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Generic Repository Concepts and Thermal Analysis

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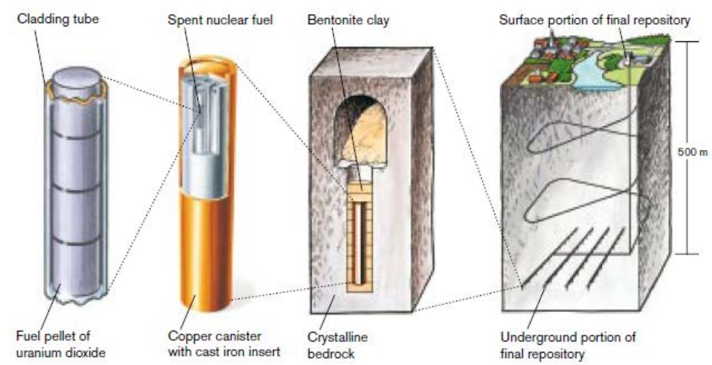
The Used Fuel Disposition Campaign

- **Scope: Identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of spent nuclear fuel (SNF) and high level waste (HLW) generated by existing and future nuclear fuel cycles**
- **The UFDC developed a set of <u>reference geologic disposal concepts</u> in FY11, that provide context for ongoing research and development activities**
  - Three mined geologic disposal concepts
    - *Clay/shale rock*
    - *Crystalline rock (granite)*
    - *Salt*
  - Deep borehole disposal system



Reference Mined Disposal Concepts: Open vs. Enclosed Emplacement Modes

- **The emplacement mode directly affects repository thermal management**
  - Open: excavated emplacement openings persist
    - *Heat spread by thermal radiation → lower temperature at the waste package*
    - *Pre-closure ventilation possible (e.g., Yucca Mountain License Application)*
  - Closed: emplacement openings close (salt, clay/shale) and/or clay buffer surrounds the waste package (crystalline rock)
    - *Greater thermal resistance than radiation across a gap → higher temperature at the waste package (e.g., KBS-3, Dossier 2005, other international concepts)*
- **Temperature limits selected for this analysis are based on material degradation properties**
  - 100^{o}C for clay/shale media and buffer material (e.g., Swedish SR-Can assessment 2006)
  - 200^{o}C for salt (e.g., Salt Repository Project 1986)
- **Final temperature constraints will be site- and design-specific**

Disposal Concept Definition: Three Main Elements

1. **Waste inventory**
   - Waste types from a sample of possible future commercial fuel cycles (Carter et al. 2011a)
   - *Inventory is the link to fuel cycle options and upstream technologies*
2. **Geologic setting**
   - Clay/shale, crystalline rock, bedded salt, and deep crystalline basement
3. **Engineering concept of operation**
   - Clay/shale repository (Andra, Dossier 2005)
   - KBS-3 (vertical) disposal (SKB, SR-Can 2006)
   - Generic salt repository (Carter et al. 2011b)
   - Deep borehole concept (Brady et al. 2009)

Carter, J., A. Luptak, and J. Gastelum 2011a. *Fuel cycle potential waste inventory for disposition.* FCR&D-USED-2010-000031, Rev. 3. April, 2011.

Carter, J.T., F. Hansen, R. Kehrman, and T. Hayes 2011b. *A generic salt repository for disposal of waste from a spent nuclear fuel recycle facility.* SRNL-RP-2011-00149 Rev. 0. Savannah River National Laboratory.

Brady, P.V., B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, and J.S. Stein 2009. *Deep borehole disposal of high-level radioactive waste.* SAND2009-4401. Sandia National Laboratories.

Analysis Approach

- **Develop a thermal model for generic repository concepts**
  - Evaluate temperature histories in the repository (waste package outer surface)
  - Multiple combinations of waste types, age (duration of decay storage), and disposal concepts
  - Waste from advanced fuel cycles
- **Compare peak temperatures with assumed temperature limits for engineered and natural system components**
- **Estimate decay storage duration needed for each disposal concept and waste type**
  - For SNF plot decay storage duration vs. # of assemblies per waste package

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Six Heat-Generating Waste Types (FY11)

Strategy Sampled	Description	Waste Types (Carter et al. 2011a)	Example Source
Once-Through	Direct disposal of high-burnup (60 GW-d/tHM) LWR UOX SNF	• UOX SNF	• Generation III+ LWRs (e.g., Sevougian et al. 2011, Option O-T/2A)
Modified-Open	Reprocessing of LWR UOX used fuel (51 GW-d/tHM) to produce MOX fuel, which is used once (50 GW-d/tHM) then directly disposed	• MOX SNF • Co-Extraction HLW borosilicate glass	• "Transitional" variation of the French strategy with direct disposal of MOX SNF • Irradiated MOX fuel from Pu-disposition program (~500 MTHM)
Closed	Reprocessing of LWR UOX used fuel (51 GW-d/tHM) to produce U-TRU metal fuel for SFRs (0.75 conversion ratio), and repeated recycle of the SFR used fuel (99.6 GW-d/tHM)	• "New-Extraction" HLW borosilicate glass • Electrochemical ceramic HLW • Electrochemical fission-product metal HLW	• "Transitional" fast-spectrum burner strategy with TRU recycling (e.g., similar to Sevougian et al. 2011, Option F-R/60)

Sevougian S. D., M. Gross, E. Hardin, E. Hoffman, R. MacKinnon, L. Price, W. Halsey, J. Buelt, J. Gehin, M. Mullen, T. Taiwo, M. Todosow, and R. Wigeland 2011. Initial Screening of Fuel Cycle Options. FCRD-SYSE-2011-000040 Rev. 0. U.S. Department of Energy Fuel Cycle Technologies Program. March 11, 2011.

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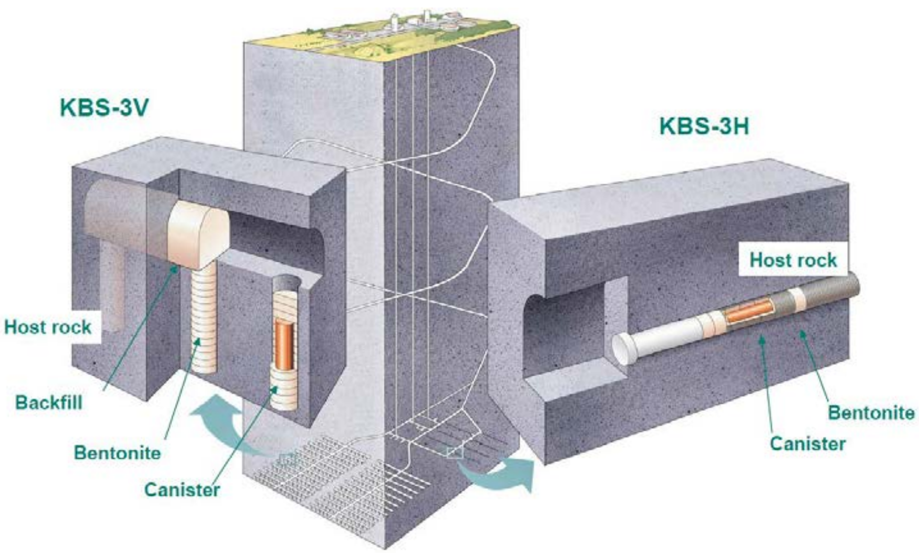
Reference Disposal Concepts: Mined Crystalline Rock with Vertical Borehole Emplacement

- Ref.: Based on KBS-3 (SKB 2006)
- Depth: ~500 m
- Hydrologic setting: Saturated
- Buffer temperature limit: 100ºC



Disposal Characteristic	SNF	HLW
Emplacement mode	Vertical boreholes	Vertical boreholes
Overpack material	Copper or steel	Steel
Borehole spacing, m	10	10
Drift spacing, m	20	20
Borehole liner material	-	-
Buffer material	Bentonite clay	Bentonite clay
Backfill material	Clay/sand mixture	Clay/sand mixture

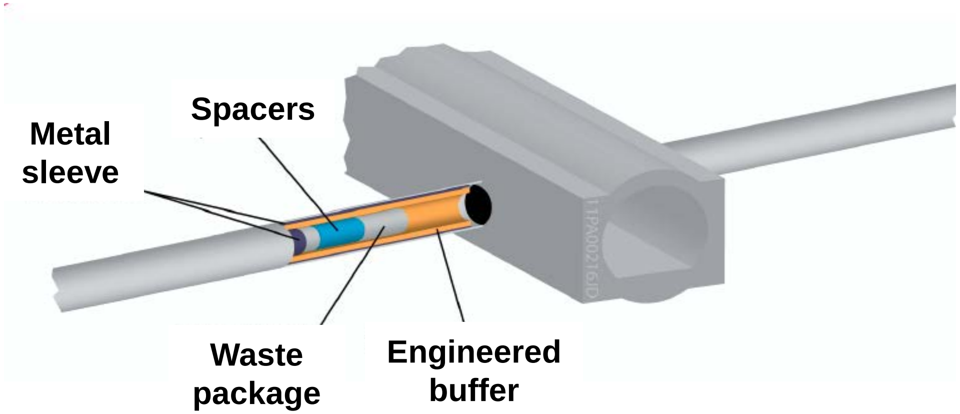
SKB (Swedish Nuclear Fuel and Waste Management Co.) 2006. *Long-term safety for KBS-3 repositories at Forsmark and Laxemar — A first evaluation.* Technical Report TR-06-09.

Reference Disposal Concepts: Mined Clay/Shale with Horizontal Emplacement

- Ref.: Based on Andra 2005
- Depth: ~500 m
- Hydrologic setting: Saturated
- Near-field temp. limit: 100ºC

Disposal Characteristic	SNF	HLW
Emplacement mode	Horizontal, in drift	Horizontal, boreholes
Overpack material	Steel	Steel
Package spacing, m	10	6
Drift (borehole) spacing, m	30	30
Borehole liner material	Steel	Steel
Buffer material	Bentonite clay	-
Backfill material	Crushed clay/shale	Crushed clay/shale

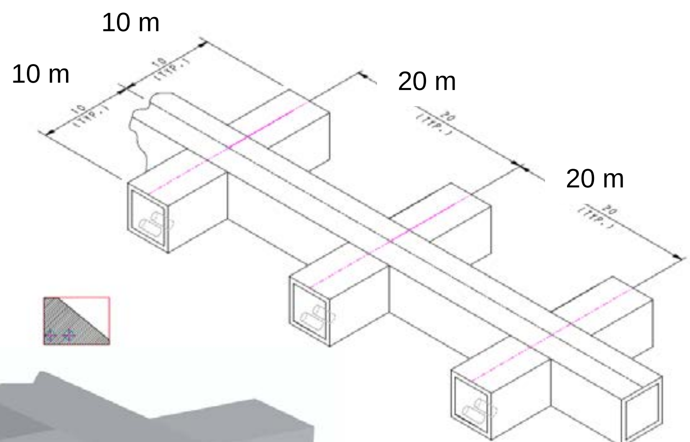
<u>HLW disposal layout</u>

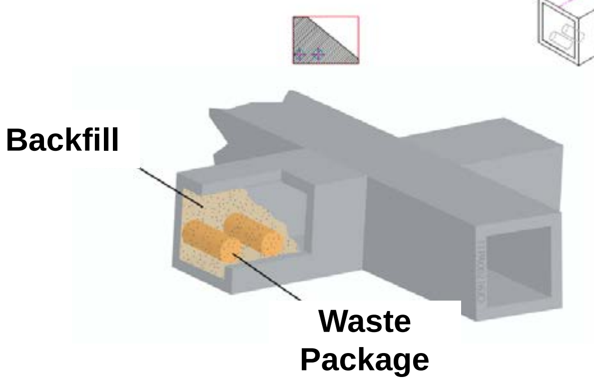


Andra 2005. *Dossier 2005 argile – architecture and management of a geological disposal system*. December 2005. http://www.Andra.fr/international/download/Andra-international-en/document/editions/268va.pdf.

Reference Disposal Concepts: Generic Salt Repository with Alcove Emplacement

- Ref.: Generic Salt Repository (Carter et al. 2011a)
- Depth: ~500 m
- Hydrologic setting: Saturated
- Salt temperature limit: 200°C





Repository characteristic	SNF	HLW
Emplacement mode	Horizontal, in alcoves	Horizontal, in alcoves
Overpack material	Steel	Steel
Alcove spacing, m	20	20
Access drift spacing, m	40	40
Borehole liner material	-	-
Buffer material	-	-
Backfill material	Crushed/ compact salt	Crushed/ compact salt

Carter, J.T., F. Hansen, R. Kehrman, and T. Hayes 2011a. *A generic salt repository for disposal of waste from a spent nuclear fuel recycle facility*. SRNL-RP-2011-00149 Rev. 0. Savannah River National Laboratory.

Reference Disposal Concepts: Deep Borehole

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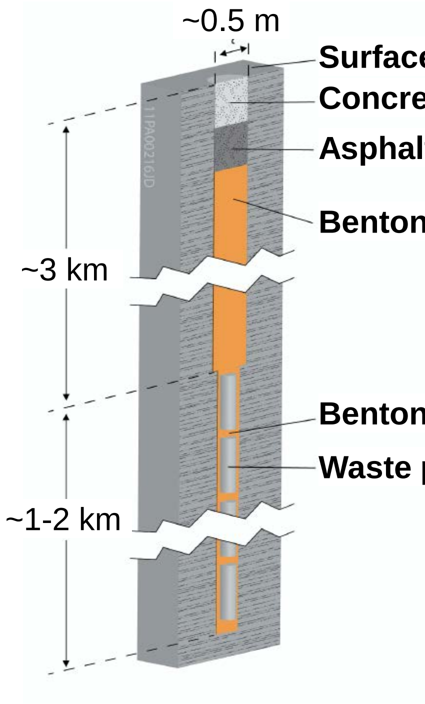
- Ref.: SNL and MIT studies
- Depth: 3 to 5 km
- Hydrologic setting: Saturated
- Temperature constraint: None



Disposal Characteristic	SNF	HLW
Emplacement mode	Vertical, stacked	Vertical, stacked
Overpack material	Steel	Steel
Package spacing, m	6	6
Borehole spacing, m	200	200
Borehole liner material	Steel	Steel
Buffer material	Water/mud	Water/mud
Backfill material	-	-

Brady, P.V., B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, and J.S. Stein 2009. *Deep borehole disposal of high-level radioactive waste*. SAND2009-4401. Sandia National Laboratories.

Semi-Analytical Thermal Model

Conduction-only heat transfer

- Convection negligible in low-permeability rock and EBS materials
- Timing of peak temperature (1 to 30 years after emplacement) limits formation of convection cells
- No significant voids (i.e., no radiative transfer)
- Demonstrated suitable for first-order prediction

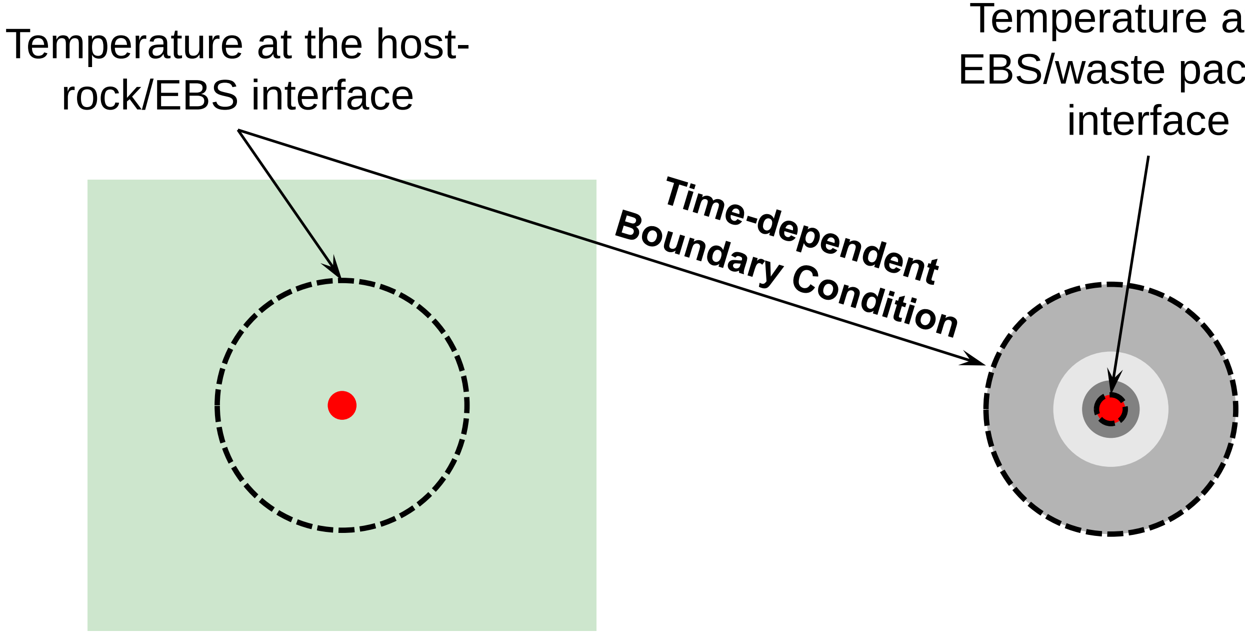
Waste package surface peak temperature

- Maximum EBS temperature outside the waste package
- Waste packages and waste forms withstand greater temperatures
- Package internal thermal performance indexed to external surface temperature
- Other measures (e.g., time-temperature) depend on design

Analysis Approach: Two Steps

Step 1: Host-rock homogeneous 3D model (transient)

Step 2: EBS heterogeneous 2D model (steady-state)



Transient 3D Superposition Solution for Multiple Packages & Drifts

- **A central waste package is modeled as a finite line source**
- **Adjacent waste packages are point sources**
- **Adjacent drifts (or emplacement boreholes) are infinite line sources**
- **Homogeneous host medium**

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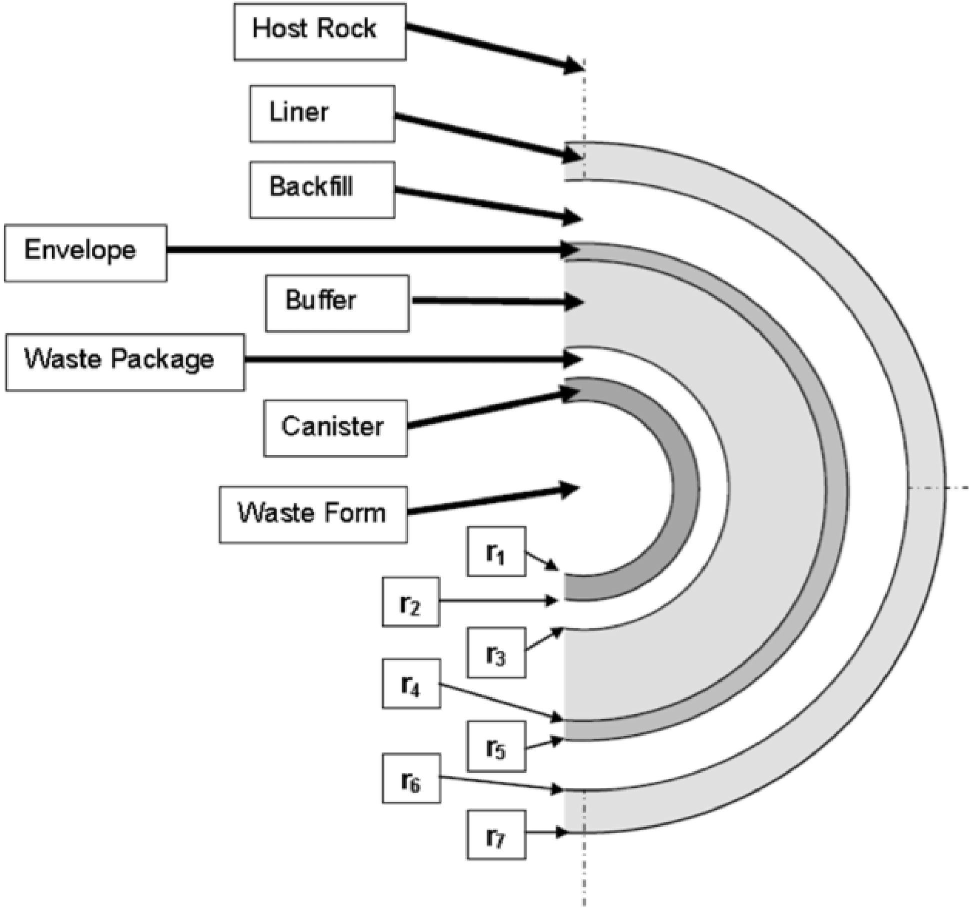
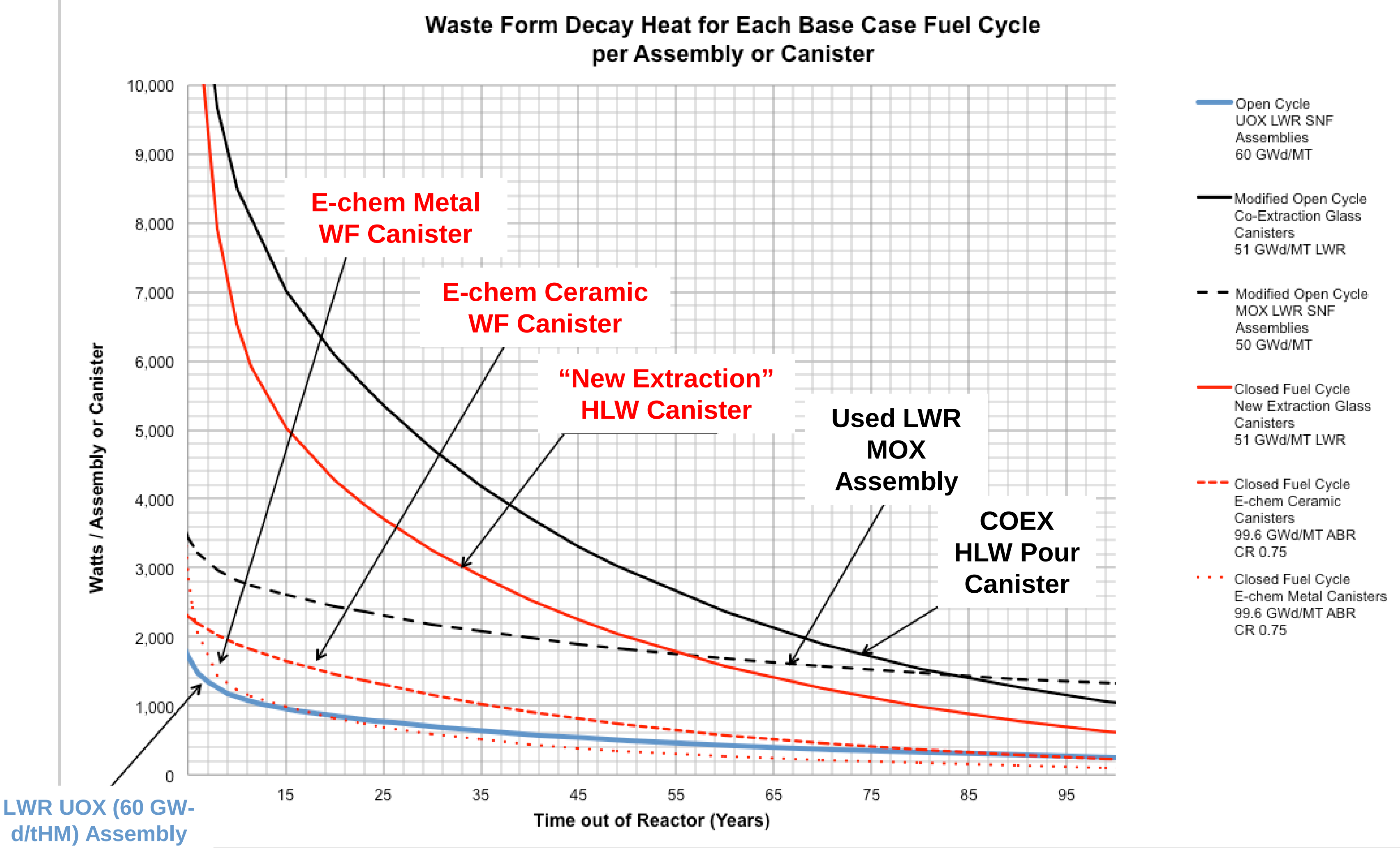
Steady-State Annular 2D Conduction Solution for EBS Layers

- Accounts for every layer between the waste package and rock wall
- Represents peak waste package temperature for all disposal concepts
- Small errors for “point” loading
- Modifies temperature history at EBS boundary from transient solution

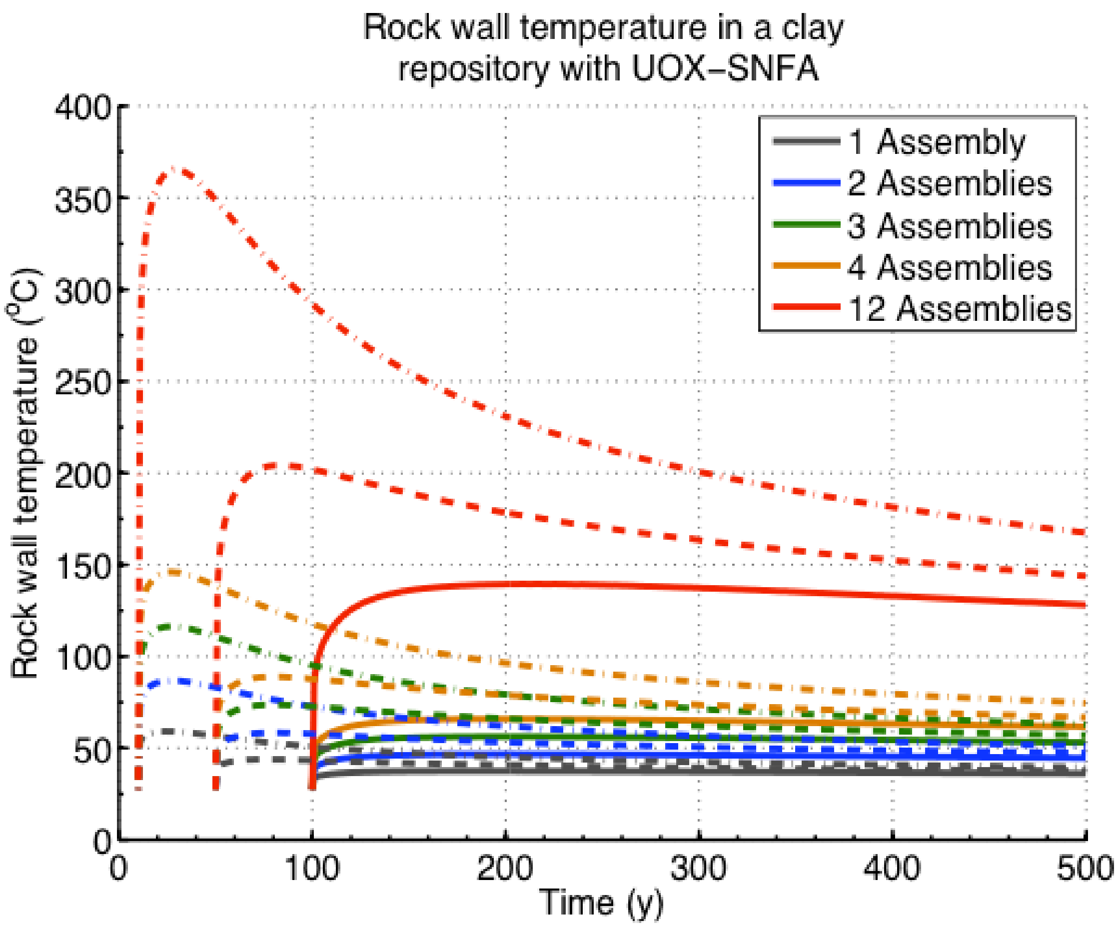


Co-Extraction and New-Extraction Glass Heat Outputs are Highest in the Near Term, MOX SNF in the Long Term



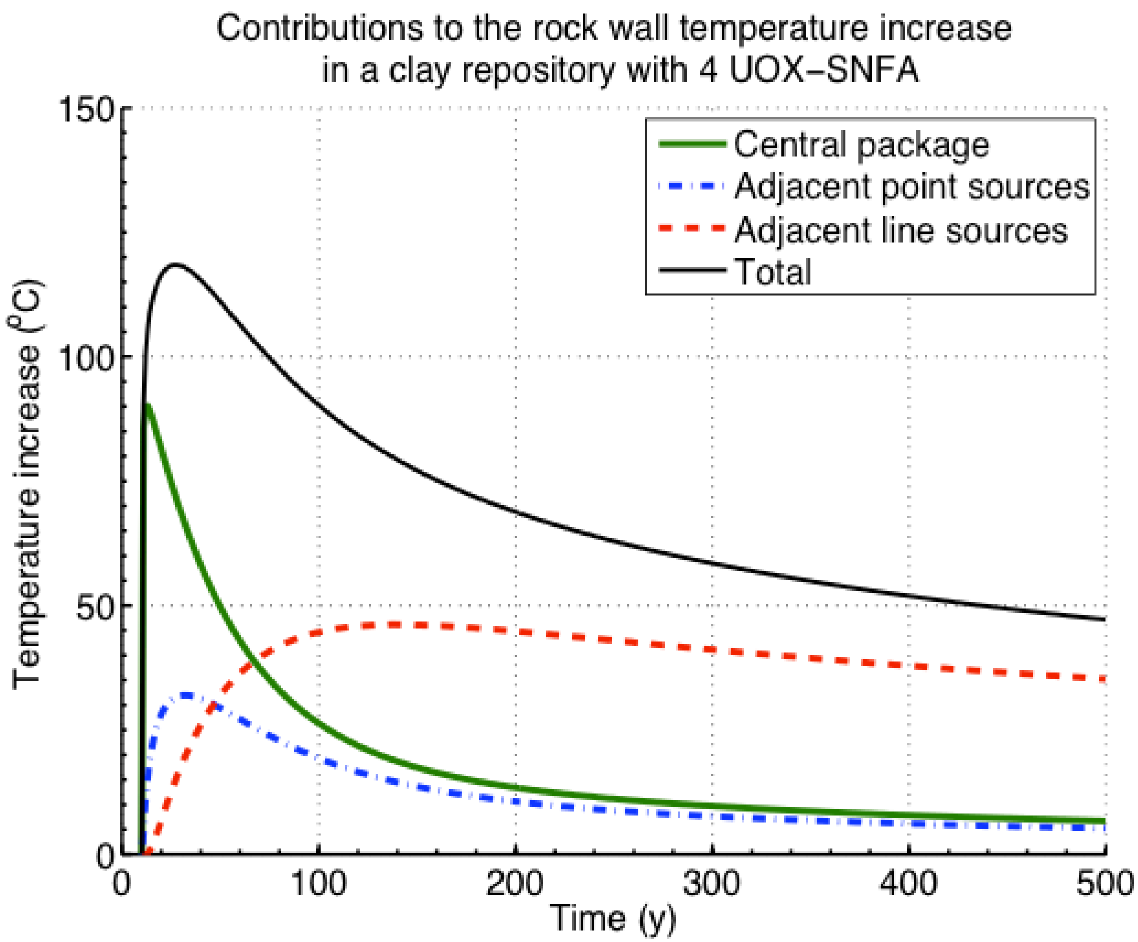
Temperature Histories for 4 Disposal Concepts and 6 Waste Types

- **Example**
  - 1 of 24 cases
- **KBS-3 type repository (crystalline rock/clay buffer)**
- **Results for host rock temperature (at EBS boundary)**
  - LWR UOX SNF (60 GW-d/tHM)
  - Calculate for different package size/capacity



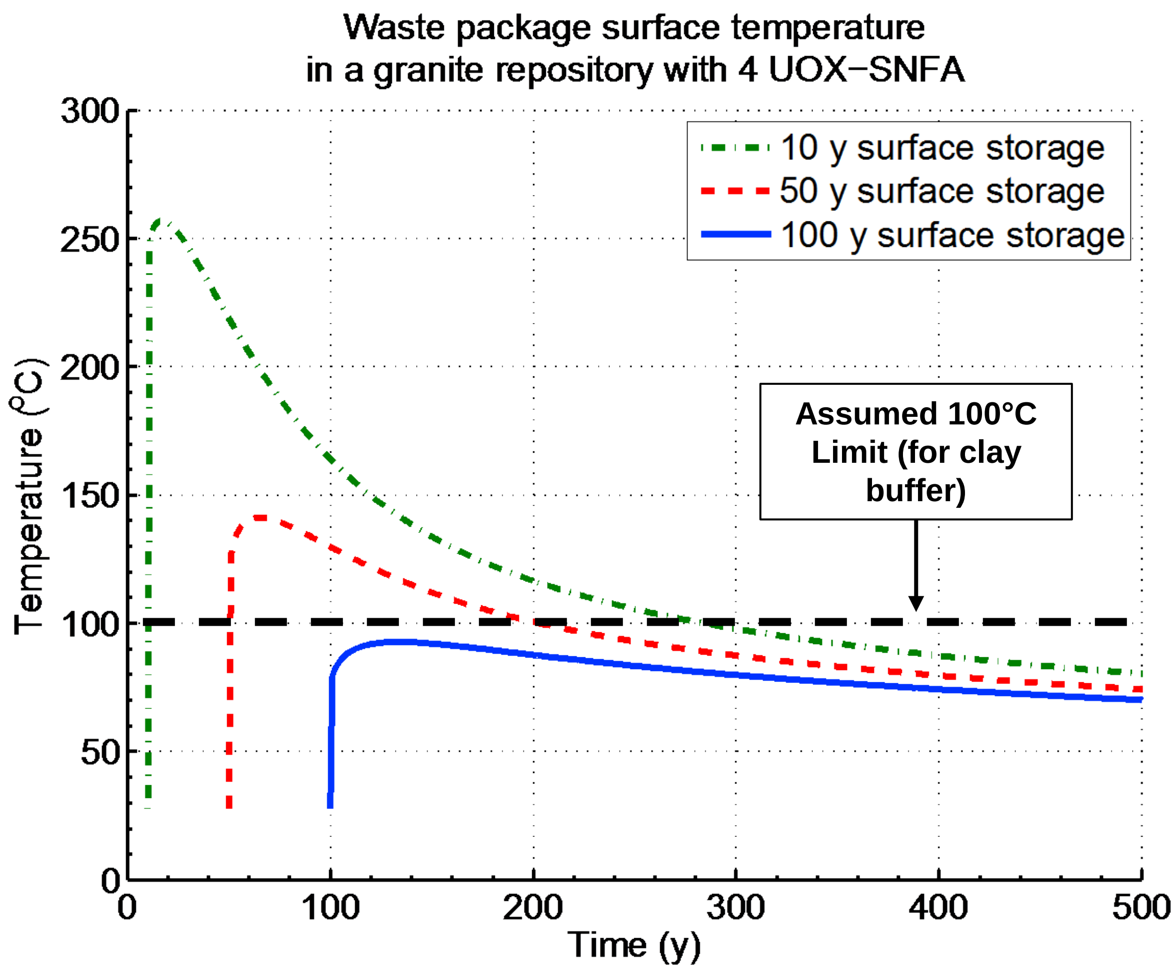
Relative Contributions to Transient Temperature Histories

- **Example**
  - Part of 1 of 24 cases
- **Relative contributions to calculated host rock temperature (at EBS boundary)**
  - LWR UOX SNF (60 GW-d/tHM)
  - 10-yr age out-of-reactor
  - 4-PWR package



Peak Temperature Dependence on Decay Storage Duration

- **Example**
  - Part of 1 of 24 cases
- **Results for waste package surface temperature**
  - LWR UOX SNF (60 GW-d/tHM)
  - 4-PWR package
  - KBS-3 type repository (crystalline rock/clay buffer)



Peak Temperatures at the Waste Package Surface, UOX and MOX SNF, All Disposal Concepts

Disposal Scenario			Peak Temperature at the Waste Package Surface, °C			
			Decay Storage Duration			
Geology	Waste Type	Assemblies/ Package	10 yr	50 yr	100 yr	200 yr
Crystalline (100°C)	UOX SNF	4	256.9	141.2	92.8	68.9
	MOX SNF	1	229.8	172.9	144.0	116.2
Clay/Shale (100°C)	UOX SNF	4	341.9	174.0	106.4	72.9
	MOX SNF	1	288.6	203.4	161.8	126.8
Salt (200°C)	UOX SNF	4	139.9	81.8	57.9	45.7
	MOX SNF	1	120.8	93.1	79.0	65.9
Deep borehole	UOX SNF	1	186.4	161.9	151.7	146.3
	MOX SNF	1	264.5	224.1	202.9	184.7

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Peak Temperatures at the Waste Package Surface, HLW Canisters, Crystalline and Clay/Shale Concepts

Disposal Scenario			Peak Temperature at the Waste Package Surface, ºC			
			Decay Storage Duration			
Geology	Waste Form	Fraction of Canister	10 yr	50 yr	100 yr	200 yr
Granite (100ºC)	Co-Extraction	1	521.2	209.9	93.6	49.8
	New-Extraction	1	396.6	149.9	65.6	31.3
	EC-Ceramic	1	142.0	72.2	41.4	28.9
	EC-Metal	1	124.8	55.7	36.0	28.3
Clay (100ºC)	Co-Extraction	1	478.0	197.3	89.5	52.4
	New-Extraction	1	355.0	141.1	62.9	31.1
	EC-Ceramic	1	133.6	69.1	40.4	28.8
	EC-Metal	1	105.0	50.8	34.6	28.2

Peak Temperatures at the Waste Package Surface, HLW Canisters, Salt and Deep Borehole Concepts

Disposal Scenario			Peak Temperature at the Waste Package Surface, °C			
Geology	Waste Form	Fraction of Canister	Decay Storage Duration			
			10 yr	50 yr	100 yr	200 yr
Salt (200°C)	Co-Extraction	1	281.5	119.1	60.4	37.8
	New-Extraction	1	218.4	89.2	46.7	29.4
	EC-Ceramic	1	85.3	50.0	34.5	28.2
	EC-Metal	1	80.3	42.6	32.1	27.9
Deep borehole	Co-Extraction	0.291	250.8	180.5	154.5	144.2
	New-Extraction	0.291	222.1	167.2	148.5	140.9
	EC-Ceramic	0.291	165.6	150.0	143.1	140.3
	EC-Metal	0.291	160.4	146.0	141.8	140.2

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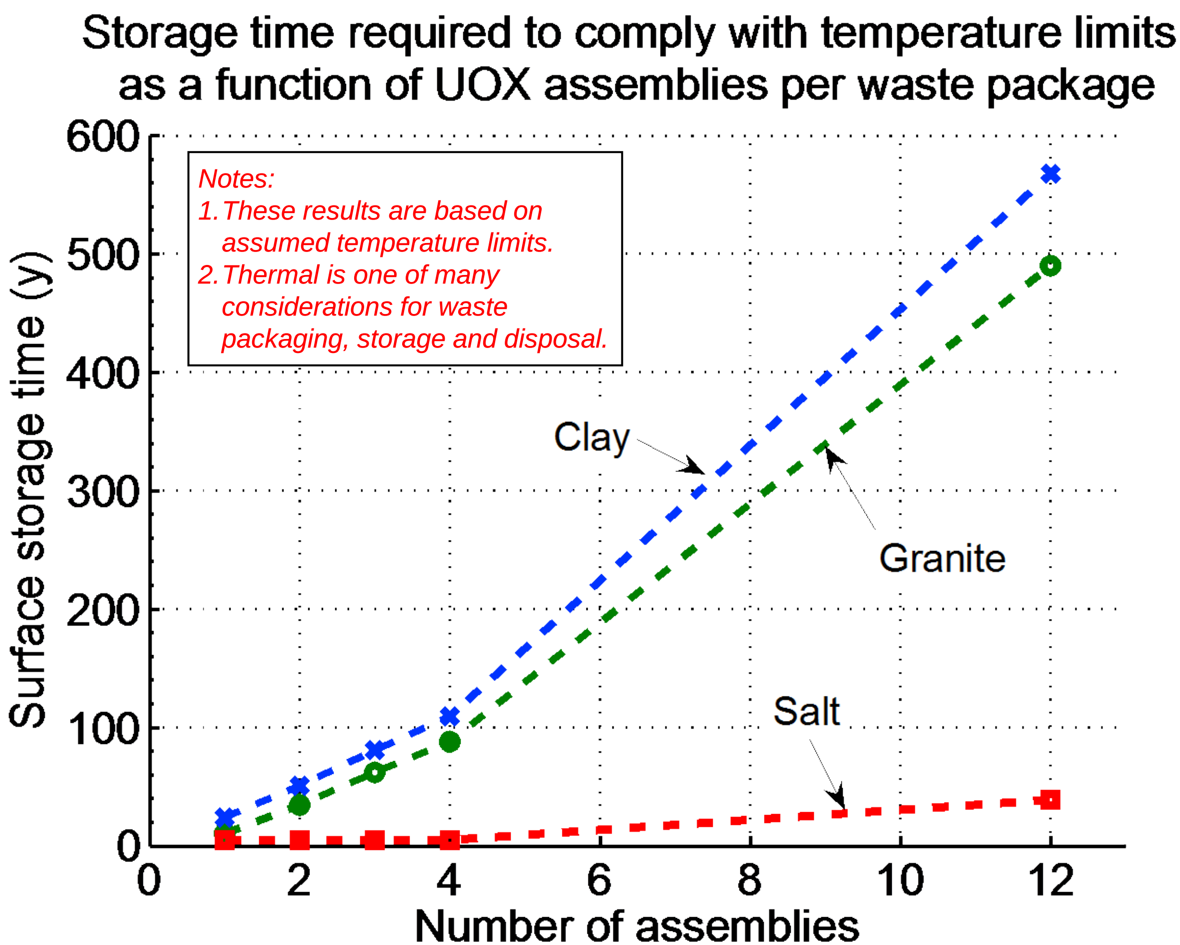
Surface Storage of ≤100 yr Limits Package Size to 4-PWR (UOX) in Crystalline and Clay/Shale Concepts



Conclusions

- **For the SNF types, disposal concepts and temperature limits evaluated, estimates are given for decay storage duration needed:**

Number of assemblies	UOX		MOX	
	Crystalline or Clay/Shale	Salt	Crystalline or Clay/Shale	Salt
1	~10 years	<10 years	300-400 years	<10 years
4	~100 years	<10 years	>500 years	~100 years

(Maximum package surface temp. 100°C for clay-based material, 200°C for salt.)

- **For the HLW forms evaluated, needed decay storage is ≤100 years for crystalline and clay/shale concepts and ≤50 years for salt**
- **Peak package surface temperature for the deep borehole concept is ≤300°C (10 years out-of-reactor)**
  - Package size is limited by borehole diameter

Continuing Work

- **Additional disposal concepts**
  - Open emplacement mode (saturated or unsaturated)
  - Waste streams: existing LWR SNF inventory (~40 GWd/tHM) and other waste types from advanced fuel cycles
  - Larger waste packages
- **Temperature limits greater than 100ºC (clay/shale host material and clay buffer) and 200ºC (salt)**
- **Temperature constraints expressed in other terms (e.g., time-temperature-moisture)**
- **Verification and uncertainty analysis for thermal calculations**
- **Disposal concept facilities description and cost estimation**

More details: E. Hardin, J. Blink, H. Greenberg, M. Sutton, M. Fratoni, J. Carter, M. Dupont & R. Howard 2011. *Generic Repository Design Concepts and Thermal Analysis (FY11)*. SAND2011-6202, August 2011.

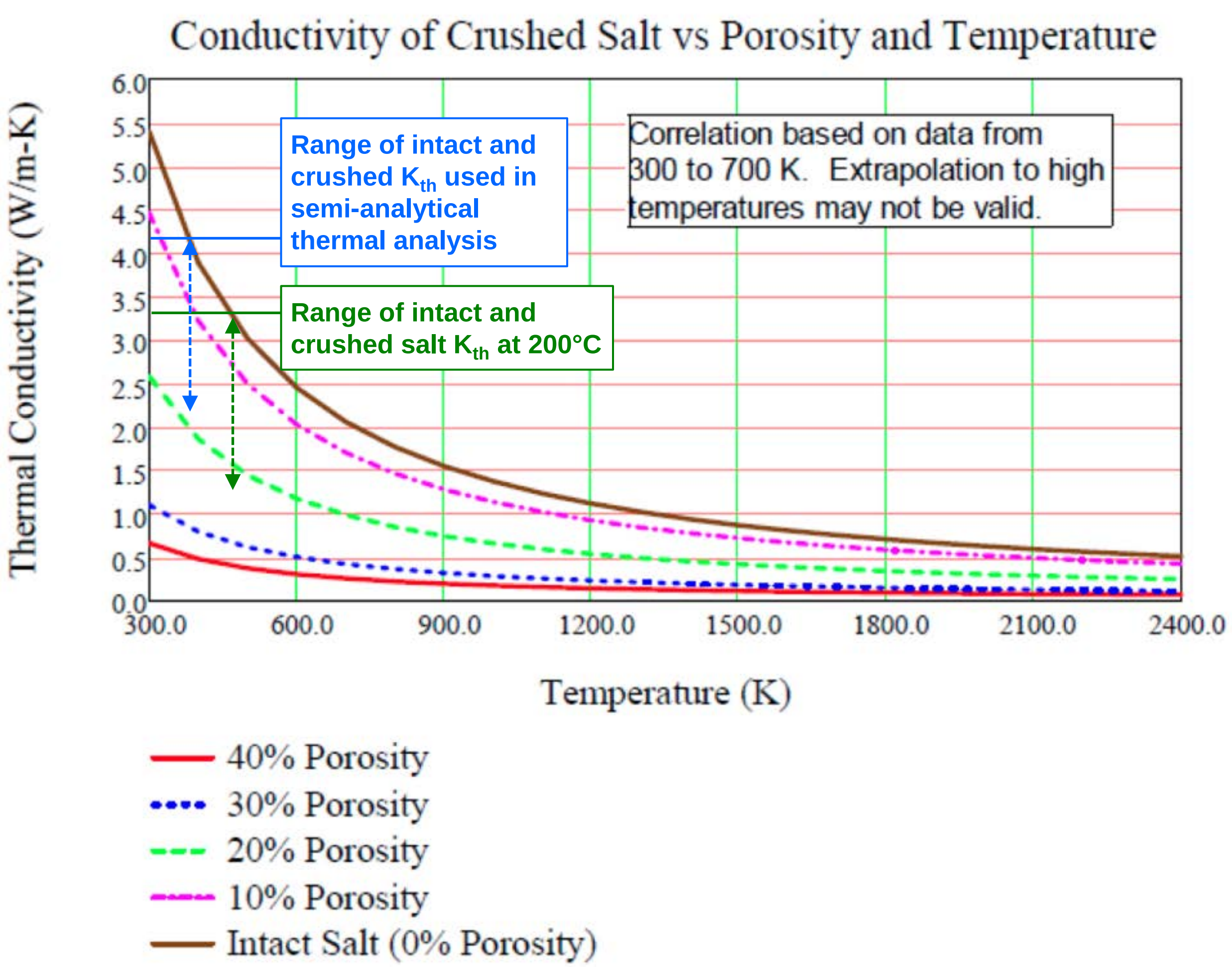
BACK-UP SLIDES

Host Rock Thermal Properties

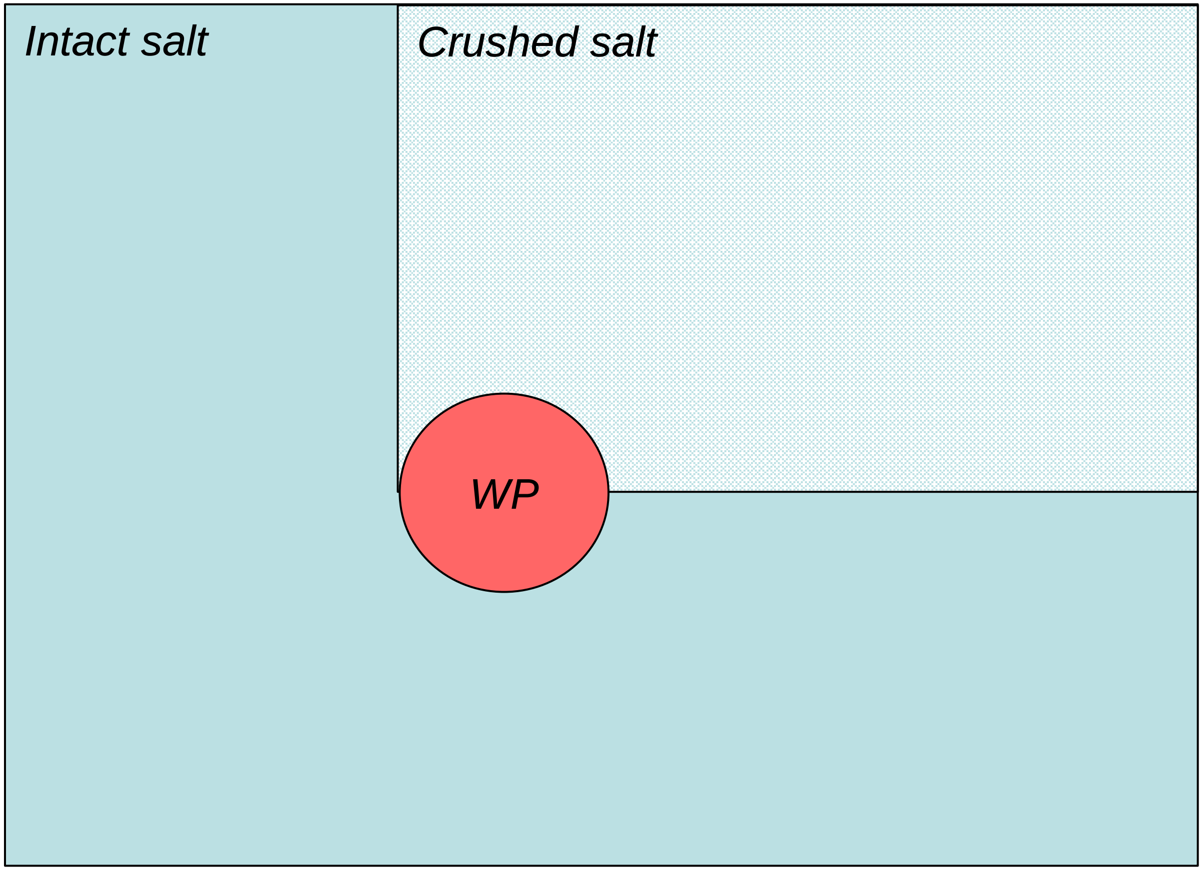
Repository	Conductivity, W/m-K	Diffusivity, m^2/s
Crystalline	2.5	1.13E-6
Clay/Shale	1.75	6.45E-7
Salt	4.2	2.07E-6
Crushed Salt	0.57 (40% porosity)	4.7E-7
Deep Basement	3.0	1.38E-6

Crushed Salt Thermal Conductivity

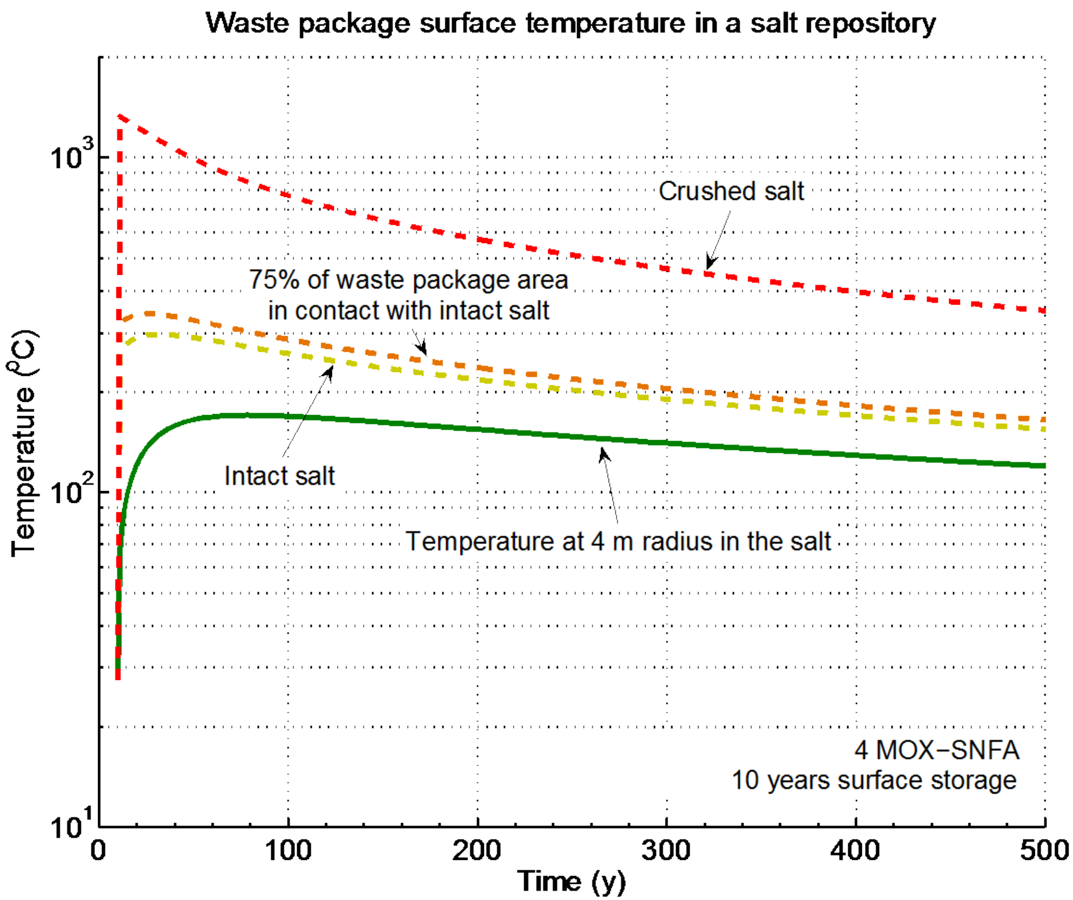
- K_{th} for crushed WIPP salt
- Based on lab data for the temperature range of interest (298K to 473K)



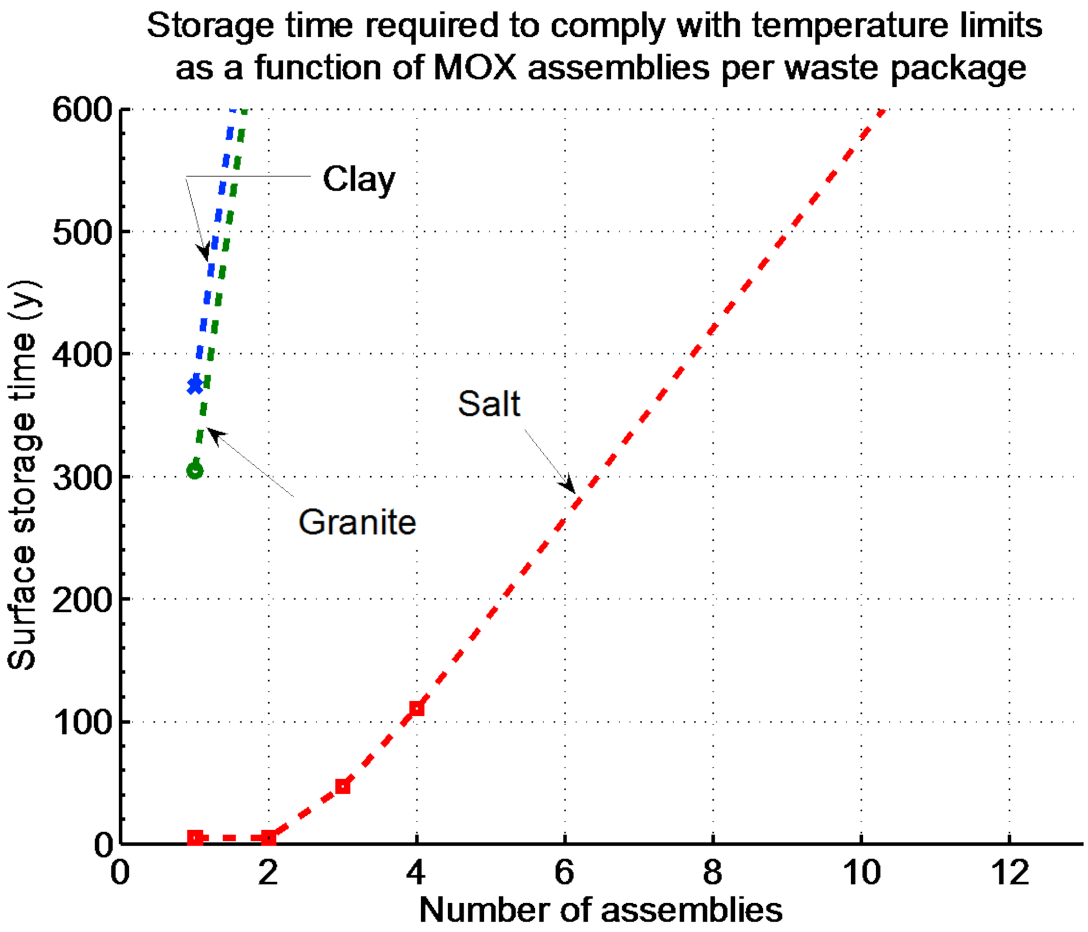
Schematic of Waste Package Emplacement in Salt



Temperature at the waste package surface for selected salt conditions



MOX SNF Emplacement in 4-PWR Packages, After ~100 yr Decay Storage, in Salt



Peak temperatures are calculated on the main package center line