U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Generic Disposal Concepts and Thermal Load Management for Larger Waste Packages

Ernest Hardin (SNL)
Jim Blink & Harris Greenberg (LLNL)
Joe Carter (SRNL)
Rob Howard (ORNL)

Nuclear Waste Technical Review Board
October 17, 2012
Idaho Falls, ID

SAND2012-8074C

Outline

- Disposal concepts ("enclosed"): crystalline, clay/shale, salt, deep borehole (Re: January, 2012 briefing)
- Thermal analysis for mined, "enclosed" concepts
- Finite element analysis for generic salt repository (waste package size up to 32-PWR)
- "Open" disposal concept development: shale unbackfilled, sedimentary backfilled, and hard-rock unsaturated (waste package sizes up to 32-PWR)
- Thermal analysis for mined, "open" concepts
- Cost estimation for 5 disposal concepts
- Summary and conclusions

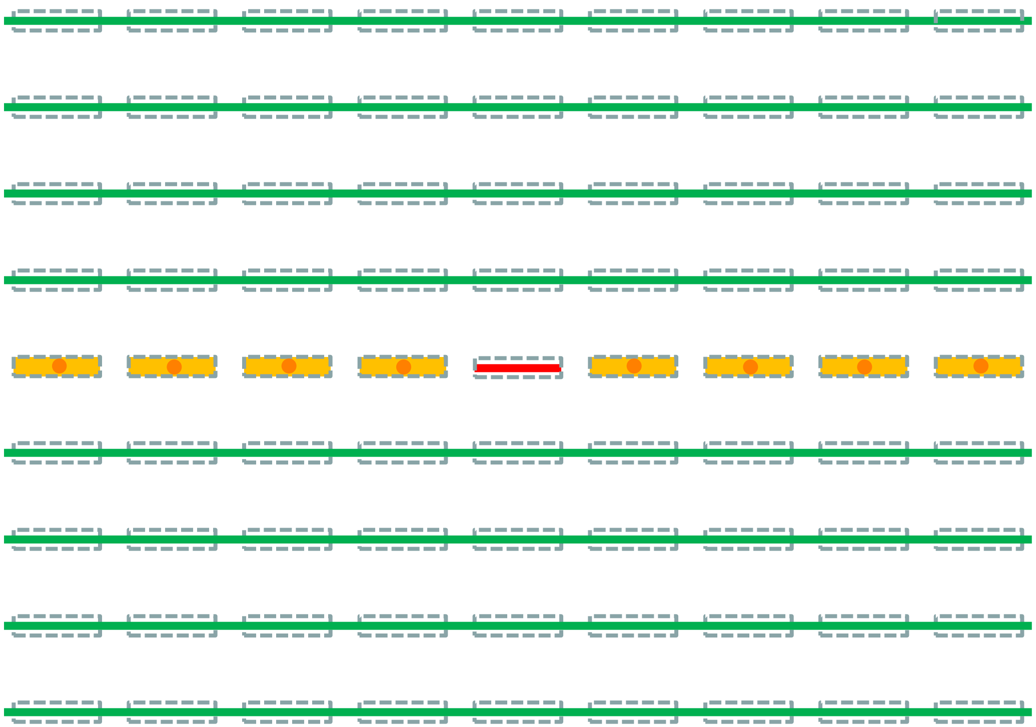
Disposal Concept Definition, and Settings Evaluated

1. **Waste inventory**
   - Commercial SNF, 40 and 60 GW-d/MT burnup (existing inventory and bounding SNF case; Carter et al. 2012a)
   - Representative MOX and HLW types (summary: Hardin et al. 2012)
2. **Geologic settings**
   - Crystalline, clay/shale, bedded salt, crystalline basement, massive shale, sedimentary (e.g., alluvium), "hard rock"
3. **Engineering concepts of operation**
   - Crystalline (enclosed)*
   - Clay/shale (enclosed)*
   - Generic salt repository (enclosed)*
   - Deep borehole*
   - Hard-rock unsaturated (open)
   - Shale unbackfilled (open)
   - Sedimentary backfilled (open)

* January, 2012 briefing

Transient Superposition Solution for Multiple Packages & Drifts

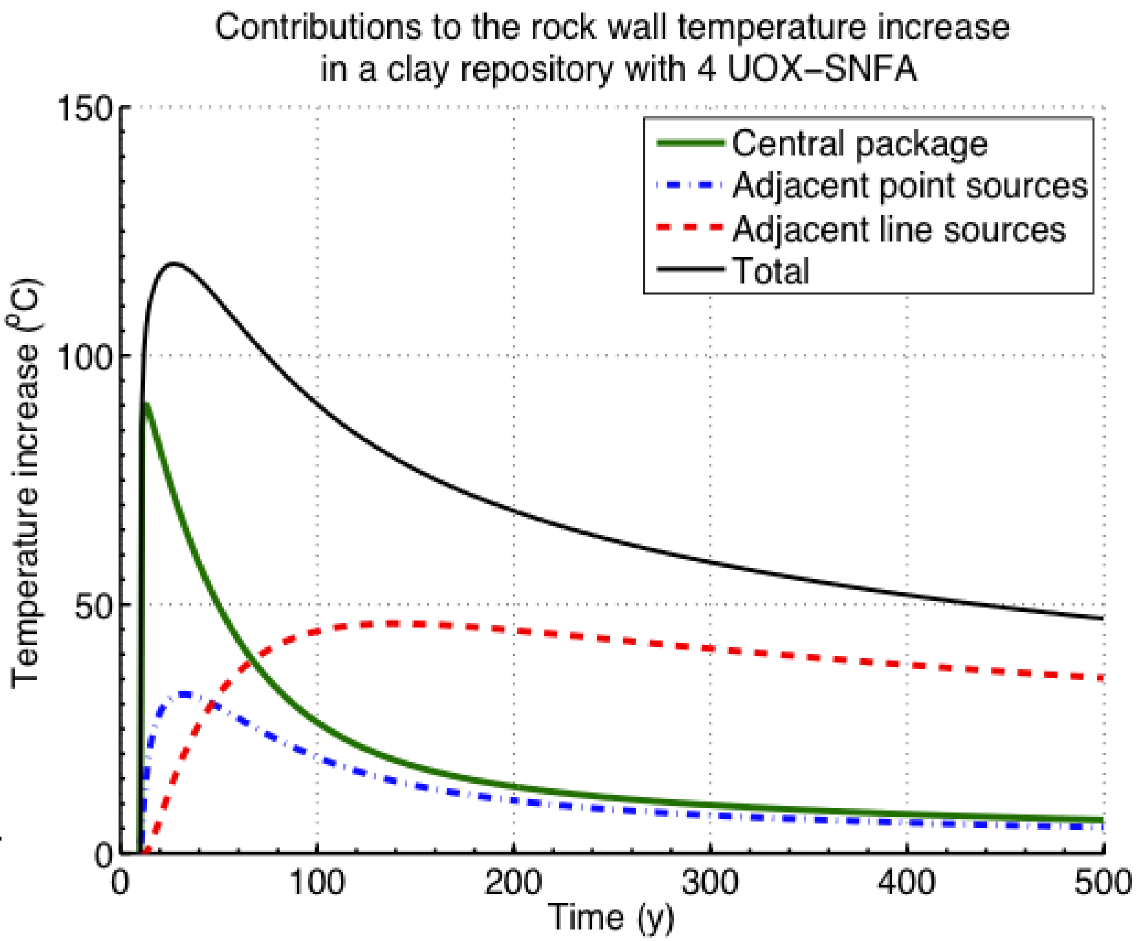
- A central waste package is modeled as a finite line source
- Adjacent waste packages are point sources
- Adjacent drifts (or emplacement boreholes) are infinite line sources
- Homogeneous host medium



Back-calculate approximate temperatures for radial layers representing the engineered barrier system.

Relative Contributions to Transient Temperature Histories

- **Example: Relative contributions to calculated host rock temperature (at EBS boundary)**
  - LWR UOX spent fuel (60 GW-d/tHM; bounding)
  - 10-yr age out-of-reactor
  - 4-PWR package
  - Clay/shale reference (enclosed) concept, similar to Andra (2005) concept for SNF



Source: Greenberg et al. 2012a.

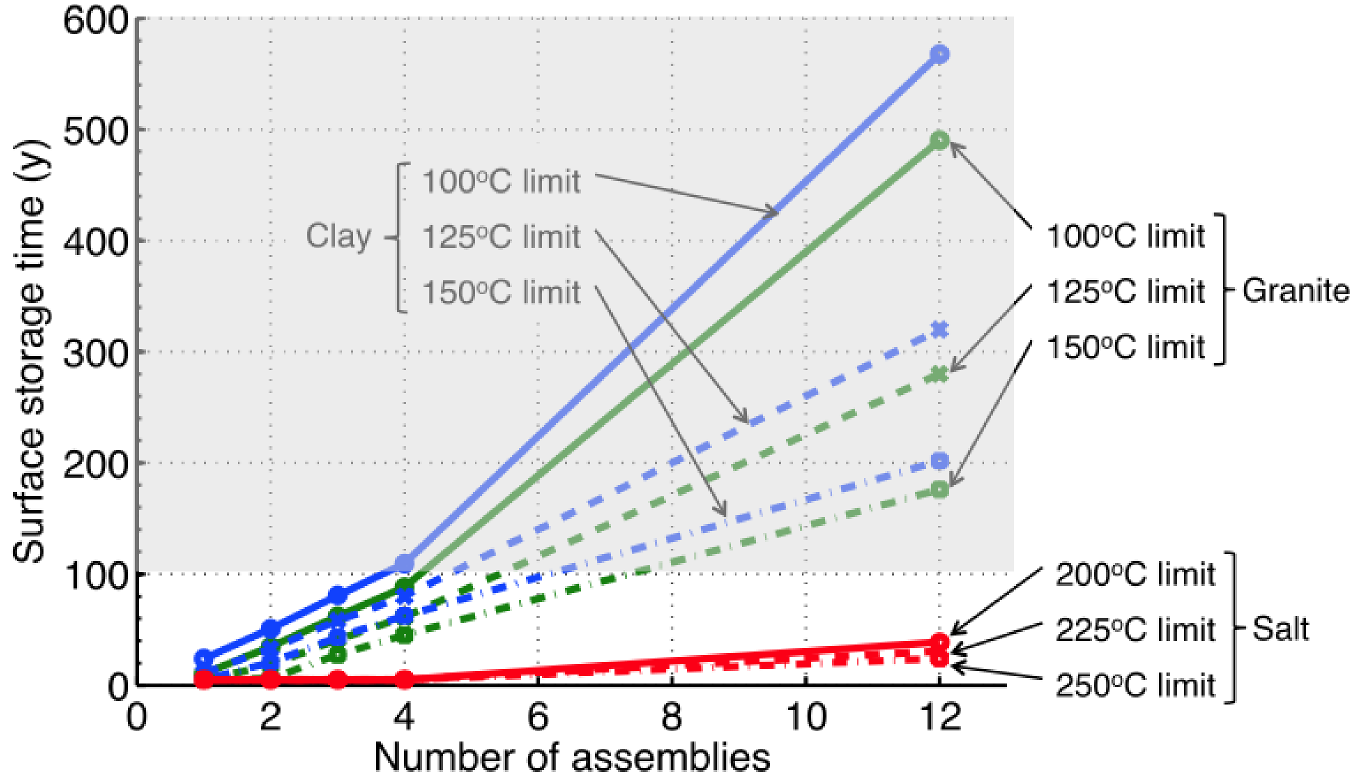
Thermal Analysis Results
Effect of Varying 100°C or 200°C Limits

Decay Storage Needed to Meet WP Surface Temperature Limits vs. WP Size or Capacity (PWR Assemblies; 60 GW-d/MT Burnup)

Temperature limits based on current international and previous U.S. concepts:

- **100ºC for clay buffers and clay/shale media (e.g., SKB 2006)**
- **200ºC for salt (e.g., Salt Repository Project, Fluor 1986)**

Final temperature constraints will be site- and design-specific

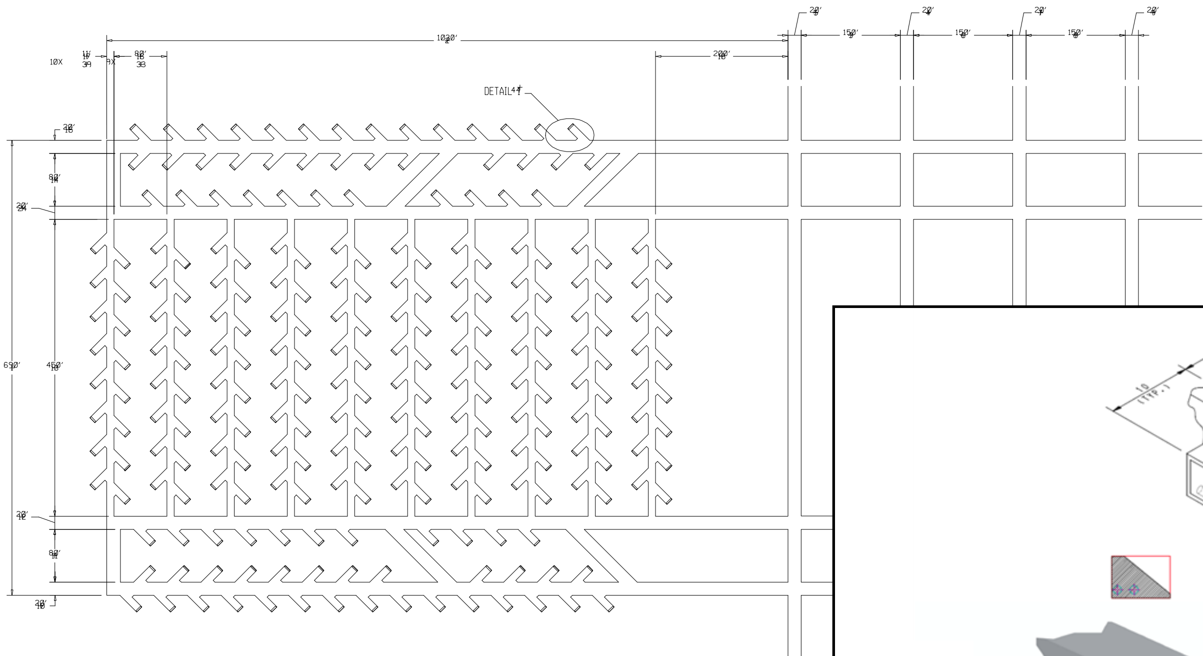


Thermal conductivity for all media selected at 100 ℃.

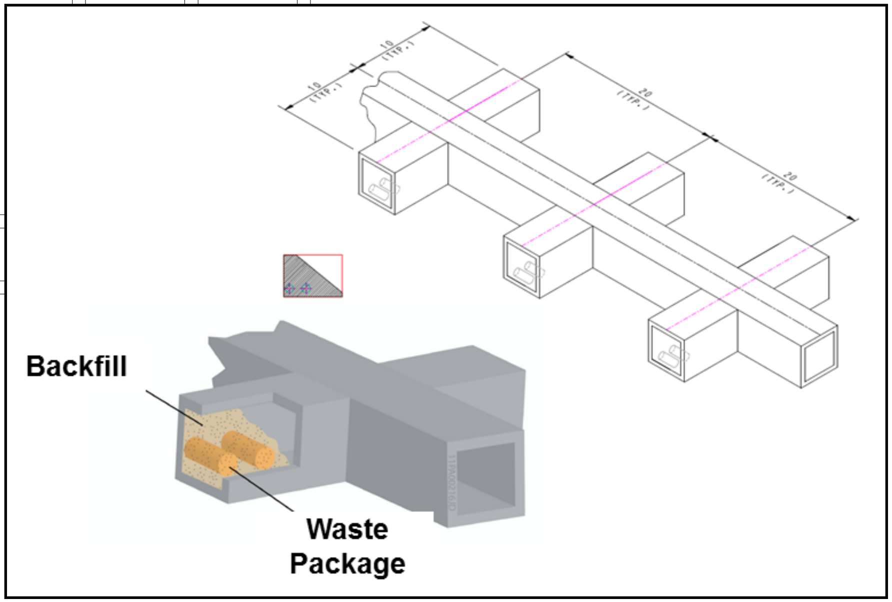
Source: Greenberg et al. 2012a.

Disposal of Large Waste Packages in Salt
Generic Salt Repository

- **Generic salt repository layout (Carter et al. 2011)**

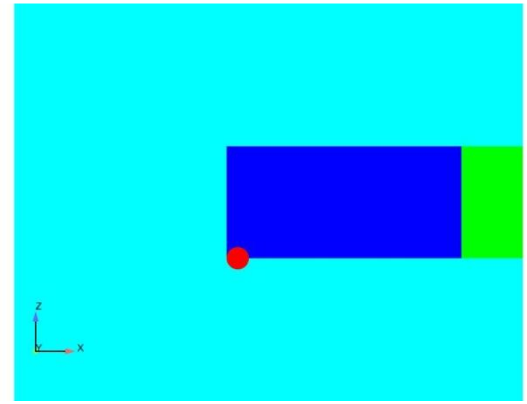


- **Abstracted to right-angle geometry (Hardin et al. 2012)**

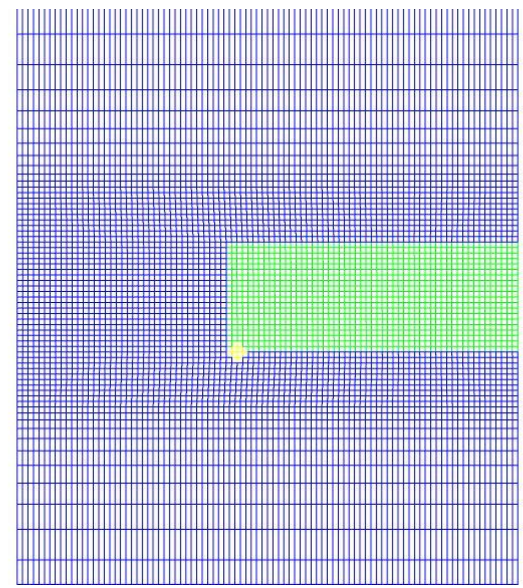


Generic Salt Repository
T-M and T-only Simulation Approach

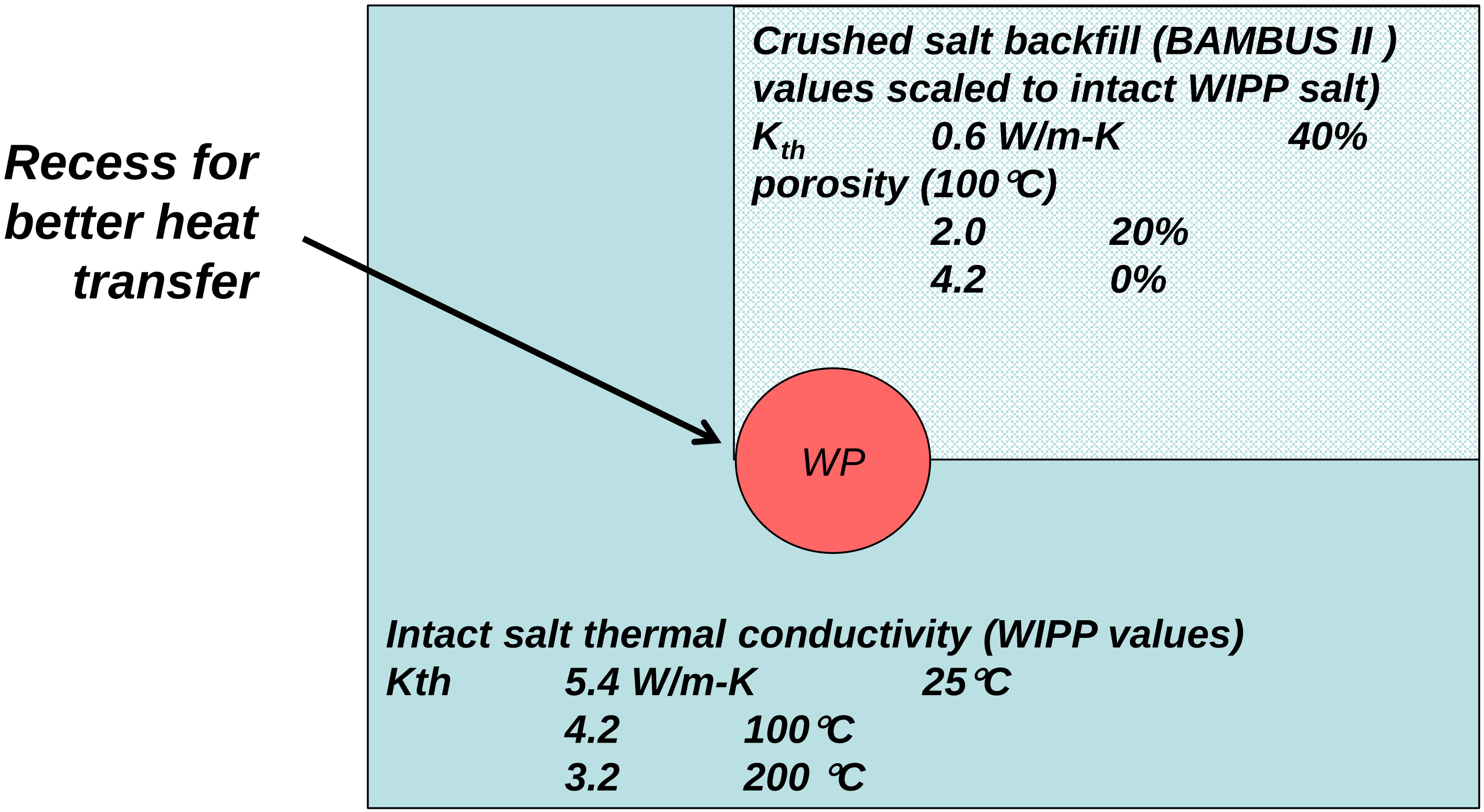
- **Coupled thermal-mechanical model (Clayton et al. 2012)**
- **Sierra codes (Sandia)**
- **Salt properties and constitutive models**
  - Multi-mechanism creep model (Munson et al. 1989)
  - Crushed salt creep (Callahan 1999)
  - Thermal conductivity (Bechthold et al. 2004)
- **Approach:**
  - Test T-M dependence for initial problem
  - Use T-only model for sensitivity analyses



Waste Package Size	Diameter (m)	Length (m)
4 PWR assemblies	0.82	5.00
12 PWR assemblies	1.29	5.13
21 PWR assemblies	1.60	5.13
32 PWR assemblies	2.0	5.13

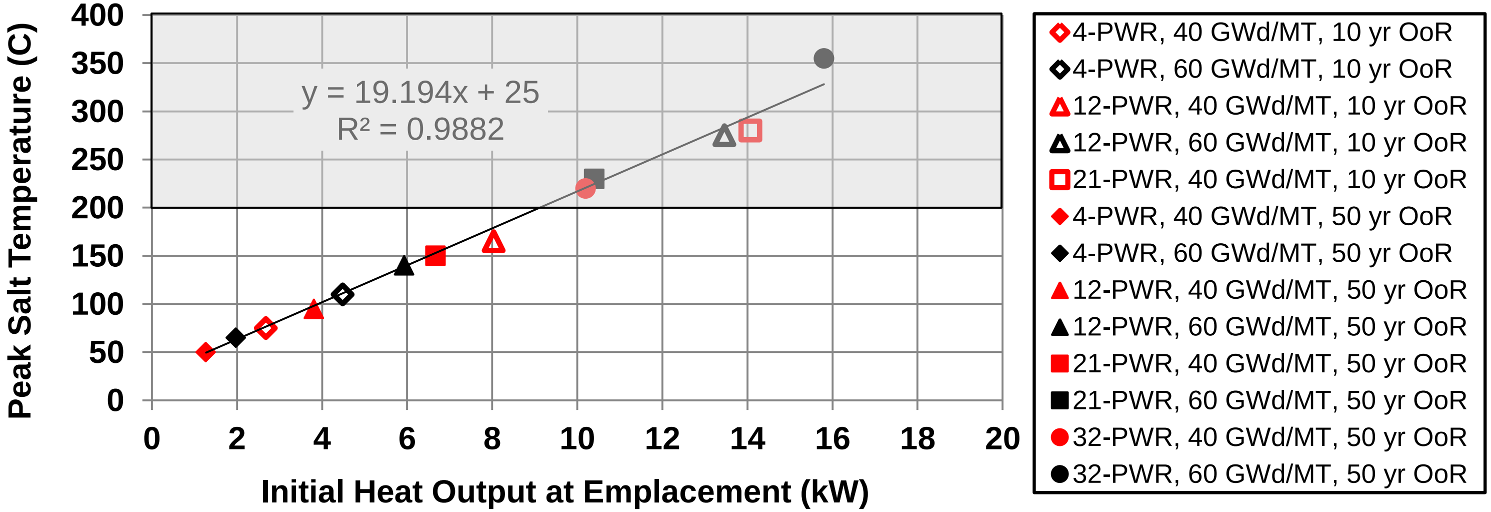


Schematic of Waste Package Emplacement in Salt



Disposal of Large Waste Packages in Salt

- **Peak salt temperature vs. initial package thermal power correlation (>200°C limit shown shaded)**
- **Burnup, age, and package dimensions are 2nd order**



- **Also true for other geologic media and disposal concepts**
- **Use waste package surface temperature to control interface with in-package analyses**

Reference Mined Disposal Concepts: Open vs. Enclosed Emplacement Modes

- **Open: excavated emplacement openings persist**
  - Heat spread by thermal radiation → lower temperature at the waste package
  - Pre-closure ventilation possible while drifts remain open for decades
- **Enclosed: emplacement openings close (salt, clay/shale) and/or clay buffer surrounds the waste package (crystalline rock)**
  - More thermal resistance than radiation across a gap→ higher peak temperature in the EBS (e.g., KBS-3, Andra 2005, others)

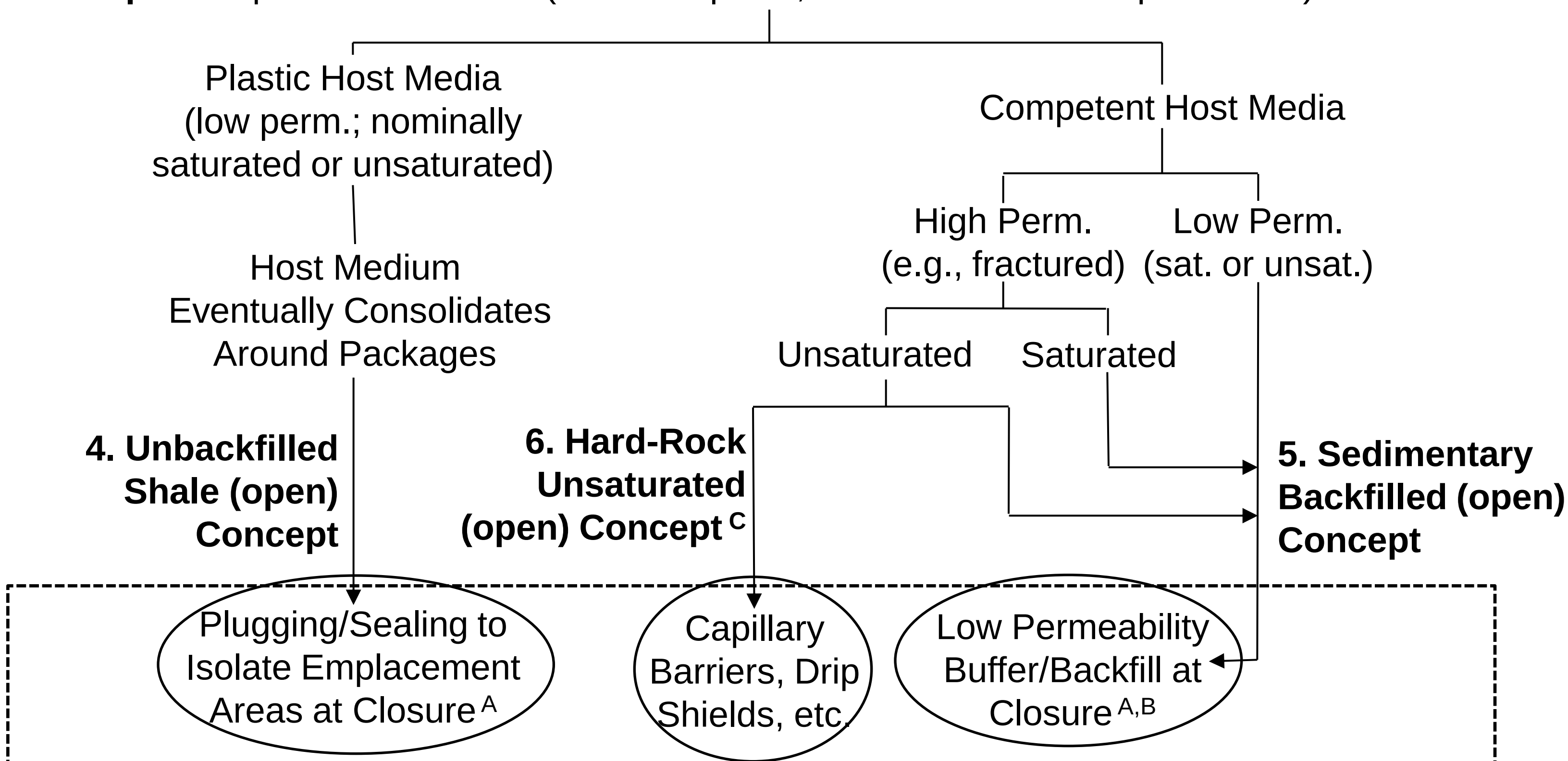
Reference Mined Disposal Concepts: Open vs. Enclosed Emplacement Modes

- **Problem Statement (discussed in January, 2012 briefing):**

  For reference portfolio: Develop (open mode) disposal concepts that allow: 1) earlier emplacement, and 2) larger waste packages. Focus on commercial SNF, using a range of geologic settings and concepts of operation.

- **Potential benefits:**
  - Improved cost/schedule efficiency
  - Flexibility not to transport SNF with age > 50 yr
  - Limit packaging and re-packaging (especially if existing storage canisters can be disposed directly)
  - Fewer package-specific operations of all types

Open Disposal Concept "Taxonomy"



Install these measures at or before repository closure, as thermal and operational conditions permit.

Notes:
A. Open modes in low-permeability host media require low-permeability backfill prior to repository closure, if the host medium will not collapse to seal openings. This prevents preferential water flow in the repository (even for unsaturated conditions).
B. For higher permeability media use low-permeability buffer and/or backfill, for water diversion and transport attenuation.
C. Includes waste packages designed for containment longevity.

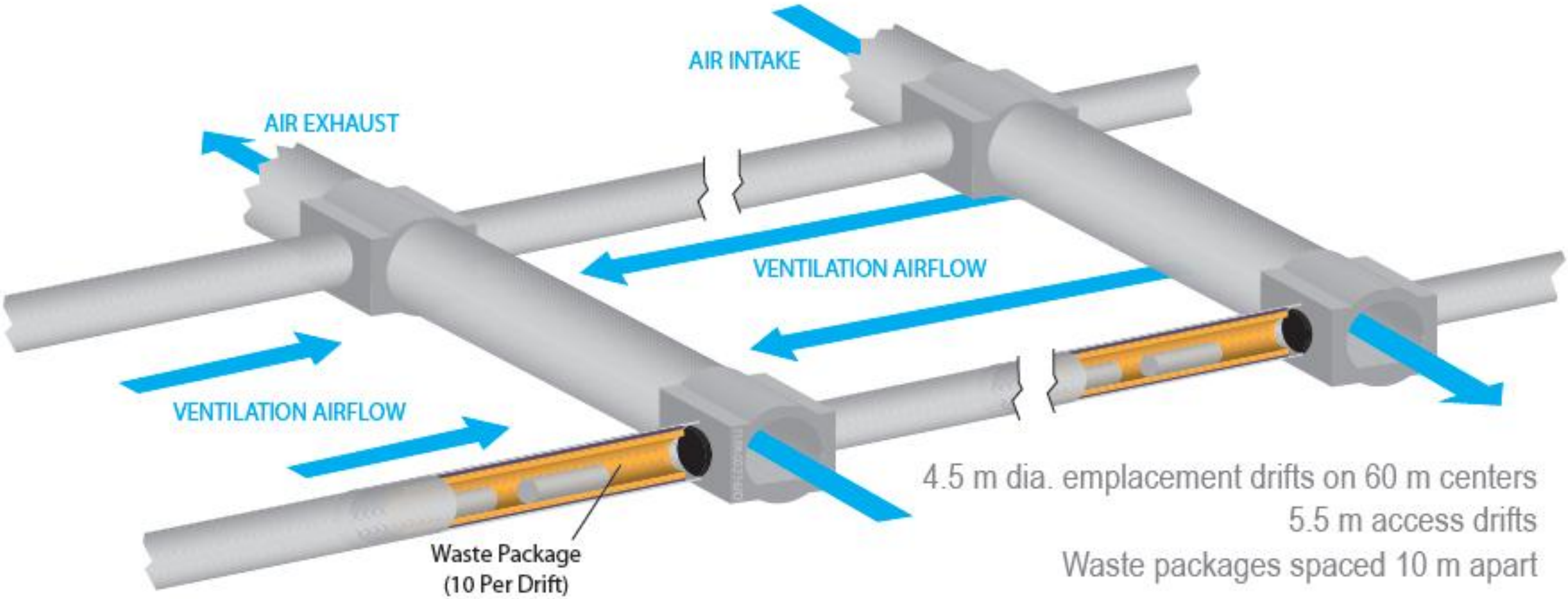
Reference Disposal Concepts

1. KBS-3 (vertical) disposal (enclosed)
2. Generic salt repository (enclosed)
3. Clay/shale repository (enclosed)
4. **Shale unbackfilled open mode**
5. **Sedimentary backfilled open mode**
6. **Hard-rock unsaturated open mode**
7. Deep borehole concept

Source: Hardin et al. (2012).

4. Shale Unbackfilled Open Mode Concept
(low-permeability, nominally sat. or unsat.)

U.S. DEPARTMENT OF ENERGY
Nuclear Energy



Drift segments containing small numbers of waste packages are isolated by plugging/sealing (backfill is retained as an option at repository closure).

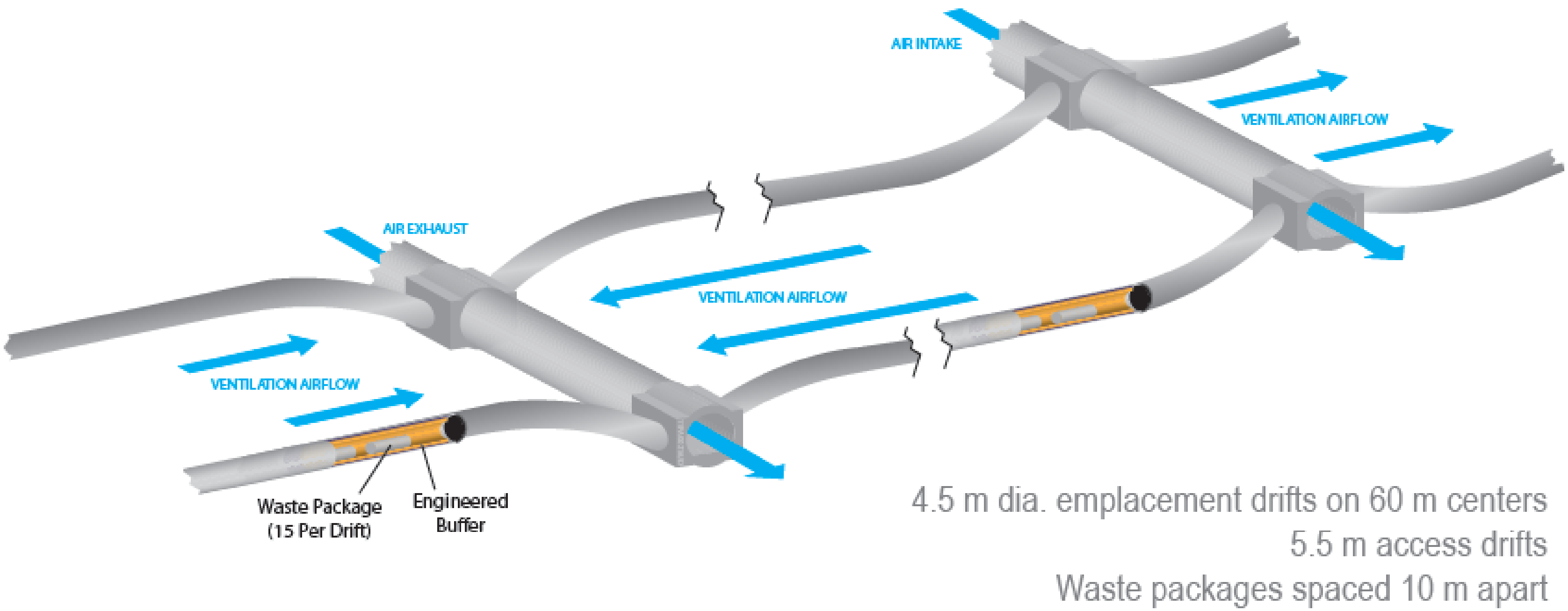
Not to Scale

Source: Hardin et al. (2012).

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

5. Sedimentary Backfilled Open Mode (high- or low-permeability; saturated or unsaturated setting)



Drift segments containing small numbers of waste packages are <u>backfilled with low permeability (e.g., clay-rich) material at closure</u>

Not to Scale

Source: Hardin et al. (2012).

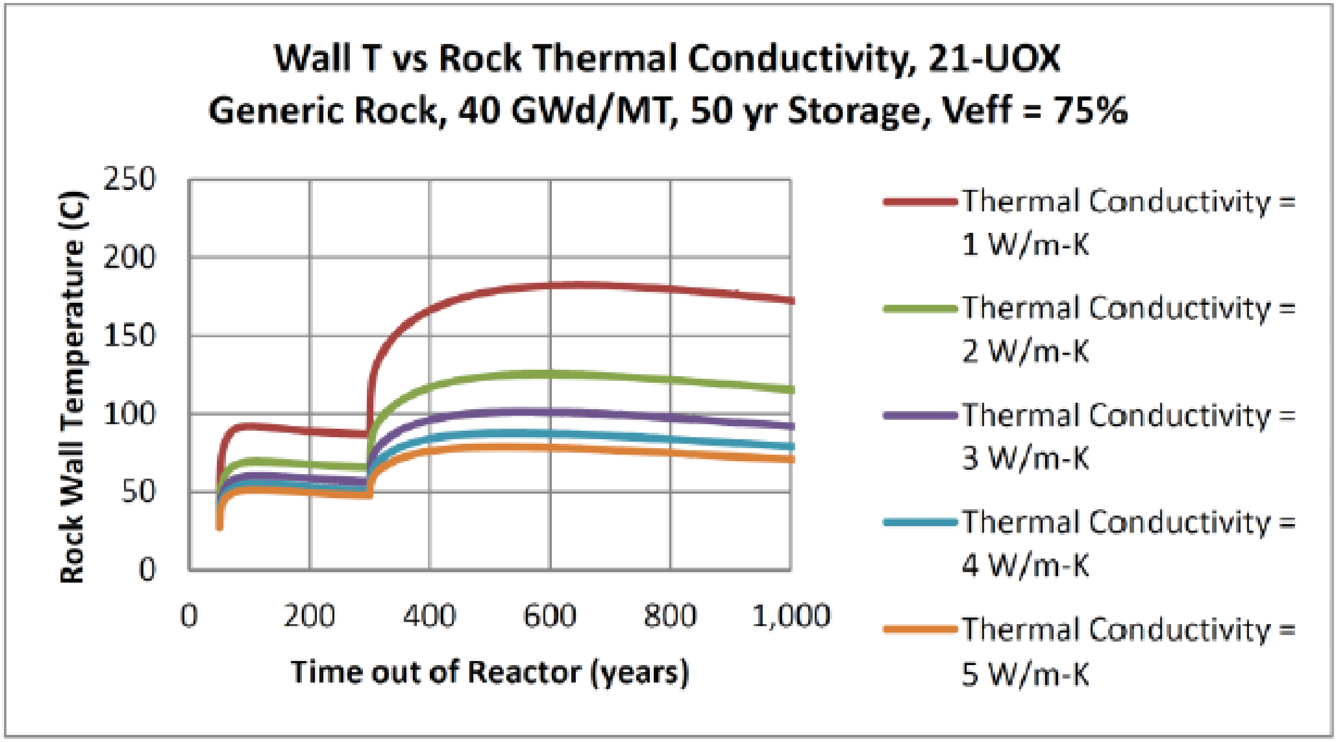
6. Hard Rock, Unsaturated Concept

- Comprehensive design selection study (CRWMS M&O 1999)
- Pre-closure ventilation for at least 50 years (all design alternatives considered in the study included this feature)
- Long-term surface decay storage is not needed
- Ventilation >> 50 years provides an option for a cooler repository
- Free drainage → No need for complete backfilling at closure
- Unsaturated → Shallow depth, facilitating ramp access

Key point: A similar open concept for saturated fractured rock would require complete backfilling at closure (remote operation) to limit groundwater movement through the repository.

Open Mode Thermal Analysis Results for Shale Unbackfilled Open Concept: Host Rock Thermal Conductivity

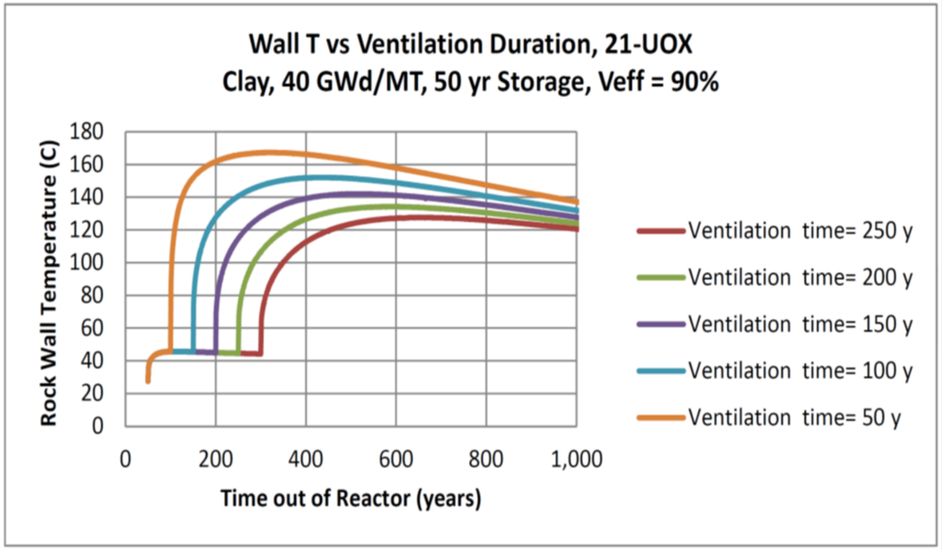
- Repository closure at 300 yr SNF age; surface storage 50 yr
- Burnup 40 GW-d/MT; V_{eff} = 75%; Package size 21-PWR
- “High” host rock K_{th} for thermal analyses is ~3 W/m-K



Source: Greenberg et al. (2012b).

Open Mode Thermal Analysis Results for Shale Unbackfilled Open Concept: Ventilation Duration and Drift Spacing

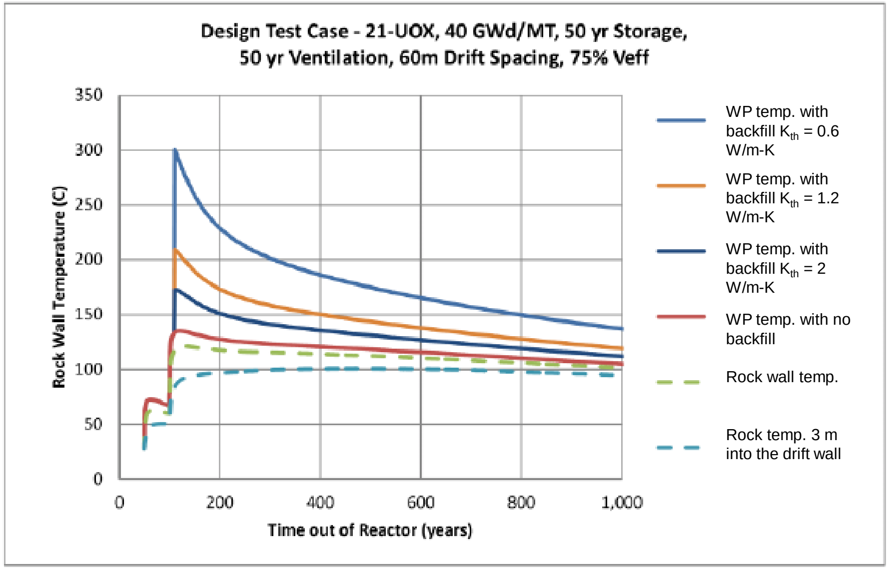
- **Surface storage 50 yr (vary SNF age at closure from 100 to 300 yr)**
- **Burnup 40 GW-d/MT; V_{eff} = 90%; Package size 21-PWR**
- **Diminishing effect from ventilation duration > 200 yr**
- **Effect from ~2X drift spacing is greater than ~3X SNF age at closure**



Ventilation Period (yr)	Drift Spacing (m)	Peak Rock Temp. (°C)	Peak Time (yr)
250	30	127.6	659
200	30	134.3	602
150	30	142.0	518
100	30	152.0	424
50	30	167.4	322
50	40	141.3	349
50	50	124.2	322

Open Mode Thermal Analysis Results for Shale Unbackfilled Open Concept: "Design Test Case"

- Surface decay storage 50 yr; repository closure at 100 to 150 yr SNF age
- Burnup 40 GW-d/MT; V_{eff} = 75%; 21-PWR; 4.5 m drift diameter
- Strategy: Heat a zone of host shale to > 100°C (3 meters into the drift wall)
- Compare no-backfill with backfill options (varying backfill K_{th})



Host Medium	Description	SNF Age at Closure (yr)	Peak Rock Temp. (°C)	Peak Time (yr)
Shale	Drift wall	100	121.3	129
	r_{DW} = 5.25 m [A]	100	100.9	470
	Drift wall	150	107.3	384
	r_{DW} = 5.25 m [A]	150	95.1	562

[A] Location 3 m into the drift wall

Sources: Greenberg et al. (2012b); Hardin et al. (2012).

Summary and Conclusions (1/4) Disposal Concepts

- **Identified 3 Generalized "Open" Disposal Concepts:**
  - **Shale Unbackfilled Open Concept**
    - Low permeability, massive shale, limited water inflow
    - Compartmentalize emplacement areas at closure (e.g., seal crossing drifts)
  - **Sedimentary Backfilled Open Concept**
    - Wide variety of potentially suitable host media (e.g., alluvium, tuff)
    - Backfill at closure (low permeability, e.g., crushed rock, swelling clay)
  - **Hard Rock Unsaturated Concept**
    - Long-term opening stability; temperature resistant host rock
    - No backfilling, plugging, or sealing required in emplacement areas
- **Thermal Analysis**
  - Larger Packages Meet Temperature Limits (200°C) in Salt the Hard Rock (<100 yr age, ≥ 21-PWR size packages)

Summary and Conclusions (2/4)
Thermal Analysis Summary

Reference Enclosed Emplacement Modes (SNF)

	High K_{th}	Tolerance (EBS up to 200°C?)	WP (PWR assy.'s)	Min. UOX Fuel Age at Emplacement (yr) [B]	Constraint
1. Crystalline	Note A		4	100	Clay-based buffer (100°C)
2. Generic Salt					
Reference	√	√	12	<50	Peak salt temp. (200°C)
21-PWR, 40 GWd/MT			21	50	
32-PWR, 40 GWd/MT or 21-PWR, 60 GWd/MT			21 or 32	<100	
3. Clay/Shale (enclosed)			4	100	Clay-based buffer (100°C)
7. Deep Borehole		√	1	10	None

[A] Host rock thermal conductivity >3 W/m-K; possible for some rock types.

[B] All age values are approximate to ±20%.

Summary and Conclusions (3/4)
Thermal Analysis

Reference Open Emplacement Modes (SNF)

	High K_{th}	Tolerance (EBS up to 200°C?)	WP (PWR assy.'s)	Min. UOX Fuel Age at Closure (yr) [B]	Constraint
4. Shale Unbackfilled			< 21	300 (for 12-PWR WP)	Host rock (100°C)
"Design Test Case"			21	<150	Host rock (100°C at 3 m into drift wall)
5. Sedimentary Backfilled			< 21	300 (for 12-PWR WP)	Clay-based buffer (100°C)
6. Hard Rock Unsat.	Note A	√	≥ 21	>50	Host rock (200°C)

[A] Host rock thermal conductivity >3 W/m-K; possible for some rock types.

[B] All age values are approximate to ±20%.

Summary and Conclusions (4/4)
Continuing Work

- **Direct Disposal of Large Canisters including Dual-Purpose Canisters (DPCs)**
  - Regulatory framework for disposal concepts
  - Key features, events and processes affected (e.g., postclosure criticality)
  - Generic performance assessments
  - Thermal and logistical analyses
  - Cost comparison with concepts using smaller packages
- **Disposal R&D**
  - Temperature limits greater than 100°C (clay buffer) and 200°C (salt)
  - Heating of host media (e.g., heating shale above 100°C in the near field)
  - Engineered materials and admixtures that improve heat transfer or thermal stability

References

Andra (2005). *Dossier 2005 argile – architecture and management of a geological disposal system.* December 2005.

Bechthold, W., E. Smailos, S. Heusermann, W. Bollingerfehr, B. Bazargan Sabet, T. Rothfuchs, P. Kamlot, J. Grupa, S. Olivella and F.D. Hansen 2004. *Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt (BAMBUS II Project), Final Report*. EUR 20621, Nuclear Science and Technology, Luxembourg.

Callahan, G.D. 1999. *Crushed Salt Constitutive Model*. Sandia National Laboratories, Albuquerque, NM. SAND98-2680.

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

Carter, J., A. Luptak, J. Gastelum, C. Stockman and A. Miller 2012a. *Fuel Cycle Potential Waste Inventory for Disposition.* FCR&D-USED-2010-000031 Rev. 5. July, 2012. U.S. Department of Energy, Used Fuel Disposition R&D Campaign.

Carter, J.T., P.O. Rodwell and M. Dupont 2012b. *Generic Repository ROM Cost Study*. FCRD-UFD-2012-000211 Rev. 1. July, 2012. U.S. Department of Energy, Used Fuel Disposition R&D Campaign.

Clayton, D.J., J.E. Bean, J.G. Arguello Jr., E.L. Hardin and F.D. Hansen 2012. “Thermal-mechanical modeling of a generic high-level waste salt repository.” In: SALTVII, 7th Conference on the Mechanical Behavior of Salt, Paris, France. April 16-19, 2012. (www.saltmech7.com).

CRWMS M&O 1999. *License application design selection report.* B00000000-01717-4600-00123 Rev. 01 ICN 01. Las Vegas, Nevada: Civilian Radioactive Waste Management System Management & Operating Contractor. MOL.19990908.0319.

Fluor (Fluor Technology Inc.) 1986. *Site Characterization Plan Conceptual Design Report for a High-Level Nuclear Waste Repository in Salt, Vertical Emplacement Mode*. U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Salt Repository Office. September, 1986.

Greenberg, H.R. et al. 2012a. *Investigations on Repository Near-Field Thermal Modeling – Repository Science/Thermal Load Management & Design Concepts.* Lawrence Livermore National Laboratory. LLNL-TR-491099 Rev. 2. August, 2012.

Greenberg, H.R. et al. 2012b. *Repository Near-Field Thermal Modeling Update Including Analysis of Open Mode Design Concepts.* LLNL-TR-572252. U.S. Department of Energy, Used Fuel Disposition R&D Campaign. August, 2012.

Hardin, E. et al. (2012). *Disposal Concepts/Thermal Load Management (FY11/12 Summary Report*). U.S. Department of Energy, Office of Used Nuclear Fuel Disposition. FCRD-UFD-2012-00219 Rev. 1.

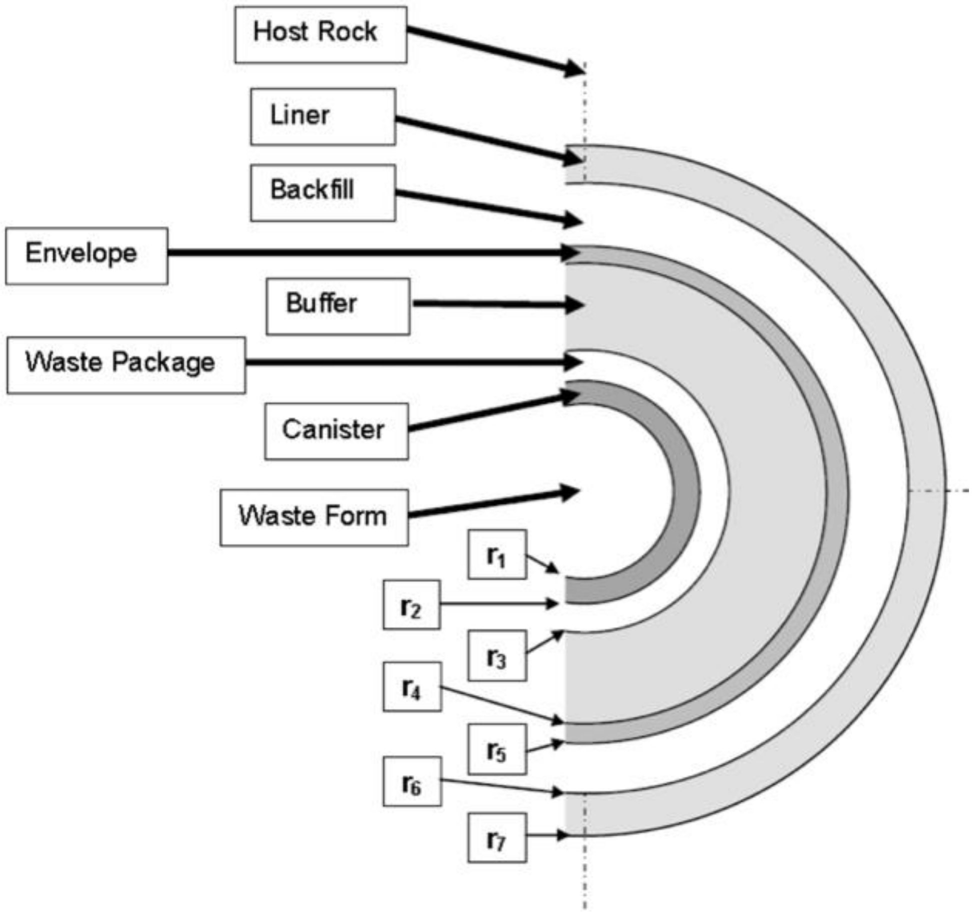
Munson, D.E., A.F. Fossum and P.E. Senseny 1989. *Advances in Resolution of Discrepancies between Predicted and Measured WIPP In-situ Room Closures*. Sandia National Laboratories, Albuquerque, NM. SAND88-2948.

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.

BACK-UP SLIDES

Steady-State Annular Conduction Solution for EBS Layers

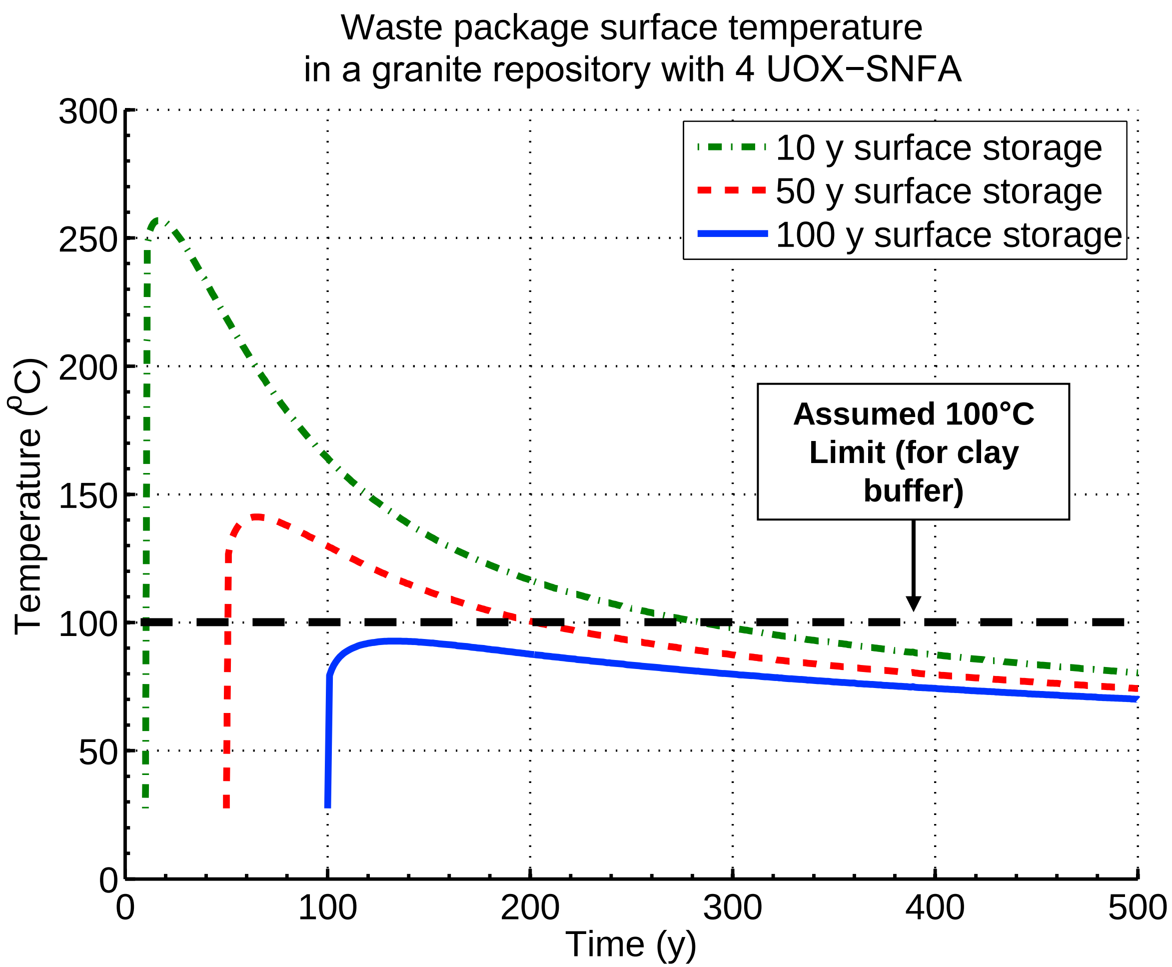
- Accounts for every layer between the waste package and rock wall
- Represents all disposal concepts (small errors for "point" loading)
- Modifies temperature history at EBS boundary, from transient solution



Source: Greenberg et al. 2012a.

Peak Temperature Dependence on Decay Storage Duration

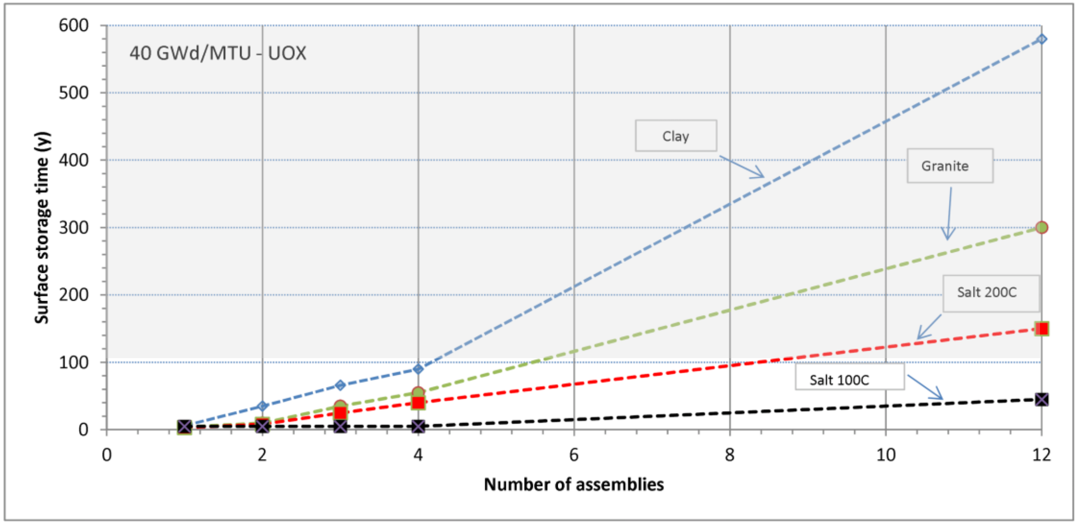
- **Example: Results for waste package surface temperature**
  - LWR UOX spent fuel (60 GW-d/tHM; bounding)
  - 4-PWR package
  - KBS-3V type repository (crystalline rock/clay buffer; SKB 2006)

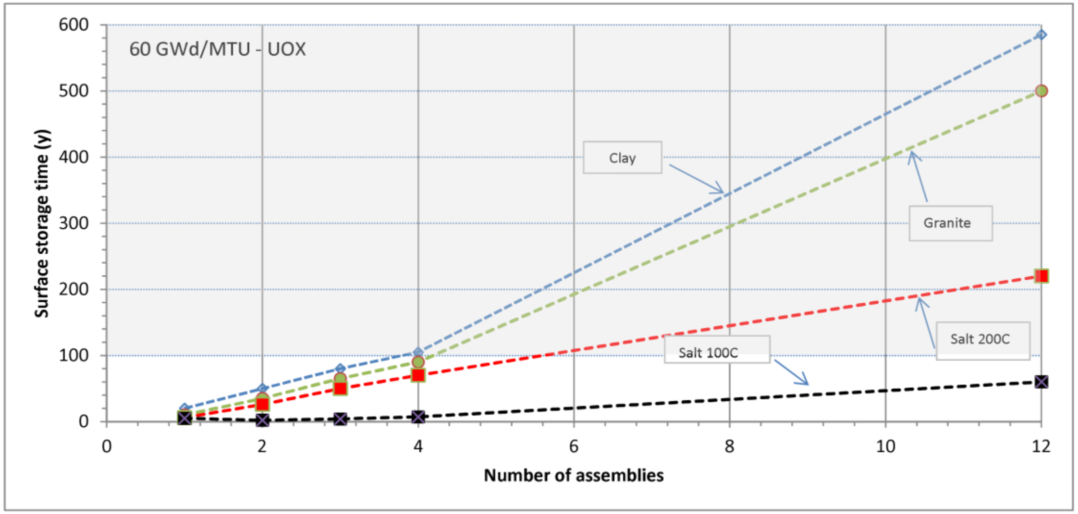


Source: Greenberg et al. 2012a.

Effect of UOX SNF Burnup and Temperature-Dependent Salt K_{th}

- **Decay storage needed to meet (WP surface) temperature limits**
  - 100°C for clay buffers and host media
  - 200°C for salt
- **Salt vs. clay-based natural and engineered materials**
  - Higher thermal conductivity
  - Higher temperature tolerance (→200°C)





Source: Greenberg et al. 2012b.

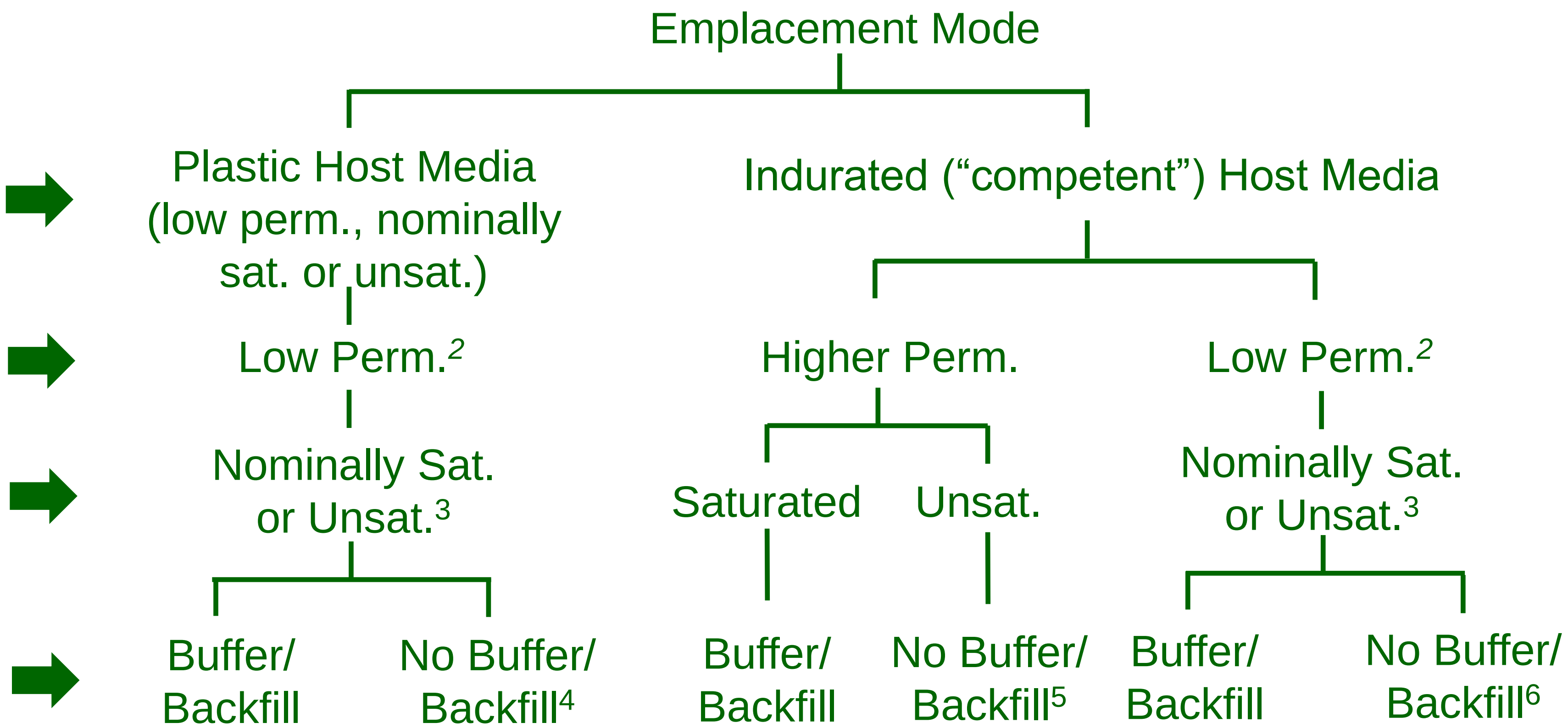
Disposal of Large Waste Packages in Salt
Thermal Analysis Results

- **FEM study results (varying WP size and aging):**

WP Type	Dimensions	Burnup (GW-d/MTU)	Fuel Mass (MT)	Fuel Age (yr)	kW at Emplacement	Peak Salt Temp. (°C)
4-PWR	0.82 m D x 5.00 m L	**40**	1.88	**10**	2.7	**75**
4-PWR	0.82 m D x 5.00 m L	**60**	1.88	**10**	4.5	**110**
12-PWR	1.29 m D x 5.13 m L	**40**	5.64	**10**	8.0	**165**
12-PWR	1.29 m D x 5.13 m L	**60**	5.64	**10**	13.5	**275**
21-PWR	1.60 m D x 5.13 m L	**40**	9.87	**10**	14.1	**280**
4-PWR	0.82 m D x 5.00 m L	**40**	1.88	**50**	1.3	**50**
4-PWR	0.82 m D x 5.00 m L	**60**	1.88	**50**	2.0	**65**
12-PWR	1.29 m D x 5.13 m L	**40**	5.64	**50**	3.8	**95**
12-PWR	1.29 m D x 5.13 m L	**60**	5.64	**50**	5.9	**140**
21-PWR	1.60 m D x 5.13 m L	**40**	9.87	**50**	6.7	**150**
21-PWR	1.60 m D x 5.13 m L	**60**	9.87	**50**	10.4	**230**
32-PWR	2.00 m D x 5.13 m L	**40**	15.04	**50**	10.2	**220**
32-PWR	2.00 m D x 5.13 m L	**60**	15.04	**50**	15.8	**355**

Source: Hardin et al. (2012).

Generic Disposal Concept "Taxonomy"



1. Consider postclosure performance, nominal scenario (disruptive scenarios are site-specific)
2. Less than ~10^{-16} m^2
3. Diffusion dominated transport
4. Rely instead on formation collapse and consolidation, and far-field plugs and seals
5. Use diversion barriers (e.g., drip shields, or capillary barriers)
6. Use plugs and seals to compartmentalize waste emplacement

Enclosed Disposal Concept "Taxonomy"

Enclosed *Emplacement Modes (mined disposal)*

- *Plastic Host Media (low perm., nominally sat. or unsat.)*
  - *Host Medium Encloses Packages at Emplacement*
    - *Unventilated* — ***Generic Salt Repository***
    - *Hybrid: Buffer/Backfill Enclosing Packages at Emplacement; with Ventilated Drifts*
  - *Low Perm. Buffer/Backfill (collapse readily occurs but delayed or incomplete due to ground control and/or rock characteristics)* — ***Clay/Shale****
- *Competent Host Media*
  - *High Perm. Host Medium (sat. or unsat.)*
    - *Low Permeability Buffer Installed Around Packages at Emplacement*
      - *Saturated* → *Low Permeability Backfill in Access Drifts At/Before Closure* [A] — ***KBS-3V*** [C]
      - *Unsaturated* → *Backfill in Access Drifts At/Before Closure* [B]
  - *Low Perm. Host Medium (sat. or unsat.)*
    - *Low Permeability Backfill/Buffer and/or Plugs/Seals Installed Around Packages at Emplacement*
      - *Low Permeability Backfill in Access Drifts At/Before Closure* [A] — ***Clay/Shale****

Notes:

A. Enclosed modes in competent, saturated host media require backfill with limited permeability to control preferential water flow after permanent closure.

B. For higher permeability, unsaturated, free-draining host media the access drift backfill can be more permeable, but may still have other functions (e.g., providing mechanical constraint of the swelling buffer).

C. Includes waste packages designed for containment longevity.

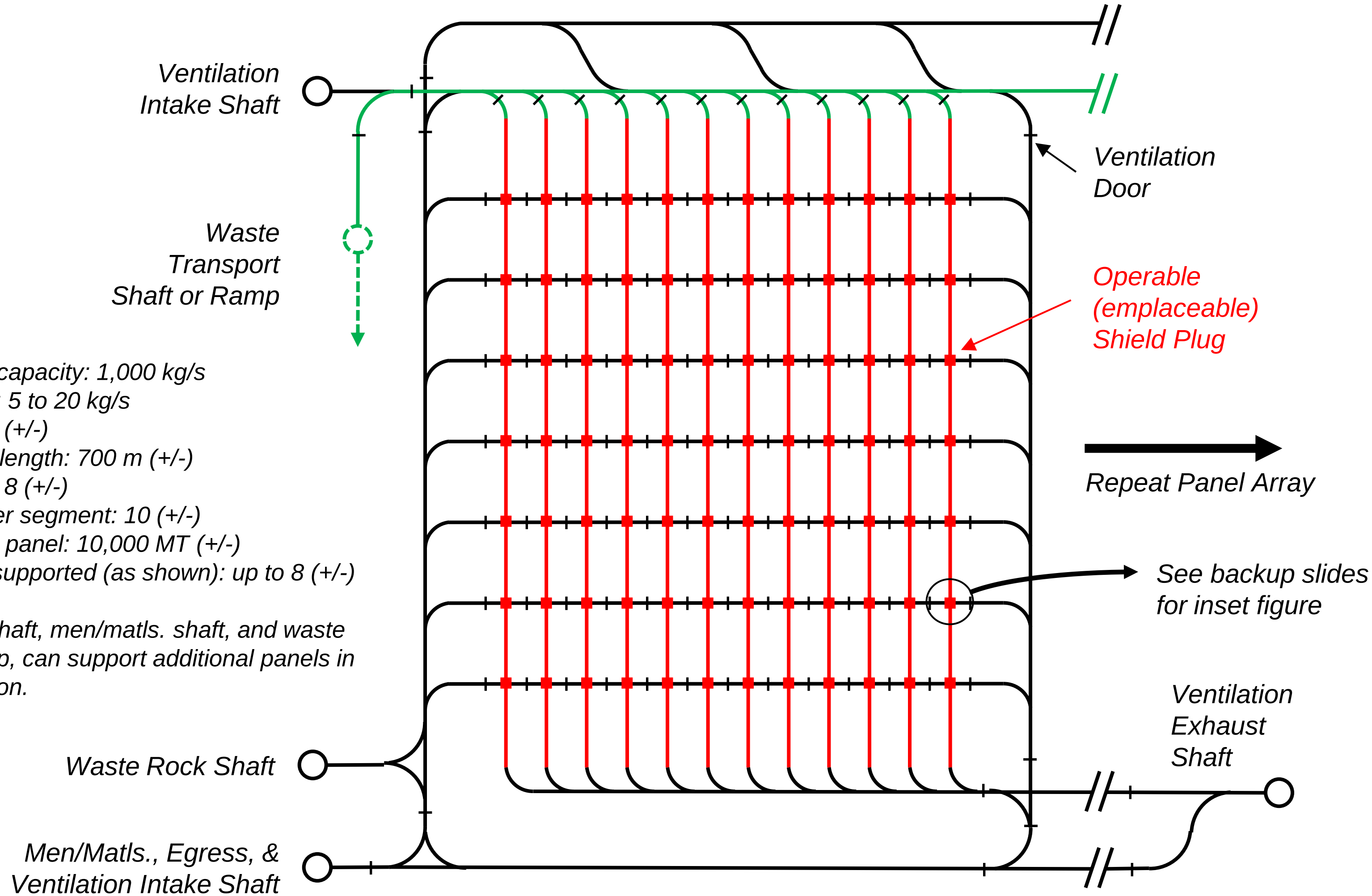
Host Rock Thermal Properties

Repository	Conductivity, W/m-K	Diffusivity, m^2/s
Crystalline	2.5	1.13E-6
Clay/Shale	1.75	6.45E-7
Clay-based buffer/backfill	0.6 (dry) 1.4 (hydrated)	
Salt	4.2 (at 100°C)	2.07E-6
Crushed Salt	0.57 (40% porosity)	4.7E-7
Sedimentary (alluvium)	1.06	7.26E-7

Mine Plan for Shale Unbackfilled Open Mode

Red = Waste Disposal, Green = Waste transit

(Green and black openings are backfilled at closure)



Ventilation system capacity: 1,000 kg/s
Ventilation per drift: 5 to 20 kg/s
Drifts per panel: 12 (+/-)
Emplacement Drift length: 700 m (+/-)
Segments per drift: 8 (+/-)
Waste packages per segment: 10 (+/-)
Waste capacity per panel: 10,000 MT (+/-)
Number of panels supported (as shown): up to 8 (+/-)

Note: Waste rock shaft, men/matls. shaft, and waste transport shaft/ramp, can support additional panels in the opposite direction.

Source: Hardin et al. (2012).

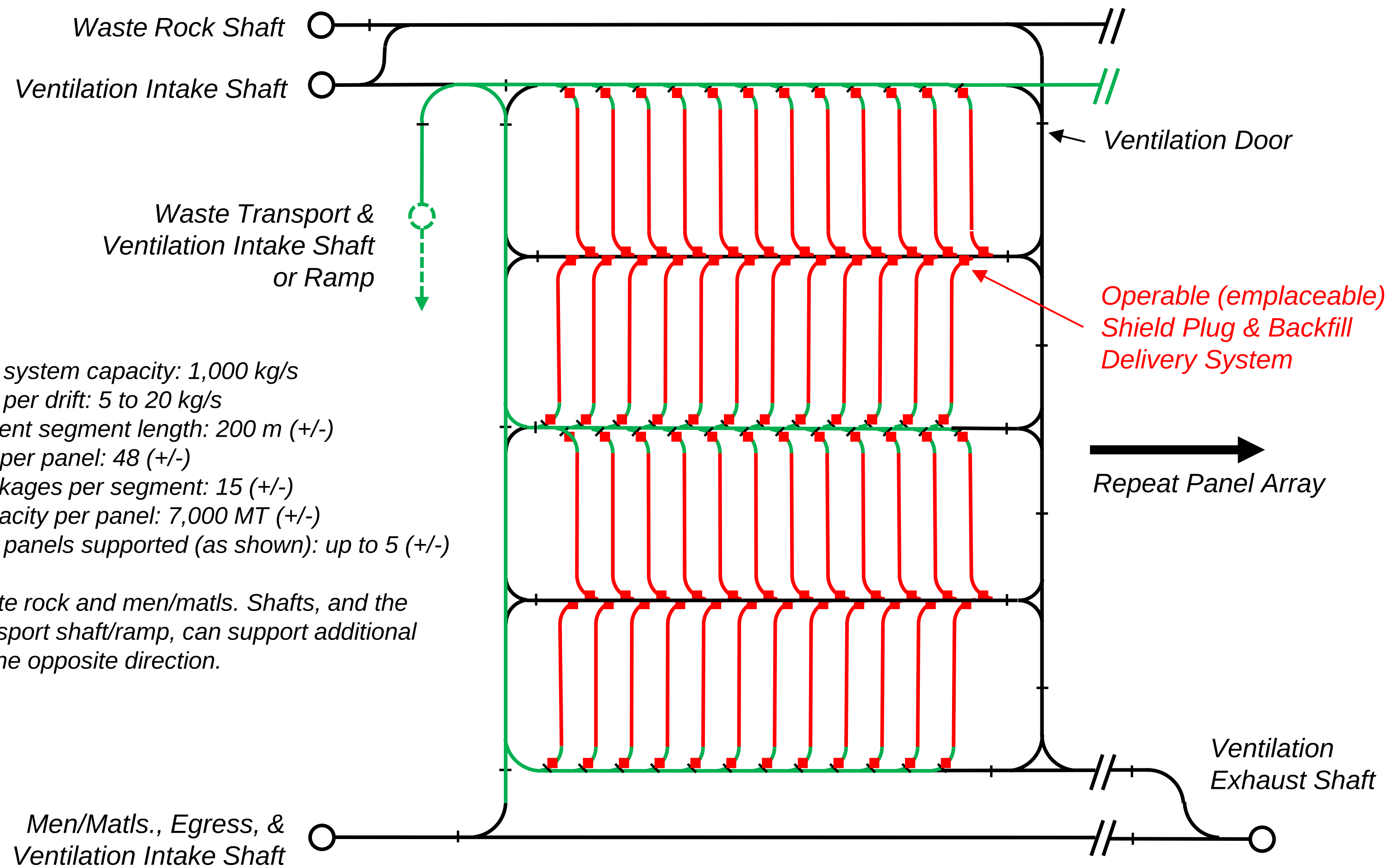
U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Mine Plan for Backfilled Open Mode

Red = Waste Disposal, Green = Waste transit

(Green and black openings are backfilled at closure)

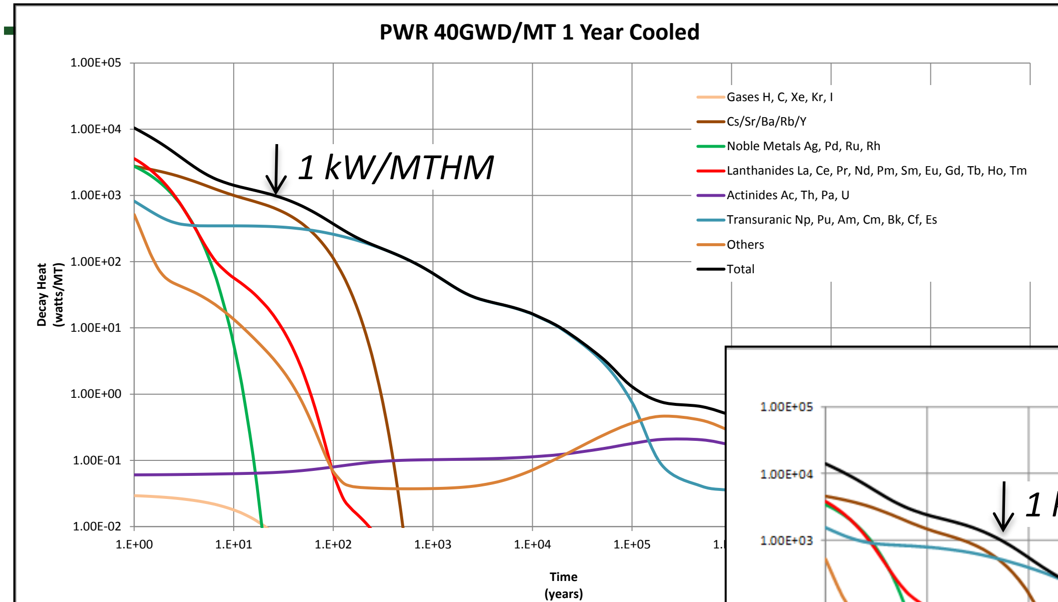


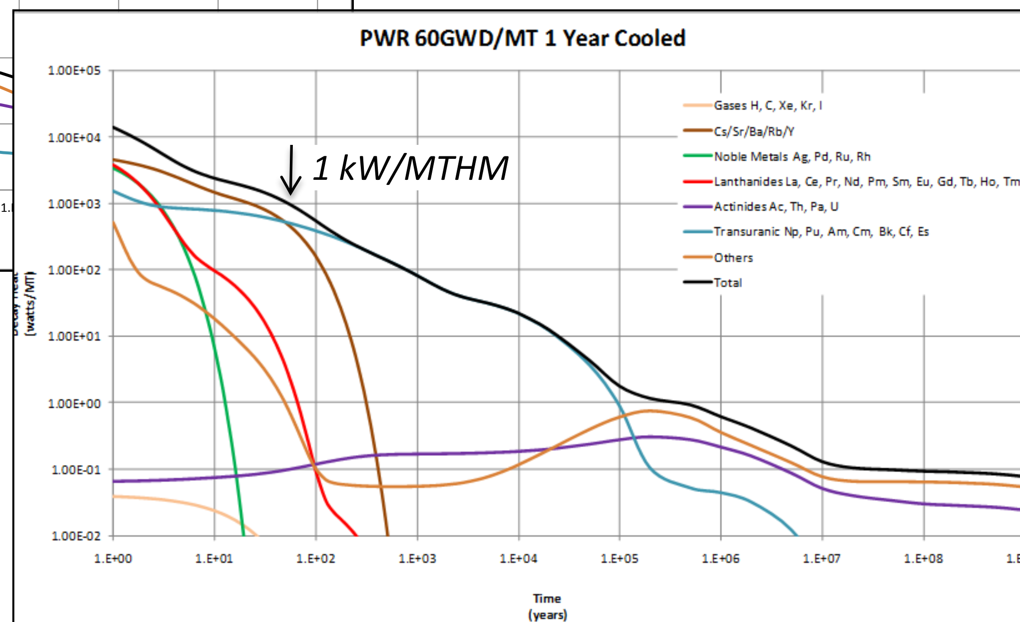
Ventilation system capacity: 1,000 kg/s
Ventilation per drift: 5 to 20 kg/s
Emplacement segment length: 200 m (+/-)
Segments per panel: 48 (+/-)
Waste packages per segment: 15 (+/-)
Waste capacity per panel: 7,000 MT (+/-)
Number of panels supported (as shown): up to 5 (+/-)

Note: Waste rock and men/matls. Shafts, and the waste transport shaft/ramp, can support additional panels in the opposite direction.

Source: Hardin et al. (2012).

LWR UOX SNF Thermal Power
ORIGEN II Based, 40 and 60 GW-d/MTU Burnup





Carter et al. (2012a)

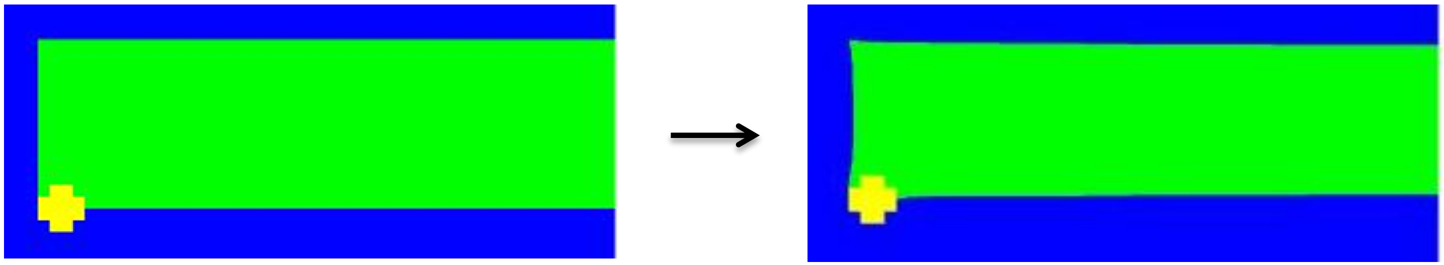
Emplacement Alcove Consolidation and Closure

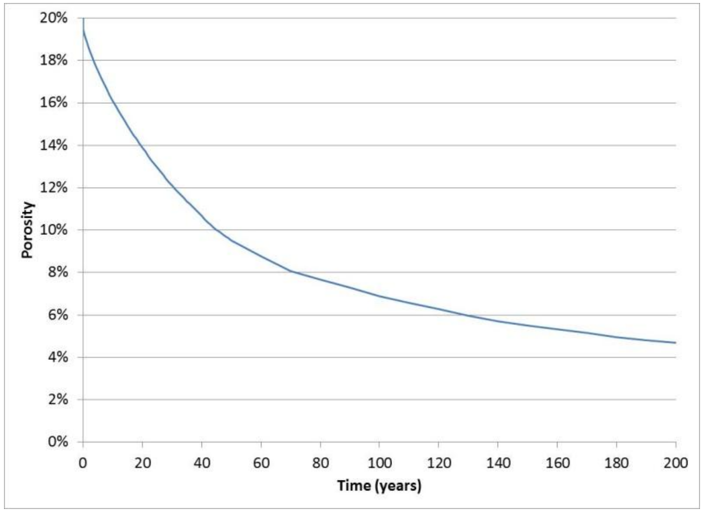
U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Closure + thermal expansion → Porosity reduction

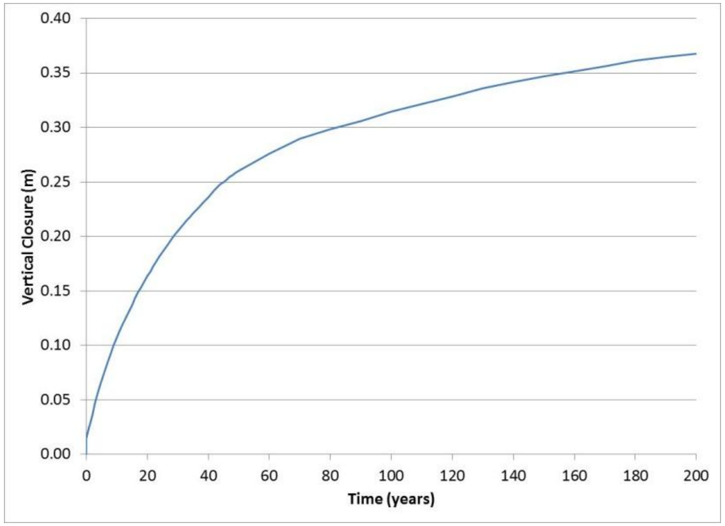
0 yr *200 yr*





<<
Averaged backfill porosity vs. time (4-PWR case)

Closure at alcove-drift exit vs. time (4-PWR case)
>>



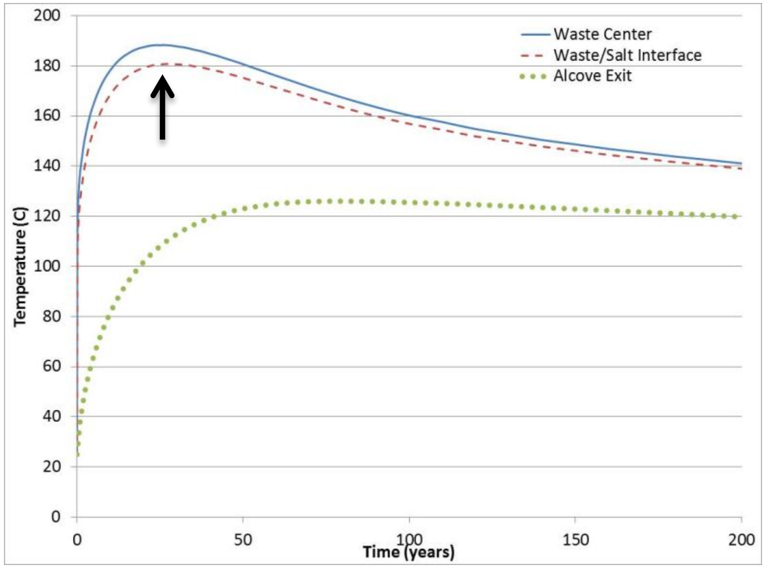
Clayton et al. (2012)

Disposal of Large Waste Packages in Salt

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

- Burnup: 40 & 60 GWd/MTU
- Fuel age: 10 & 50 yr OoR
- WP Sizes: 4-, 12-, 21- & 32-PWR (up to 14 MTHM)

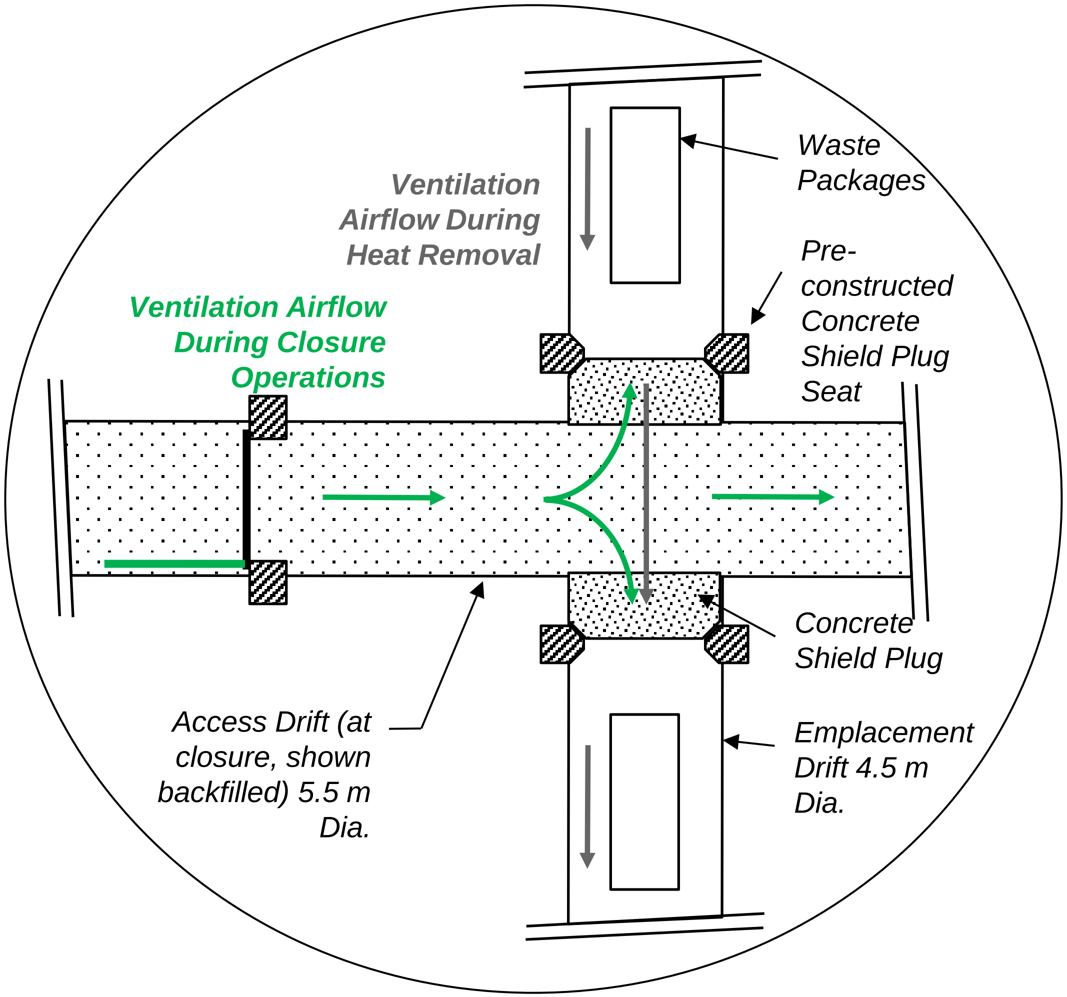
Example: Burnup 40 GW-d/MT, fuel age 50 yr out-of-reactor, 21-



- T-M Effect (Hardin et al. 2012):

WP Size	Dimensions	Burnup (GWd/MTU)	Fuel Mass (MT)	Fuel Age (yr)	Power at Emplacement (kW)	Runs Compared	Peak Salt Temperature (C)
4-PWR	0.82 m D x 5.00 m L	**40**	1.88	**10**	3.7	T, 200 yr	**100**
4-PWR	0.82 m D x 5.00 m L	**40**	1.88	**10**	3.7	TM, 200 yr	**100**
21-PWR	1.60 m D x 5.13 m L	**40**	9.87	**50**	9	T, 200 yr	**190**
21-PWR	1.60 m D x 5.13 m L	**40**	9.87	**50**	9	TM, 200 yr	**185**

Shale Unbackfilled Open Concept: Inset Figure: Configuration of Drift Intersections at Closure



Alternative to shield plugs: Construct ventilation labyrinths during emplacement (Hardin et al. 2012)

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Reference Open Emplacement Mode Concept Specifics

Host Geologic Media/Concept >>>	Shale Unbackfilled Open	Sedimentary Backfilled Open	Hard-Rock Unsaturated Open
Repository depth	~500 m	200 to 300 m	300 to 500 m
Hydrologic setting	Nominally saturated	Saturated or Unsaturated	Unsaturated
Ground support material	Shotcrete and steel supports	Rockbolts, wire cloth & shotcrete; steel supports as needed	Rockbolts; shotcrete as needed
Seals and plugs	Emplacement drift plugs Shaft & ramp plugs and seals	Shaft & ramp plugs and seals	Shaft & ramp plugs and seals
Emplacement mode	Horizontal in-drift emplacement	Horizontal in-drift emplacement	Horizontal in-drift emplacement
WP configuration	21-PWR	21-PWR	21-PWR
Overpack material	Steel	Steel or corrosion resistant	Corrosion resistant
Package dimensions	≤ 2 m D x 5 m L	≤ 2 m D x 5 m L (typ.)	≤ 2 m D x 5 m L
Drift/borehole dia.	4.5 m (drifts)	4.5 m (drifts)	5.5 m (drifts)
Drift/borehole spacing	60 m (drifts) 10 m (packages)	60 m (drifts) 10 m (packages)	60 m (drifts) 6 m (packages)
Backfill material	In crossing drifts: conditioned shale with swelling clay	In all drifts: conditioned rock with swelling clay	No backfill

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

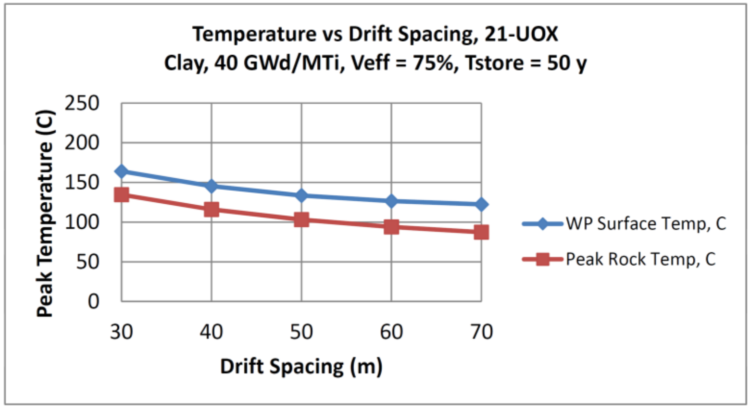
Open Mode Thermal Analysis Results for Shale Unbackfilled Open Concept: "Nominal Case"

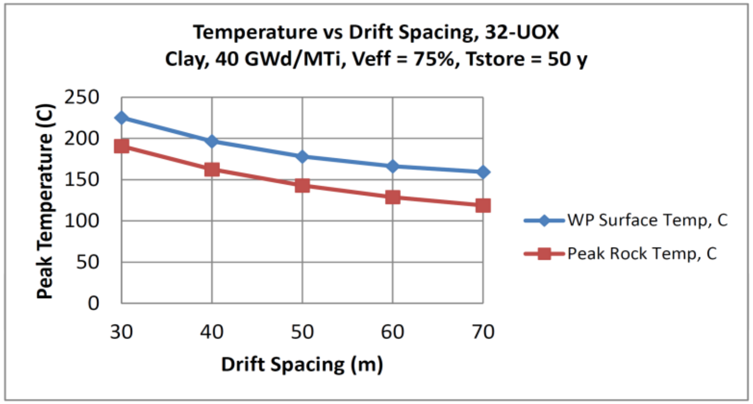
- Repository closure at 300 yr SNF age; drift spacing 30 m; 21-PWR; V_{eff} = 75%
- Minimal effect from extending surface storage to 100 yr

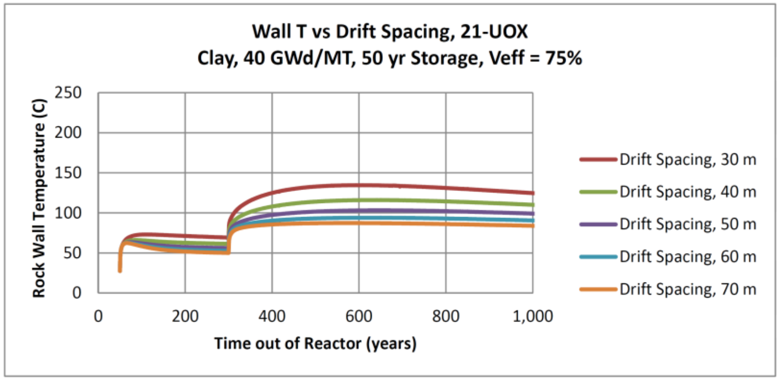
Age at Emplacement >>		Surface Storage = 50 yr				Surface Storage = 100 yr			
Host Medium	WP Size (PWR assy.'s) / Burnup (GWd/MT)	Peak Rock Temp. (°C)	Peak Time (yr)	WP Surface Temp. (°C)	Peak Time (yr)	Peak Rock Temp. (°C)	Peak Time (yr)	WP Surface Temp. (°C)	Peak Time (yr)
Shale	4-PWR / 40	47.8	593	57.6	442	47.2	624	56.6	455
	4-PWR / 60	52.6	567	64.7	410	51.5	628	63.1	423
	12-PWR / 40	88.7	593	109.4	488	86.6	628	106.7	489
	12-PWR / 60	102.7	567	128.5	442	99.5	628	124.2	470
	21-PWR / 40	134.6	593	164.1	488	131.0	624	159.5	515
	21-PWR / 60	159.1	567	195.8	468	153.4	628	188.6	496
	32-PWR / 40	190.7	593	225.2	516	185.2	628	218.6	536
	32-PWR / 60	228.0	567	271.2	487	219.4	628	260.5	496

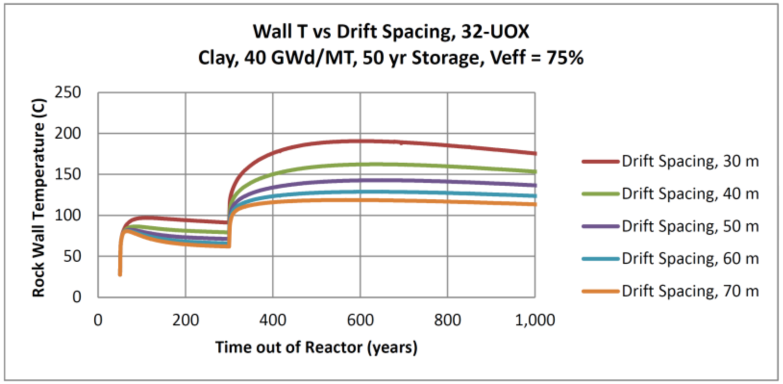
Open Mode Thermal Analysis Results for Shale Unbackfilled Open Concept: Drift Spacing

- Repository closure at 300 yr SNF age; surface storage 50 yr
- Burnup 40 GW-d/MT; V_{eff} = 75%
- Diminishing effect from drift spacing > ~60 m (temperature histories are flat)









Source: Greenberg et al. (2012b).