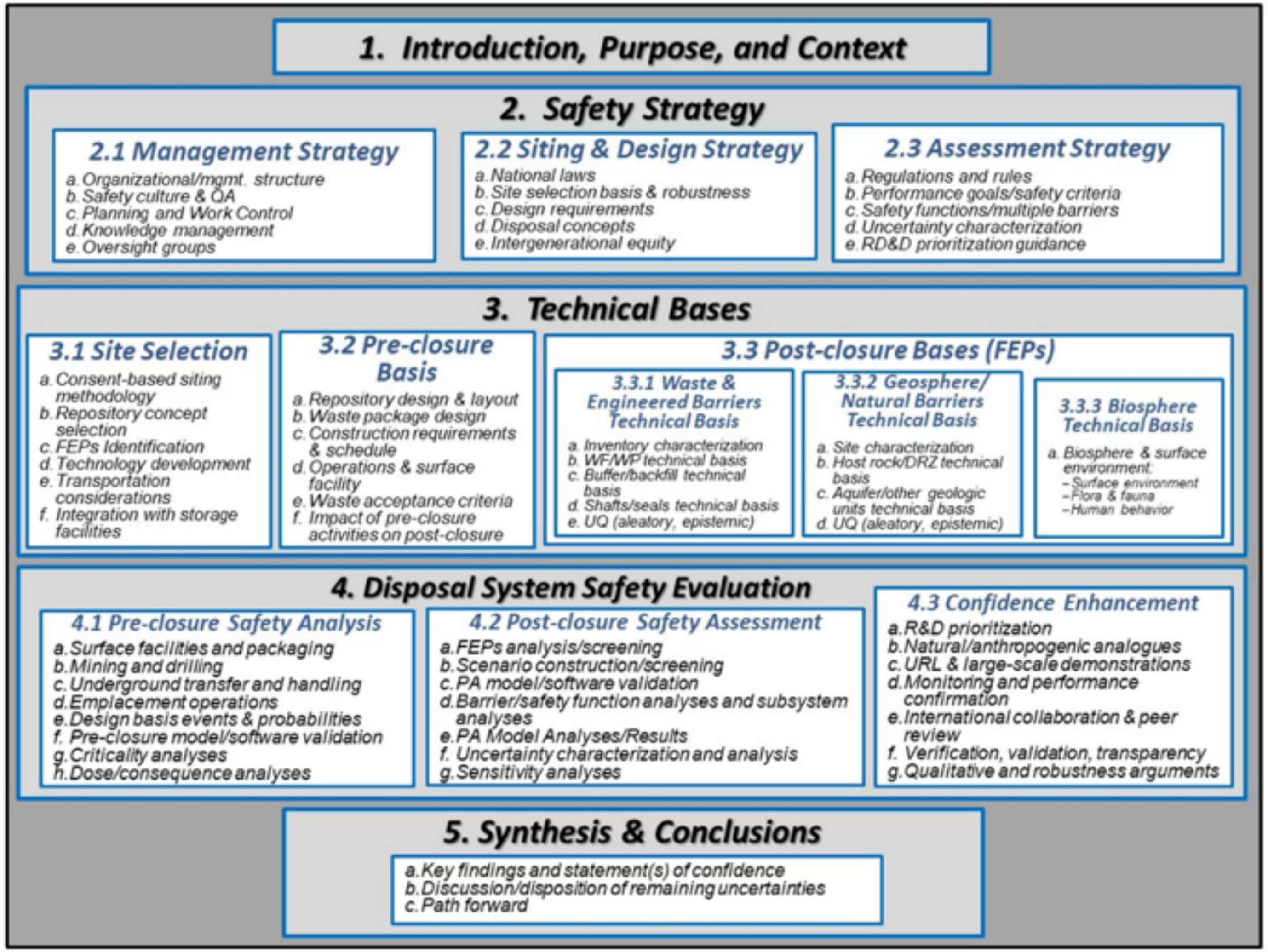
Repository Science Basics, the Safety Case

Waste Isolation is "measured" by the Safety Case.

The **Performance Assessment** is a critical outcome of the Safety Case.

Elements of the Safety Case

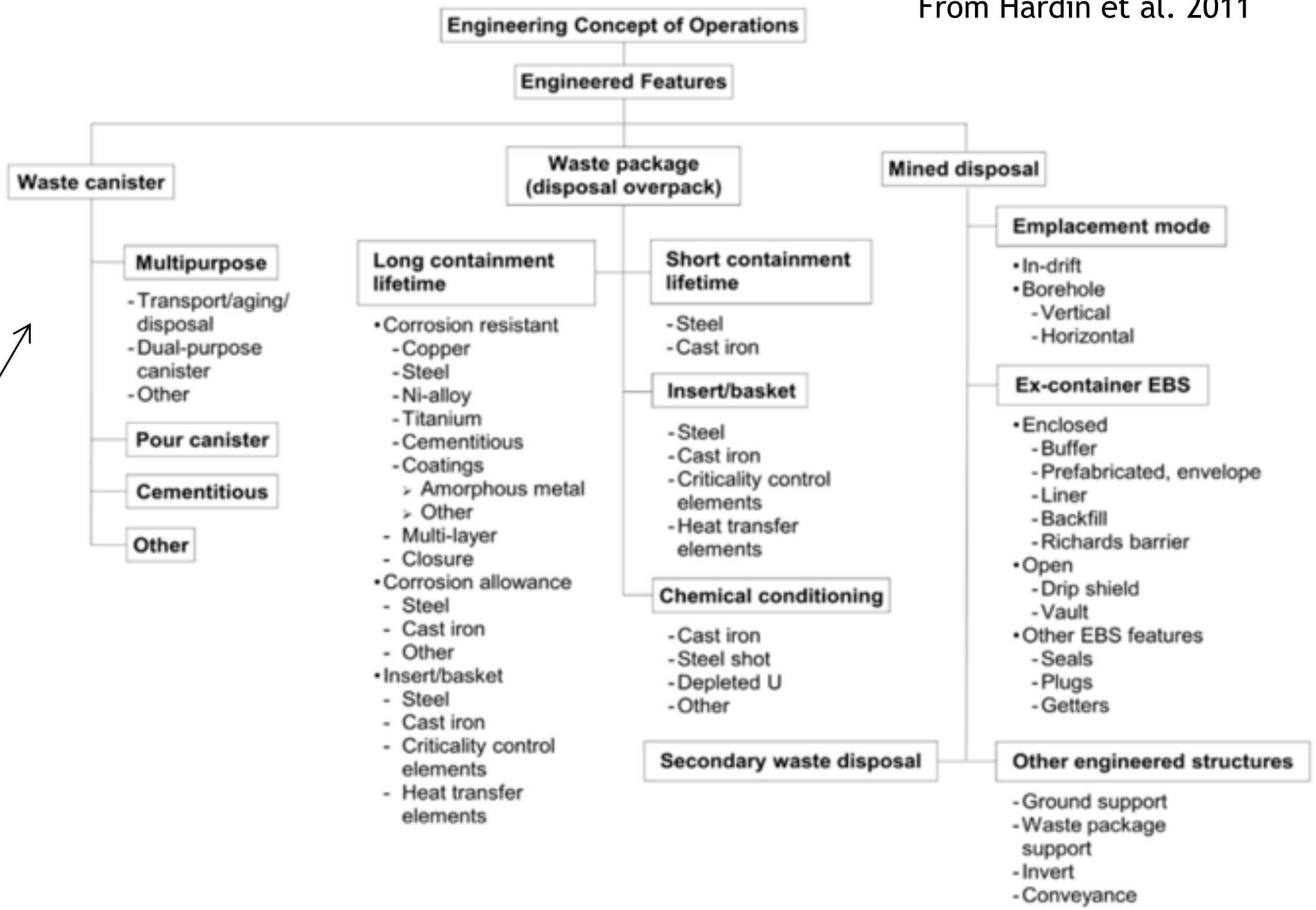


The Preliminary Design Concept, is a product of Inventory and the Natural System

From Hardin et al. 2011

Inventory
- Dimensions
- Quantity
- Thermal output

Design Concepts
- Packaging and repository layout



Disposal Media

<u>The preliminary design concept originates with the Inventory</u>:

-waste form, quantity, dimensions of waste package (WP)

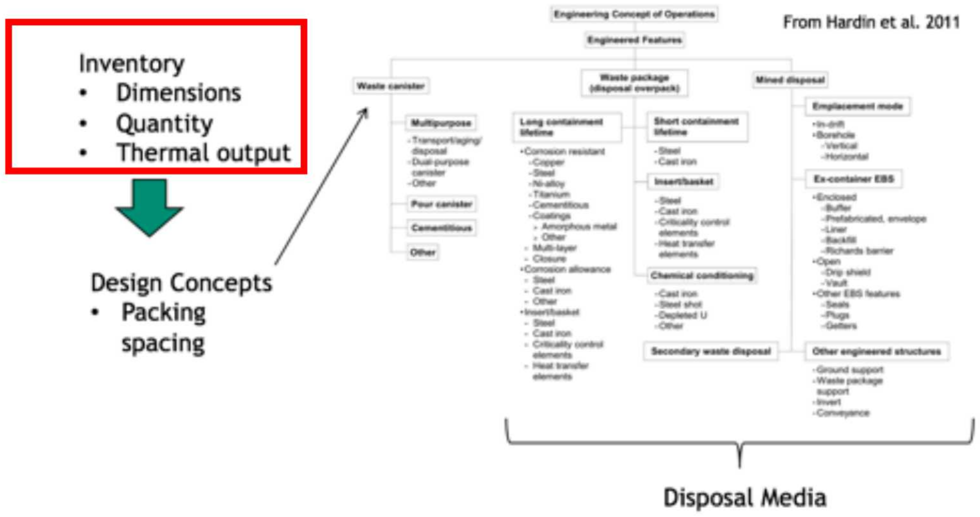
<u>Ratio of WP to thermal output</u>

-determines WP spacing -> repository footprint -> site selection?

e.g., in the US domal salt formations are well-suited to a co-mingled US repository, but were in consideration for a defense waste only repository

-determines WP spacing -> repository footprint -> impact on EBS/PA

Minimizing excavation volumes can be a design consideration, esp. in low permeability host media, where release scenarios may be driven by release along excavation pathways



Generic Disposal Concepts for HLW in Crystalline Rock:
Identify Candidate Concepts for Evaluation

Objectives for Review: safety, cost, portability

Disposal Concept ≡ WF + geologic setting + concept of ops.

- **Waste form:**
  - Mostly HLW glass, low heat output, SS pour canisters
  - DSNF of various types, pre-canistered
- **Geologic setting:**
  - Competent rock (UCS > excavation stresses), thermally resistant (200°C), conductive faults/fractures, groundwater (or saltwater) saturated
  - Depth 500 m (boiling temp. >>200°C), shaft or ramp accessible
- **Concept of operations?**

Generic Disposal Concepts for HLW in Crystalline Rock:
Defense Waste Characteristics

- Low-thermal (up to 1 kW per 3- or 5-m canister)
- Long-lived radionuclides (~10^6-year assessment)
- Large numbers of canisters (data from Carter et al. 2012)
  - 3,542 DSNF (99.4% < 1 kW in 2030)
  - 23,032 HLW (SRS, Hanford & Idaho; all < 1 kW)
- Small canisters (mostly 18- and 24-inch diameters)
  - Neglecting Naval SNF which is most similar to CSNF
  - (Assume Idaho calcine is package in standardized canisters.)
- Relatively lightweight (canister + contents; no overpack)
  - DSNF 5,000 to 10,000 lb
  - HLW 5,512 yto 9,260 lb
- Material: stainless steel (welded, no heat treat, sensitized)
- All require some shielding (±)

Generic Disposal Concepts for HLW in Crystalline Rock:
Crystalline Rock Geologic Settings

Competent Rock

- Only minor concrete/shotcrete
- Large openings possible
- Dimensional stability

Brackish/Briny Formation Fluid

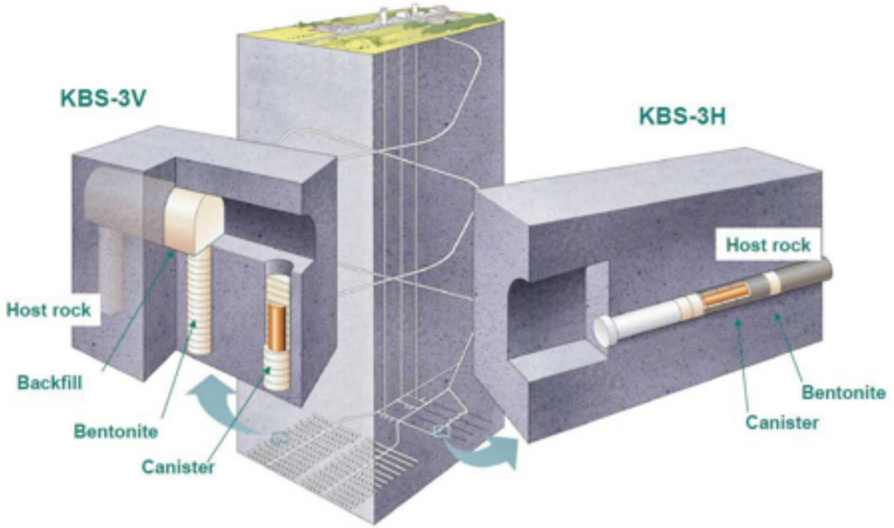
Fracture/Fault Permeability

Hydraulic Gradients Present

- Even small gradients require low-k backfill

Ramp Access

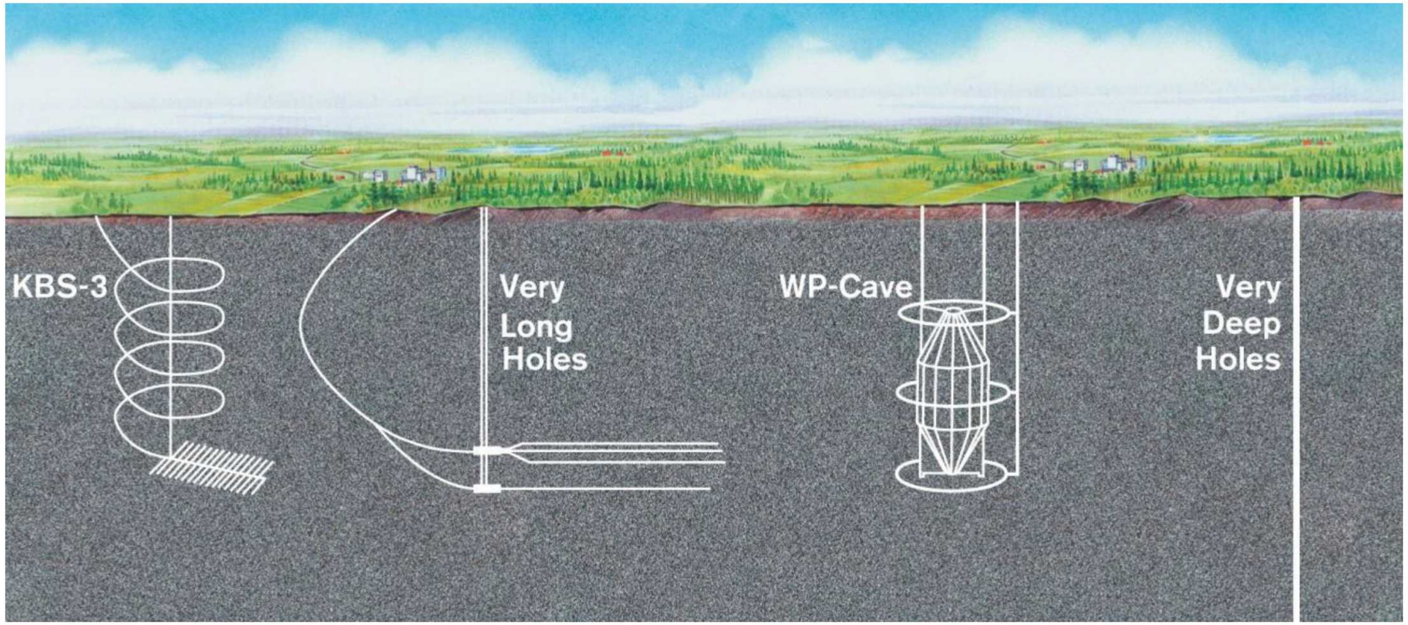
- Any conveyance; heavy loads > 100 MT



Generic Disposal Concepts for HLW in Crystalline Rock: "Optioneering" KBS-3 (1/2)

Emplacement mode

- KBS-3V vs. KBS-3H
- WP-Cave and deep borehole
- In-drift emplacement



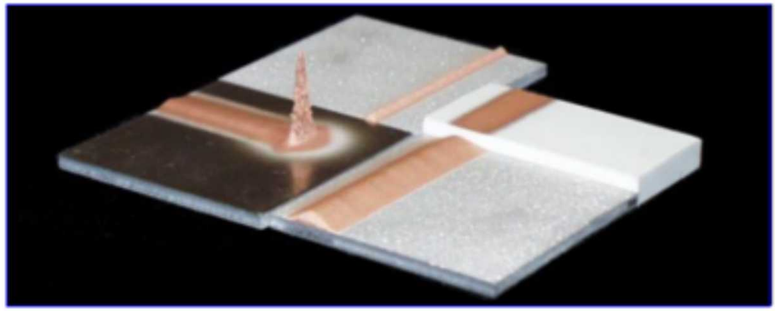
Source: SKB International Report 166: Spent Fuel Geologic Repository Consultation. Prepared for Savannah River Nuclear Solutions, LLC. Final Report, September, 2013.

Generic Disposal Concepts for HLW in Crystalline Rock: "Optioneering" KBS-3 (1/2)

Canister
- Cu canister with a steel or cast iron insert
- Cu canister made by hot isostatic pressing or cold-spray
- E-beam, friction-stir welding
- Steel, ceramic (Al_2O_3), or Ti-alloy canister
- Coatings (amorphous metals, cerramic)

Buffer materials
- Cementitious, sandstone, clay-sand

Super-containers



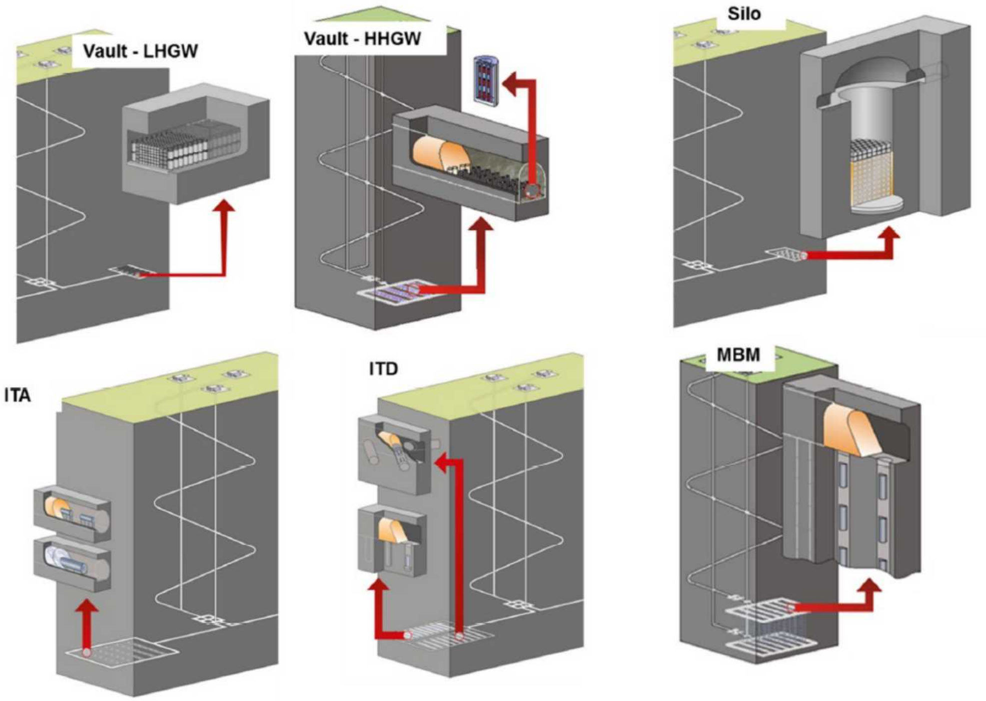
Examples of Materials Successfully Deposited at Sandia

Active Braze Alloy	Fe_3Pt	Polymer
Aluminum	Molybdenum	StelCar
Aluminum Bronze	Monel	Tantalum
Copper	80Ni/20Cr	Tin
304 Stainless Steel	NiCrAlY	Titanium
420 Stainless Steel	$NiCr\text{-}Cr_3C_2$	WC-Co (nanophase)

- **Construction methods**
  - TBM vs. drill and blast, shaft vs. ramp, buffer/backfill and closure options
- **Emplacement equipment**
  - Transporters, hoists, water/air bearings, tractor-pushers, shielding
- **Filler materials (molten lead, cement, glass beads)**
- **Rod consolidation**

Generic Disposal Concepts for HLW in Crystalline Rock:
KBS-3 + Other Crystalline Concepts

- **Pinawa (AECL, Canada)**
  - Ti or Cu packaging
  - Vertical-borehole emplacement
  - Buffer and backfill
  - Clay and/or cement-based
- **Mizunami (PNC, Japan)**
  - KBS-3H and KBS-3V reference
  - Concrete vaults
- **UK (RWM Ltd.) concepts >>>**
  - Vaults, in-drift and borehole
  - Pumpable buffer/backfill



Source: Watson, S. et al. 2014. Disposal Concepts for Multi-Purpose Containers. QRS-1567G-R7 Version 1. Radioactive Waste Management, Ltd., UK.

Generic Disposal Concepts for HLW in Crystalline Rock: NDA/EPRI Options Studies (1/5)

Table B-2
Key features and variants leading to the UNF and HLW disposal Concepts.

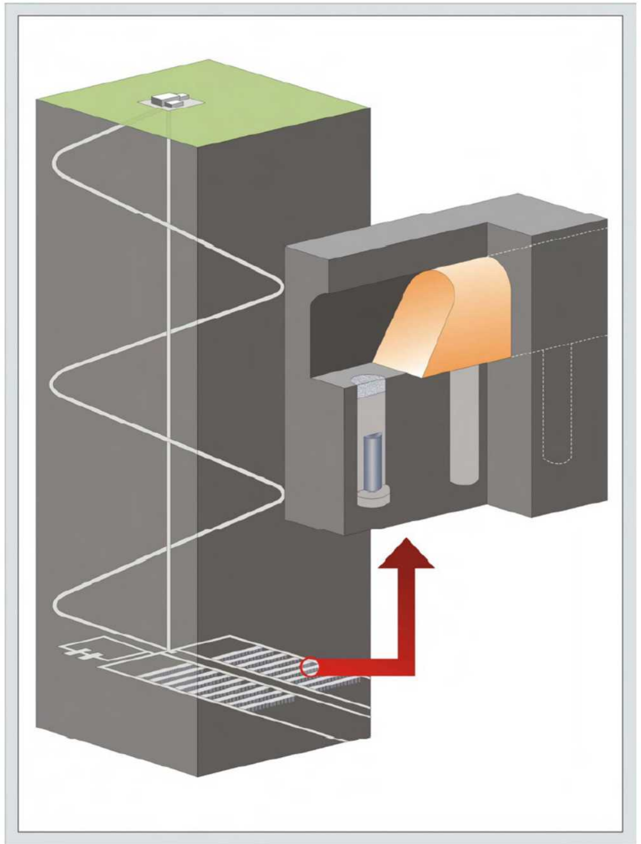
Key Feature	Variants	Concept No.
In-tunnel (borehole)	Vertical borehole	1
	Horizontal borehole	2
In-tunnel (axial)	Short-lived canister	3
	Long-lived canister	4
In-tunnel (axial) with supercontainer	Small working annulus	5
	Small annulus + concrete buffer	6
	Large working annulus	7
Caverns with cooling, delayed backfilling	Steel MPC + bentonite backfill	8
	Steel or concrete/DUCRETE container + cement backfill	9
Mined deep borehole matrix		10
Hydraulic cage	Around a cavern repository	11
Very deep boreholes		12

Sources for this and slides 9 - 13:

EPRI Review of Geologic Disposal for Used Fuel and High Level Radioactive Waste Volume III—Review of National Repository Programs. 1021614. December, 2010.

(After Baldwin, T., et al. 2008. Geological Disposal Options for High-Level Waste and Spent Fuel. Prepared for the UK Nuclear Decommissioning Authority, January, 2008.)

Generic Disposal Concepts for HLW in Crystalline Rock:
NDA/EPRI Options Studies (2/5)

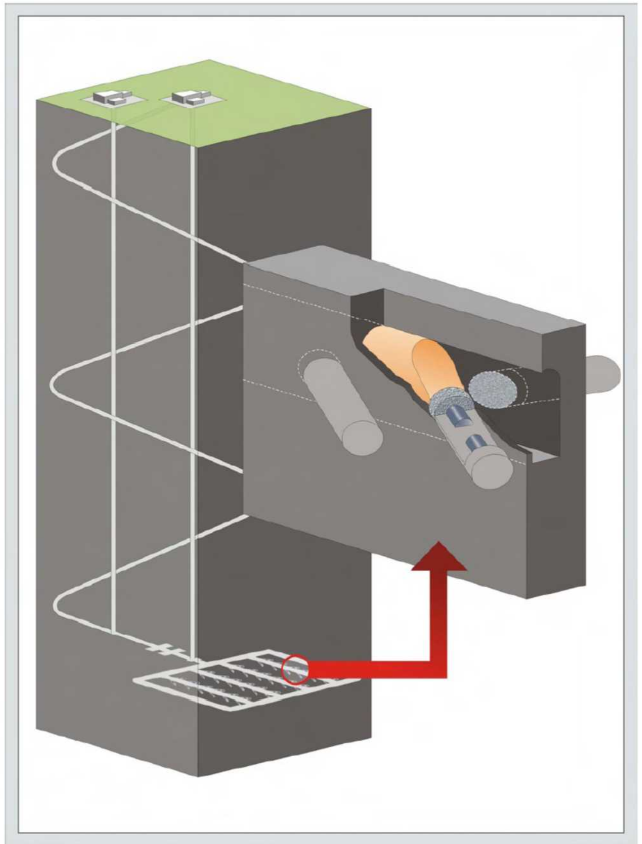


<<< #1

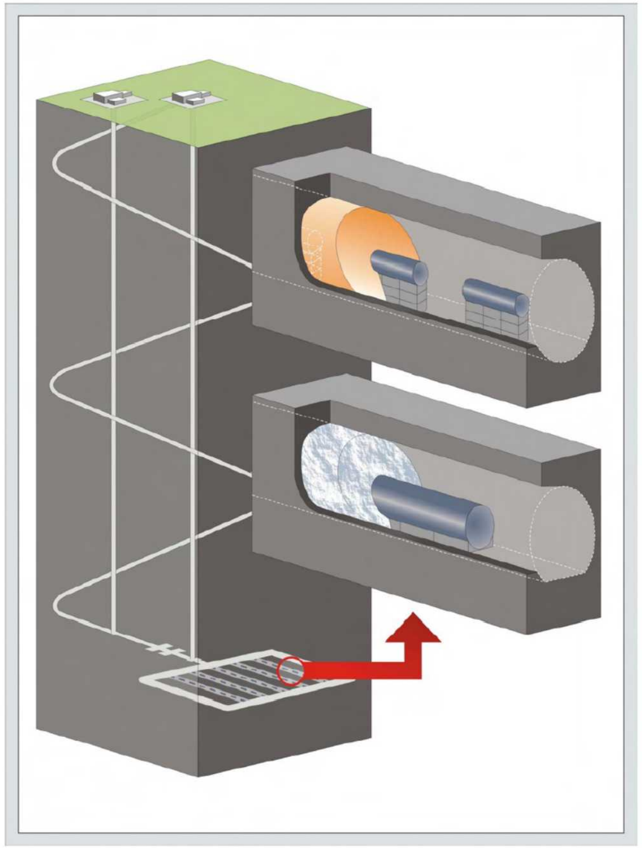
- Vertical borehole, outside DRZ
- Clay-based buffer & backfill
- Long-lived WP (Cu or Ti) for SNF IRF
- Short-lived for glass
- Mature (KBS-3V)

#2 >>>

- Slant/horiz. holes
- Clay-based buffer and backfill
- Developed for clay
- Highly retrievable
- Low maturity



Generic Disposal Concepts for HLW in Crystalline Rock:
NDA/EPRI Options Studies (3/5)



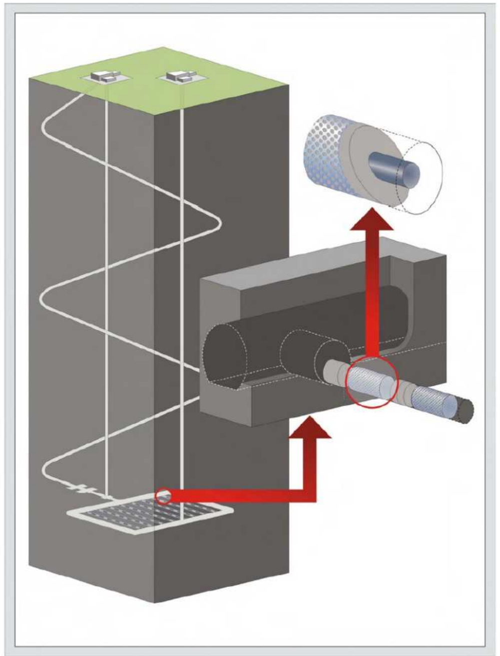
<<< #3

- In-drift axial
- Steel WP
- Thick clay-based buffer
- For relatively dry rock, limited DRZ
- Developed for clay
- Mature for clay, crystalline

<<< #4

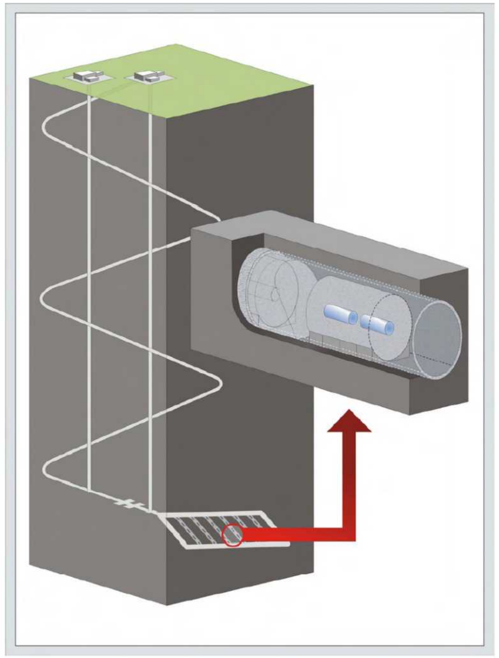
- OPG concept for crystalline (shown for salt)
- Corrosion resistant WP (Cu or Ti)
- Multi-part buffer/backfill
- Pre-fabricated compacted clay buffer
- Smaller packages may be side-by-side in pairs
- Adapt to highly stressed rock
- Mature

Generic Disposal Concepts for HLW in Crystalline Rock:
NDA/EPRI Options Studies (4/5)



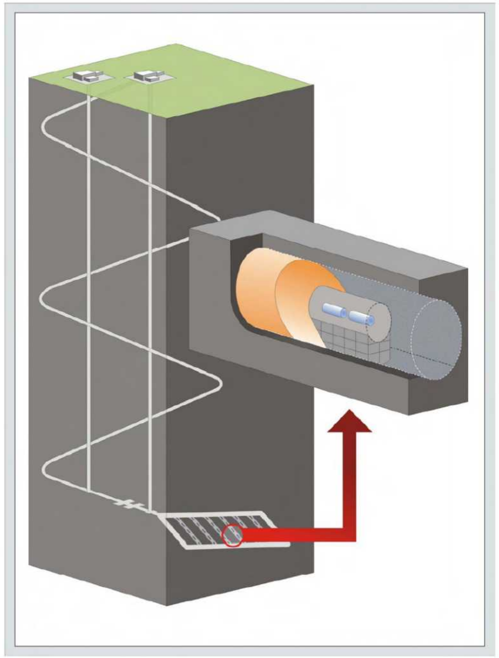
↑ **#5**

- **Supercontainer, small annulus**
- **Corrosion resistant WP**
- **Water/air bearing**
- **Inflow rate critical**
- **Mature (KBS-3H)**



↑ **#6**

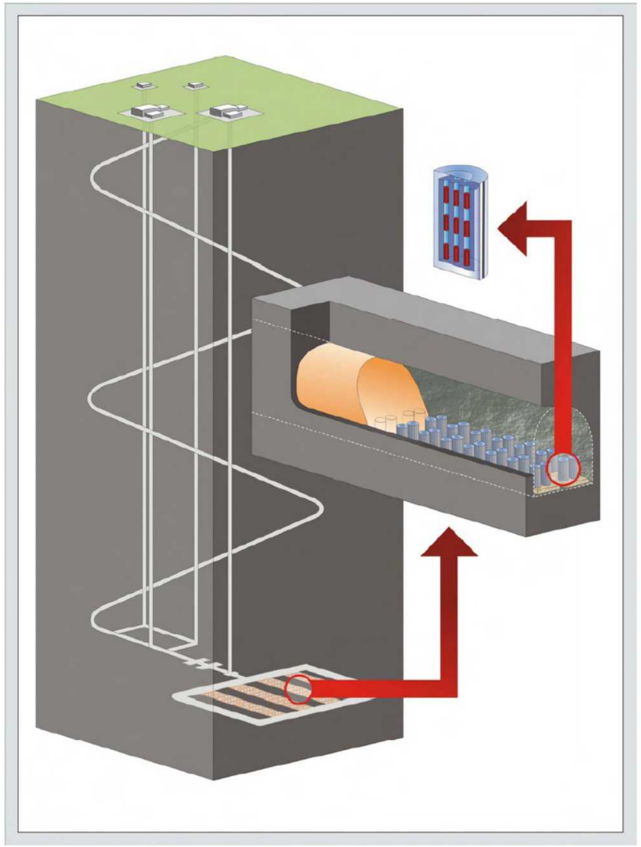
- **Supercontainer with concrete buffer**
- **Long- or short-lived WP**
- **Mature for clay**
- **OPC interactions R&D**



↑ **#7**

- **Supercontainer, large annulus**
- **Corrosion resistant WP**
- **Clay-based buffer and backfill**
- **Low maturity**

Generic Disposal Concepts for HLW in Crystalline Rock:
NDA/EPRI Options Studies (5/5)

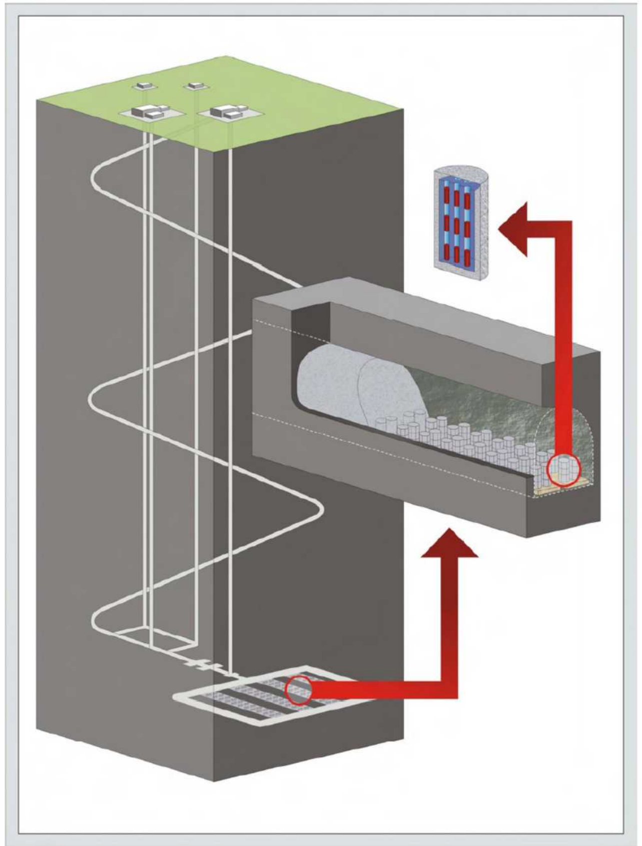


<<< #8

- **Steel MPC, self-shielding**
- **Clay backfill**
- **Extended cooling**
- **Small footprint**
- **Highly retrievable (→300 yr)**
- **Backfilling method?**
- **Low maturity**

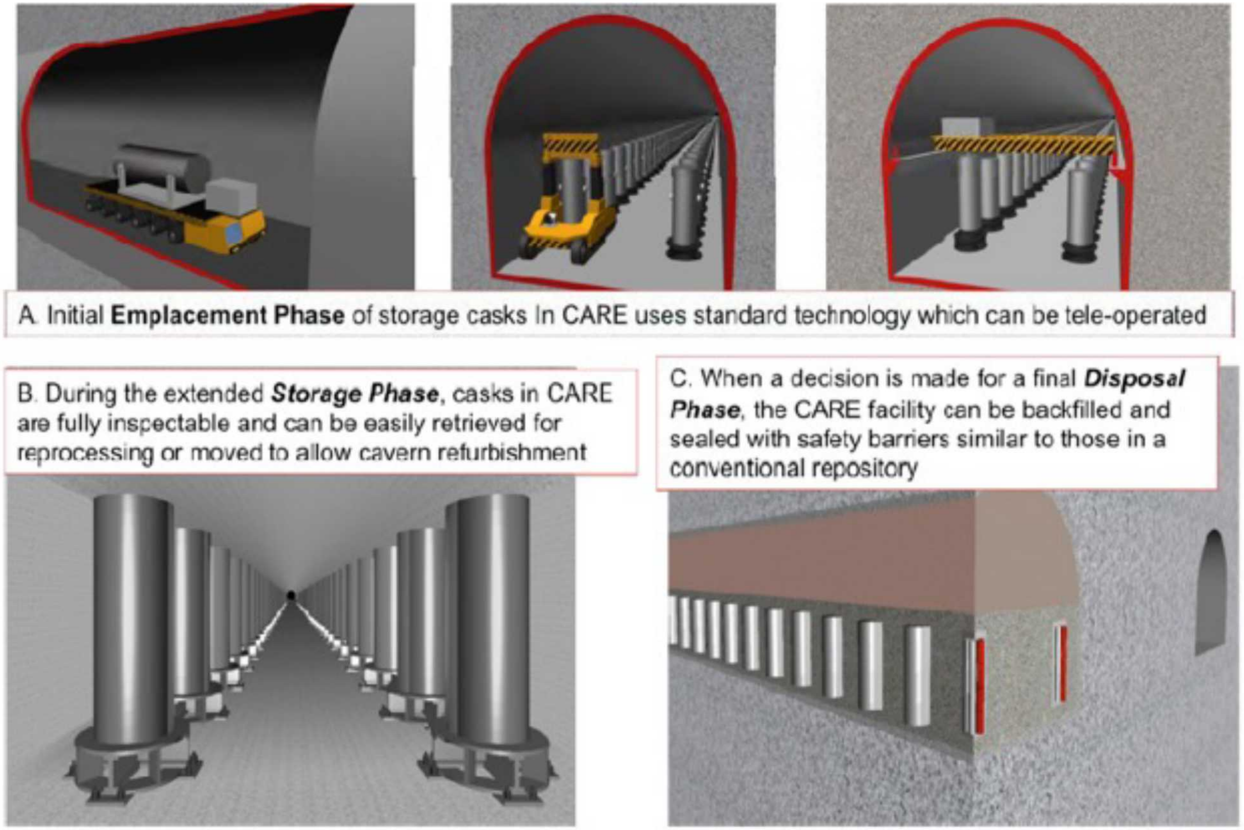
#9 >>>

- **Steel MPC or concrete/DUCRETE casks, self-shielding**
- **Clay or cement backfill (pump-able?)**
- **Highly retrievable**
- **Low maturity**



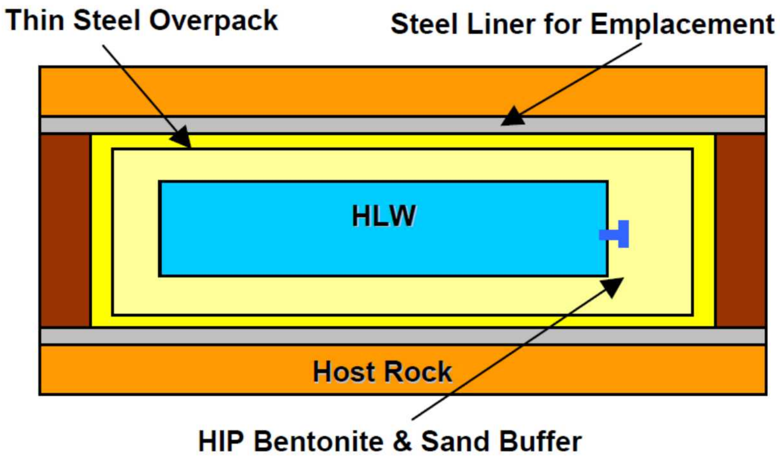
Generic Disposal Concepts for HLW in Crystalline Rock:
Cavern-Retrievable (CARE) Concept

- After McKinley et al. (2008)
- Combine long-term retrievable storage
- Highly competent rock (relatively dry?)
- Self-shielded WPs
- Extended cooling
- Small footprint
- Highly retrievable (→300 yr)

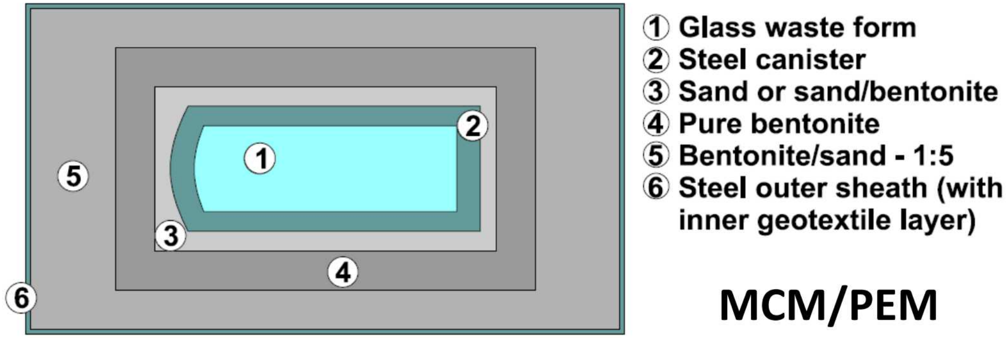


Generic Disposal Concepts for HLW in Crystalline Rock: "2nd Generation" Concepts (McKinley, Apted, et al.)

- "Integrated waste package" >>>
  - Pressed buffer in steel overpack
- **"Multi-component module"**
  - Use of sand-clay mixtures inside and outside pure clay buffer
- Prefabricated EBS Module (PEM)
  - Up to 3 HLW canisters, bentonite, steel sheath
- Sealants
  - Inhibit inflow at the tunnel wall
- Sandstone Buffers
  - Flux diversion, package sinking, gas dispersion



IWP



MCM/PEM

Source: McKinley et al. 2001. "Moving HLW-EBS Concepts into the 21st Century." Mat. Res. Soc. Symp. Proc. Vol. 663.

Generic Disposal Concepts for HLW in Crystalline Rock:
What if the Host Rock is Unsaturated?

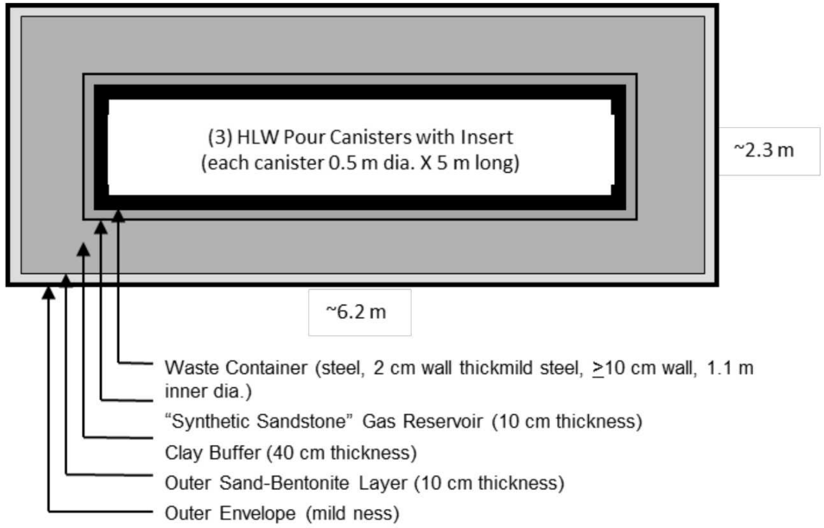
Natural smectite is a common secondary mineral in many settings, at oxidizing conditions

Buffer erosion from higher flux, e.g., glacial onset/retreat

Erosion insignificant (immeasurable) for pore flow velocities < 10^{-5} m/sec

Piping could result from nonuniform initial saturation

- SR-Can excludes piping for inflow < 0.1 L/min per package
- Equivalent to 500 mm/yr average flux (very unlikely for UZ settings)



- **Total PEM weight ~90 MT depending on insert material**
- **Inserted into a vertical/horizontal mined/drilled opening**

Source: Hardin and Sassani 2011. "Application of the Prefabricated EBS Concept in Unsaturated, Oxidizing Host Media." International High-Level Radioactive Waste Management. SAND2011-2426C.

Generic Disposal Concepts for HLW in Crystalline Rock:

So How Can We Improve on These EBS Concepts For Crystalline Rock?

Address published approaches

Identify R&D opportunities:

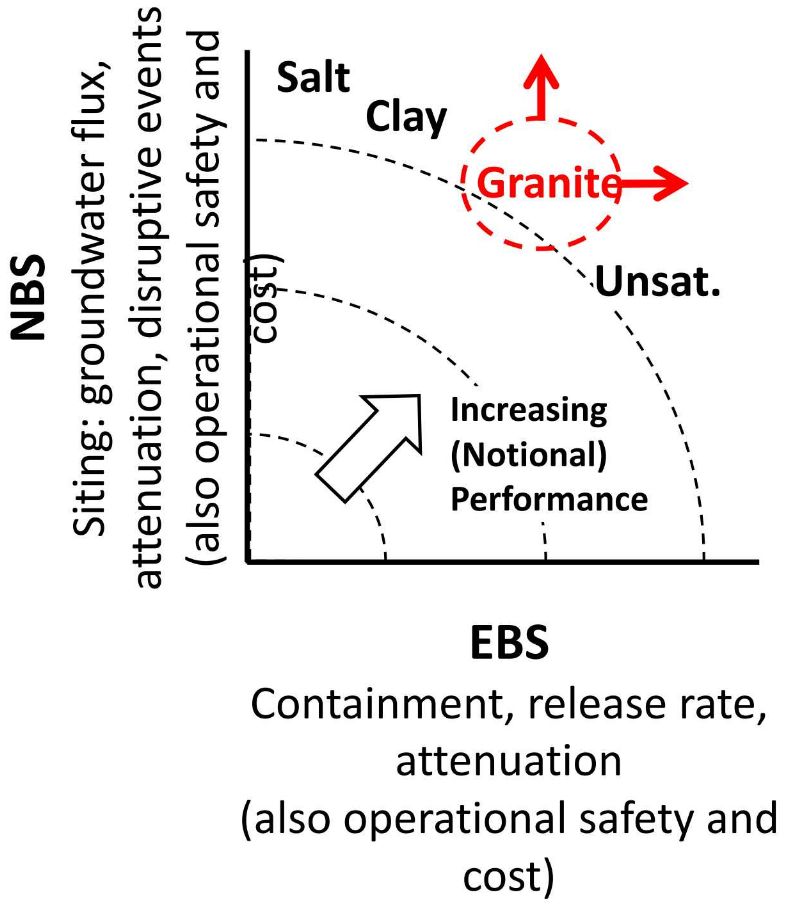
- Packaging materials
  - Metals, coatings
- Buffer materials
  - Clay, clay-sand & cementitious
- Pre-fabrication
  - Buffer density, erosion & piping
- Construction methods

Use waste characteristics

- Small, cool canisters & modest shielding

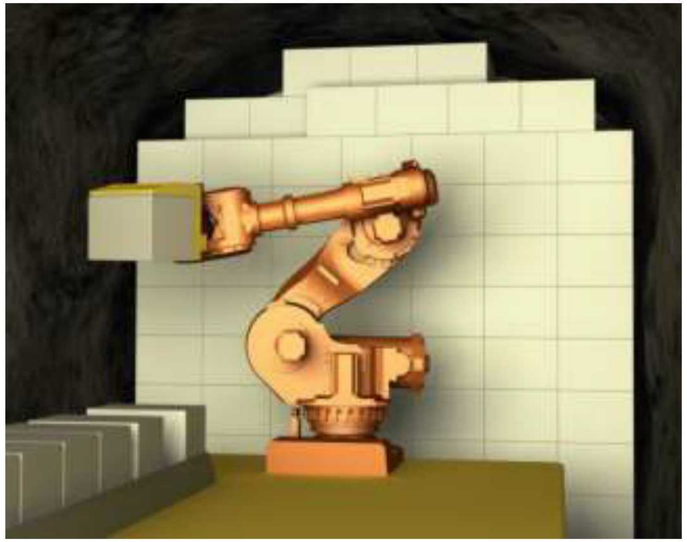
Opt for simplicity & technical maturity

- Claim published performance (generic) with favorable site characteristics
- Claim constructability and low cost, with engineering R&D



Generic Disposal Concepts for HLW in Crystalline Rock:
R&D Opportunities

- Waste Forms
  - Design for instant release fraction?
- Package Materials
  - Corrosion allowance or resistant?
  - Fabrication methods & coatings
- Buffer/Backfill
  - Mass transport, piping/erosion
- Super-Containers
  - Pre-fabrication, self-shielding
- Moving Heavy Packages
  - Conveyances & running surfaces
  - Tight drift clearances, water/air bearings
- Bulk Material Delivery
  - Pellet delivery, pumpable materials



Generic Disposal Concepts for HLW in Crystalline Rock:
Defense Crystalline Repository Options

Panel Layout by Waste Form*

Corrosion-Resistant Packaging*

- Use existing HLW and DSNF canisters
- Corrosion-resistant overpack performance

Low-Permeability Buffer and Backfill Materials*

- Clay-based materials

In-Drift Emplacement (larger packages)*

- Minimize tunnel volume, characterize inflow conditions

Borehole Emplacement*

- Short vertical or horizontal boreholes, smaller packages

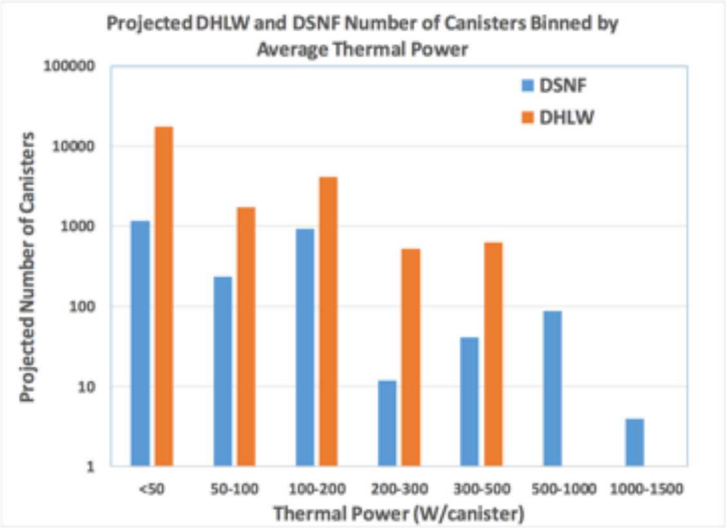
- **Favorable Site Characteristics***

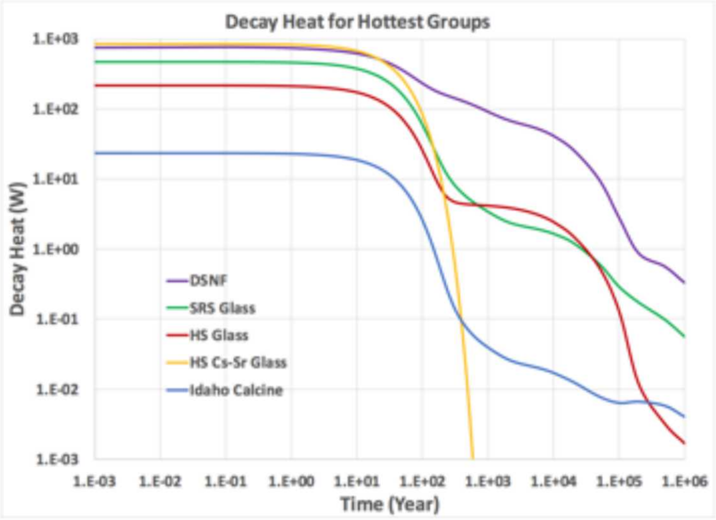
*** Used in current PA models**

Example of HLW, thermal decay curves and thermal load management to determine WP spacing

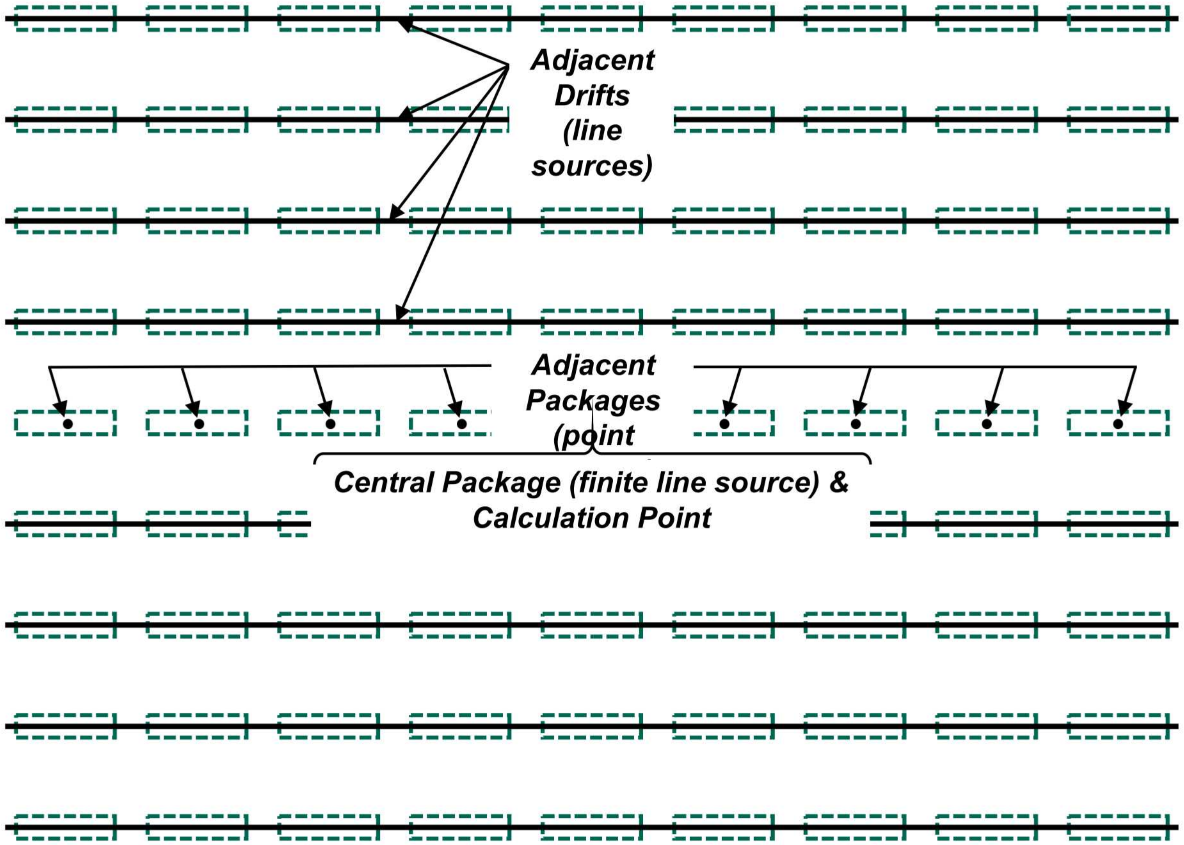
1) Thermal decay will be determined from radionuclide composition

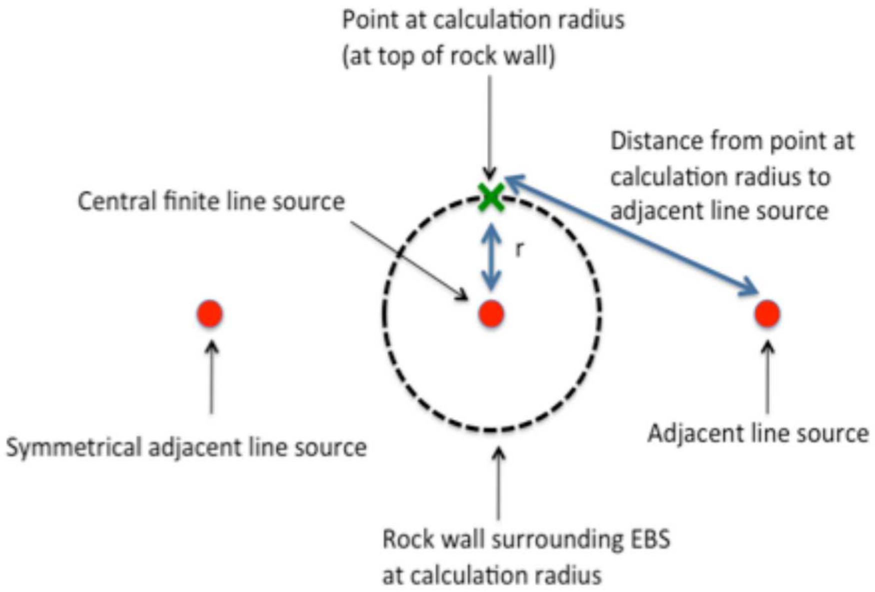
2) Waste package spacing is typically investigated via semi-analytic models





Example of HLW, thermal decay curves and thermal load management





Hardin et al., 2012

Material Properties of the Natural System

Case #1 - Base Case – same material properties assumed for host rock, backfill and waste package

- Thermal Conductivity – 0.57 W/m/K
- Density – 2200 kg/m^3
- Heat Capacity – 931 J/kg/K

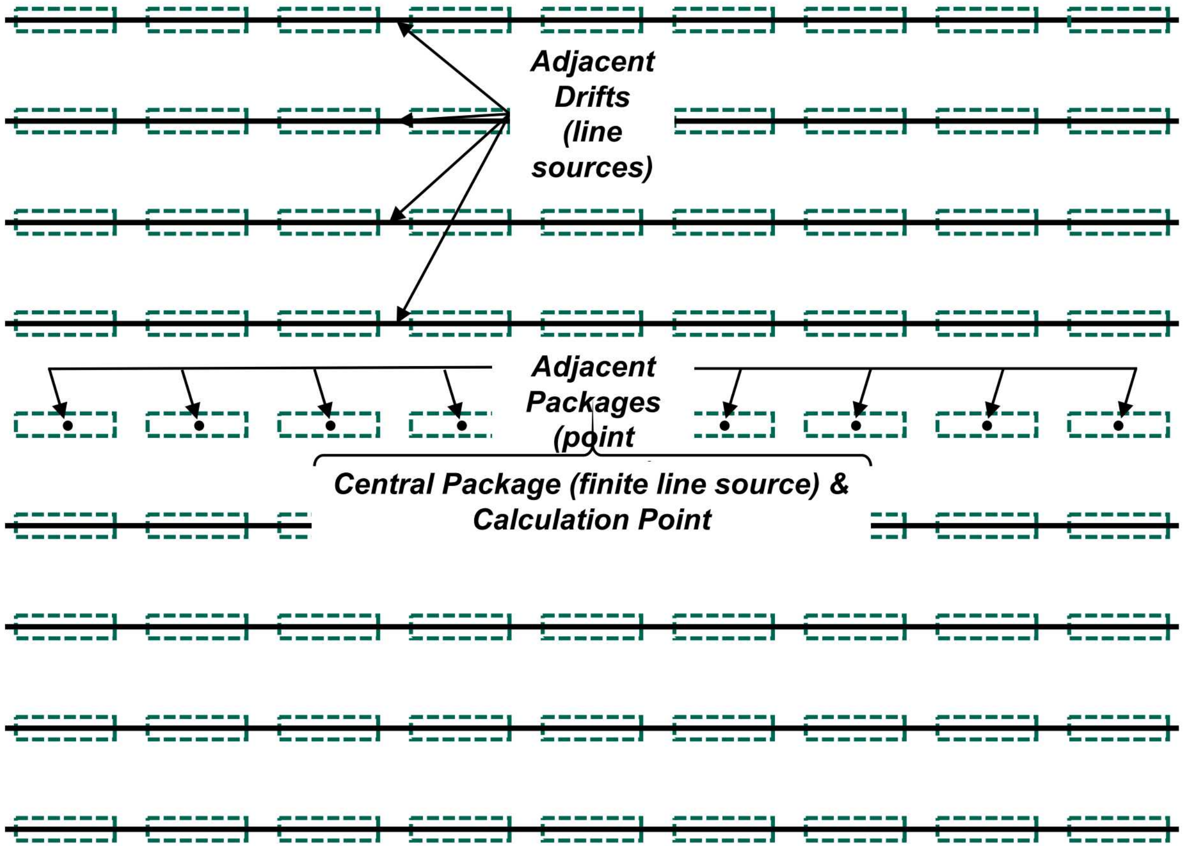
Case #2 – Representative material properties used for each material (for numerical method only)

Material	Thermal Conductivity (W/m/K)	Density (kg/m^3)	Heat Capacity (J/kg/K)	Thermal Diffusivity (m^2/s)
Intact salt	3.20	2200	931	1.562 x 10^{-6}
Crushed salt	0.57	2200	561.6	4.613 x 10^{-7}
Waste package	1.0	2700	800	4.630 x 10^{-7}

Representation of Semi-analytical Analysis Method

Thermal-only analysis based on semi-analytical solution

Based on method of superposition



Hardin et al., 2012

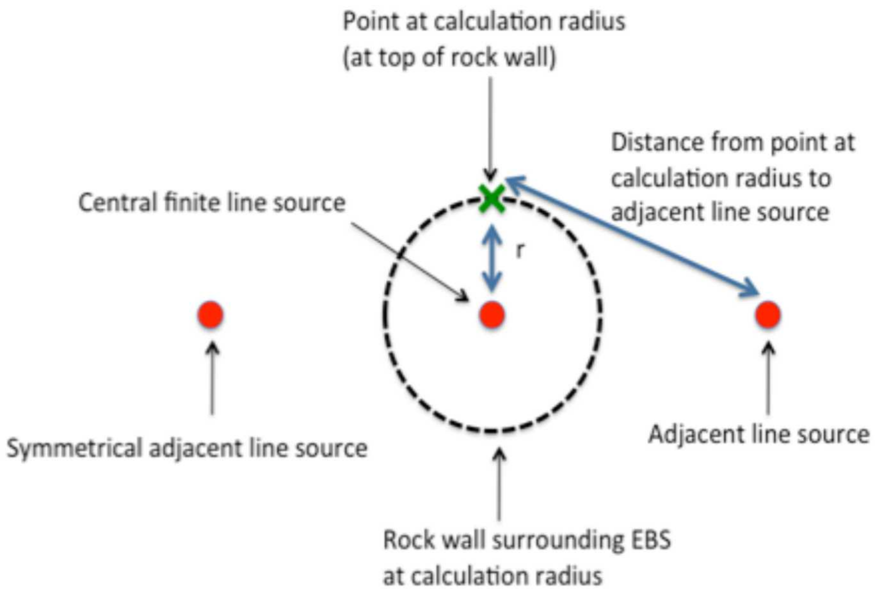
MathCad-Based Thermal Analysis Code

MathCad-based semi-analytical transient thermal model

Based on analytical solution of heat transport (i.e., Carlslaw and Jaeger, 1959)

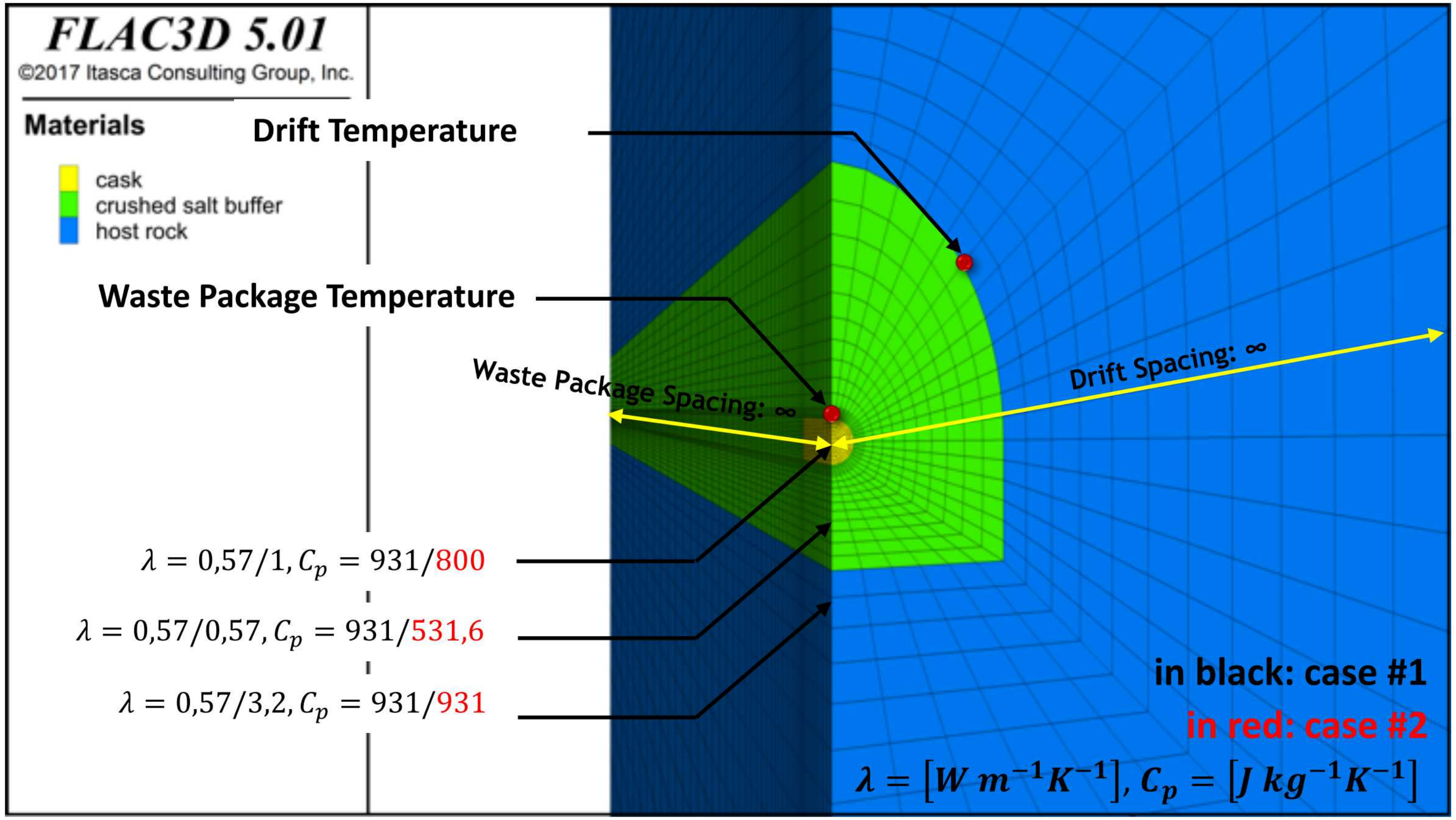
Model includes other processes such as radiation heat transfer and ventilation

Thermal conduction solution: linear superposition of components



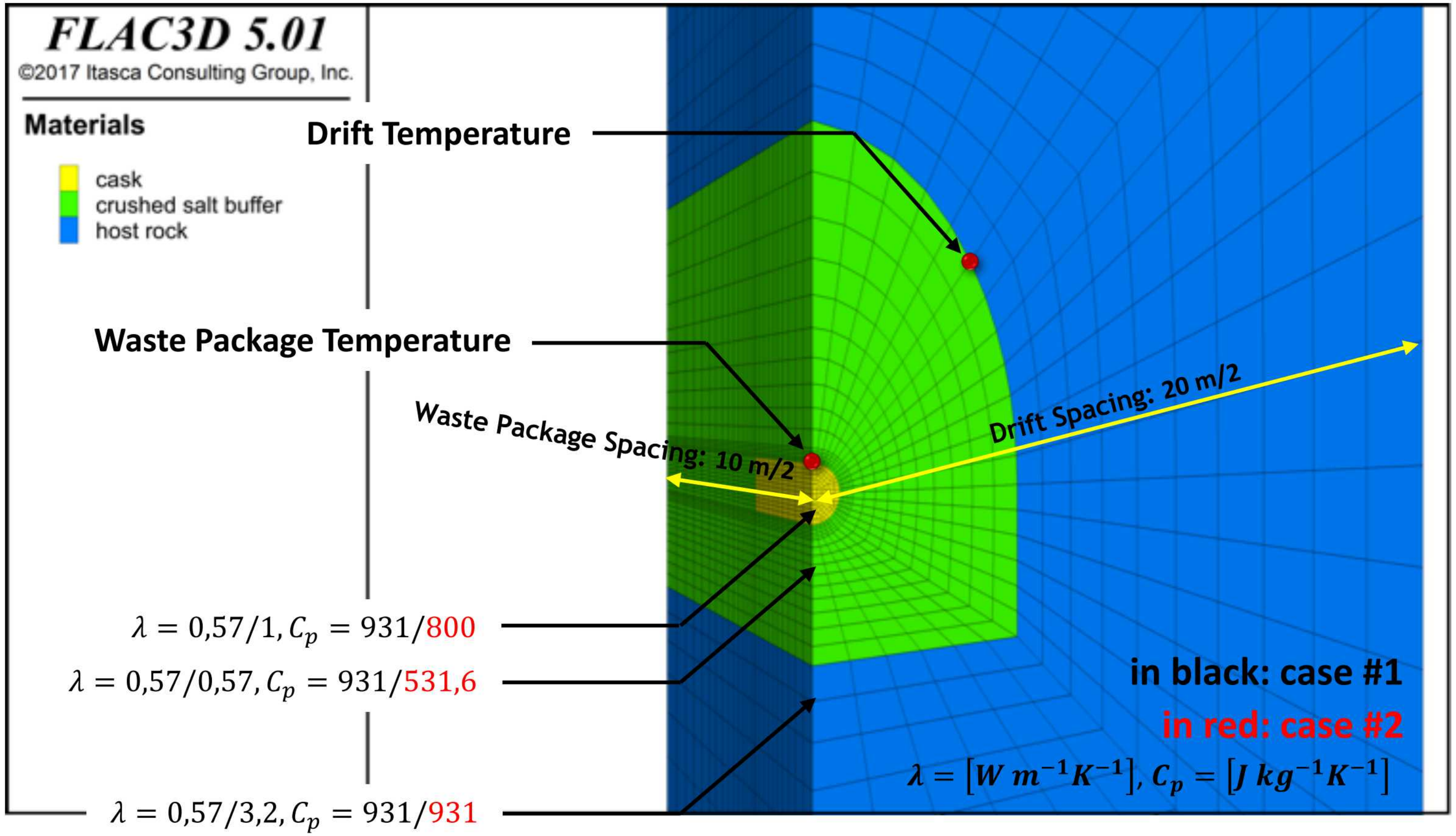
Benchmark Modeling Cases, 1/2

Configuration 1: A single waste package emplaced in an infinite medium



Benchmark Modeling Cases, 2/2

Configuration 2: representative repository layout with given waste package spacing and drift spacing



Simulation Cases

FLAC3D Simulation with homogeneous parameter (Case #1 - Base Case)

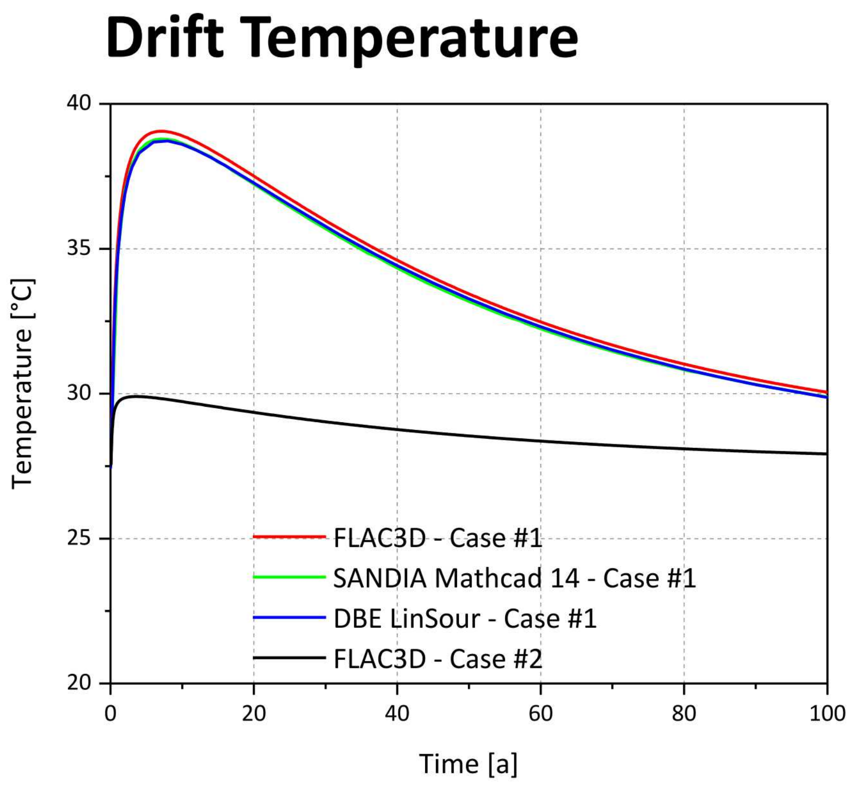
DBE LinSour Calculation with homogeneous material properties (Case #1 - Base Case)

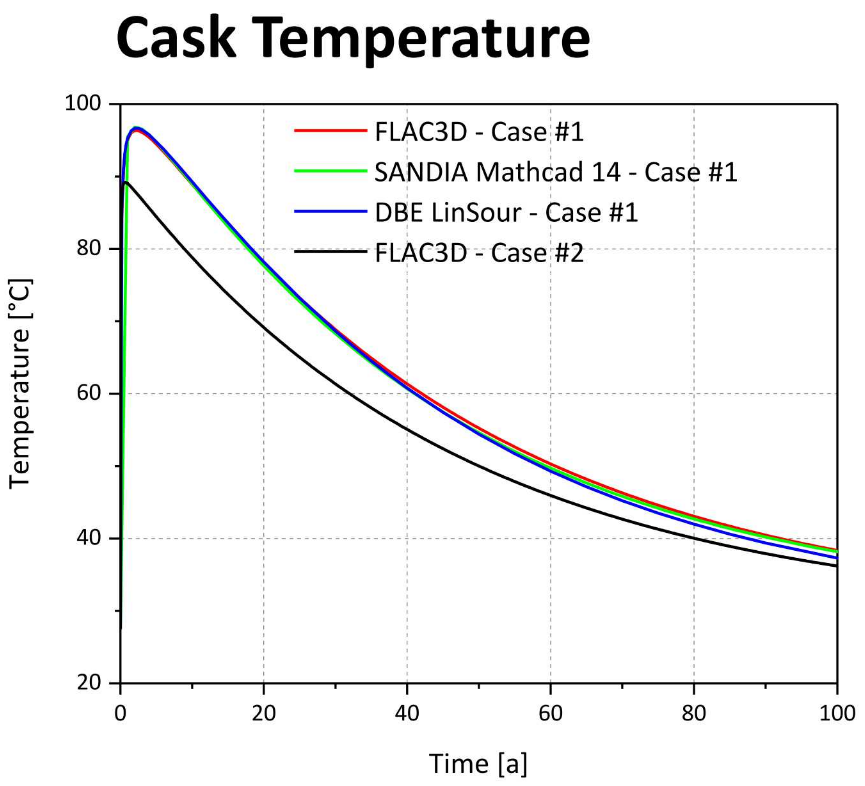
SANDIA MathCad 14 Calculation with homogeneous material properties (Case #1 - Base Case)

FLAC3D Simulation with real material properties: more realistic case (Case #2)

Simulation Results, 1/2

Single Waste Package

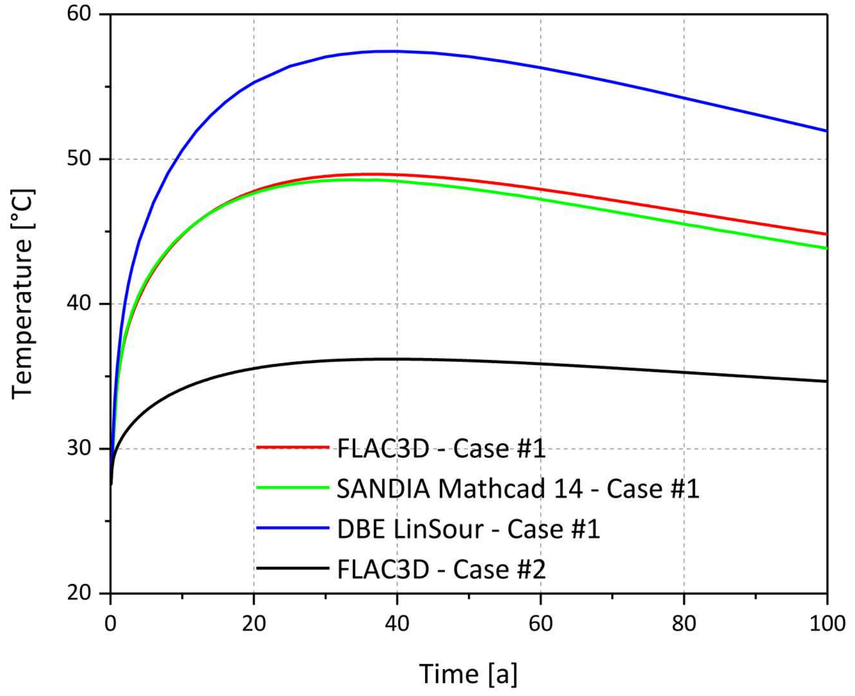




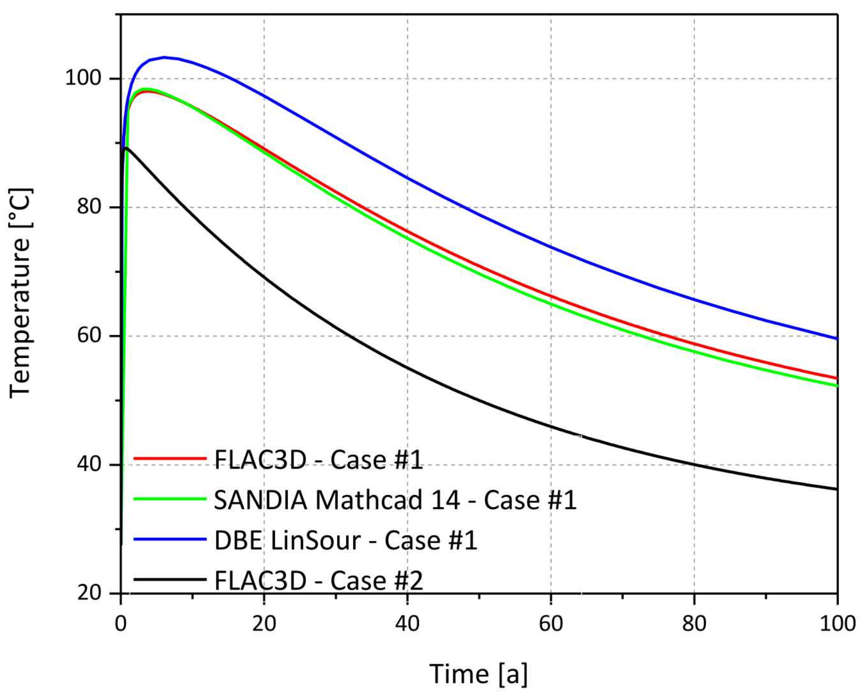
Simulation Results, 2/2

Multiple Waste Packages

Drift Temperature



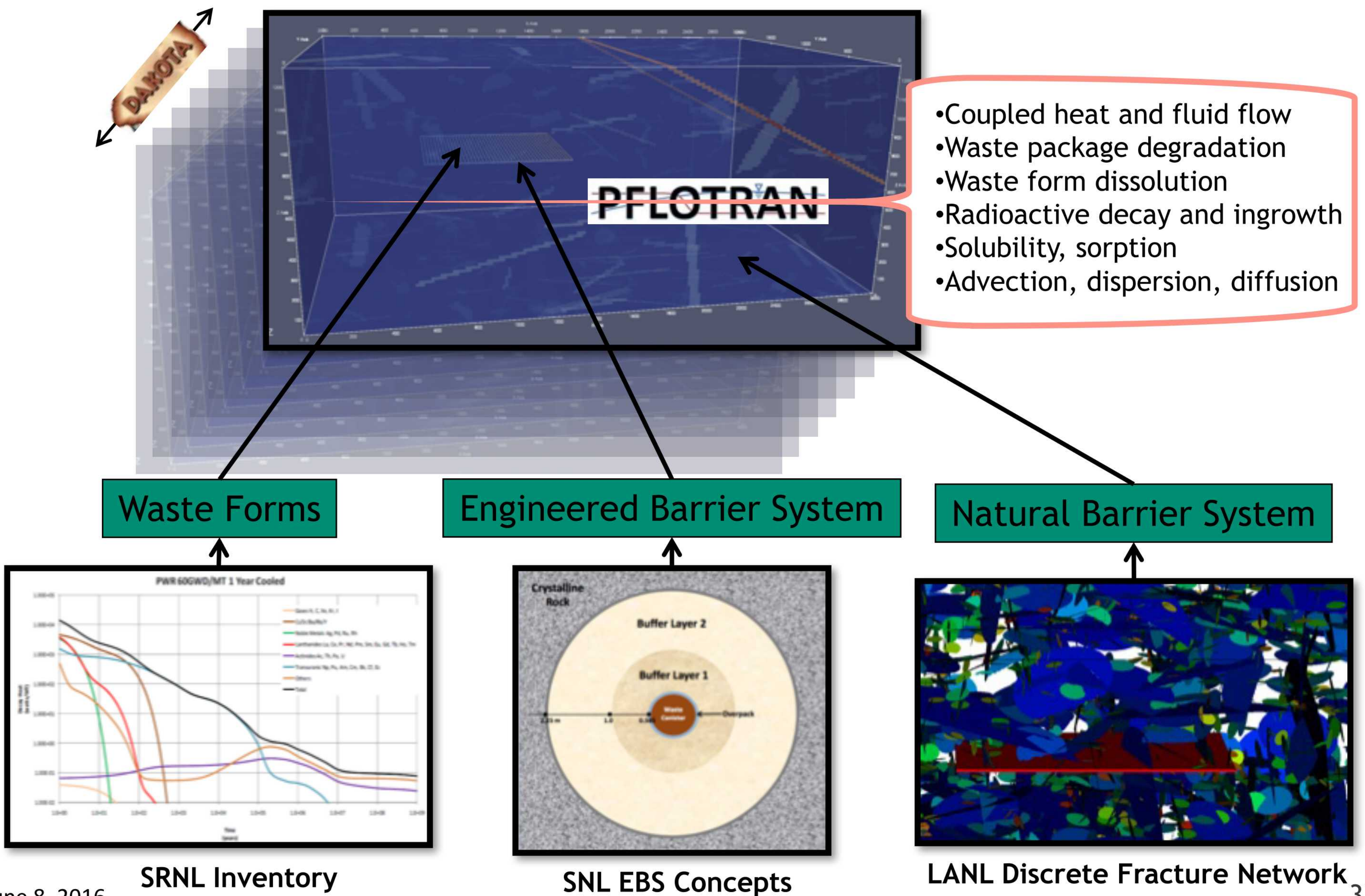
Cask Temperature



Conclusions

- Under identical initial and boundary conditions:
  - Mathcad 14 Code performs as well as the numerical Code FLAC3D
  - LinSour did not calculate thermal superposition with accuracy
- Under realistic initial and boundary conditions
  - Analytical codes tend to be more conservative
  - Although, the temperature limit are always met
- The accuracy of semi-analytical codes can be improved:
  - by parameter calibration using a numerical model (LinSour)
  - by considering multiple material properties (MathCad 14)
  - by using non-constant material properties (MathCad 14)
- The results show that the analytical codes studied are suitable for thermal design of a HLW repository

Performance Assessment



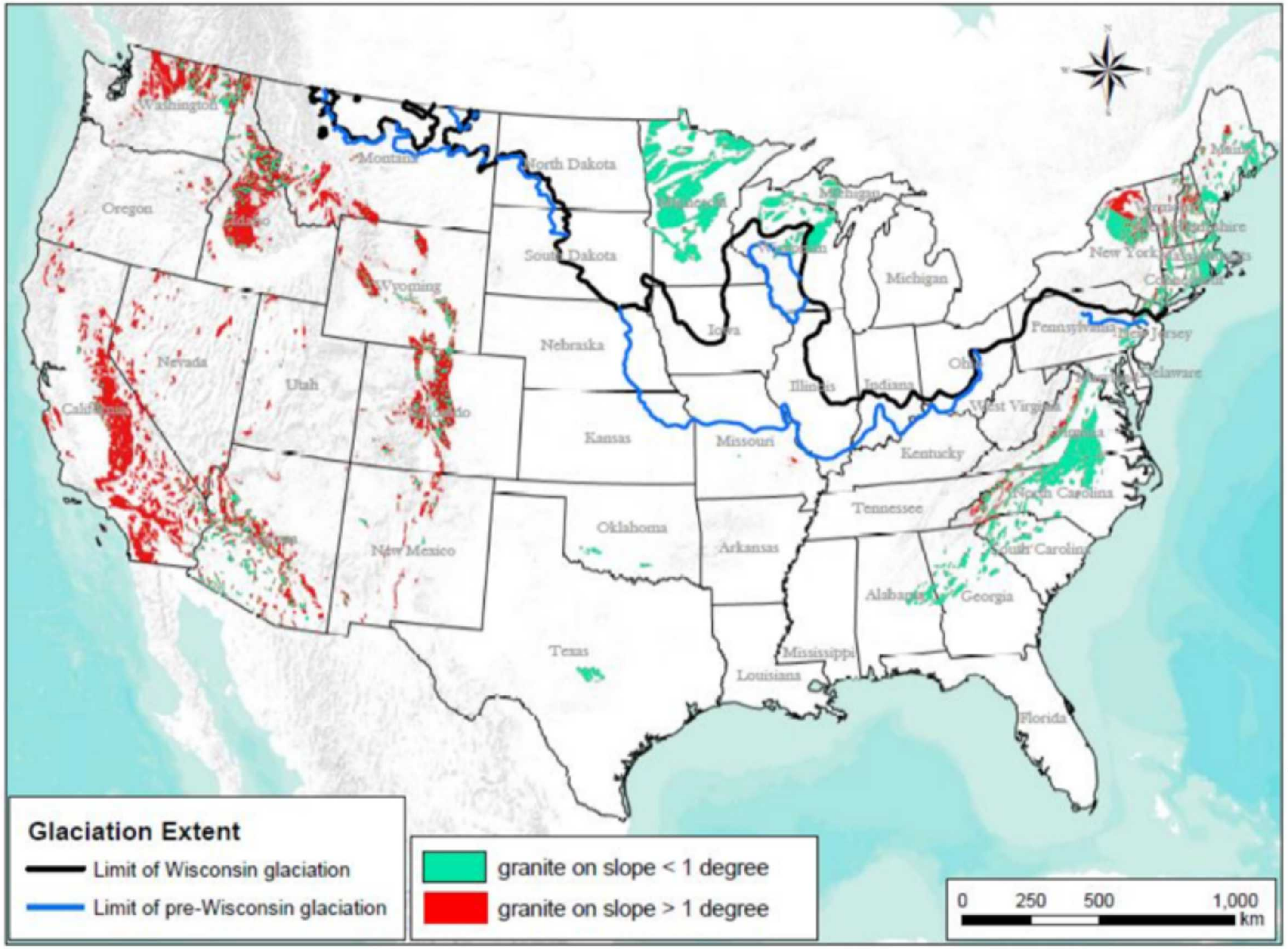
Natural Barrier System

Exposed crystalline basement

Slope < 1 degree

Topographically controlled water table

Consistent with international concepts.



Perry et al., 2014

Natural Barrier System

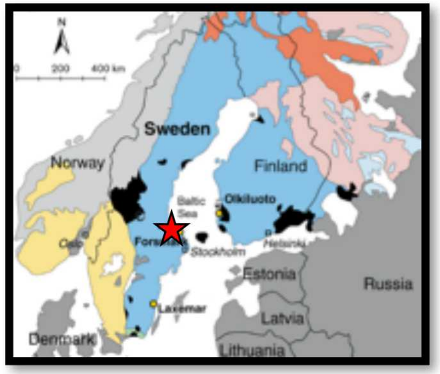
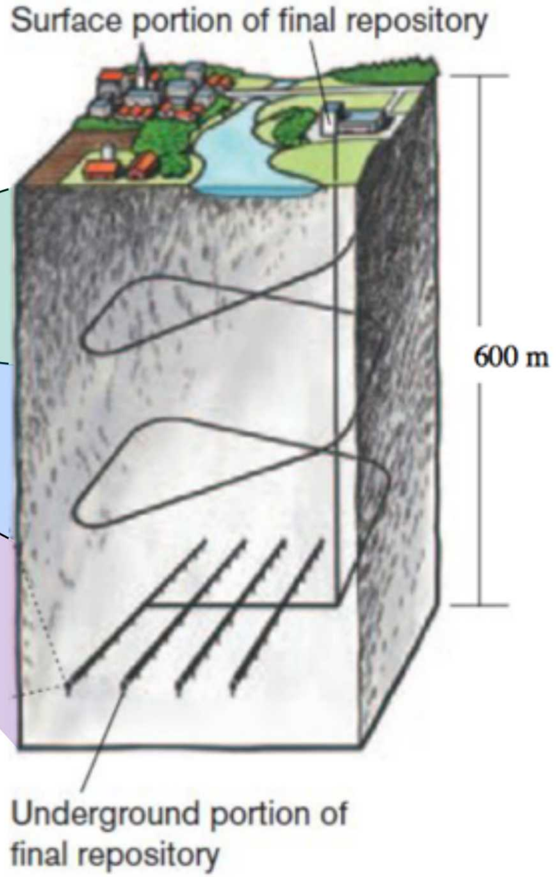


Table 2 Hydrogeological DFN parameters for each fracture domain, fracture set and depth zone

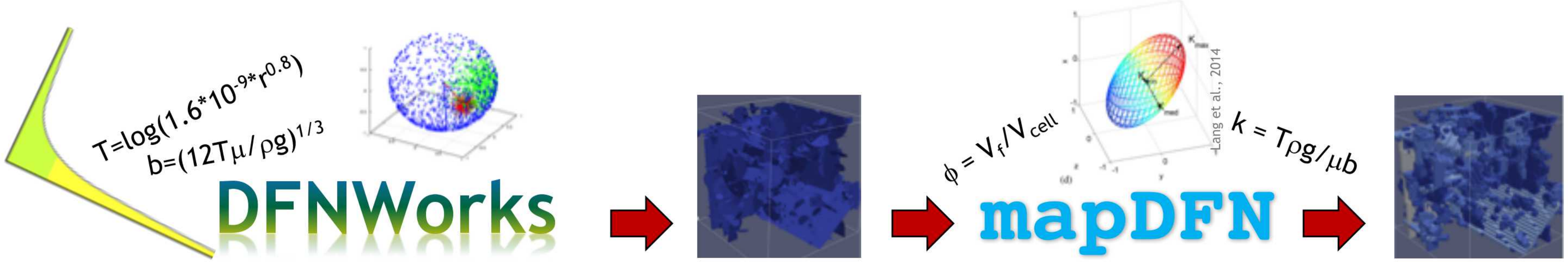
Fracture domain/elevation (m.a.s.l)[a]	Fracture set name	Orientation set pole: (trend, plunge), conc.	Size model, power-law (r_0, k_r) (m, −)	Intensity, (P_{32}), valid size interval: r_0 to 564 m (m^2/m^3)	Parameter values for the transmissivity models: Semi-correlated (a,b,σ)	Correlated (a,b)	Uncorrelated (μ,σ)
FFM01 and FFM06>−200	NS	(292, 1) 17.8	(0.038, 2.50)	0.073	$6.3 \cdot 10^{-9}$, 1.3, 1.0	$6.7 \cdot 10^{-9}$, 1.4	−6.7, 1.2
	NE	(326, 2) 14.3	(0.038, 2.70)	0.319			
	NW	(60, 6) 12.9	(0.038, 3.10)	0.107			
	EW	(15, 2) 14.0	(0.038, 3.10)	0.088			
	HZ	(5, 86) 15.2	(0.038, 2.38)	0.543			
FFM01 and FFM06 −200 to −400	NS	(292, 1) 17.8	(0.038, 2.50)	0.142	$1.3 \cdot 10^{-9}$, 0.5, 1.0	$1.6 \cdot 10^{-9}$, 0.8	−7.5, 0.8
	NE	(326, 2) 14.3	(0.038, 2.70)	0.345			
	NW	(60, 6) 12.9	(0.038, 3.10)	0.133			
	EW	(15, 2) 14.0	(0.038, 3.10)	0.081			
	HZ	(5, 86) 15.2	(0.038, 2.38)	0.316			
FFM01 and FFM06<−400	NS	(292, 1) 17.8	(0.038, 2.50)	0.094	$5.3 \cdot 10^{-11}$, 0.5, 1.0	$1.8 \cdot 10^{-10}$, 1.0	−8.8, 1.0
	NE	(326, 2) 14.3	(0.038, 2.70)	0.163			
	NW	(60, 6) 12.9	(0.038, 3.10)	0.098			
	EW	(15, 2) 14.0	(0.038, 3.10)	0.039			
	HZ	(5, 86) 15.2	(0.038, 2.38)	0.141			
FFM02>−200	NS	(83, 10) 16.9	(0.038, 2.75)	0.342	$9.0 \cdot 10^{-9}$, 0.7, 1.0	$5.0 \cdot 10^{-9}$, 1.2	−7.1, 1.1
	NE	(143, 9) 11.7	(0.038, 2.62)	0.752			
	NW	(51, 15) 12.1	(0.038, 3.20)	0.335			
	EW	(12, 0) 13.3	(0.038, 3.40)	0.156			
	HZ	(71, 87) 20.4	(0.038, 2.58)	1.582			
FFM03, FFM04 and FFM05>−400	NS	(292, 1) 17.8	(0.038, 2.60)	0.091	$1.3 \cdot 10^{-8}$, 0.4, 0.8	$1.4 \cdot 10^{-8}$, 0.6	−7.2, 0.8
	NE	(326, 2) 14.3	(0.038, 2.50)	0.253			
	NW	(60, 6) 12.9	(0.038, 2.55)	0.258			
	EW	(15, 2) 14.0	(0.038, 2.40)	0.097			
	HZ	(5, 86) 15.2	(0.038, 2.55)	0.397			
FFM03, FFM04 and FFM05<−400	NS	(292, 1) 17.8	(0.038, 2.60)	0.102	$1.8 \cdot 10^{-8}$, 0.3, 0.5	$7.1 \cdot 10^{-9}$, 0.6	−7.2, 0.8
	NE	(326, 2) 14.3	(0.038, 2.50)	0.247			
	NW	(60, 6) 12.9	(0.038, 2.55)	0.103			
	EW	(15, 2) 14.0	(0.038, 2.40)	0.068			
	HZ	(5, 86) 15.2	(0.038, 2.55)	0.250			

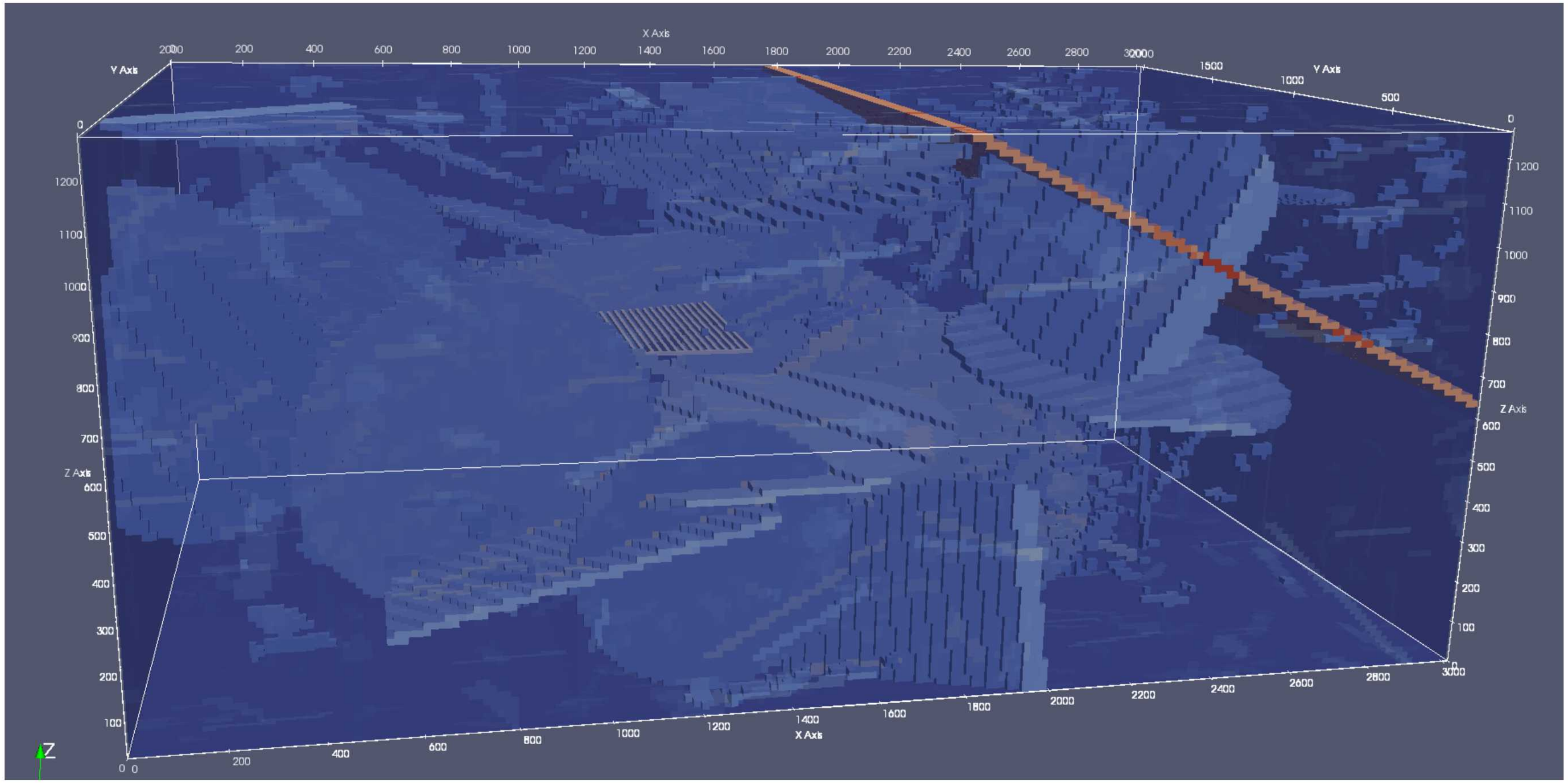
[a] Meters above sea level



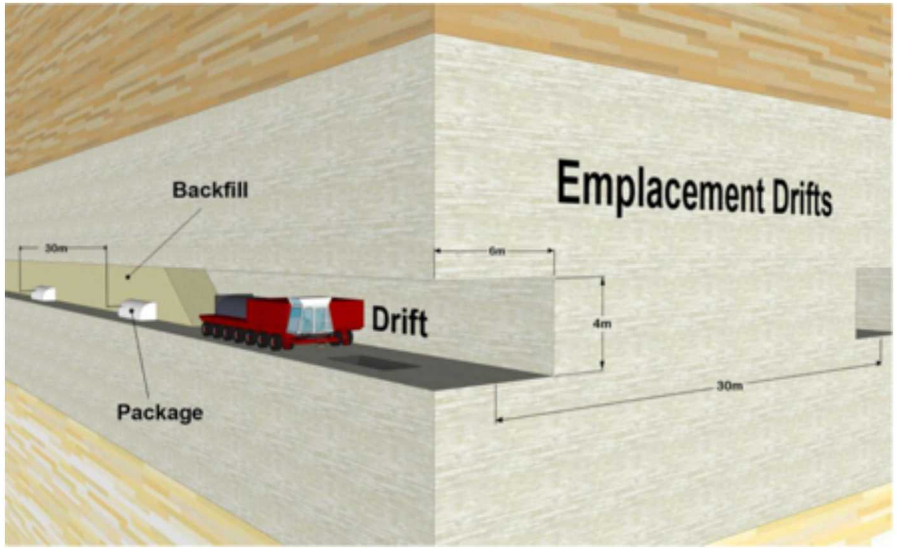
Joyce et al., Hydrogeology Journal (2014) 22:1233-1249

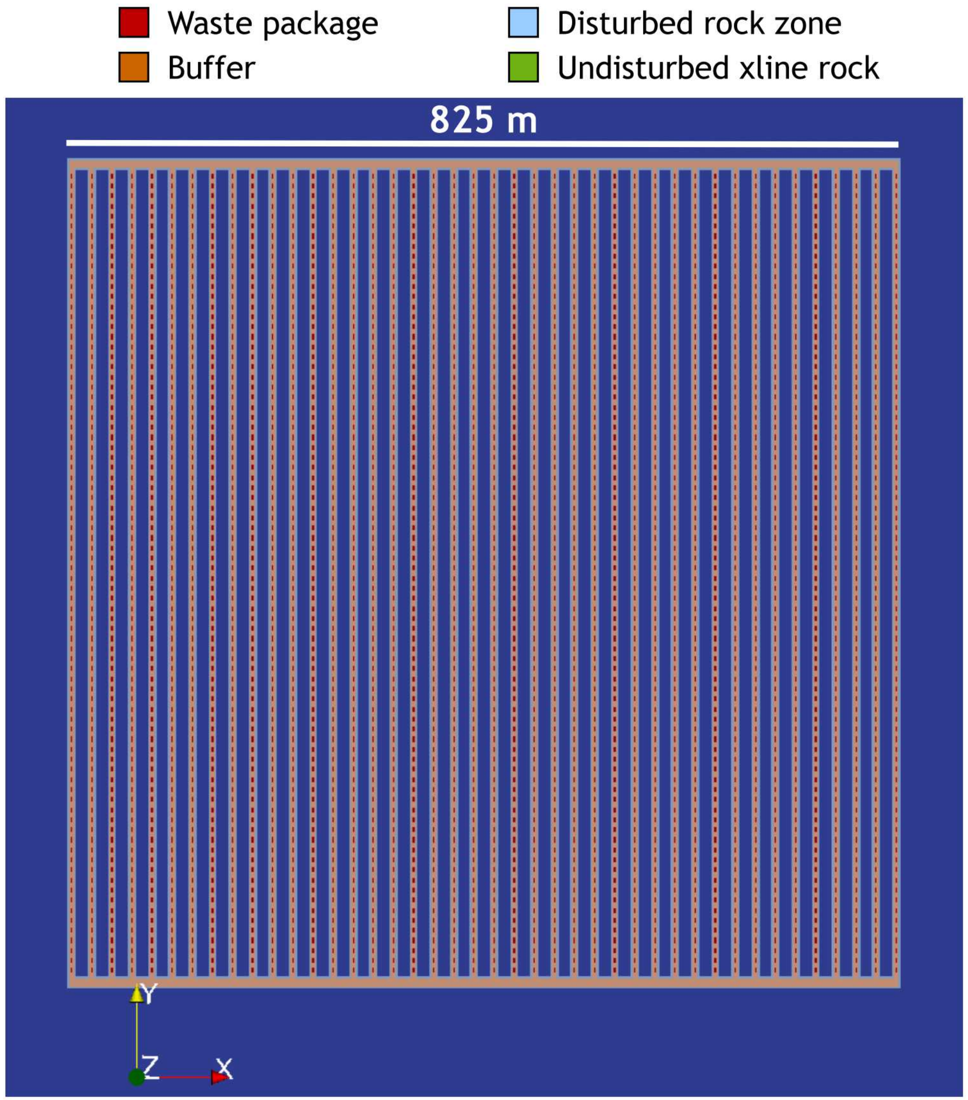
Natural Barrier System





Engineered Barrier System





- Stainless steel waste packages
- Bentonite buffer
- Horizontal, in-drift emplacement
- Access halls, ramp, shafts

- 42 800-m drifts (80 WP/drift)
- ¼ of a 70,000 MTHM repository

Waste Inventory

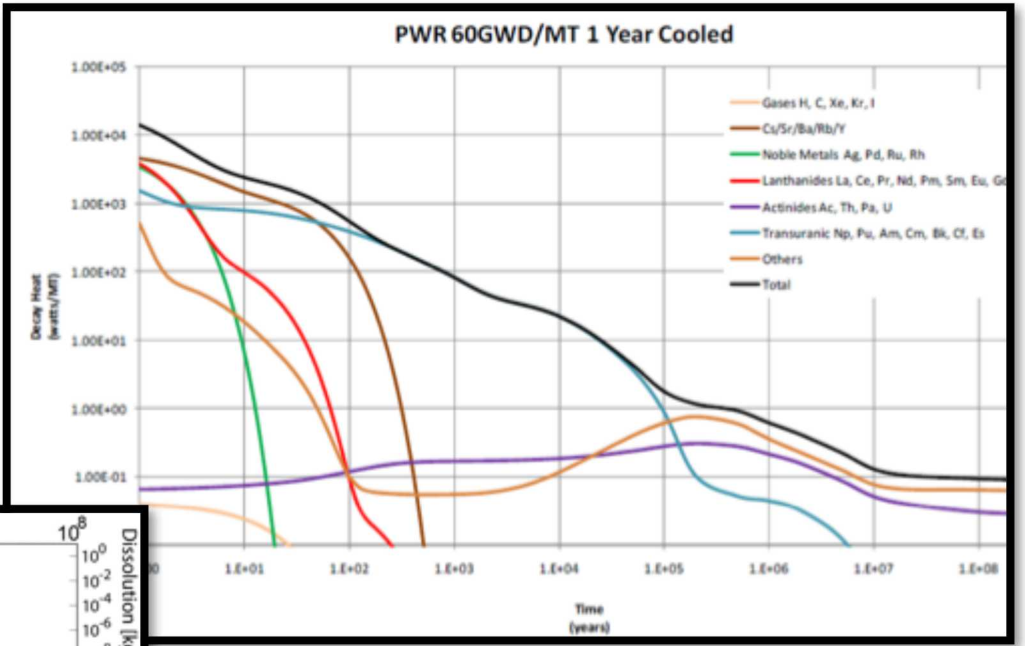
12-PWR waste packages

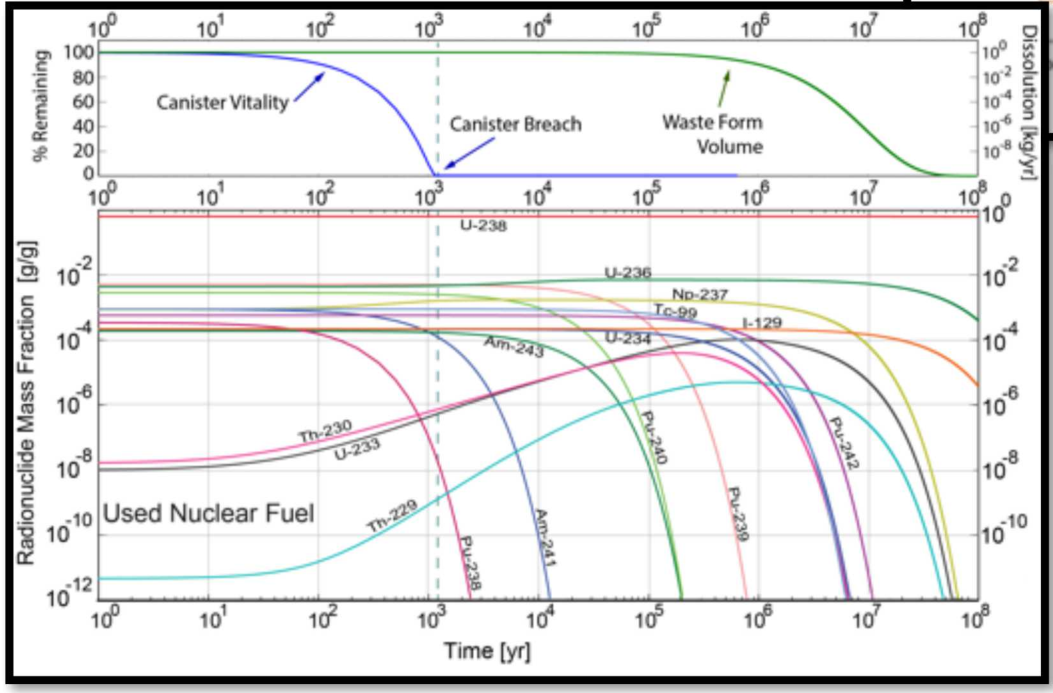
60 GWD/MT burn-up

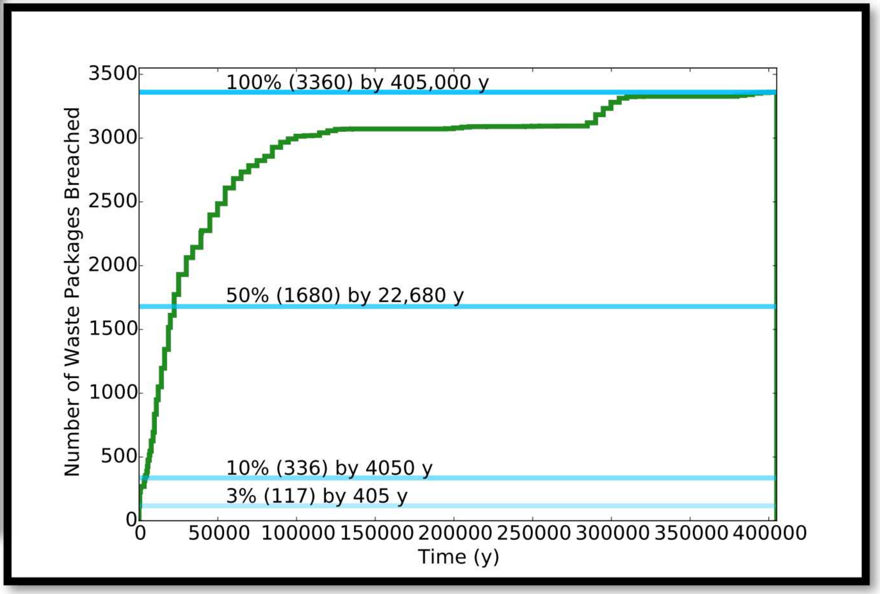
4.73 wt% ^{235}U enrichment

100 yrs OoR

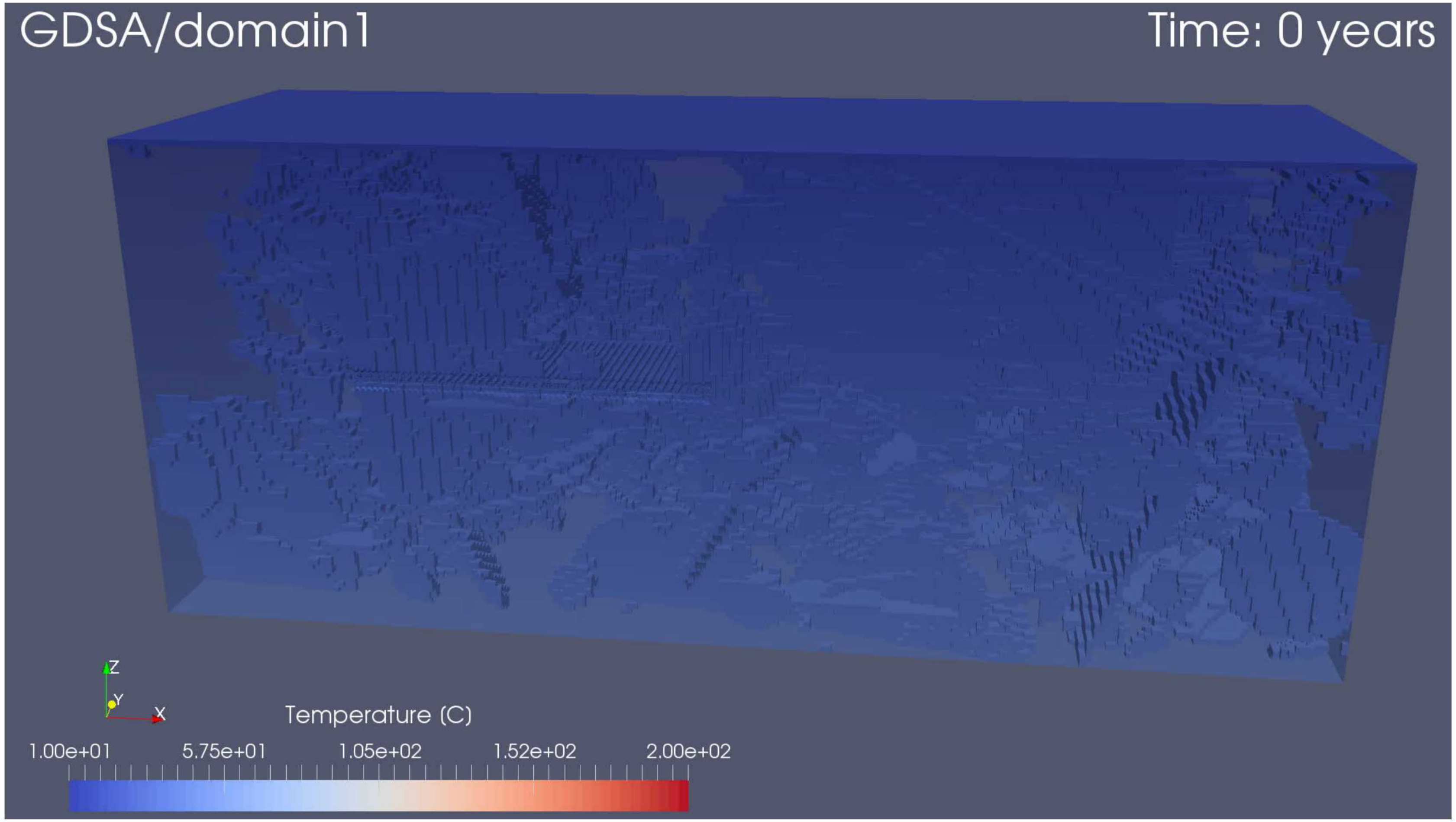
Uniform WF diss. rate (10^{-7}/y)



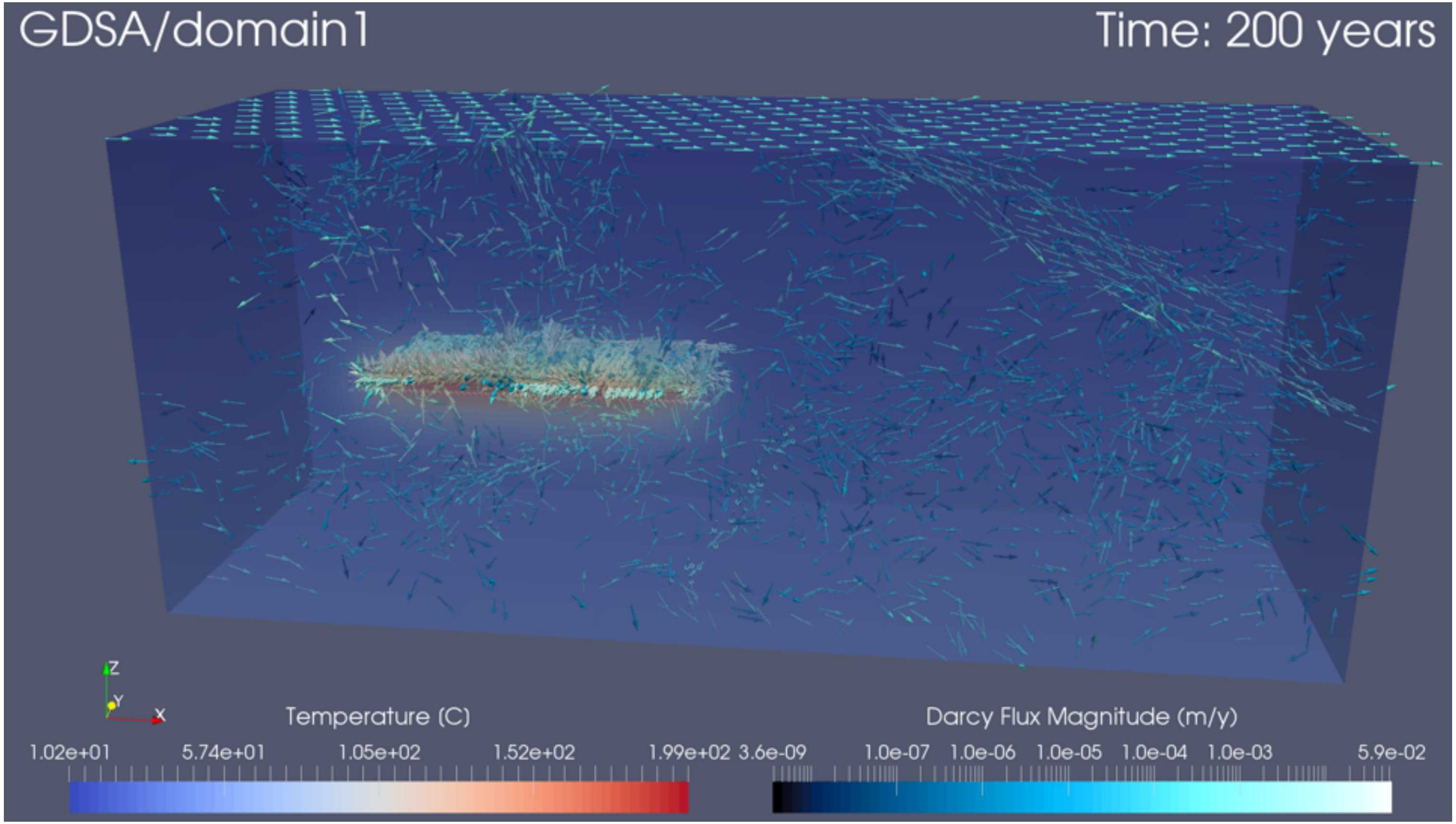




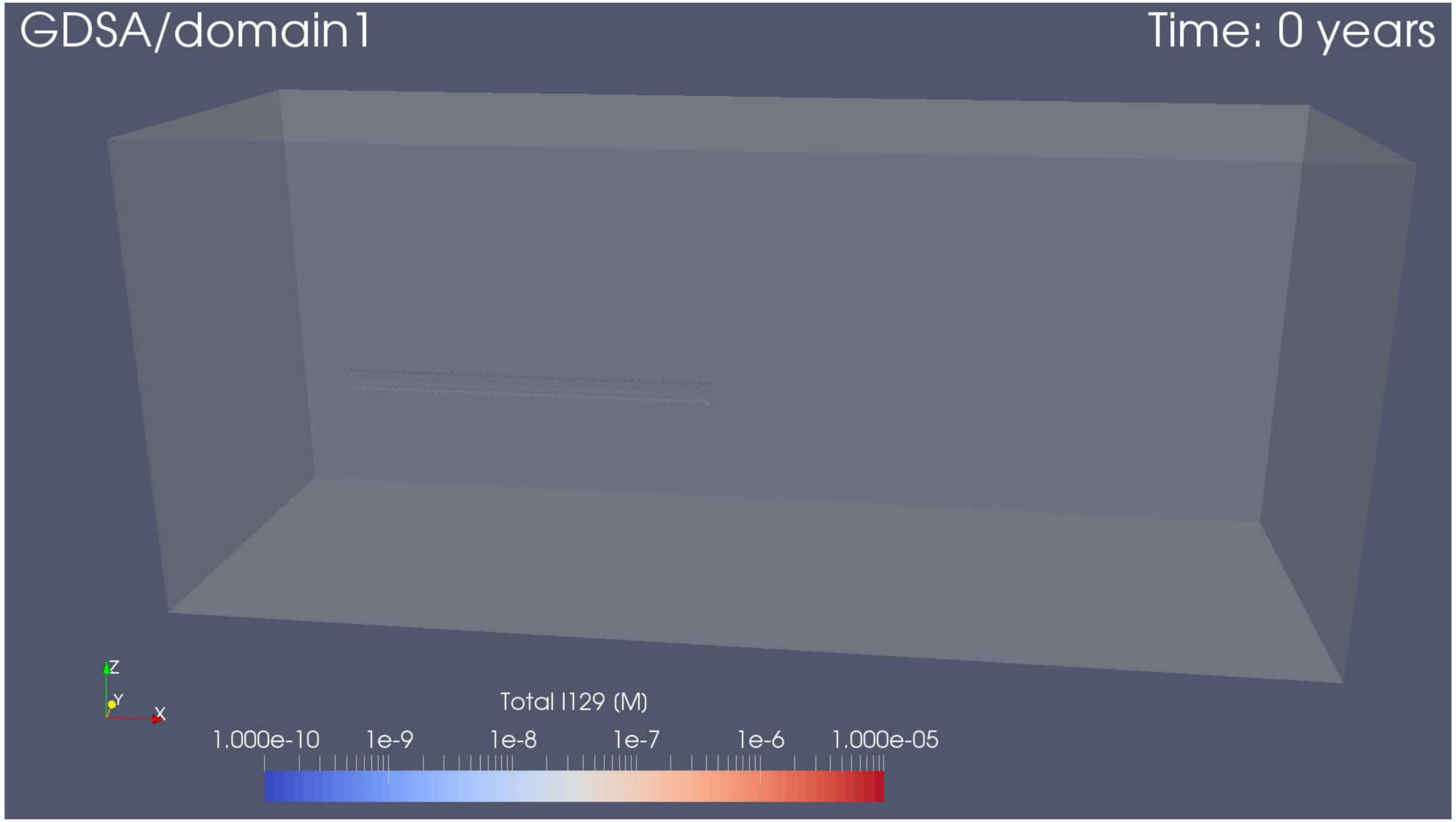
Deterministic Results: Temperature



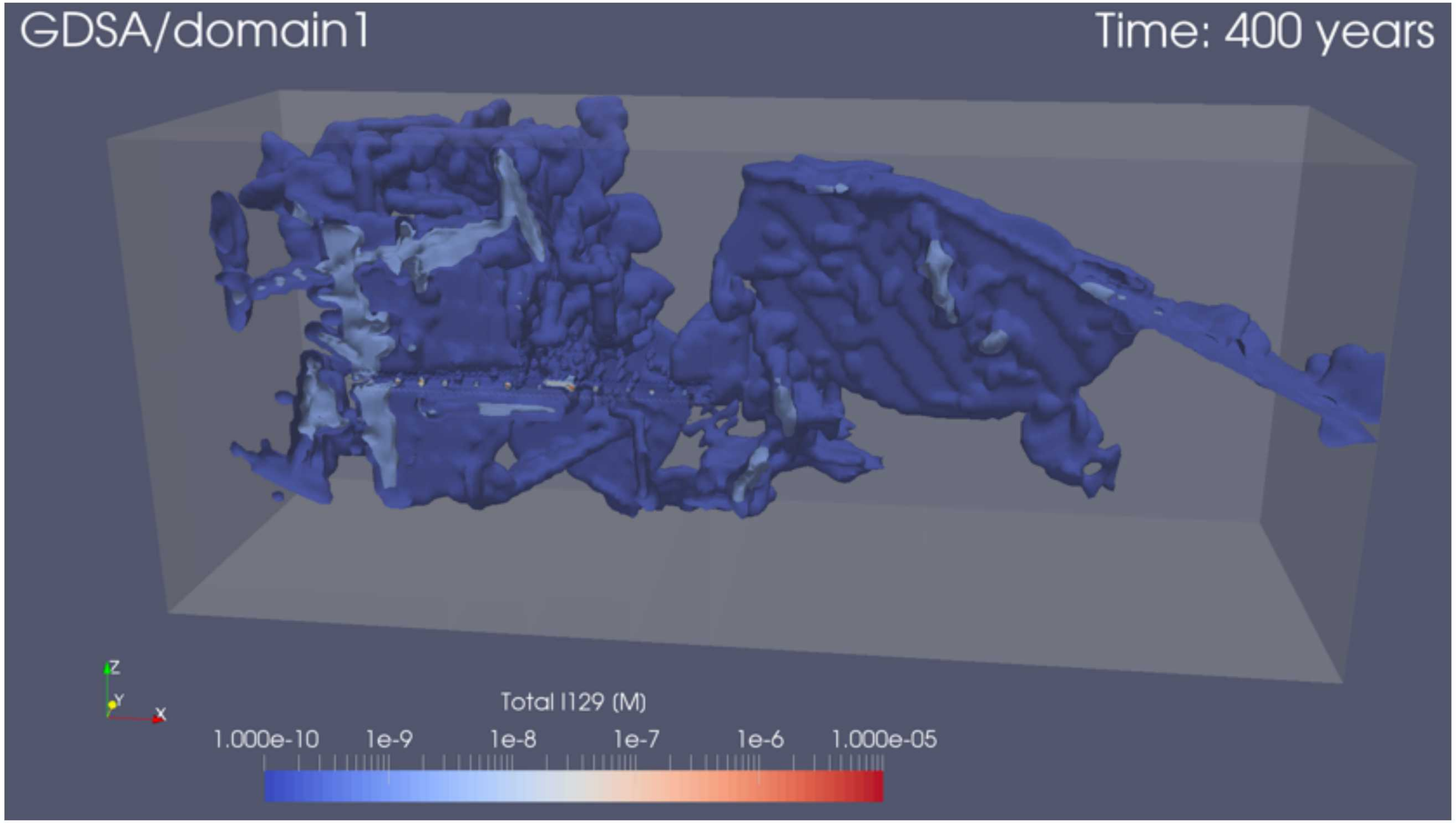
Deterministic Results: Darcy Flux



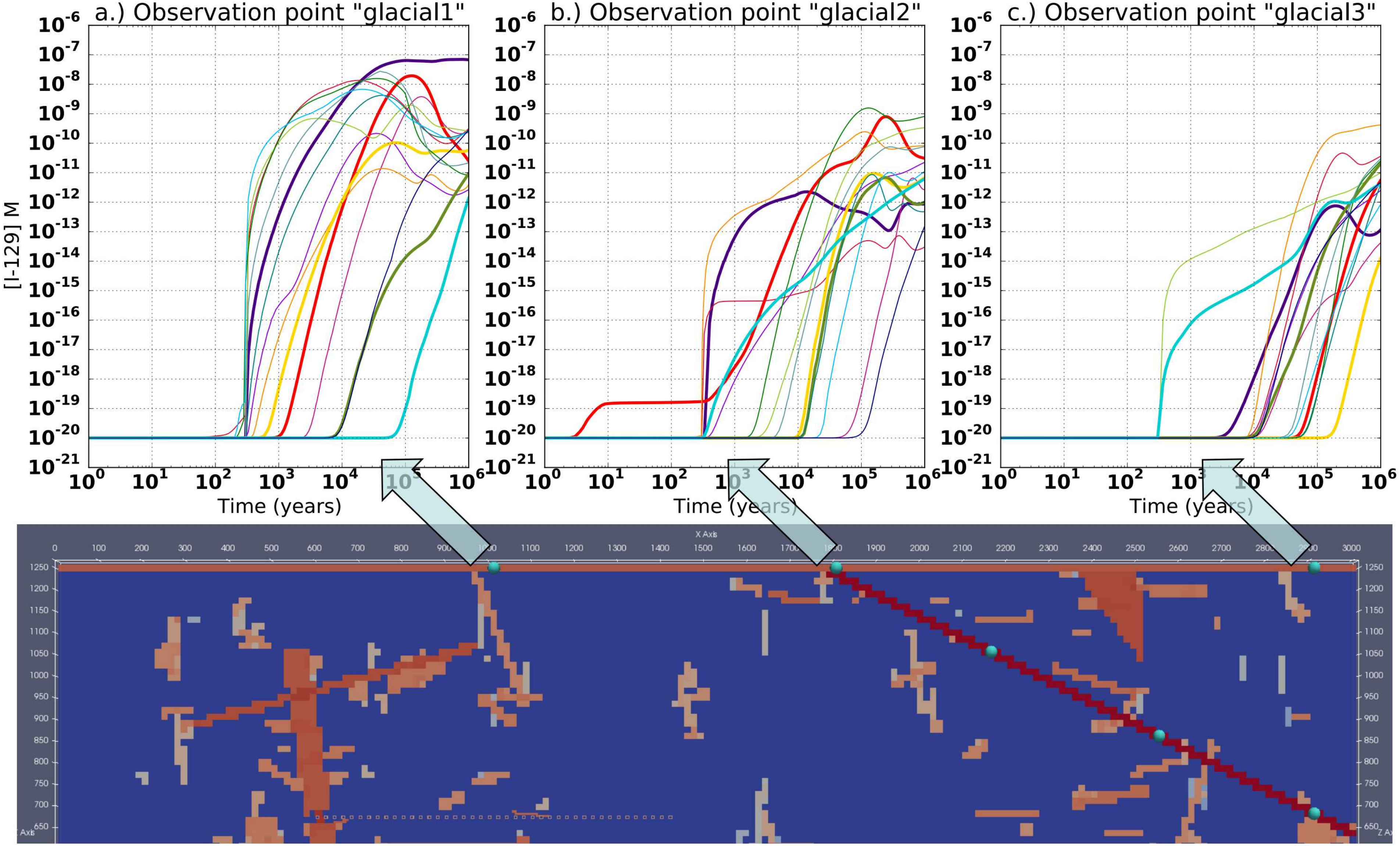
Deterministic Results: ^{129}I Concentration



Deterministic Results: ^{129}I Concentration



Uncertainty due to fracture realization



Probabilistic: Sampled Parameters

Parameter	Distribution	Lower Bound	Upper Bound
Glacial k (m^2)	Log uniform	10^{-16}	10^{-13}
Waste package tortuosity	Log uniform	0.01	1.0
Mean waste package degradation rate (1/yr)	Log uniform	$10^{-5.5}$	$10^{-4.5}$
UNF dissolution rate (1/yr)	Log uniform	10^{-8}	10^{-6}
DRZ porosity	Uniform	0.005	0.05
Buffer porosity	Uniform	0.1	0.4

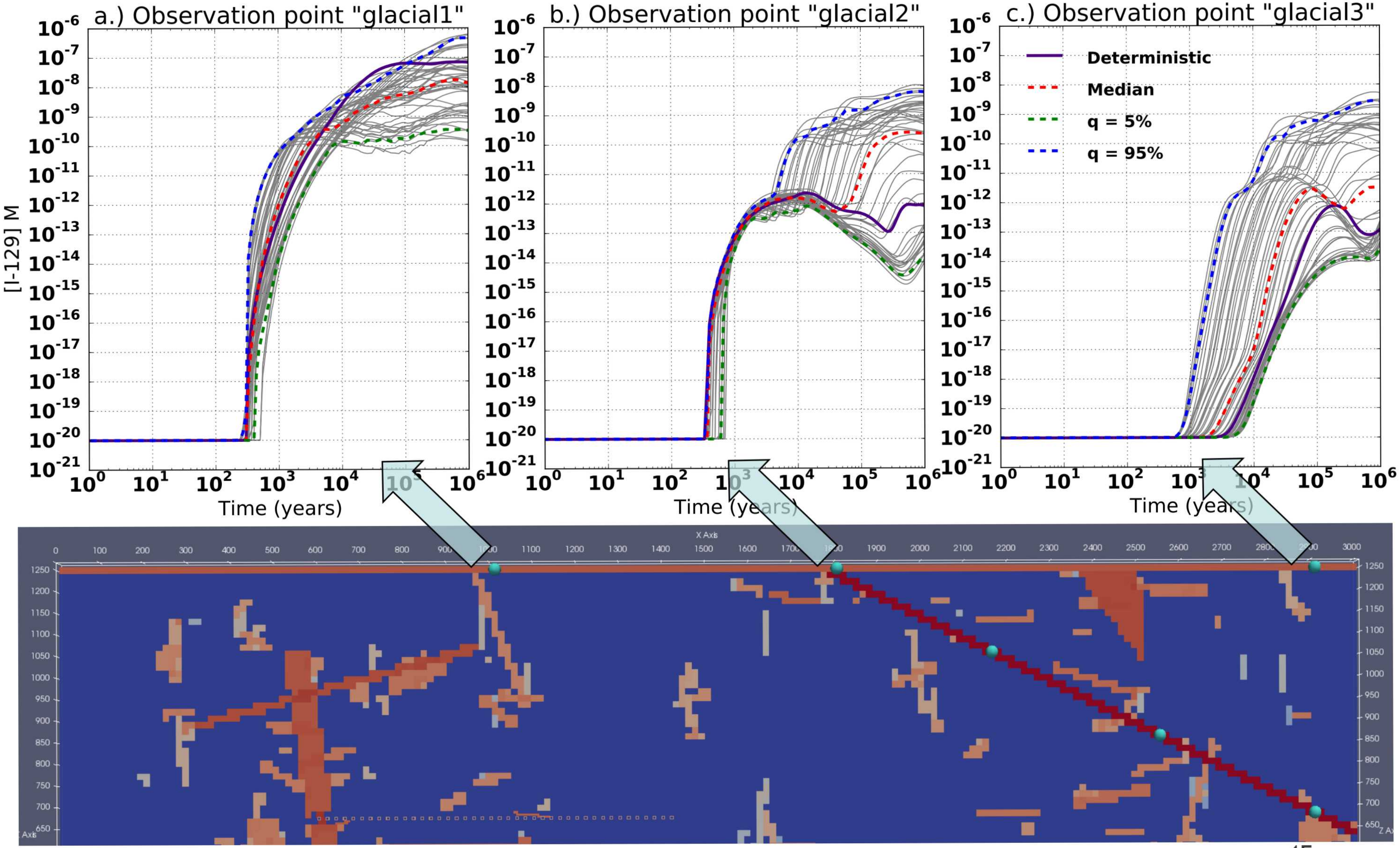
Example of capability only!
Have yet to explore:

Sensitivity to sampled range

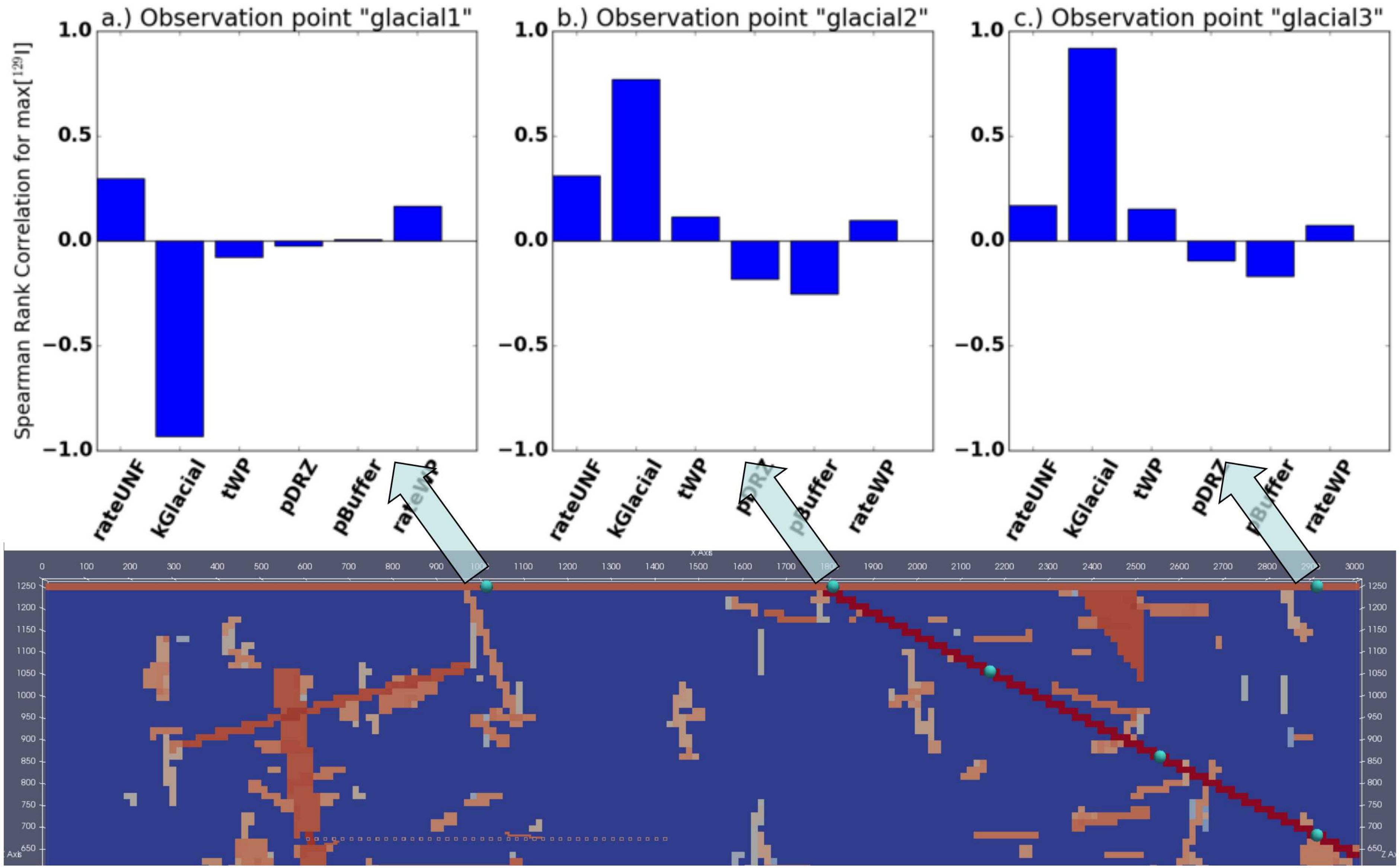
Sensitivity to Kd, etc.

Most appropriate metric in fractured rock

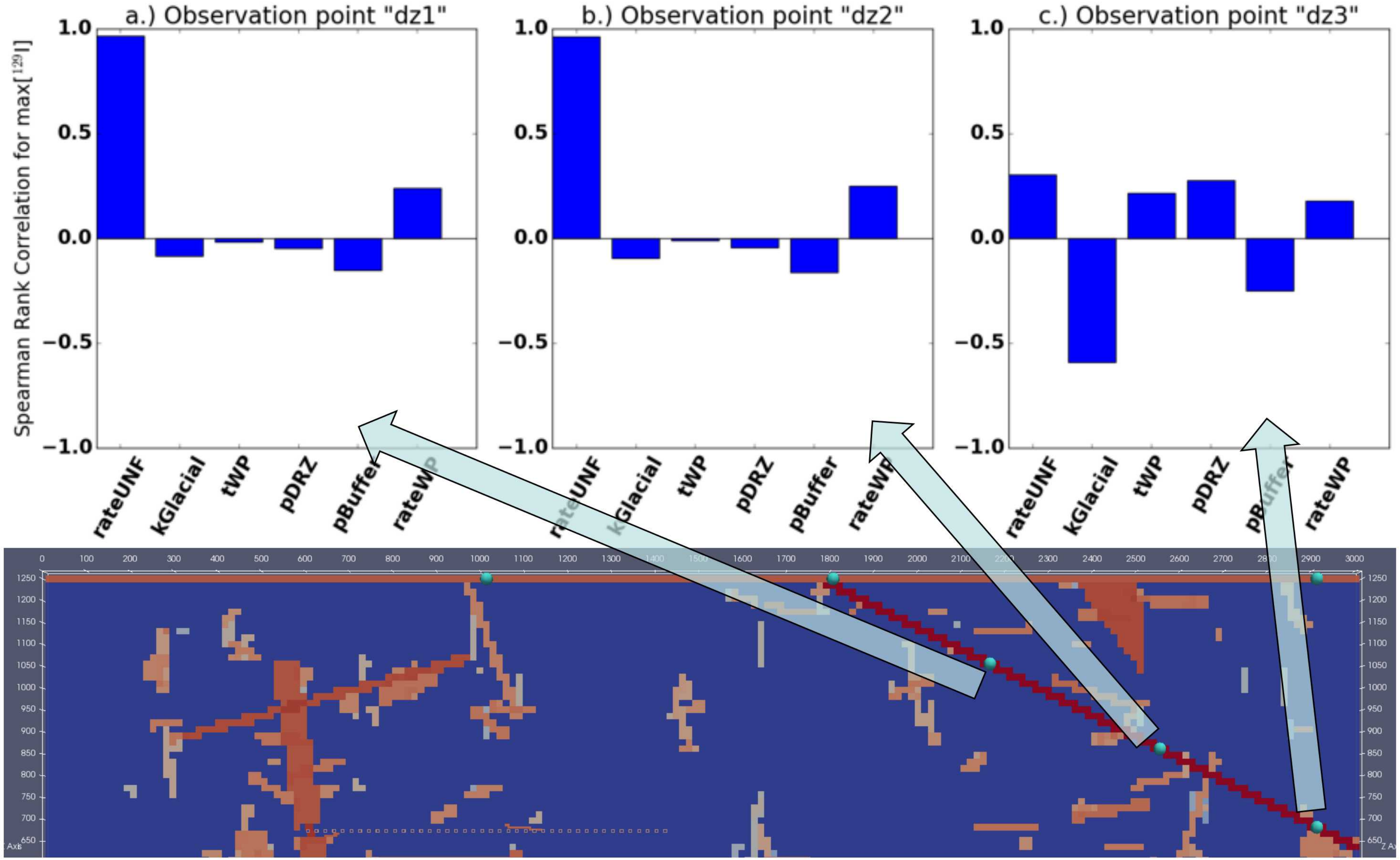
Probabilistic Results: Uncertainty due to sampled parameters



Probabilistic Results: Sensitivity



Probabilistic Results: Sensitivity



Crystalline PA: R&D Future

How to ensure isolation in a fractured host rock?

Generic Performance Assessment can identify:

Components of the Engineered Barrier System capable of ensuring isolation, *e.g., long-lasting copper waste packages with compatible buffer material.*

Features of the Natural Barrier System sufficient and/or necessary to ensure robust isolation from the biosphere, *e.g., lack of fracture connectivity, deep unsaturated zone, or thick sedimentary overburden.*

Need-to-know aspects of fractured rock characterization, *e.g., spacing of deformation zones.*

Appropriate performance metrics for uncertainty and sensitivity analyses in fractured rock.

Overly conservative assumptions, *e.g. fully saturated system at* $t = 0$.

References

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