SAND2012-1317C

Generic Repository Concepts and Thermal Analysis for Advanced Fuel Cycles

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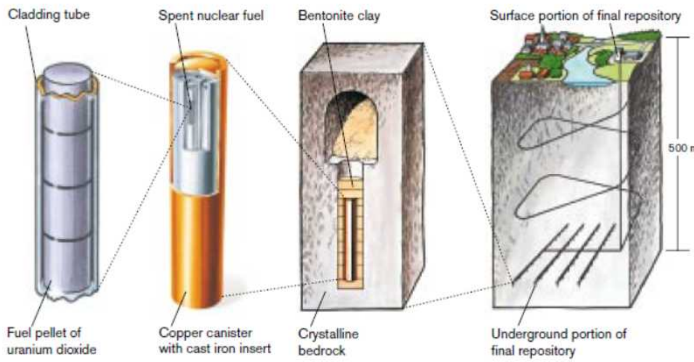
The Used Fuel Disposition Campaign

- ***Scope: Identify alternatives and conduct scientific to R&D 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 has developed a set of <u>reference geologic disposal concepts</u> that provide context for ongoing R&D**
  - Three mined geologic disposal concepts
    - Clay/shale rock
    - Crystalline rock (granite)
    - Salt
  - Deep borehole disposal system



Hardin et al., WM2012, Generic Repository Concepts (SAND2012-XXXXC)

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 across gaps
    - Pre-closure ventilation possible (e.g., Yucca Mountain design)
  - **Enclosed**: emplacement openings enclose waste packages (salt, clay/shale) and/or clay buffer surrounds the waste package (crystalline rock)
    - Greater near-field thermal resistance → higher temperature at the waste package (e.g., KBS-3, Dossier 2005, other international concepts)

Reference Mined Disposal Concepts Temperature Limits

- **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)
  - No limit identified for deep crystalline basement rock
- **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
   – *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.

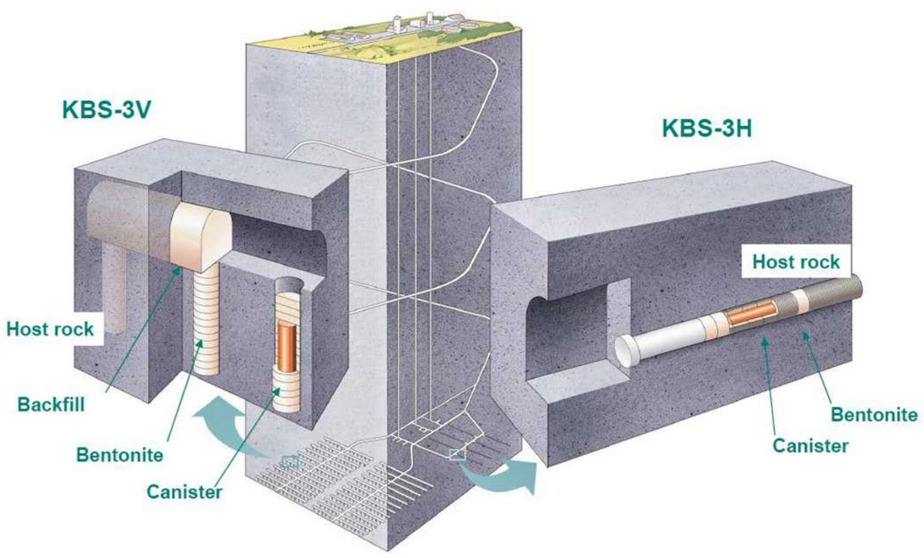
Brady, P.V., B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, and J.S. Stein 2009. *Deep borehole disposal of high-level radioactive waste.* SAND2009-4401. Sandia National Laboratories.

Six Heat-Generating Waste Types

Strategy Sampled	Description	Waste Types (Carter et al. 2011a)	Example Source
Once-Through	Direct disposal of high-burnup (60 GW-d/MTHM) LWR UOX SNF	• UOX SNF	• Generation III+ LWRs
Modified-Open	Reprocessing of LWR UOX used fuel (51 GW-d/MTHM) to produce MOX fuel that is used once (50 GW-d/MTHM) 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/MTHM) to produce U-TRU metal fuel for SFRs (0.75 conversion ratio), and repeated recycle of the SFR used fuel (99.6 GW-d/MTHM)	• "New-Extraction" HLW borosilicate glass • Electrochemical ceramic HLW • Electrochemical fission- product metal HLW	• "Transitional" fast-spectrum burner strategy with TRU recycling

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: 100°C



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.

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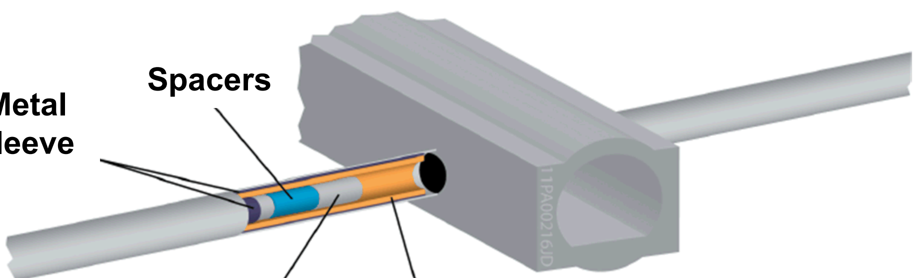
Reference Disposal Concepts Mined Clay/Shale with Horizontal Emplacement

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

HLW disposal layout



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

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.

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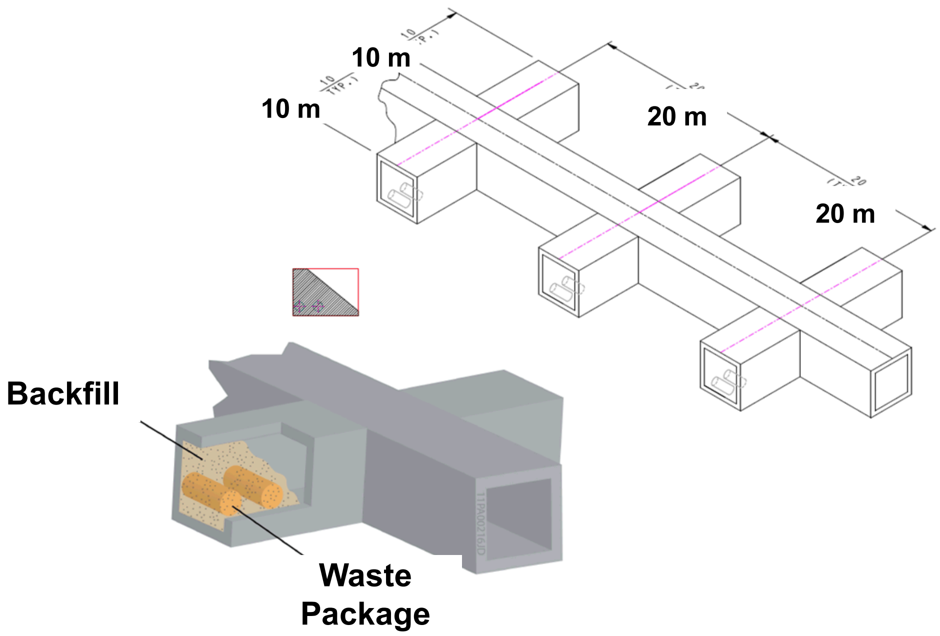
Reference Disposal Concepts Generic Salt Repository with Alcove Emplacement

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

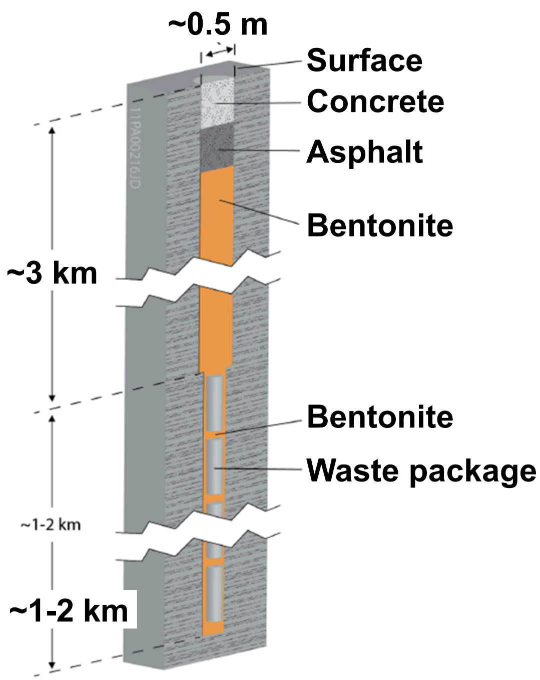


Repository characteristic	SNF	HLW
Emplacement mode	Horizontal, in alcoves	Horizontal, in alcoves
Overpack material	Steel	Steel
Alcove spacing, m	20	20
Access drift spacing, m	40	40
Borehole liner material	-	-
Buffer material	-	-
Backfill material	Crushed/ compact salt	Crushed/ compact salt

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

- 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

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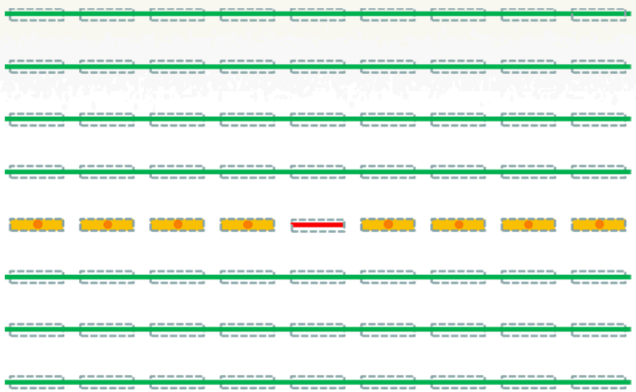
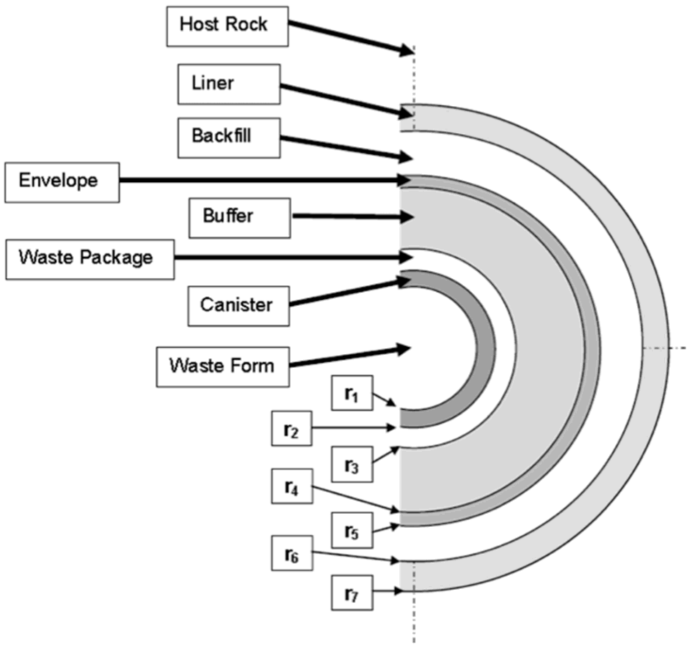
Analysis Approach

Superposition: Waste Package/Drift Array





- **Thermal model for generic repository concepts**
  - Evaluate temperature histories on waste package outer surface
  - Multiple combinations of waste types, age, and disposal concepts
- **Compare peak temperatures with assumed limits for engineered or natural materials**
- **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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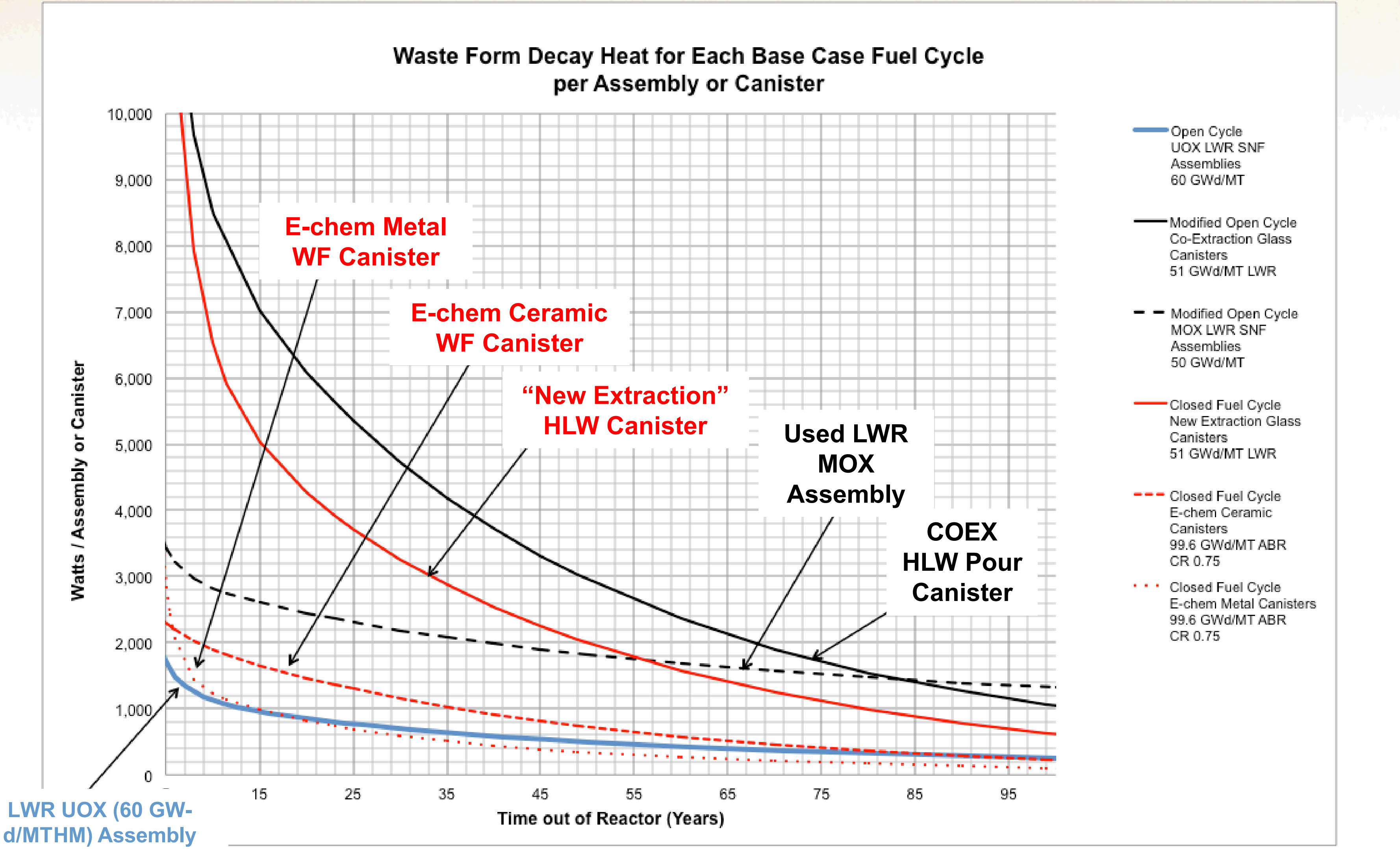
HLW Glass Heat Outputs are Highest in the Near Term, MOX SNF in the Long Term



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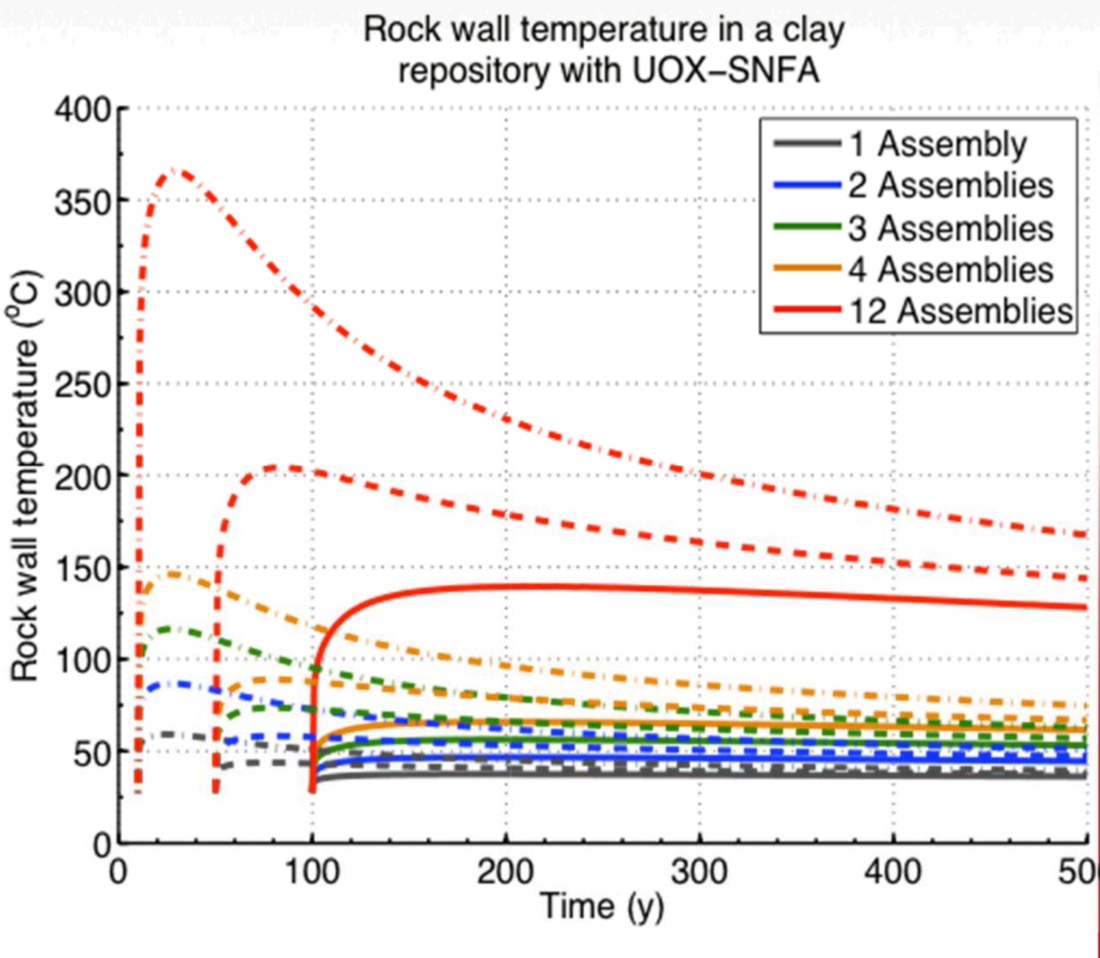
Temperature Histories for 4 Disposal Concepts and 6 Waste Types

- **Example**
- **Clay/shale repository**
  - Results for host rock temperature (at EBS boundary)
  - LWR UOX SNF (60 GW-d/MTHM)
  - Calculate for different package size/capacity



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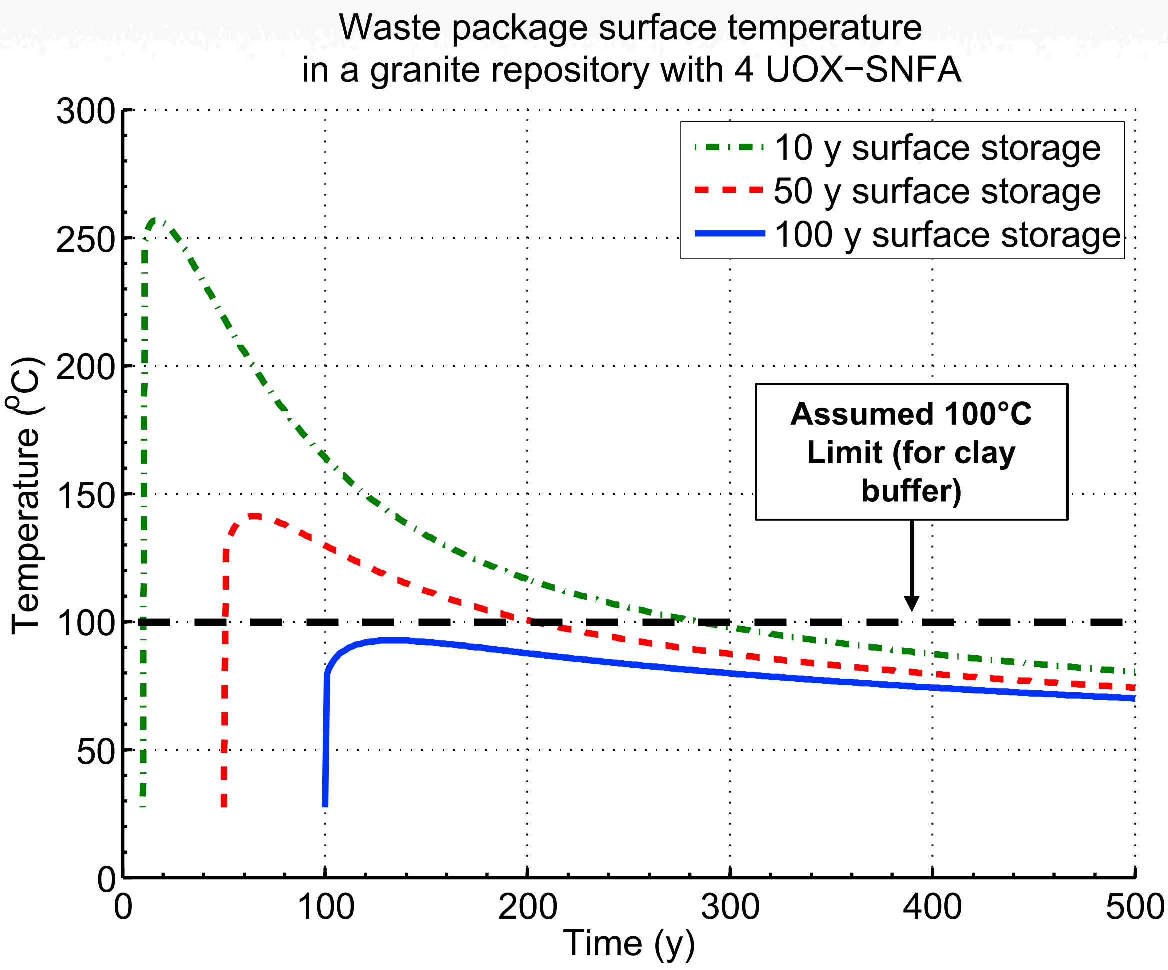
Peak Temperature Dependence on Decay Storage Duration

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



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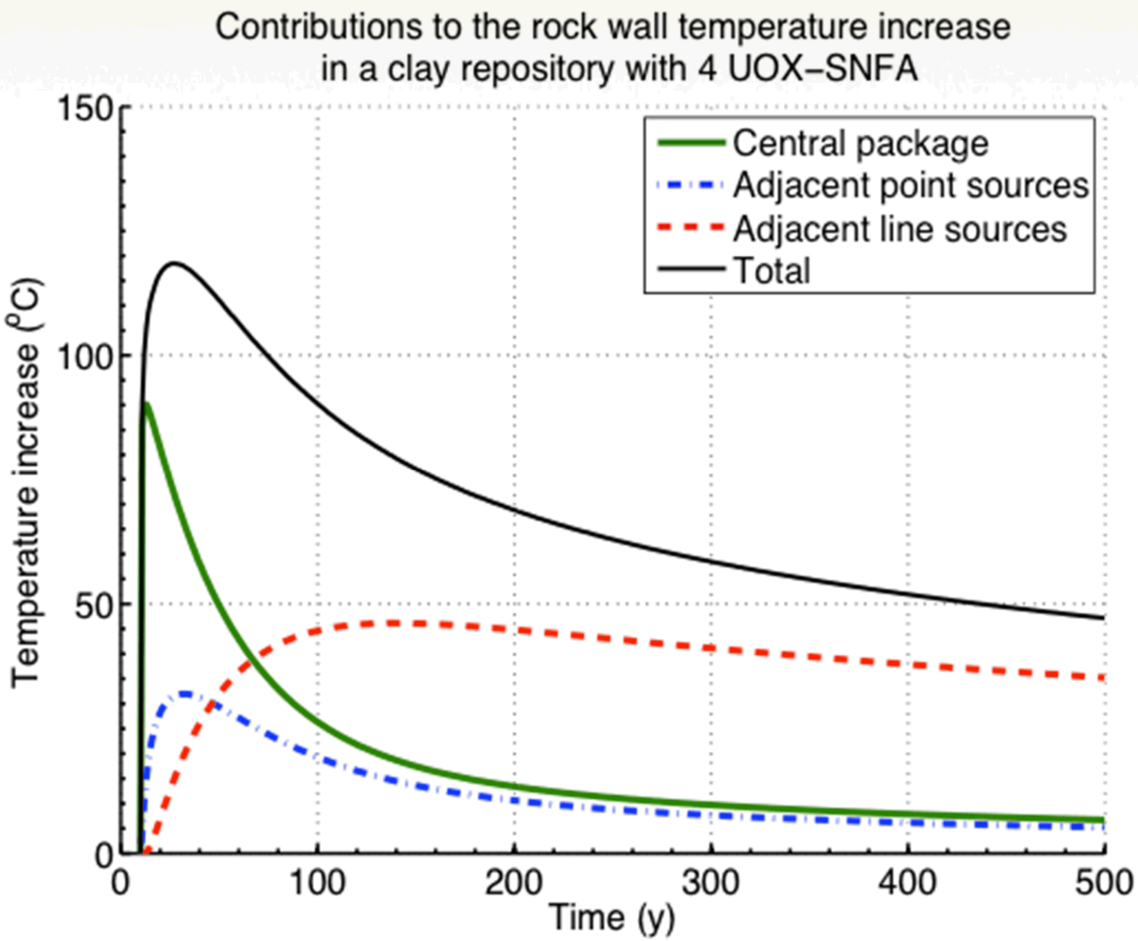
Relative Contributions to Transient Temperature Histories

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



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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, °C			
Geology	Waste Form	Fraction of Canister	Decay Storage Duration			
			10 yr	50 yr	100 yr	200 yr
Granite (100°C)	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 (100°C)	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

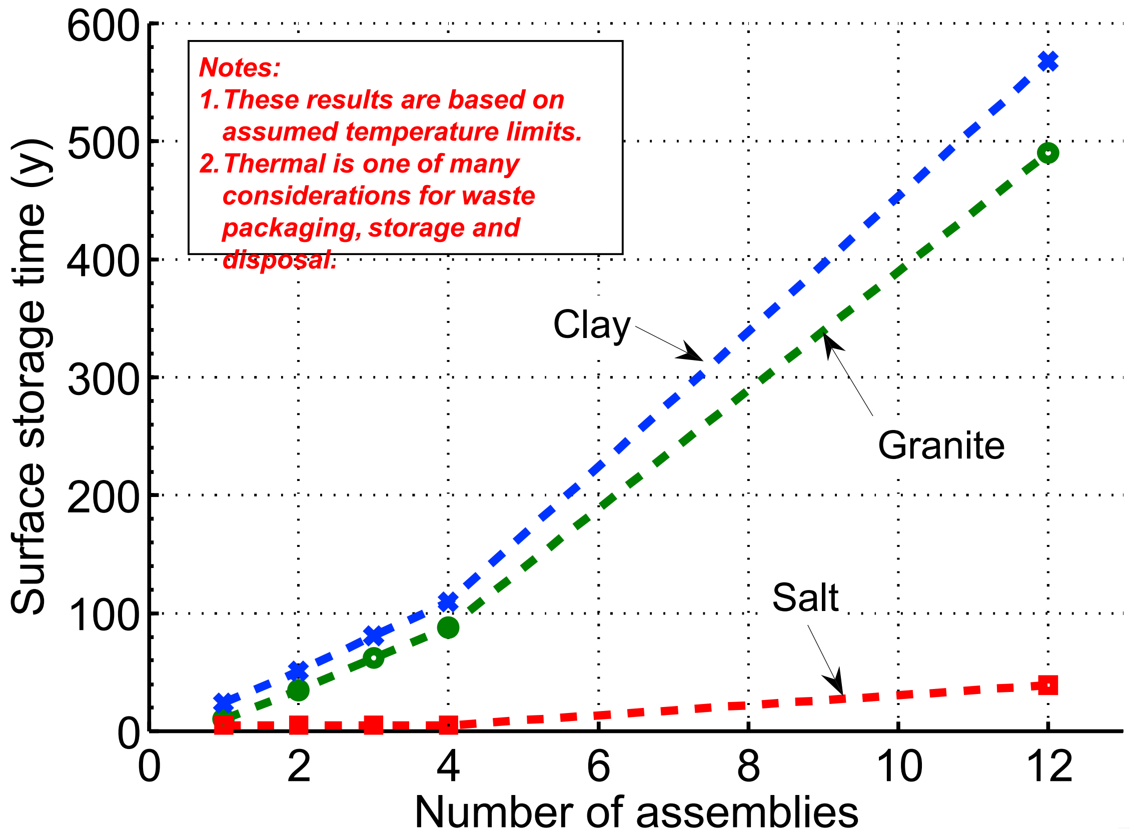
Peak Temperatures at the Waste Package Surface, HLW Canisters, Salt and Deep Borehole Concepts

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

Hardin et al., WM2012, Generic Repository Concepts (SAND2012-XXXXC)

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

Storage time required to comply with temperature limits as a function of UOX assemblies per waste package



Hardin et al., WM2012, Generic Repository Concepts (SAND2012-XXXXC)

Conclusions

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

Number of assemblies	UOX (60 GW-d/MT)		MOX (50 GW-d/MT)	
	Crystalline or Clay/Shale	Salt	Crystalline or Clay/Shale	Salt
1	~10 years	<10 years	300 to 400 years	<10 years
4	~100 years	<10 years	>500 years	~100 years
12	~500 years	<50 years	Not analyzed	>500 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

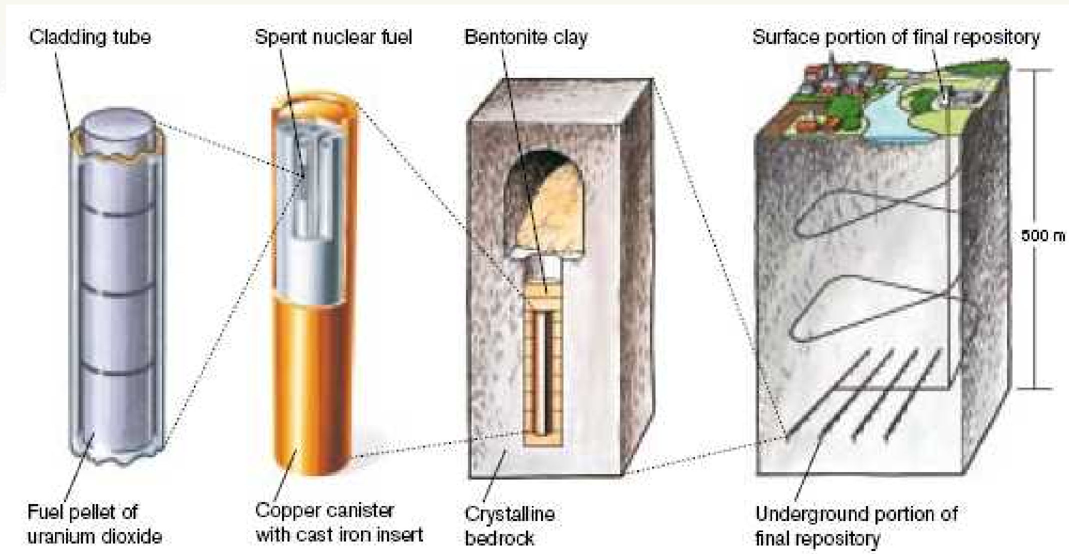
Continuing Work

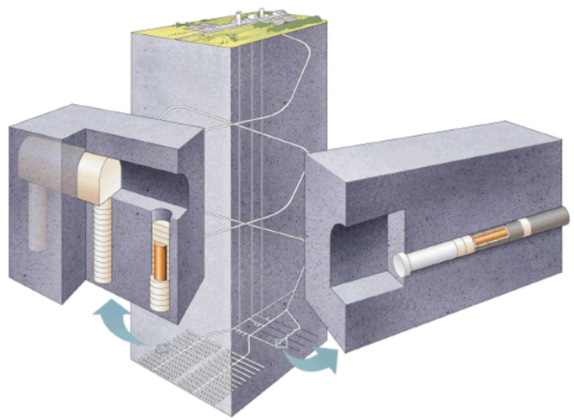
- **Develop Reference Open Emplacement Concepts**
  - Ventilated repositories in shale and alluvium
  - “Hybrid” mode in bedded salt
  - Larger waste packages, ramp access
  - Yucca Mountain concept
- **Additional waste streams (incl. existing LWR SNF inventory, ~40 GW-d/MTHM)**
- **Higher temperature limits**
- **Verification and uncertainty analysis**
- **Disposal concept facilities description and cost estimation**

Backup Slides

KBS-3 Crystalline Rock
Clay Buffer Disposal Concept (Sweden)

KBS-3 Concept;
SKB,SR-Can 2006.

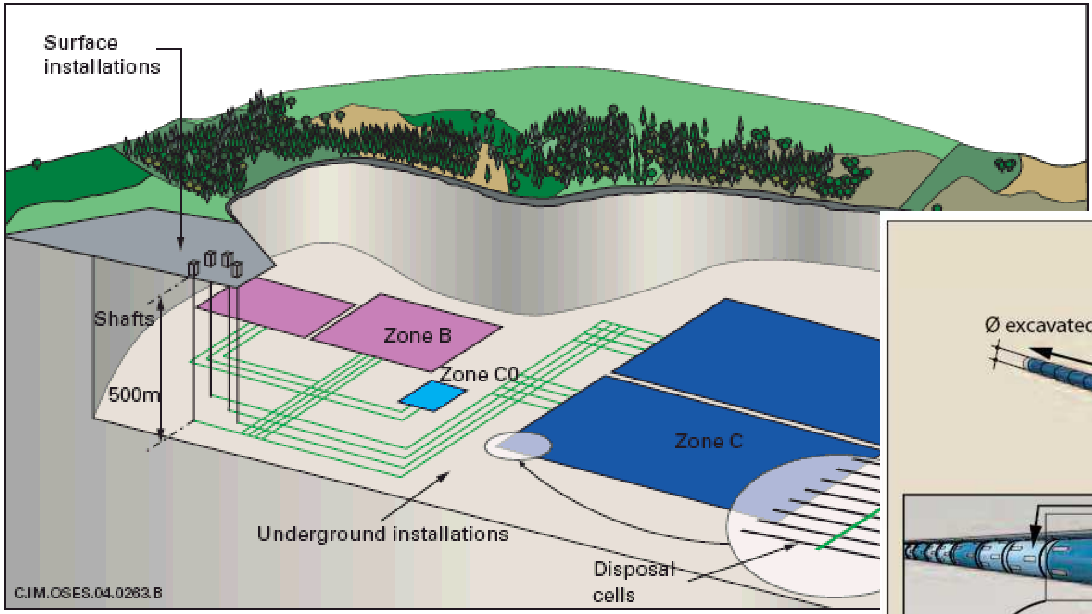


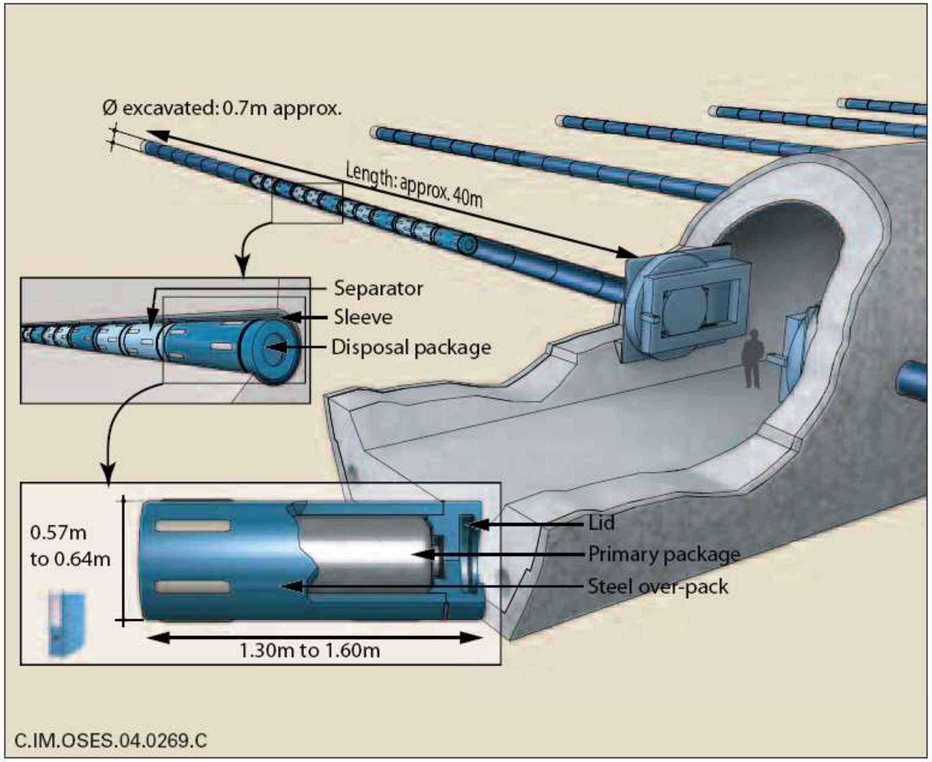


Conceptual View - Forsmark Repository, Power Station, and SFR

Clay/Shale Disposal Concept (France)

Conceptual View of a Repository - Zones for Disposal of Waste Types





Andra, Dossier 2005 Argile

Salt Disposal Concepts (U.S.)

Generic salt repository layout concept (HLW): Carter et al. 2011

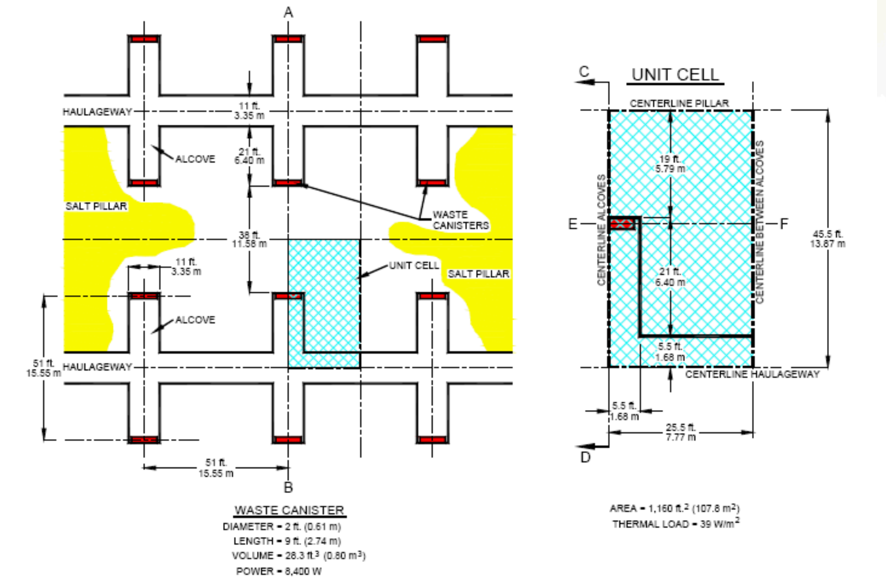
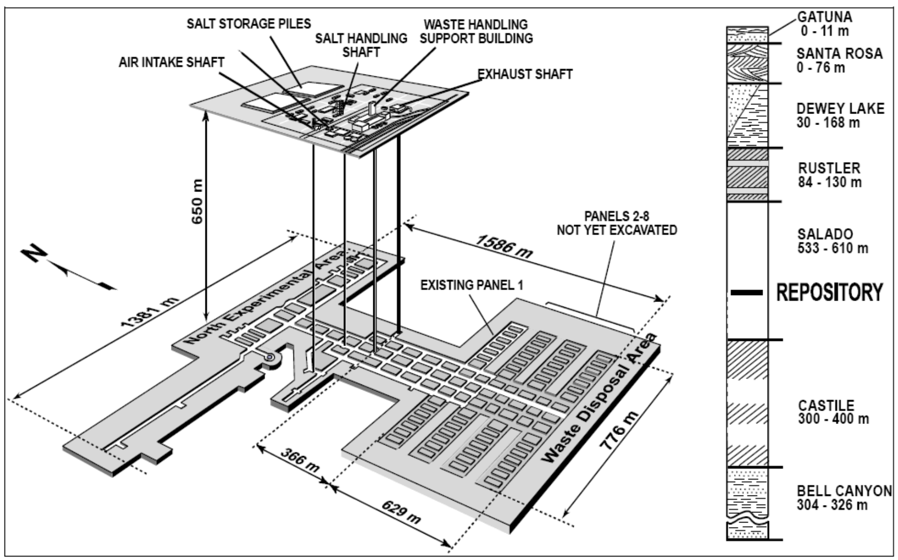


Figure 2 Conceptual Salt Repository Thermal Model Schematic

Figure 3 Elevation Views of the Preliminary Design for the Thermal Modeling

WIPP surface and subsurface schematic (reference only)



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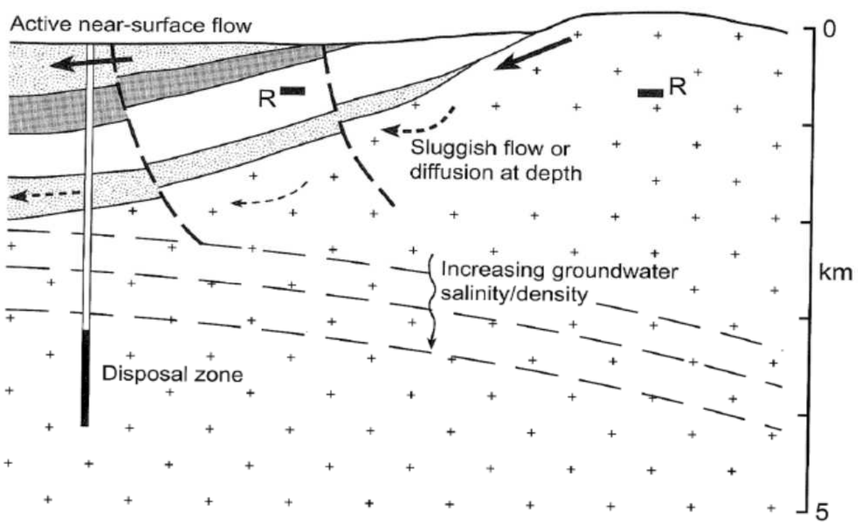
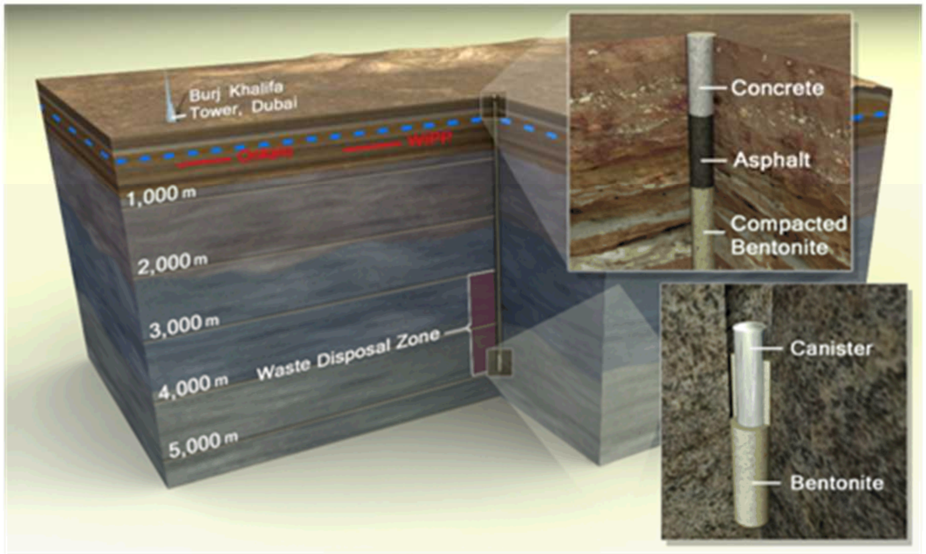
Deep Borehole Disposal Concept

Figure 5: Example of Borehole Disposal Concept Showing Placement of Borehole within Surrounding Geology



After Arnold et al. 2010

After Chapman and Gibb 2003



Deep borehole disposal concept, with buffer and seals

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Comparison of Disposal Concepts

After Hansen et al. 2011

Table 2. Qualitative comparison of geologic media as HLW repository host

	Salt	Shale	Granite	Deep Boreholes
Thermal Conductivity	High	Low	Medium	Medium
Permeability	Practically impermeable	Very low to low	Very low (unfractured) to permeable (fractured)	Very low
Strength	Medium	Low to medium	High	High
Deformation behavior	Visco-plastic (creep)	Plastic to brittle	Brittle	Brittle
Stability of cavities	Self-supporting on the scale of decades	Artificial reinforcement required	High (unfractured) to low (highly fractured)	Medium at great depth
In situ stress	Isotropic	Anisotropic	Anisotropic	Anisotropic
Dissolution behavior	High	Very low	Very low	Very low
Sorption behavior	Very low	Very high	Medium to high	Medium to high
Chemistry	Reducing	Reducing	Reducing	Reducing
Heat resistance	High	Low	High	High
Mining experience	High	Low	High	Low
Available geology	Wide	Wide	Medium	Wide
Geologic stability	High	High	High	High
Engineered barriers	Minimal	Minimal	Needed	Minimal

Favorable quality — Average or variable quality — Unfavorable property

Reference Design Concept Specifics

Geologic Media/Concept	Mined Granite	Mined Clay/shale	Mined Salt	Deep Borehole
Repository depth	500 m	500 m	500 m	>3000 m
Hydrologic setting	Saturated	Saturated	Saturated	Saturated
Emplacement mode (UNF)	Horizontal emplacement, boreholes in wall	Horizontal emplacement, boreholes in wall	Horizontal emplacement, boreholes in wall	Vertical emplacement, stacked
Emplacement mode (HLW)	Same	Same	Horizontal emplacement in alcoves	Same
Normalized areal loading (GWe-yr/acre) *	1 to 10	1 to 10	1 to 10	<1
Drift/borehole spacing	20 m	20 m	20 m	>100 m
Drift/borehole diameter	~1 m	~1 m	~1 m boreholes; 4 m for alcoves	>30 cm
Waste package arrangement	Point	Line	Point for SNF boreholes; point for HLW in alcoves	Line
Liner material	Steel	Steel	Not used	Steel
Overpack material	Copper or steel	Steel	Steel	Steel
Maximum SNF waste package capacity (size)	4-PWR	4-PWR	12-PWR	1 PWR assembly
Buffer material	Bentonite clay	Not used	Not used	Bentonite clay
Radiation shield plug	Required	Required	Required	Not used
Backfill material	Clay/sand mixture	Clay/shale	Crushed salt	Not used
Invert material	Reinforced concrete	Reinforced concrete	Reinforced concrete	Not used
Ground support material	Rockbolts, wire cloth & shotcrete	Steel sets & shotcrete	Rockbolts	Not used
Seals and plugs	Shaft and tunnel	Shaft and tunnel	Shaft and tunnel	Not used

* Magnitude of allowable thermal loading for these concepts depends on waste heat output at emplacement.

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