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Geologic Disposal Concepts for HLW and Spent Nuclear Fuel

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Outline

- U.S. defense waste inventory and commercial SNF projection
- Reference concepts for HLW/SNF disposal
- Temperature limits and thermal analysis
- “Open-mode” disposal concepts
- Direct disposal of SNF in existing dual-purpose canisters
- Postclosure criticality control
- Deep borehole disposal R&D
- Summary

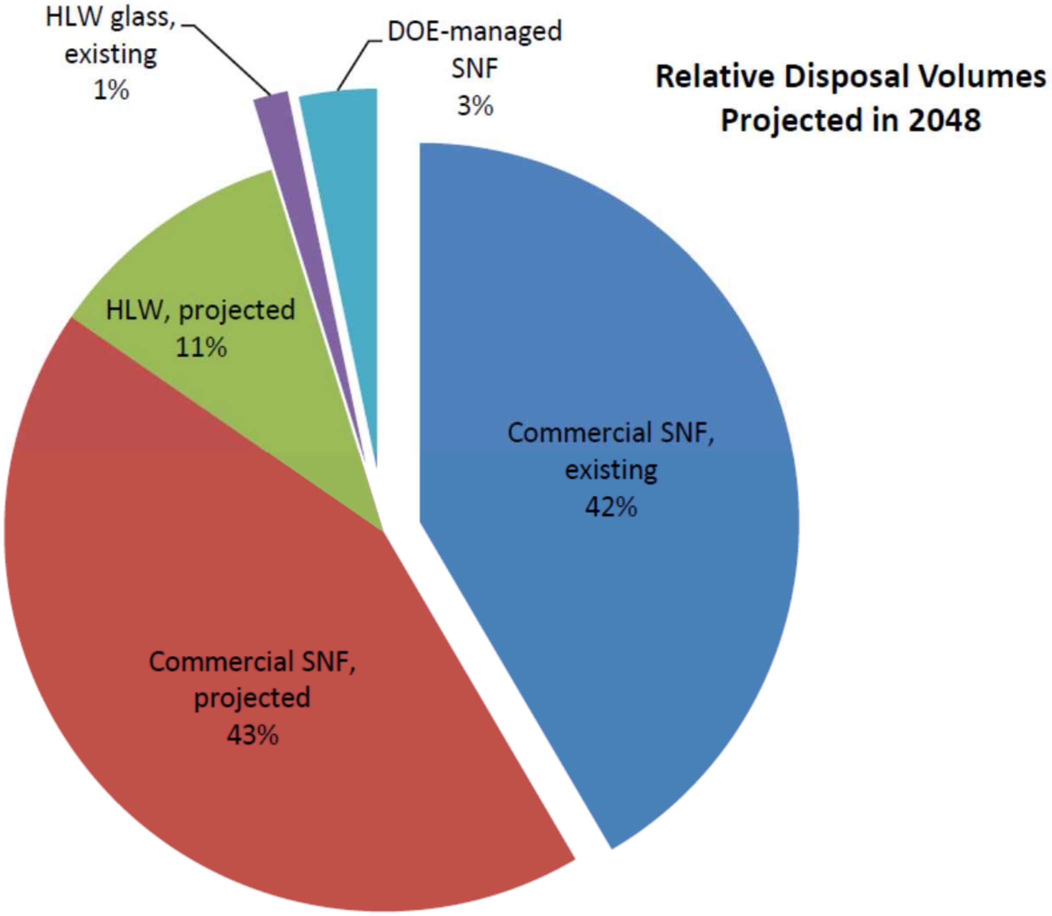
U.S. High-Level Waste and Spent Nuclear Fuel Inventory for Disposal

Disposal Concept Definition: Three Elements

1. **Waste inventory**
   - Waste types from a sample of possible future commercial fuel cycles (Carter et al. 2012a)
2. **Geologic setting**
   - Clay/shale, crystalline rock, bedded salt, and deep crystalline basement
3. **Engineering concept of operation**
   - Examples:
     - KBS-3 (vertical) disposal (SKB, SR-Site 2011)
     - Clay/shale repository (Andra, Dossier 2005)
     - Generic salt repository for SNF in large packages (Hardin et al. 2013a)
     - Generic salt repository for defense HLW and SNF (Carter et al. 2011)
     - Deep borehole concept (Brady et al. 2009)

Total Projected U.S. SNF and HLW Inventory (2014)

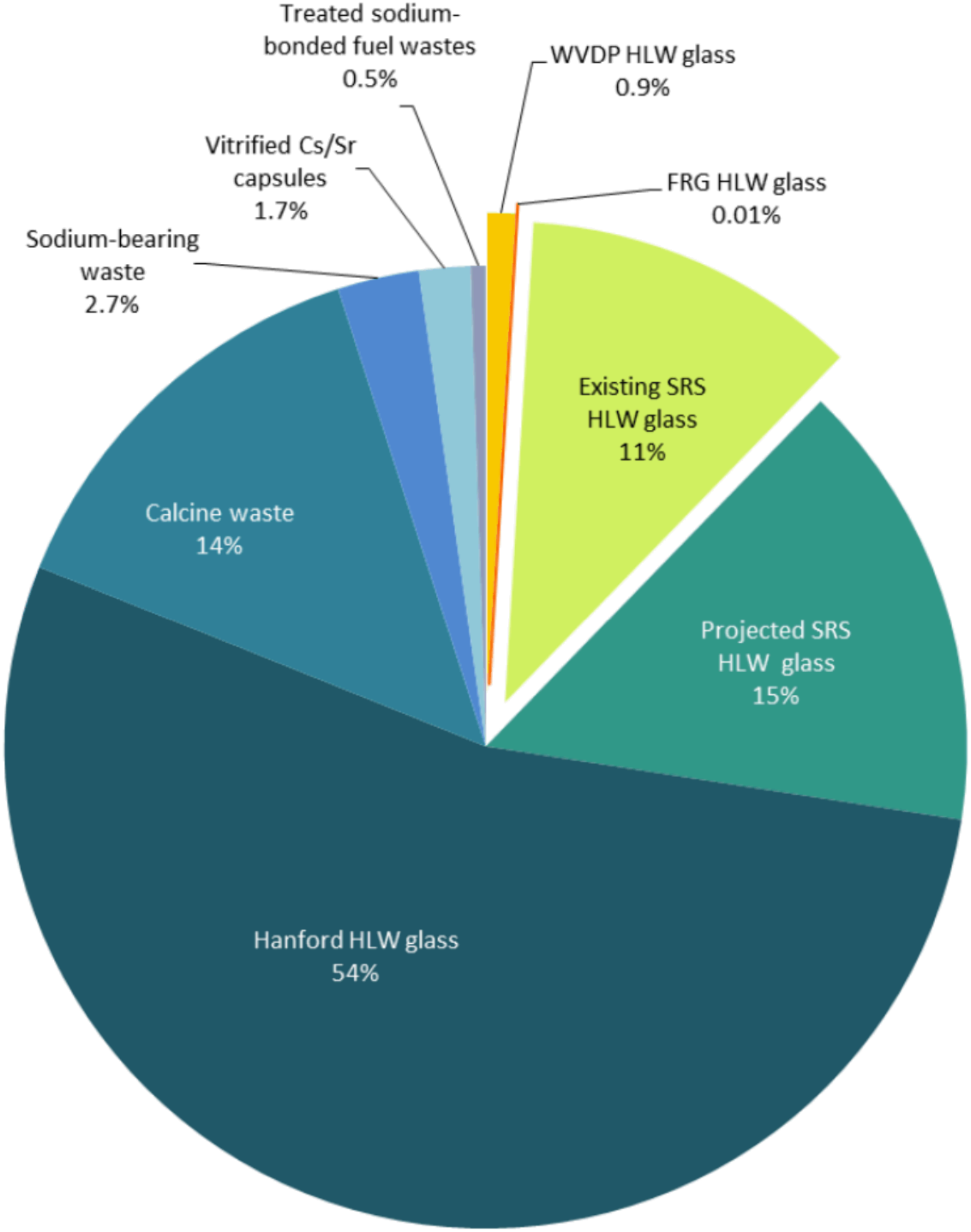
- Normalized based on estimated volume
- Assumptions
  - All commercial SNF disposed in DPC-based packages
  - Based on existing NPPs with 60-yr life extensions (140,000 MTU total)
  - Calcine waste is hot-isostatic pressed with RCRA additives
  - ~3,500 m^3 of naval SNF remains to be generated



Source for this and Slide 7: SNL (Sandia National Laboratories) 2014. *Evaluation of Options for Permanent Geologic Disposal of Spent Nuclear Fuel and High- Level Radioactive Waste in Support of a Comprehensive National Nuclear Fuel Cycle Strategy*. FCRD-UFD-2013-000371, Revision 1 (3 volumes).

Projected U.S. Defense Waste Inventory

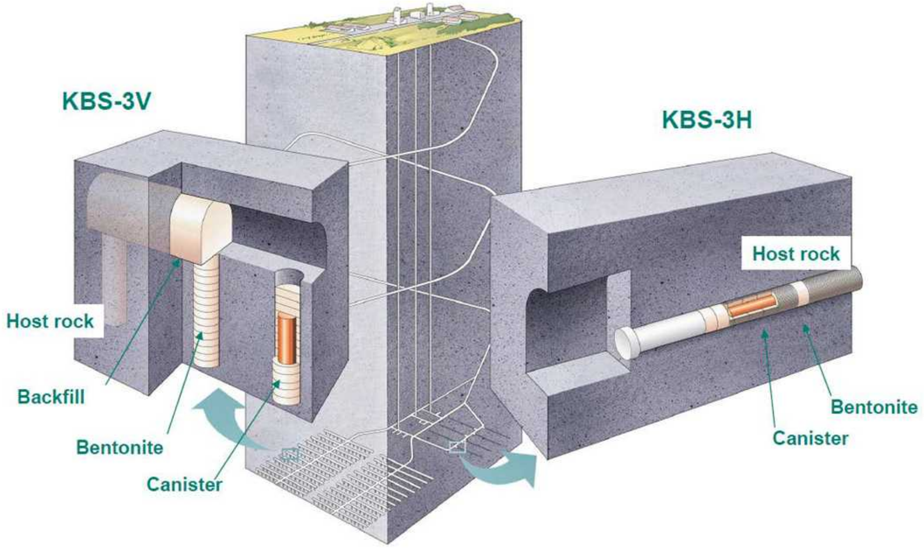
- **Locations**
  - Hanford Site
  - Savannah River Site
  - Idaho National Lab
  - West Valley Facility
- **Treatment Processes**
  - Borosilicate vitrification (HLW from Pu production)
  - Calcining (may be hot-isostatic pressed for disposal)
  - Steam reforming (Na-bearing neutralized tank waste)
  - Electro-metallurigical processing (advanced fuels and Na-bonded fuel)



Reference Disposal Concepts:
Mined Crystalline Rock with Vertical Borehole Emplacement

- Ref.: Based on KBS-3 (SKB 2011)
- Depth: ~500 m
- Hydrologic setting: Saturated
- Buffer temperature limit: 100°C
- # of 4-PWR size packages for U.S. SNF: 82,583

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

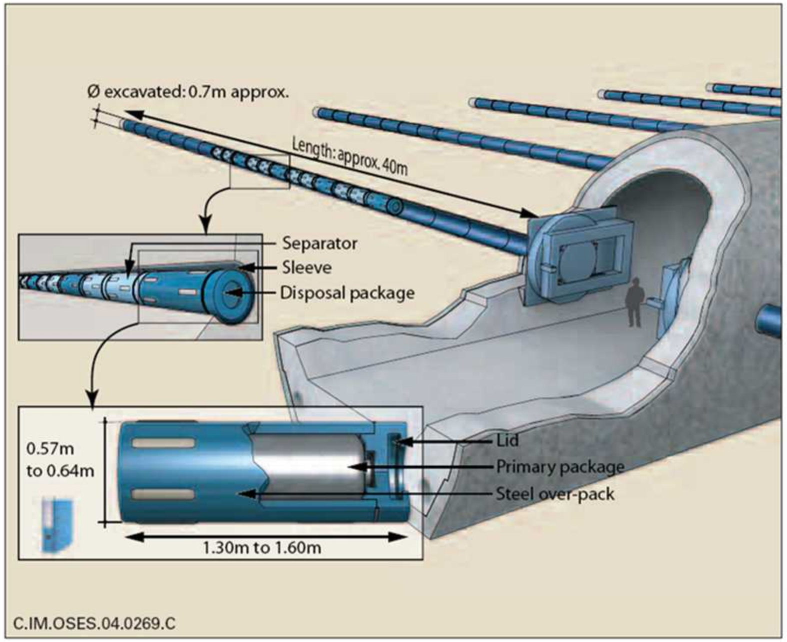


SKB (Swedish Nuclear Fuel and Waste Management Co.) 2011. *Long-term safety for the final repository for spent nuclear fuel at Forsmark: Main report of the SR-Site project, Volume* I. TR-11-01.

Hardin, E. & E. Kalinina 2016. *Cost Estimation Inputs for Spent Nuclear Fuel Geologic Disposal Concepts (Rev. 1)*. SAND2016-0235. Sandia National Laboratories.

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**
- **# of 4-PWR size packages for U.S. SNF: 82,583**



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

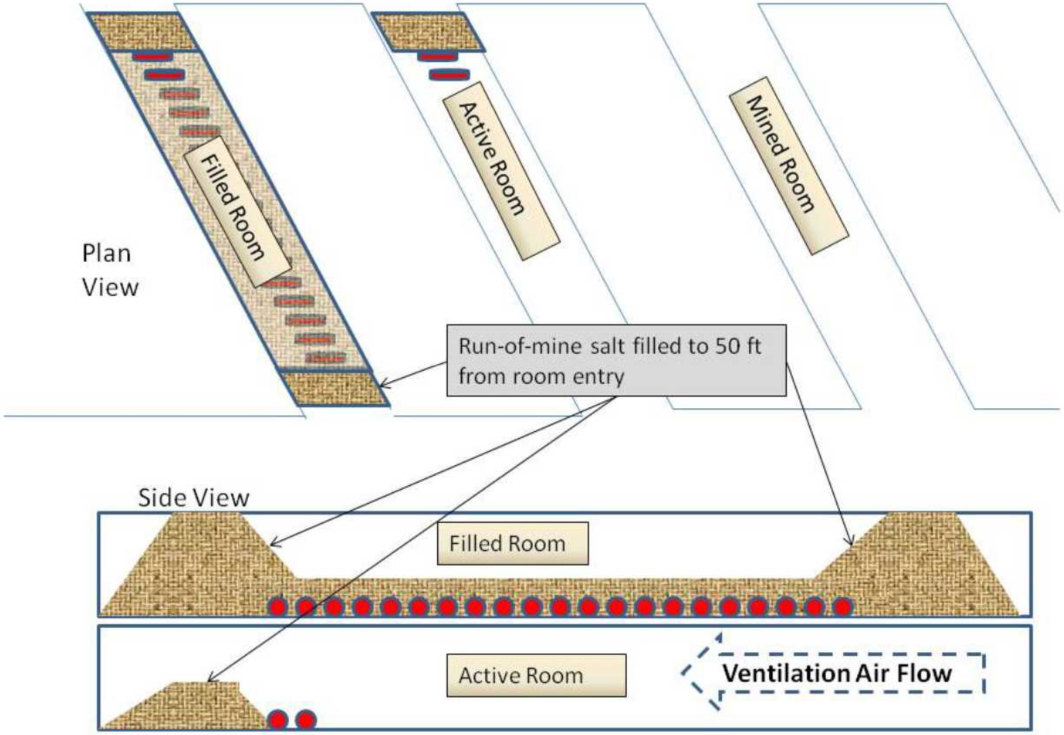
(left) Andra HLW disposal concept (no buffer).

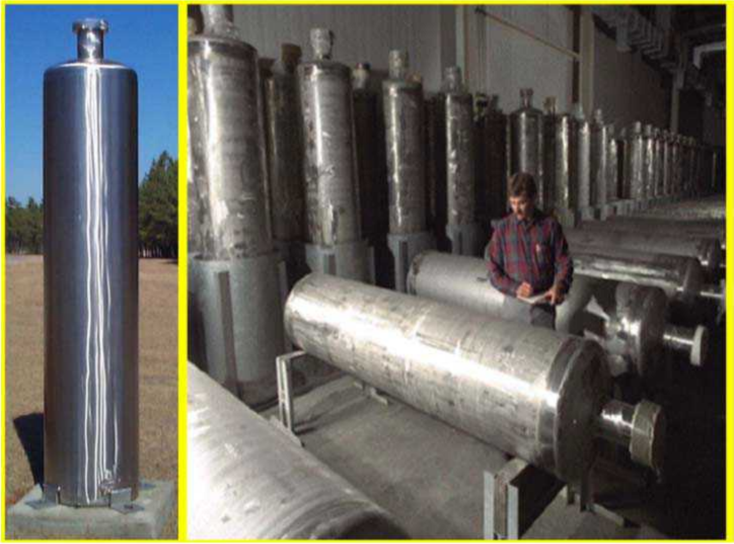
Sources: Andra 2005. *Dossier 2005 argile – architecture and management of a geological disposal system.* December, 2005.

Hardin, E. & E. Kalinina 2016. *Cost Estimation Inputs for Spent Nuclear Fuel Geologic Disposal Concepts (Rev. 1).* SAND2016-0235. Sandia National Laboratories.

Reference Disposal Concepts:
Defense HLW and SNF in a Salt Repository

- **In-drift, transverse emplacement**
- **No overpacks**
- **Low heat output defense waste**

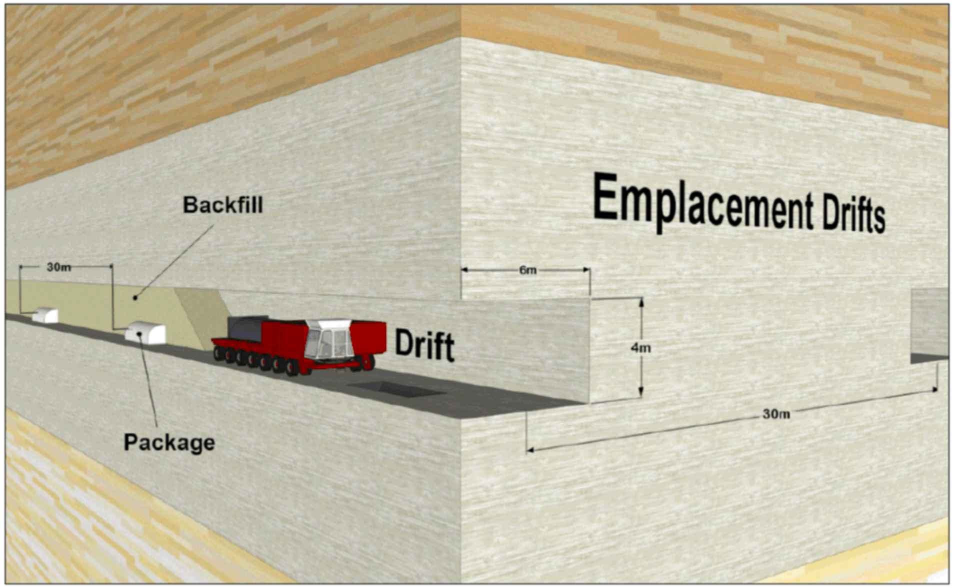




Source: Carter et al. 2012b. *Defense Waste Salt Repository Study*. FCRD-UFD-2012-000113.

Reference Disposal Concepts:
Generic Salt Concept for Large SNF Packages

- **Depth: ≥ 500 m**
- **Hydrologic setting: Nominally saturated**
- **Salt temperature limit: 200°C**
- **# of waste packages for U.S. SNF:**
  - **16,157 (21-PWR or BWR equiv.)**
  - **28,792 (12-PWR or BWR equiv.)**
  - **82,583 (4-PWR or BWR equiv.)**



Disposal characteristic	SNF	HLW
Emplacement mode	**Horizontal, in-drift (axial)**	**Horizontal, in drifts or alcoves (transverse)**
Overpack material	**Steel**	**Steel**
Package spacing, m	**Up to 30 m**	**2 m (in-drift) to 20 m (alcove)**
Borehole liner material	**-**	**-**
Buffer material	**-**	**-**
Backfill material	**Crushed salt**	**Crushed salt**

Carter et al. 2011. *A generic salt repository for disposal of waste from a spent nuclear fuel recycle facility*. SRNL-RP-2011-00149 Rev. 0.

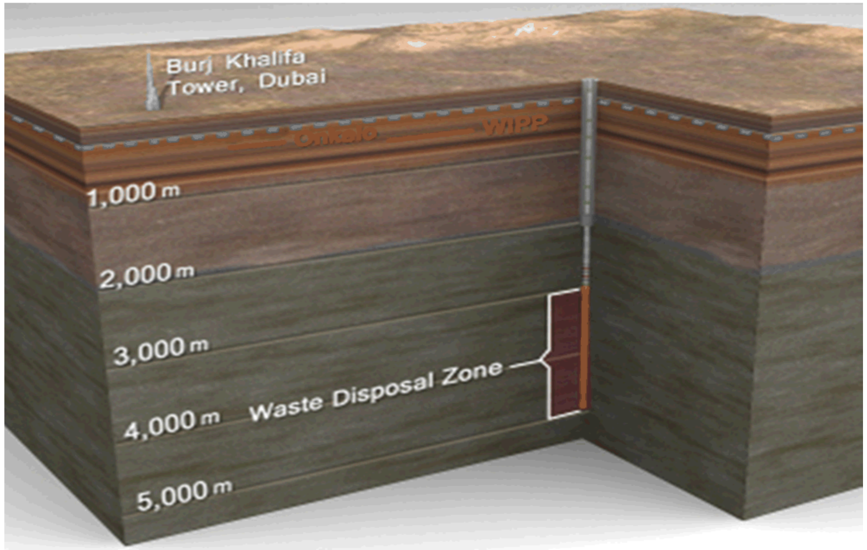
Hardin et al. 2013a. *Preliminary Report on Dual-Purpose Canister Disposal Alternatives*. FCRD-UFD-2013-000171 Rev. 0.

Hardin, E. & E. Kalinina 2016. *Cost Estimation Inputs for Spent Nuclear Fuel Geologic Disposal Concepts (Rev. 1)*. SAND2016-0235. Sandia National Laboratories.

Reference Disposal Concepts:

Deep Borehole Disposal

- **Ref.: SNL and MIT studies**
- **Depth: 3 to 5 km**
- **Hydrologic setting: Saturated (ancient brine)**
- **Temperature constraint: waste package material strength (~250°C)**



Disposal Characteristic	SNF & HLW
Emplacement mode	Vertical, stacked
Overpack material	Steel
Package-package spacing, m	~5
Borehole-borehole spacing, m	200
Borehole liner	Steel
Buffer material	Brine
Backfill material	Cement (partial)

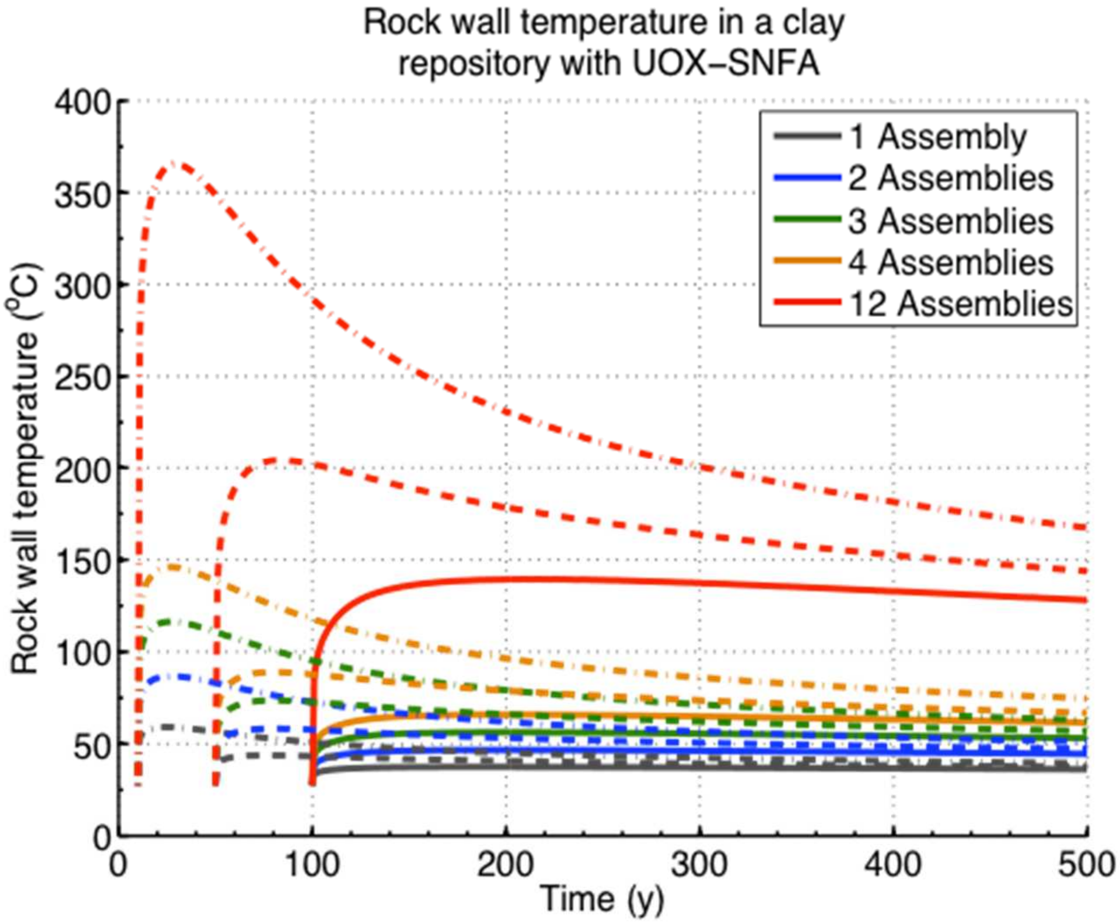
Sources: Brady et al. 2009. *Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2009-4401.
Arnold et al. 2011. Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste. SAND2011-6749.
SNL (Sandia National Laboratories) 2016. *Deep Borehole Field Test Conceptual Design Report.* FCRD-UFD-2016-000070 Rev. 1.

Reference Mined Disposal Concepts:
Temperature Limits (Targets)

- **Based on material degradation processes:**
  - 100°C for clay/shale media and swelling clay-based buffer material (multiphase-moisture reactive transport processes)
  - 200°C for salt (polyhalite decomposition at ~200°C, and salt decrepitation from pore water flashing at ~270°C)
  - 200°C for hard rock (differential thermal expansion microfracture damage)
  - 170 to 250°C for deep boreholes (limited by waste package material strength)
- **Final temperature constraints will be site- and design-specific**

Thermal Analysis – Example Temperature Histories

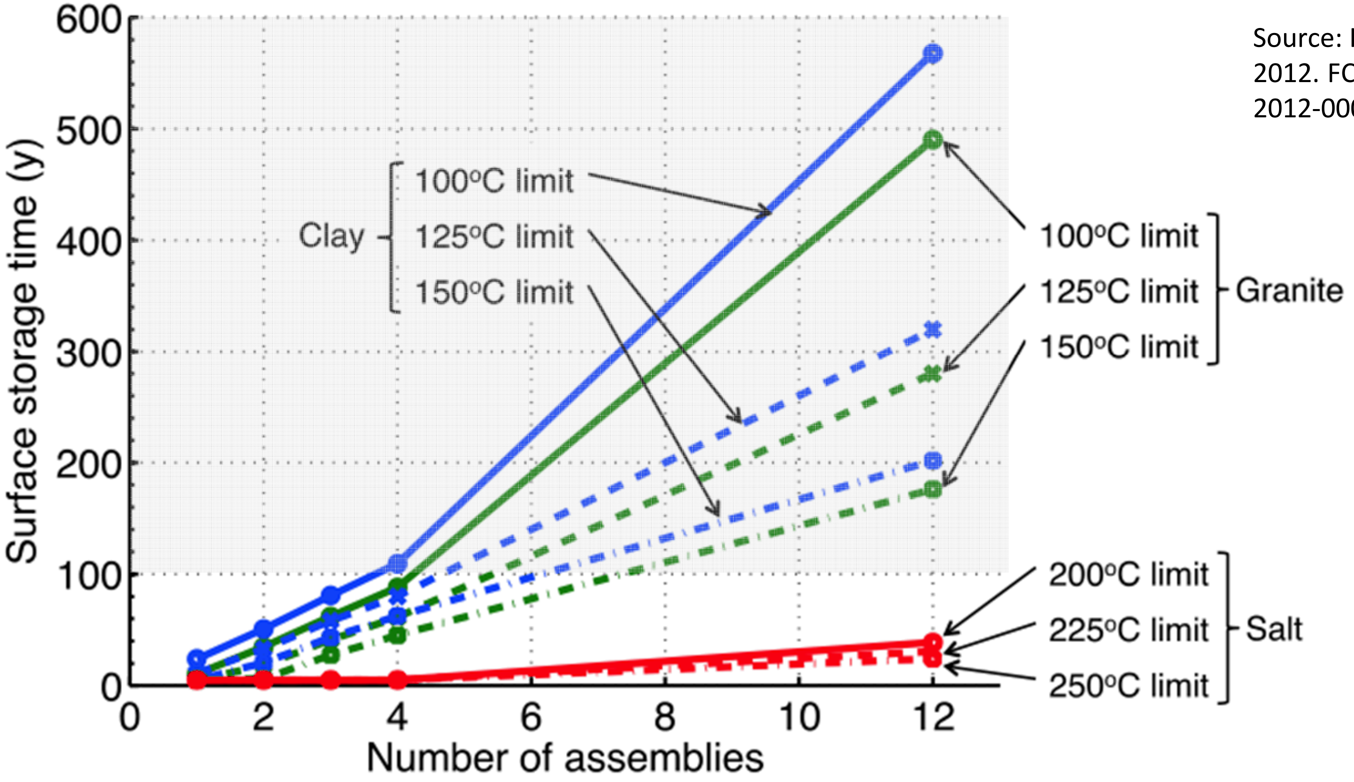
- **Example: clay/shale repository**
  - Host rock temperature (at rock wall)
  - LWR UOX SNF (60 GW-d/MTU)
  - Calculate for different package size/capacity



Source: Hardin, et al. 2012. FCRD-USED-2012-000219 Rev. 2.

International/Enclosed Concept Thermal Analysis & Effect of Varying 100°C or 200°C Limits

Decay Storage Needed to Meet WP Surface Temperature Limits vs. WP Capacity (PWR assemblies; 60 GW-d/MT burnup)



Source: Hardin, et al. 2012. FCRD-USED-2012-000219 Rev. 2.

Thermal conductivity for all media selected at 100°C.
Granite and clay concepts use clay-based buffer material around waste packages.

Mined Disposal Concepts:

Open vs. Enclosed Emplacement Modes

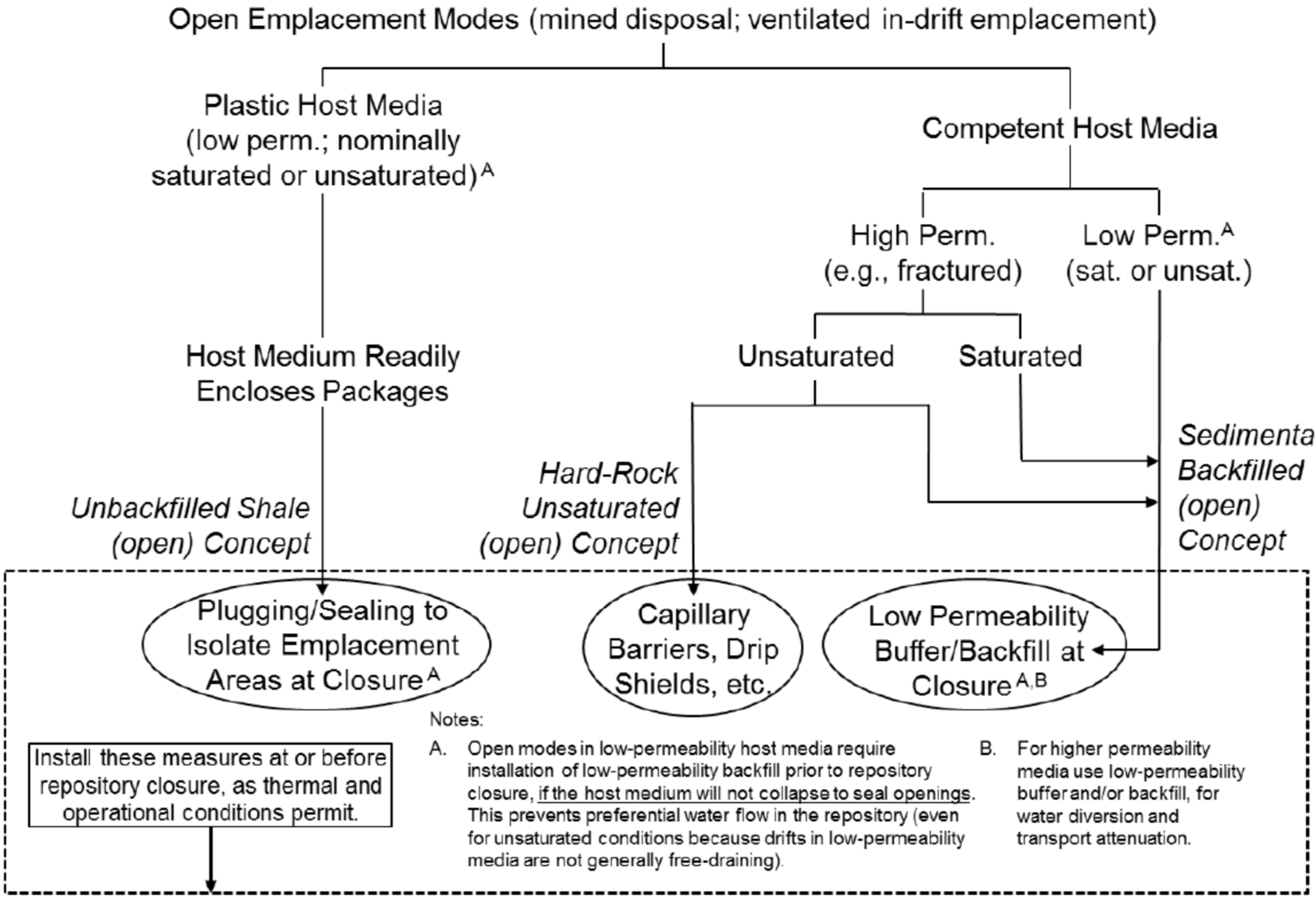
- **Enclosed: Buffer, backfill or host rock material encloses and contacts waste packages immediately after emplacement**
  - **International concepts**
  - **Thermal resistance through buffer/backfill**
- **Open: Openings persist around waste packages for 100 to >10^4 years**
  - **Simple "in-drift" emplacement**
  - **Heat spread by thermal radiation across air gaps**
  - **Pre-closure ventilation possible to remove heat**
  - **Backfilling may be necessary at closure**

Open Emplacement Mode Rationale

Why has the U.S. embraced open-mode disposal before?

- **System Operation**
  - **Accomplish geologic disposal sooner**
  - **Decrease the extent of interim storage**
  - **Retrievable (at least through ventilation period)**
  - **Potential to enable direct disposal of existing dual-purpose canisters (e.g., salt or unsaturated hard rock)**
- **System Economics**
  - **Larger waste packages cost less per MTU (economies of scale)**
  - **Earlier investment in disposal facilities and waste packaging (inter-generational equity)**
  - **Reduce life-cycle cost, but with extended repository operations**

Open Emplacement Mode “Taxonomy”



Open Emplacement Modes (mined disposal; ventilated in-drift emplacement)

Plastic Host Media (low perm.; nominally saturated or unsaturated)[A]

Competent Host Media

High Perm. (e.g., fractured)

Low Perm.[A] (sat. or unsat.)

Unsaturated

Saturated

Host Medium Readily Encloses Packages

Sedimentary Backfilled (open) Concept

Unbackfilled Shale (open) Concept

Hard-Rock Unsaturated (open) Concept

Plugging/Sealing to Isolate Emplacement Areas at Closure[A]

Capillary Barriers, Drip Shields, etc.

Low Permeability Buffer/Backfill at Closure[A,B]

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

Notes:

A. Open modes in low-permeability host media require installation of 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 because drifts in low-permeability media are not generally free-draining).

B. For higher permeability media use low-permeability buffer and/or backfill, for water diversion and transport attenuation.

Source: Hardin et al. 2012. FCRD-UFD-2012-000219 Rev. 2.

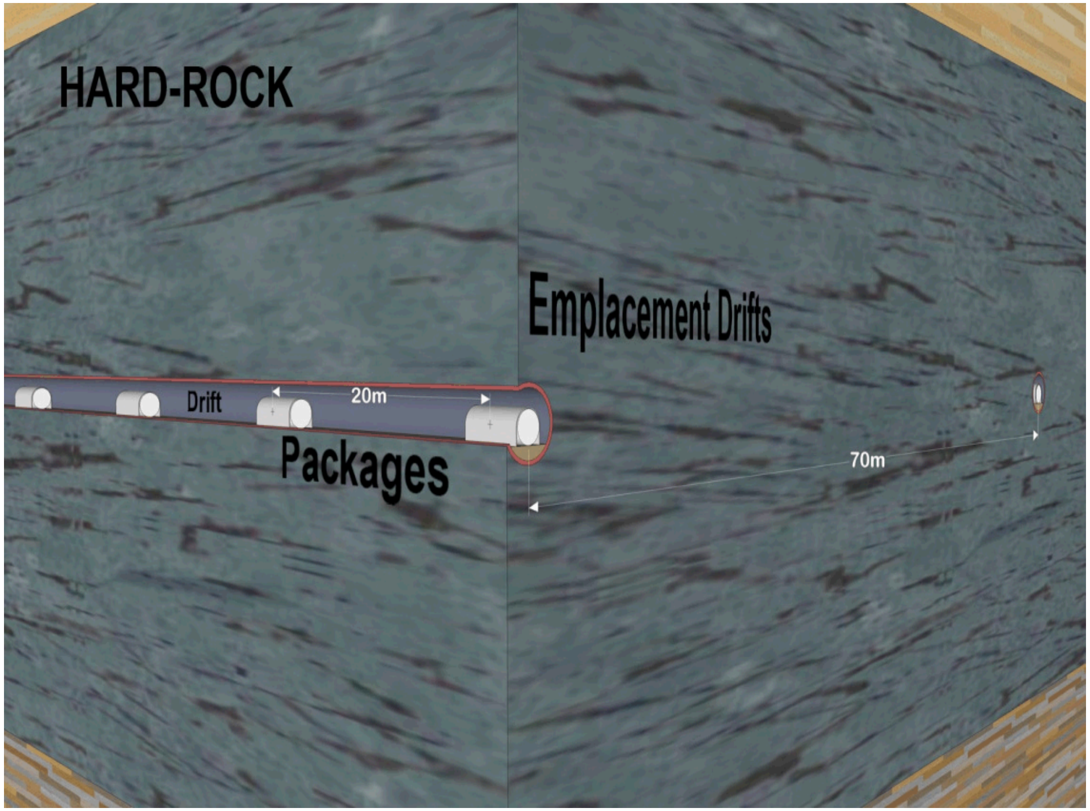
Reference Disposal Concepts

1. Clay/Shale Repository (e.g., French Cigeo project)
2. KBS-3 (vertical) Repository (e.g. Swedish and Finnish projects)
3. Generic Salt Repository (defense waste or larger SNF packages)*
4. Deep Borehole (small-volume waste streams)
5. **Hard-Rock Unsaturated Unbackfilled Open Mode Concept***
6. **Sedimentary Backfilled Open Mode***
7. **Cavern-Retrievable Concept***

** Concepts suitable for larger, hotter waste packages*

Hard-Rock Unbackfilled Open Concept

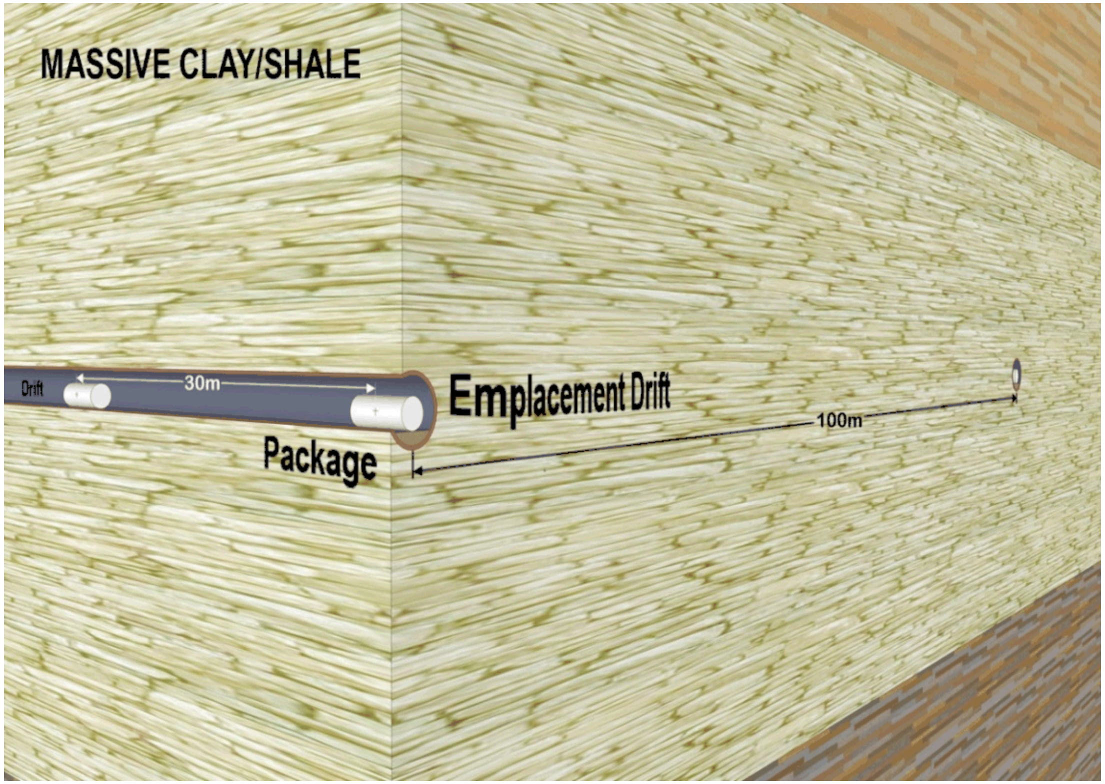
- **Up to 32-PWR size or larger**
- **In-drift emplacement**
- **Emplace SNF at 50 to 100 years OoR**
- **Ventilate up to 50 years, closure at ≤150 years OoR**
- **Unbackfilled, for unsaturated settings**
- **Corrosion resistant waste packaging**
- **Additional engineered barriers may be installed at closure**
- **Long-term opening stability can be expected**



Source: Hardin et al. 2013a. FCRD-UFD-2013-000171 Rev. 0.

Sedimentary Backfilled Open Concept

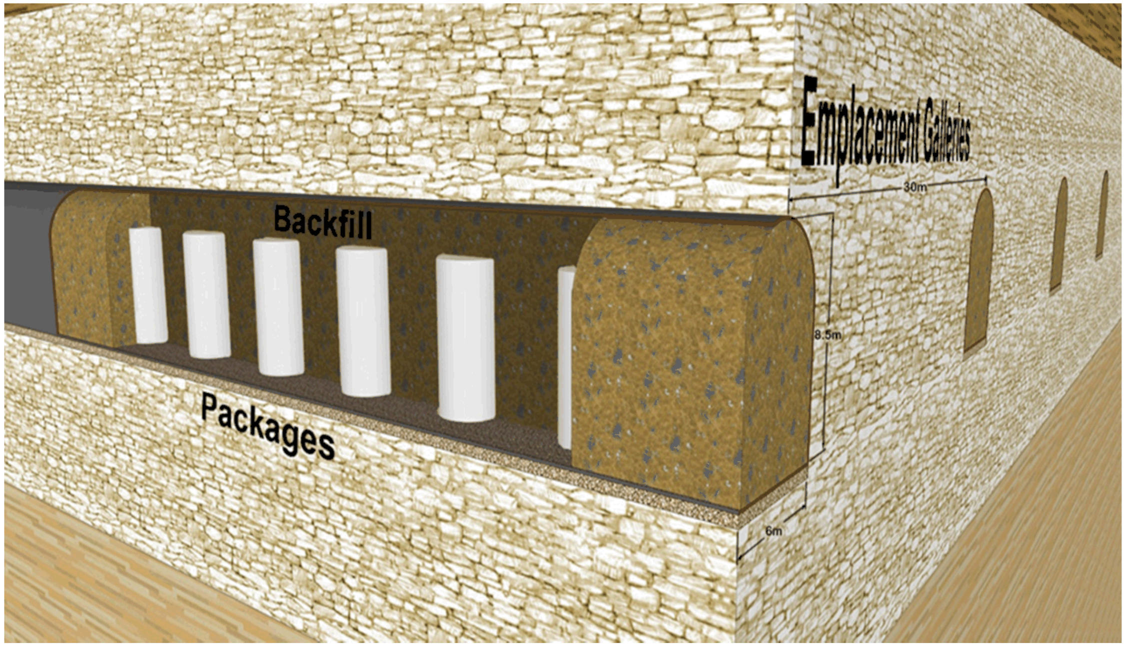
- Massive, soft clay/shale
- 32-PWR size or larger
- In-drift emplacement
- Emplace SNF at 50 to 100 years OoR
- Backfilling at closure (peak backfill T >> 100°C)
- Closure at 100 to >200 years OoR (limited by host rock)
- Possible local heating of host rock >100°C
- Steel or corrosion resistant waste packaging as needed



Source: Hardin et al. 2013a. FCRD-UFD-2013-000171 Rev. 0.

Cavern-Retrievable Storage-Disposal Concept

- Use existing dry storage systems
- Large galleries
- Extended ventilation (>100 yr)
- Unsaturated settings preferred
- Engineered barrier(s) installed at closure: development needed



Concept from McKinley, Apted et al. 2008; figure from Hardin et al. 2013a.

Thermal Management for Larger/Hotter Packages

Example Results for 32-PWR Size Packages & Current Temperature Limits

Time to Repository (or Panel) Closure for Representative Disposal Concepts

Thermal Mgmt. Degrees of Freedom:

- Package SNF capacity
- Burnup
- Age at emplacement
- Repository ventilation
- Host rock properties
- Spacings
- Use of backfill
- Backfill properties

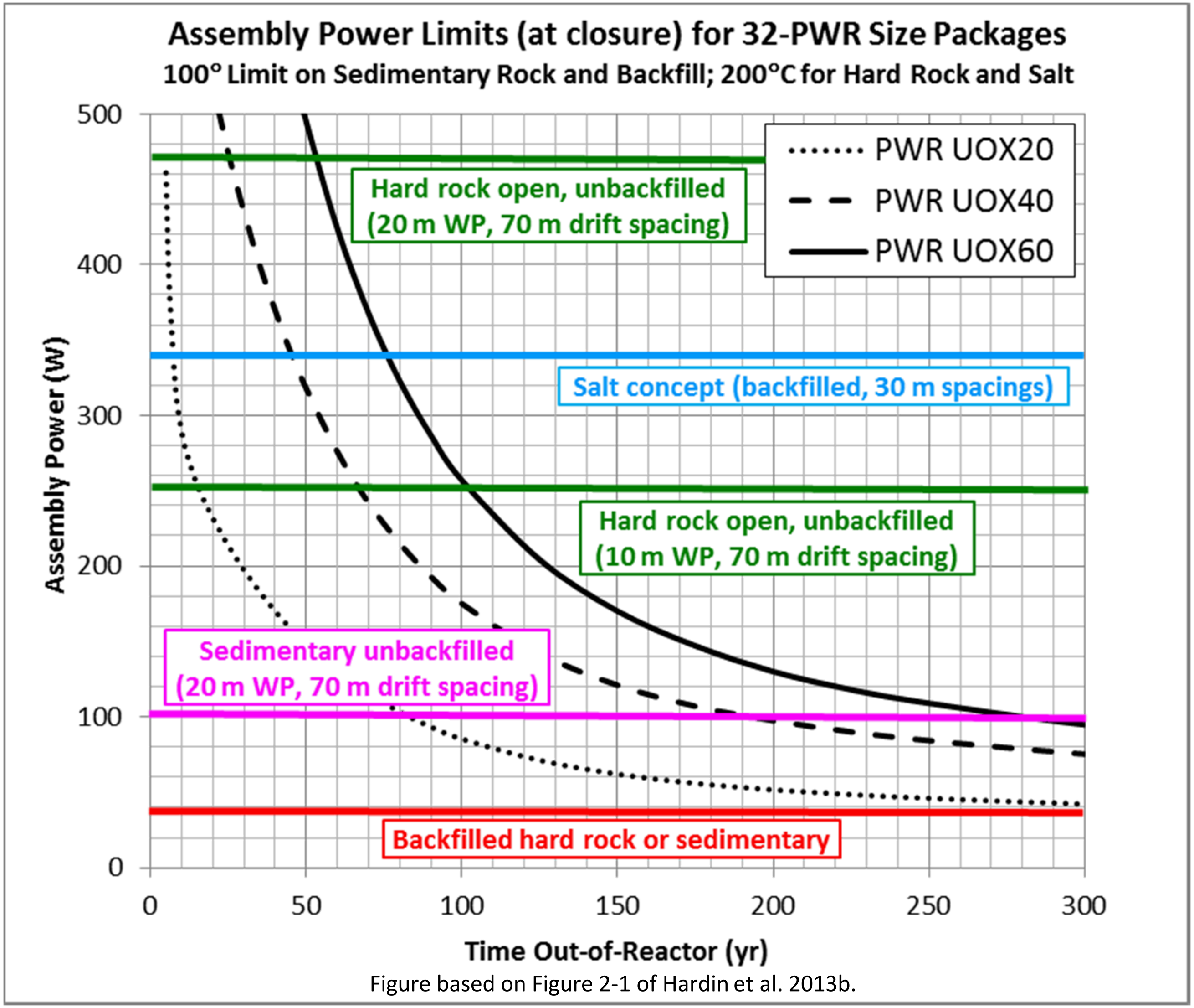
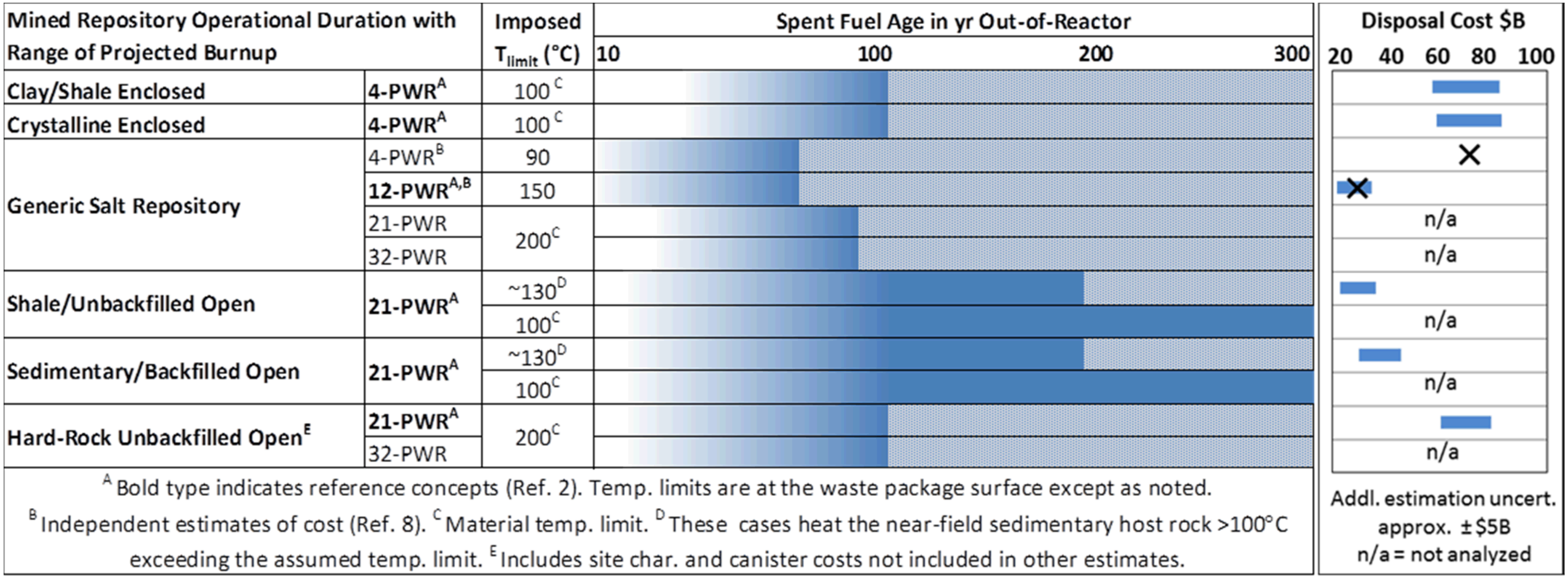


Figure based on Figure 2-1 of Hardin et al. 2013b.

Reference Concept Comparison
SNF Disposal Duration and Cost

- **Stylized depiction of disposal timing based on SNF age out-of-reactor**
- **Disposal of 140,000 MT SNF**
- **Concepts and cost estimates (Hardin et al. 2012; Hardin & Kalinina 2016)**
- **Shading indicates range of possible age at emplacement (e.g., burnup)**



Mined Repository Operational Duration with Range of Projected Burnup		Imposed T_{limit} (°C)	Spent Fuel Age in yr Out-of-Reactor 10 100 200 300	Disposal Cost $B 20 40 60 80 100
Clay/Shale Enclosed	**4-PWR**[A]	100 [C]		
Crystalline Enclosed	**4-PWR**[A]	100 [C]		
Generic Salt Repository	4-PWR[B]	90		×
	12-PWR[A,B]	150		×
	21-PWR	200[C]		n/a
	32-PWR			n/a
Shale/Unbackfilled Open	**21-PWR**[A]	~130[D]		
		100[C]		n/a
Sedimentary/Backfilled Open	**21-PWR**[A]	~130[D]		
		100[C]		n/a
Hard-Rock Unbackfilled Open[E]	**21-PWR**[A]	200[C]		
	32-PWR			n/a

[A] Bold type indicates reference concepts (Ref. 2). Temp. limits are at the waste package surface except as noted. [B] Independent estimates of cost (Ref. 8). [C] Material temp. limit. [D] These cases heat the near-field sedimentary host rock >100°C exceeding the assumed temp. limit. [E] Includes site char. and canister costs not included in other estimates.

Addl. estimation uncert. approx. ±$5B
n/a = not analyzed

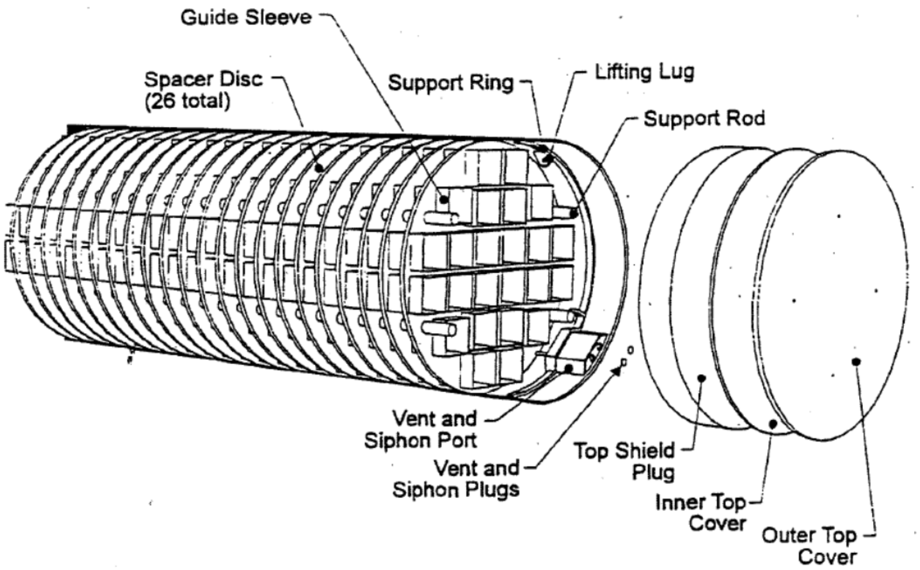
Direct Disposal of SNF in Dual Purpose (Storage-Transportation) Canisters

Technical Feasibility Study

Some Terminology

- **Canister** ≡ Sealed, unshielded vessel for storing, transporting and possibly disposing of spent fuel (using different overpacks). Also, a sealed vessel containing HLW. Typically welded closure (NRC annual inspection requirements for bolted closures). Example tradenames: NUHOMS, TSC, MPC, Magnastor, etc. (3 major vendors Transnuclear/Areva, Holtec, NAC International).
- **Storage Cask** ≡ Shielded (possibly self-shielded as with CASTOR) container for stationary storage. Typically bolted closure. Examples: Licensed storage systems for canisters listed above.
- **Transportation Cask** ≡ Shielded (possibly self-shielded as with CASTOR) container for transporting SNF in canisters, or as “bare” fuel assemblies. Typically bolted closure. Examples: Licensed transportation systems for canisters listed above.
- **Transfer Cask** ≡ Used locally to transfer unshielded canisters from fuel pools to storage casks, or from storage to any other system, e.g., for transport or disposal.

Typical DPC Canister/Cask System - NUHOMS



- NUHOMS® (TransNuclear/Areva)
- ~1/3 of existing U.S. DPC fleet
- NUHOMS®–24P, –24PHB, –24PTH, –32PT, –32PTH1, –52B, –61BT,–61BTH, and –69BTH
- Welded SS304 construction typical (fuel pool compatibility)

- Over 50% of U.S. UNF is stored in Transnuclear (TN) designed systems (part of AREVA Group)
- >650 TN storage casks
- >23,000 assemblies
- 31 U.S. sites at the end of 2010

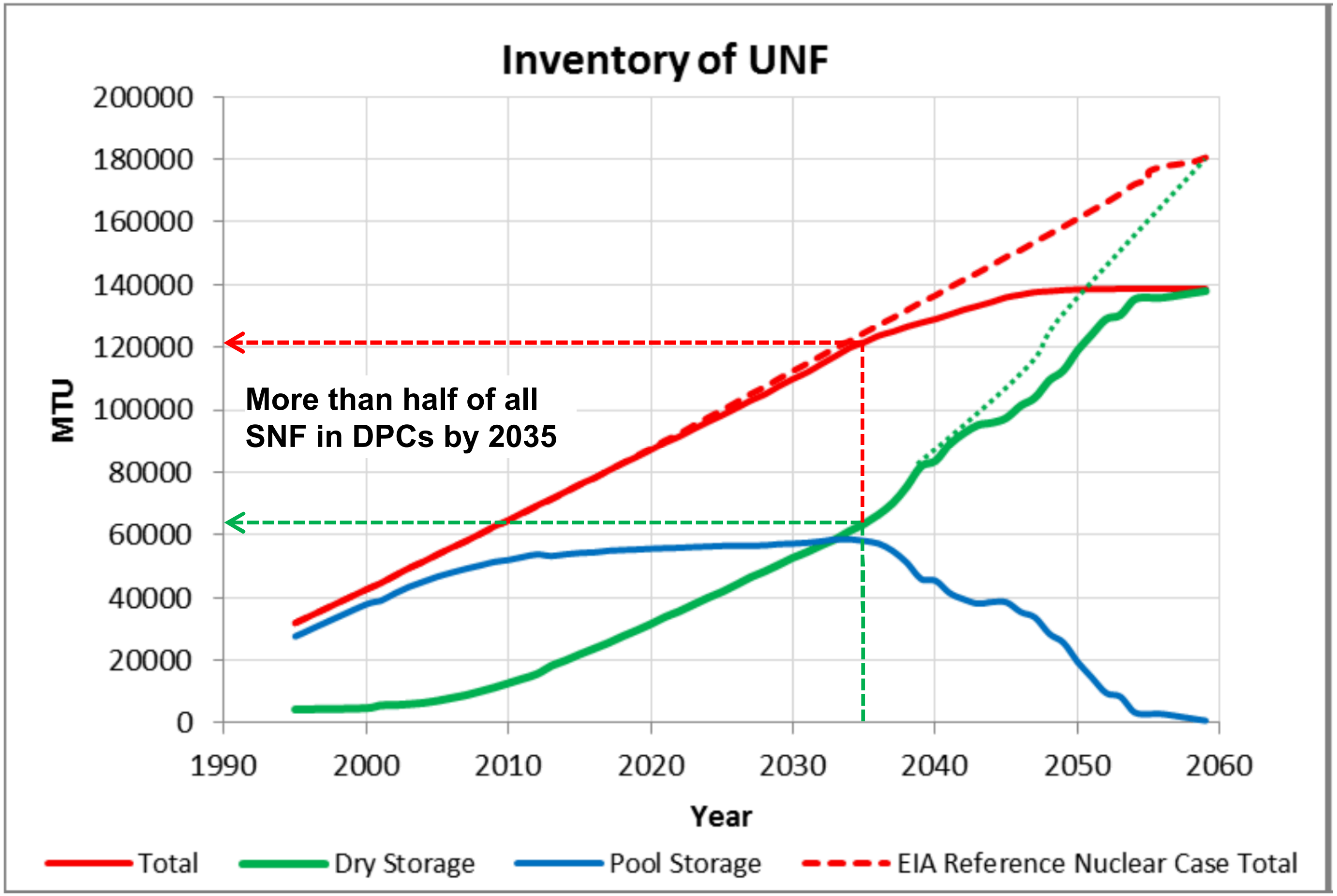

Pictures and data from Transnuclear/AREVA

Largest, Recent DPC Designs

- Example: Magnastor DPC system (NAC International)
- Recently brought to market
- Capacity 37-PWR (equiv.)
- Thermal limits: 35.5 kW storage/24 kW transport
- Fuel cool time >4 yr OoR
- Size evolution (free market): burnup credit analysis, heat transfer features, transportation needs.

Pictures and data from NAC International website 31Mar2012

Spent Fuel Projection – TSL-CALVIN* Accumulation of Heavy Metal (MTU)

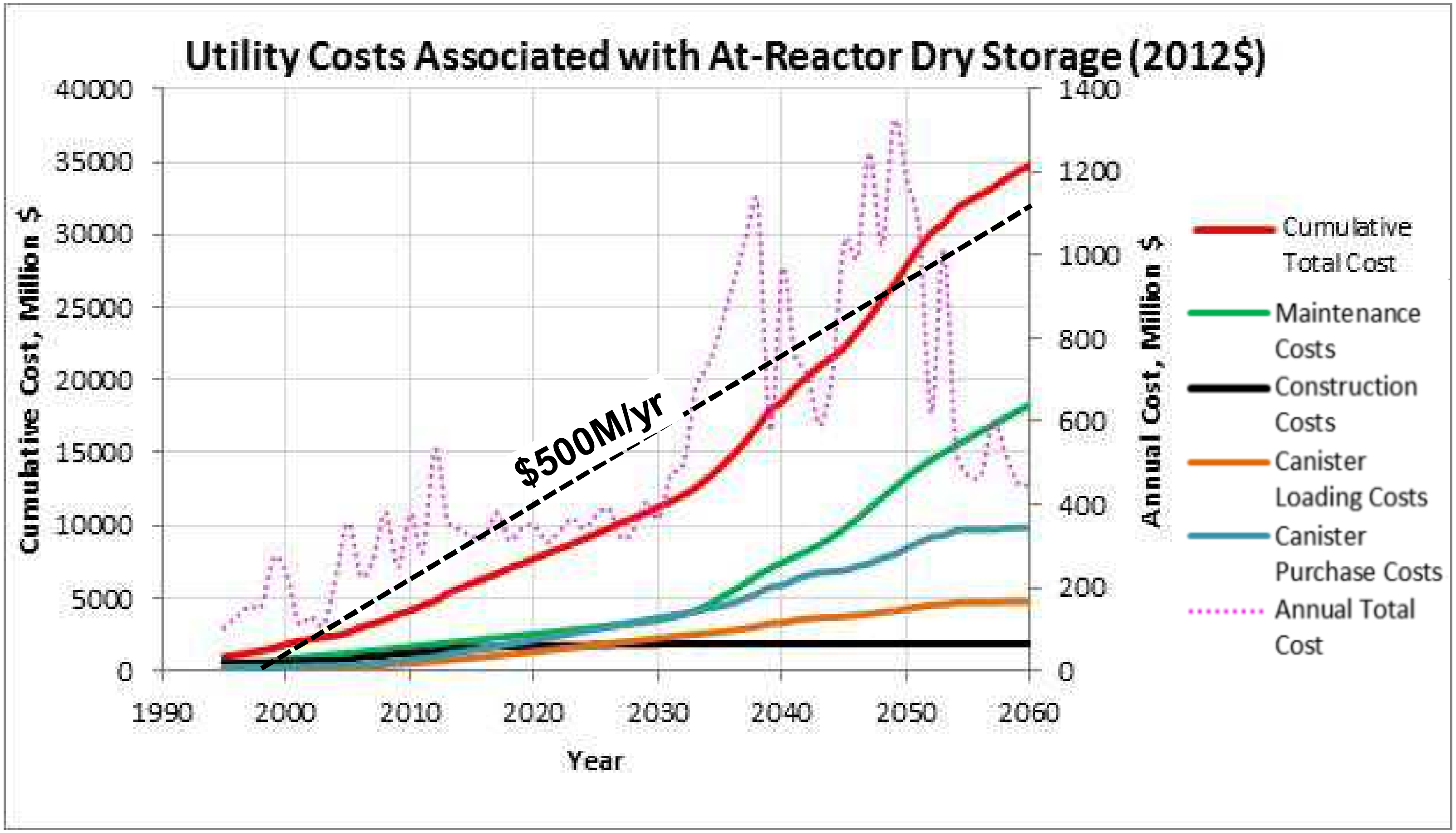


More than half of all SNF in DPCs by 2035

Assume Life Extensions (to 60 yr) for the Currently Operating Fleet.

Nutt et al. 2012. *Transportation Storage Logistics Model – CALVIN (TSL-CALVIN).* FCRD-NFST-2012-000424.

Dry Storage Projection – TSL-CALVIN
Utility SNF Management Costs



Assume presently used DPC types, no SNF shipments from existing dry storage, and life extensions (to 60 yr) for the current operating fleet.

“Hallway Rumors"About DPC Direct Disposal

- “DPCs are much heavier than YM SNF canisters.”

  Loaded Magnastor 37-PWR DPC (47 MT) vs. loaded YM canister (≤ 49.3 MT)

- “DPCs are much larger than YM TADs.”

  Magnastor canister (1.80 m D x 4.87 m L → 12.4 m^3) vs. YM canister dimensional envelope (1.69 m D x 5.39 m L → 12.1 m^3)

- “DPC-based waste packages would be too heavy to lower down a shaft.”

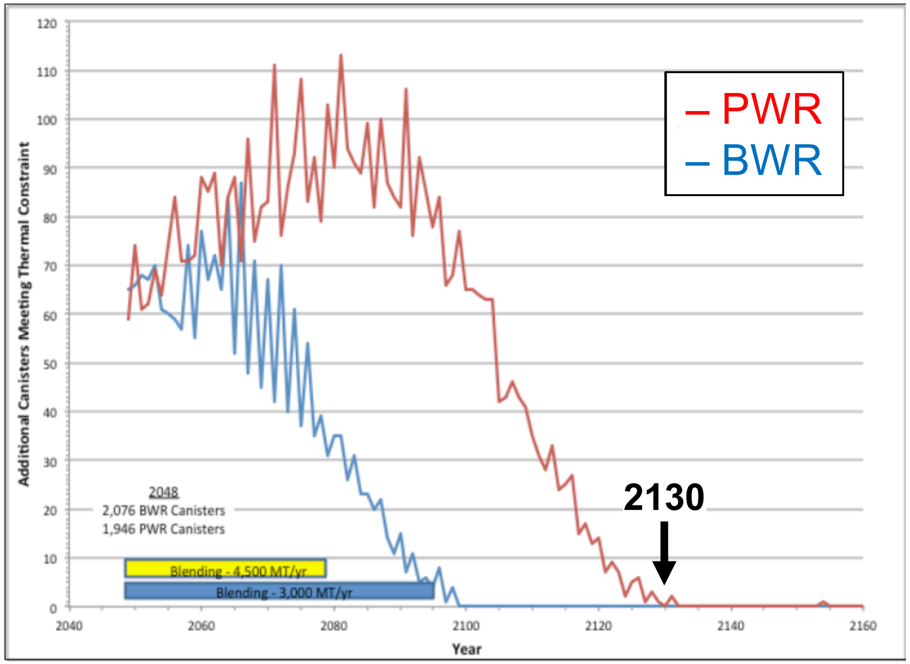
  Not necessarily, e.g., DPC package (70 MT) with shield (75 MT) + carriage < 175 MT (DBE TEC “DIREGT” conceptual hoist design)

- “DPC-based packages would be too big/hot/heavy for a salt repository.”

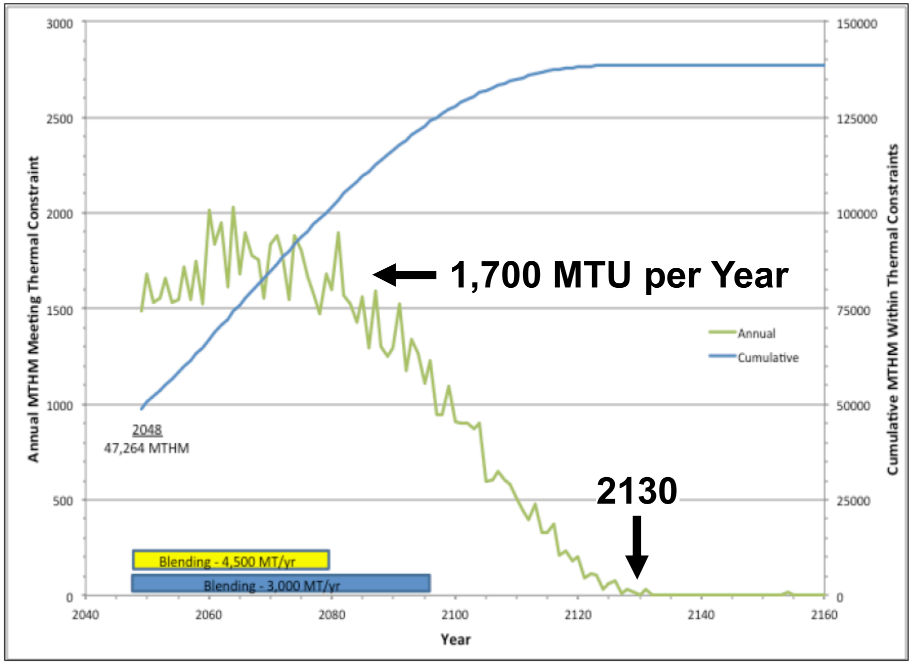
  Package bearing stress is small (< 50 kPa) and even creep models calibrated to recent low-stress, low-strain-rate data produce < 0.5 m of sinking in 10^4 years, without interbeds.

Cooling Time for DPC Direct Disposal

- **Example Results (10 kW power limit, typical for salt):**
  - Emplacement operations would be substantially done by 2130
  - Additional ventilation time would be needed for hard rock (up to 50 yr) and sedimentary (100 to >200 yr) concepts



# of Canisters per Year Cooling to 10 kW

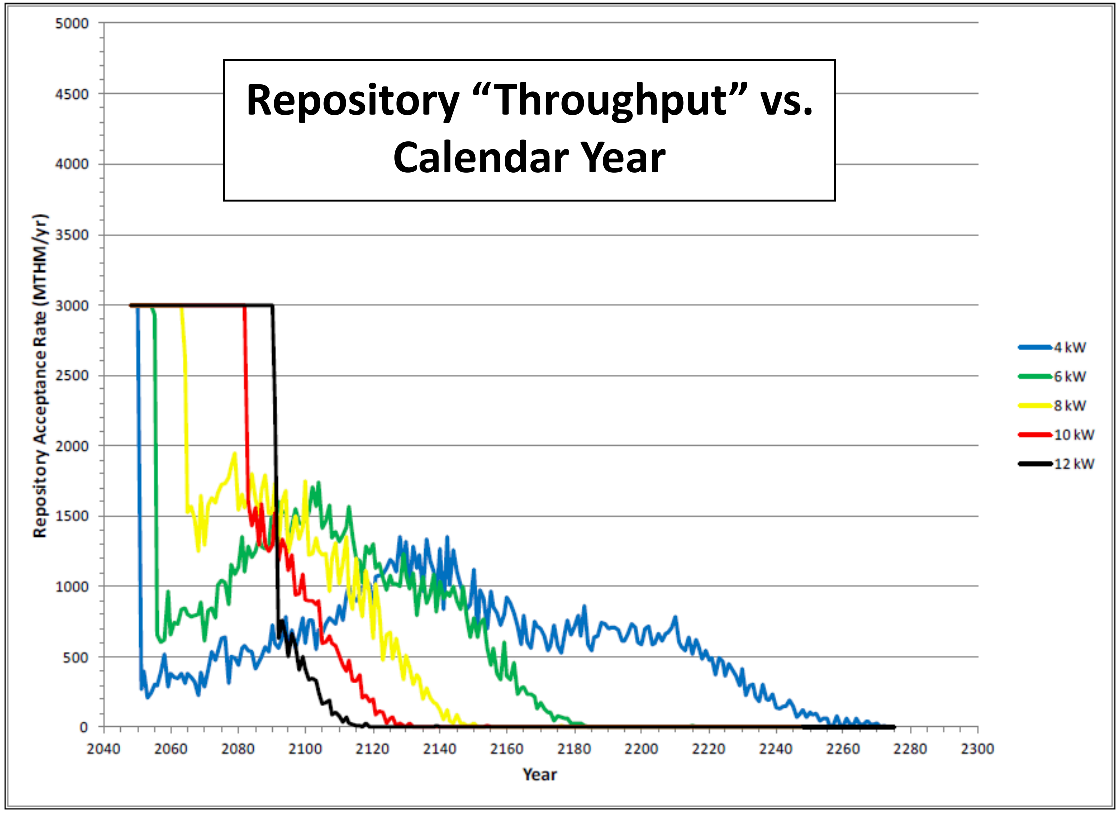


SNF per Year (MTU) Cooling to 10 kW

Source: Nutt, W.M. 2013. FCRD-UFD-2013-000184.

Repository Acceptance Rates for DPC Direct Disposal Scenarios

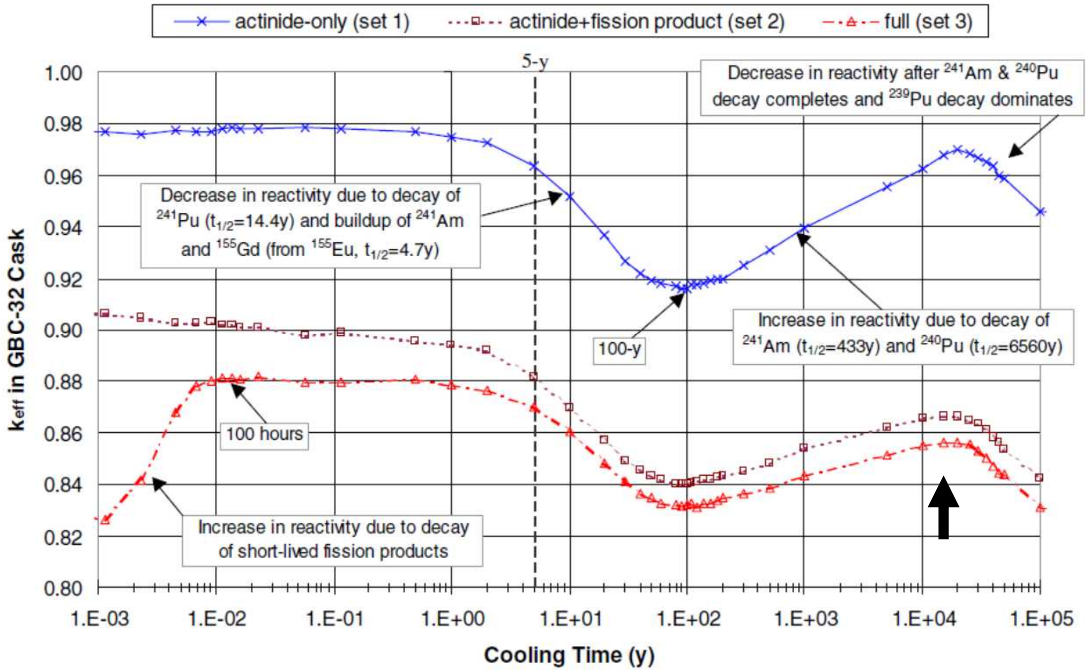
- Simulation imposes 3,000 MTU/yr maximum throughput, further limited by emplacement power
- Emplacement power limits 4, 6, 8, 10 and 12 kW/package
- Optimal throughput is < 3,000 MTU/yr



Source: Nutt, W.M. 2013. FCRD-UFD-2013-000184.

Post-Closure SNF Criticality Control

- Environment
  - Groundwater availability
  - Water composition
  - Presence of chloride brine
- Moderator exclusion
  - Package integrity
- Moderator displacement
  - Fillers (e.g., B_4C loaded grout?)
- As-loaded reactivity
  - 3-D; axial burnup profiles (more difficult to characterize for BWRs)
  - Operation histories (from utilities)
  - Burnup credit
- Degradation of fuel basket and neutron absorbers



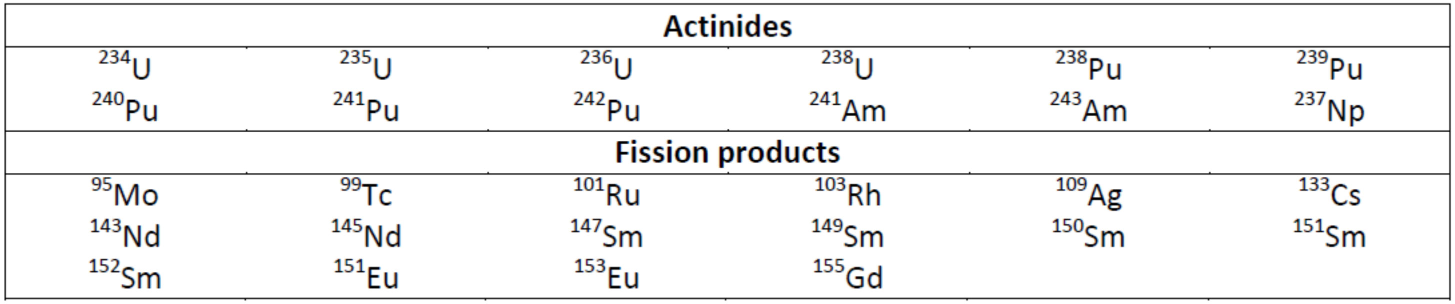
32-PWR Reactivity vs. time

Source:
Wagner, J. and C. Parks 2001. NUREG/CR-6781.(Fig. 3).

Generic burnup-credit 32-PWR cask
PWR fuel (4% enriched, 40 GW-d/MT burnup)

DPC Criticality Analysis (ORNL)

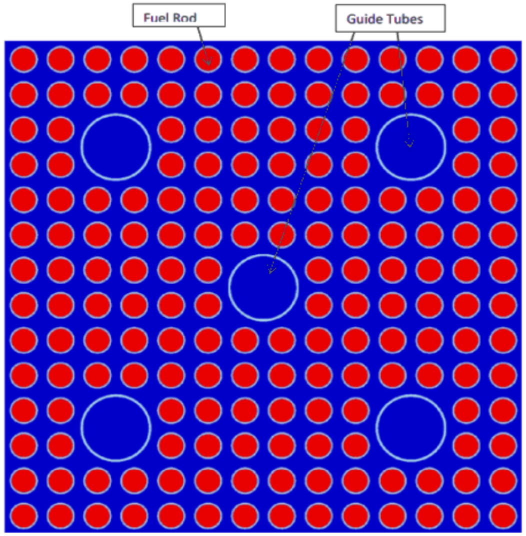
- **Most DPCs use neutron absorbers that readily corrode in groundwater (e.g., Boral, Al-B4C metal matrix composites)**
- **Legacy approach: YM topical report**
  - **Flooded (precedent in 10CFR71.55 analysis)**
  - **Degraded Case 1: Loss of absorber (based on laboratory corrosion data)**
  - **Degraded Case 2: Eventual basket collapse (e.g., general corrosion of stainless steel)**
- **Need reactivity margin to apply against degradation conditions**
  - **Use as-loaded configurations**
  - **Burnup credit (better for early canisters designed for fresh fuel)**
  - **Disposal environment (e.g., brine)**



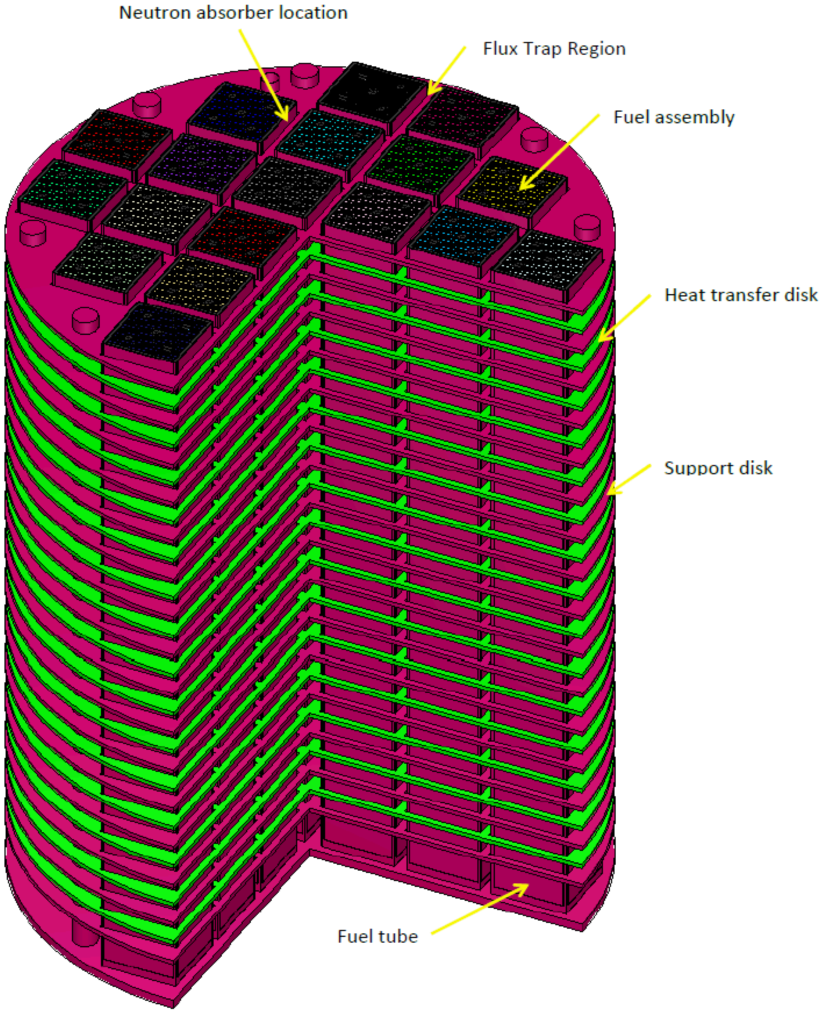
Actinides					
^{234}U	^{235}U	^{236}U	^{238}U	^{238}Pu	^{239}Pu
^{240}Pu	^{241}Pu	^{242}Pu	^{241}Am	^{243}Am	^{237}Np
Fission products					
^{95}Mo	^{99}Tc	^{101}Ru	^{103}Rh	^{109}Ag	^{133}Cs
^{143}Nd	^{145}Nd	^{147}Sm	^{149}Sm	^{150}Sm	^{151}Sm
^{152}Sm	^{151}Eu	^{153}Eu	^{155}Gd		

Clarity, J.B. and J.M Scaglione 2013. *Feasibility of Direct Disposal of Dual-Purpose Canisters-Criticality Evaluations*. ORNL/LTR-2013/213.

Reactivity Scoping Analysis, Example “Site A”



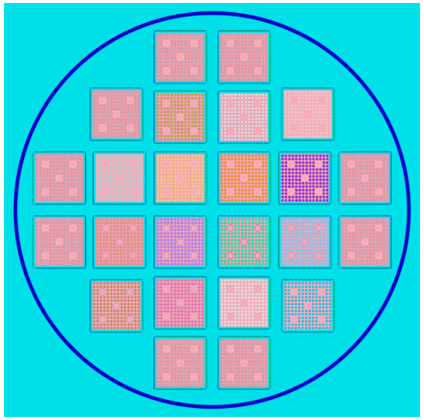
Model array representing Westinghouse 17x17 standard assembly in cross-section.



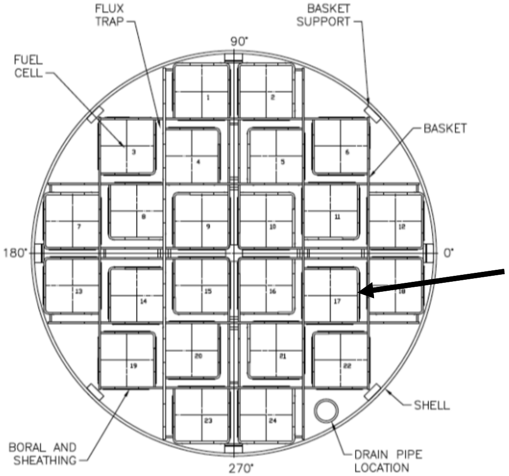
- **3-D numerical model of TSC-24 canisters (NAC Int’l.) from “Site A” (31 analyzed)**
- **ORNL database UNF-ST&DRDS**
- **Software/data**
  - **SCALE code system (ORNL 2011)**
- **Also analyzed: more than 200 other PWR and BWR SNF DPCs**

ORNL (Oak Ridge National Laboratory) 2011. ORNL/TM-2005/39 Version 6.1.
Also: Clarity, J.B. and J.M Scaglione 2013. ORNL/LTR-2013/213.

Basket Configurations for TSC-24 System: "Site A"

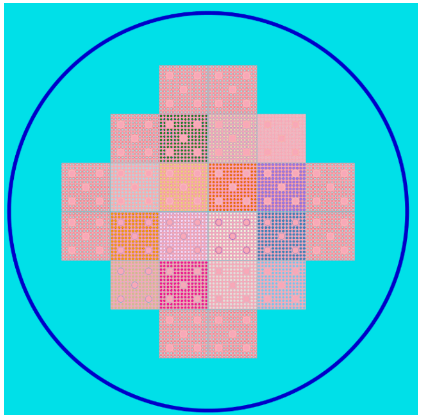


Intact Basket
(as considered for preclosure safety analysis)

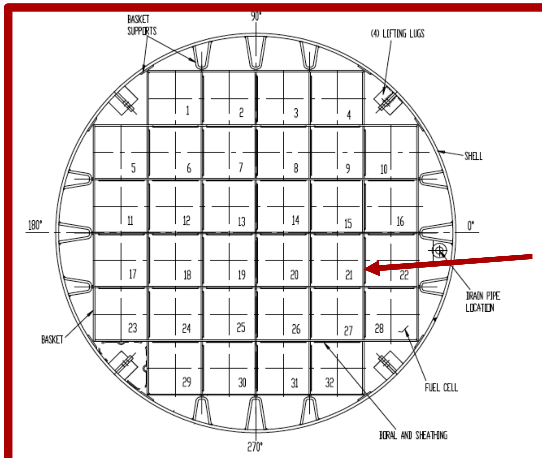


Fuel-tube type basket (e.g., TSC-24)

Boral sheets attached with thin-gauge SS sheathing (welded)



Collapsed Basket, (and loss of neutron absorbers, in disposal environment)



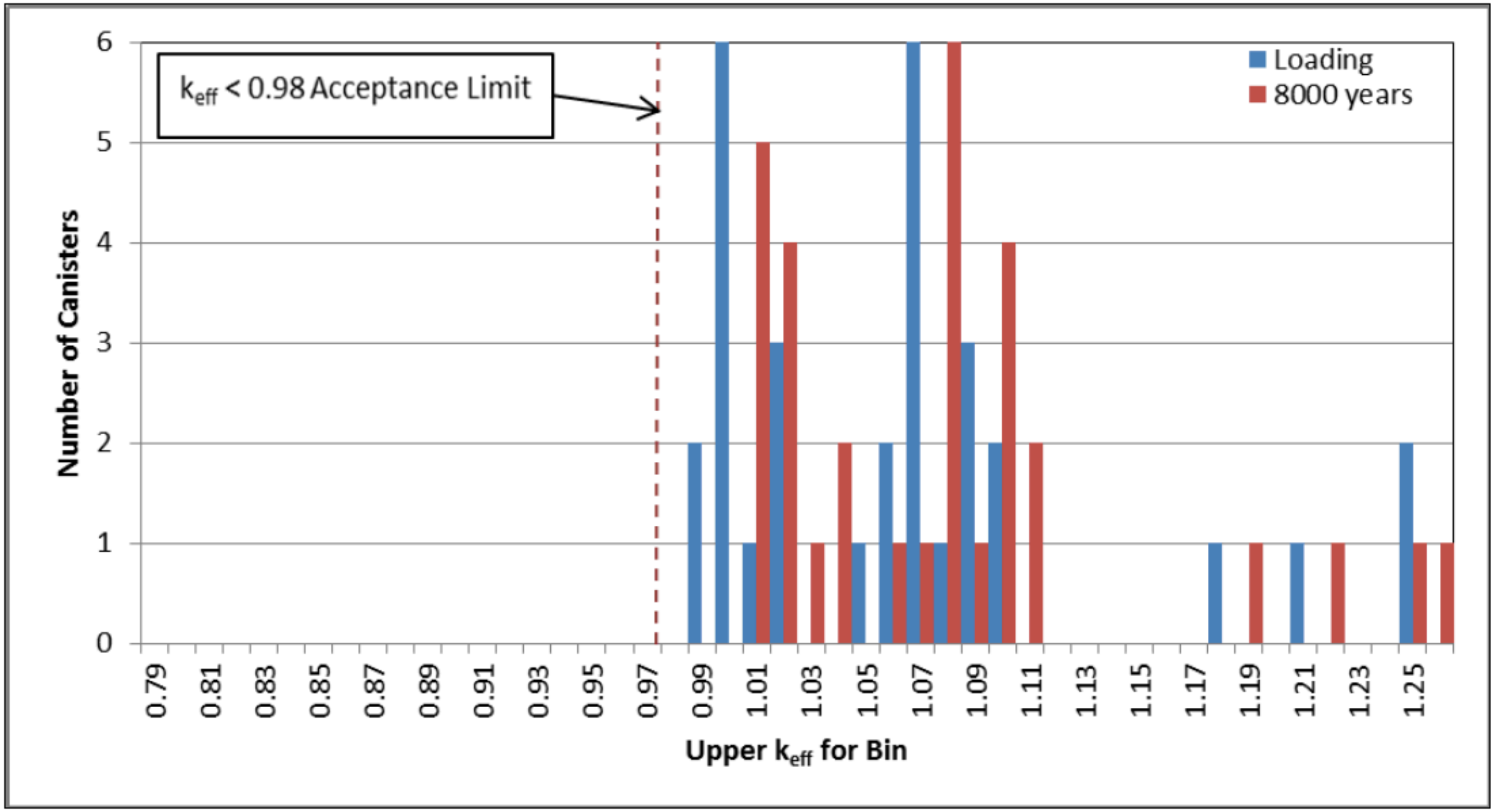
Egg-crate type basket (e.g., Holtec MPC-32)

Boral sheets attached with thin-gauge SS sheathing (welded)

Clarity, J.B. and J.M Scaglione 2013. ORNL/LTR-2013/213. Also: Hardin et al. 2012. FCRD-UFD-2012-000219 Rev. 2.

Reactivity Scoping Results for "Site A"

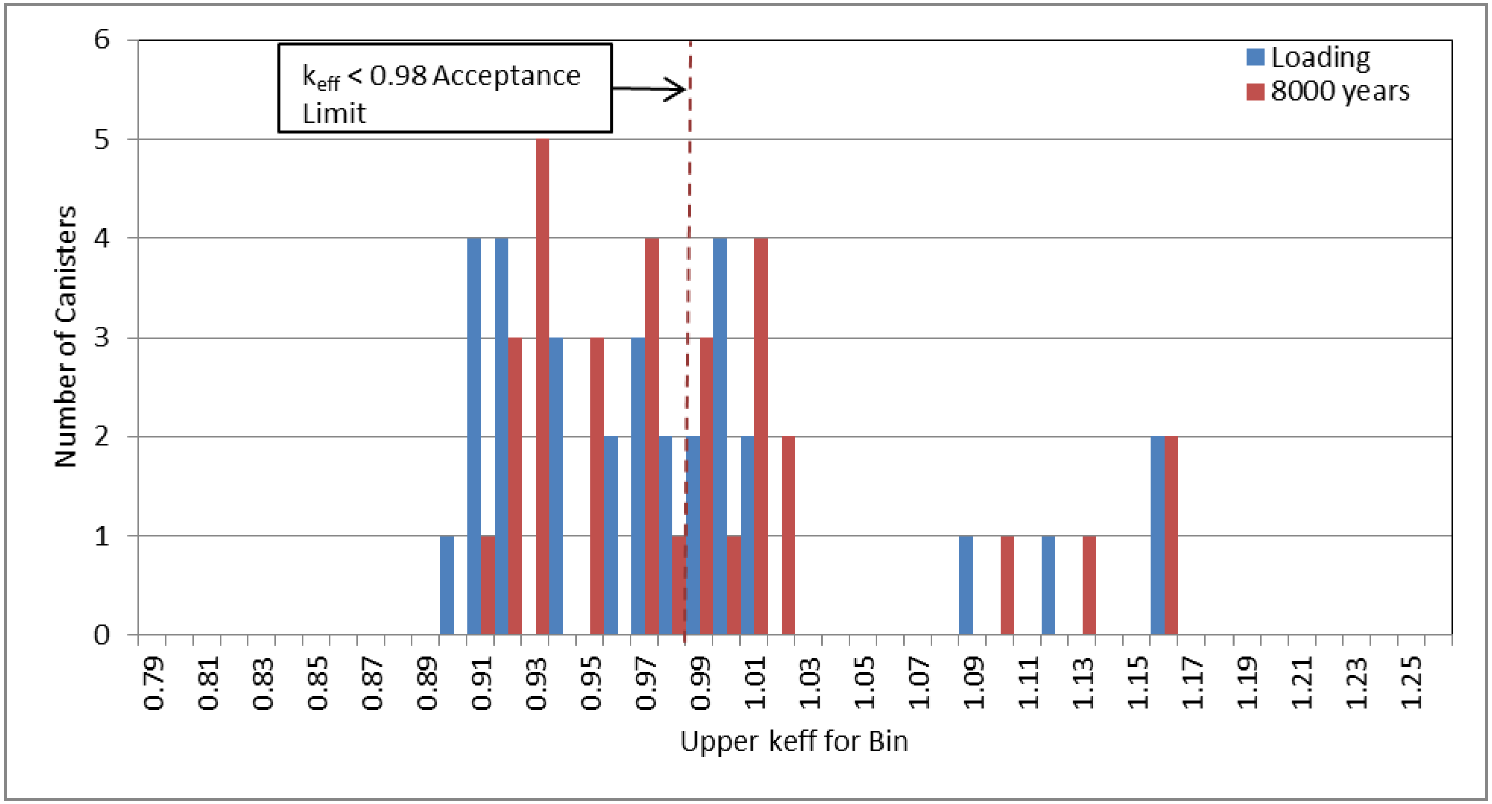
- **Degraded basket (worst) case** (and loss of B_4C absorber), flooded with fresh water
- Analyzed as-loaded with PWR SNF, with burnup credit (no mis-load)



Source:Clarity, J.B. and J.M Scaglione 2013. ORNL/LTR-2013/213.

Reactivity Scoping Results for "Site A"

- **Degraded basket case** (and loss of B_4C absorber), flooded with 1 molal NaCl brine (saturated brine is > 4 molal)
- Analyzed as-loaded with PWR SNF, with burnup credit (no mis-load)



Source:Clarity, J.B. and J.M Scaglione 2013. ORNL/LTR-2013/213.

Source: Clarity, J. and J. Scaglione 2013. ORNL/LTR-2013/213.

ROM Cost Analysis for DPC Direct Disposal vs. Re-Packaging of All Commercial SNF

	Unit Cost $	CSNF Quantity, MTU	Typical DPC Capacity, MTU	# DPCs	Cost $B
Projected sunk costs based on DPC status quo:					
Procure, load and store existing DPCs ($/MTU) [1]	100,000	25,000	14.4	2,100	3.0
Cost to continue status quo through >2055 ($/MTU) [1]	100,000	115,000	16.7	6,592	11.0
Disposal re-packaging costs for all CSNF, current fleet:					
Unload all DPCs ($/MTU)	10,000	140,000		8,692	1.4
Transport and dispose of each DPC hull ($/DPC)	150,000			8,692	1.3
Re-canister for disposal ($/MTU) [2]	100,000	140,000			14.0
Re-packaging facility capital cost [2]					5.0
Re-packaging facility operating cost for 30 years ($/yr) [3]	200,000,000				6.0
Total cost to re-package commercial SNF for disposal					**35.7**
Potential cost savings from direct disposal of DPCs					**21.7**

Notes:

1. Estimates do not include on-site storage, new facility construction, or maintenance, which could add $20B or more.
2. Assume repository is available for re-packaged SNF, so no dedicated interim storage facility is needed.
3. Re-packaging facility operating cost could might also need to include transportation to/from storage.

Alternative: Switch to Disposable MPCs for Half of Commercial SNF

	Unit Cost $	CSNF Quantity, MTU	Typical DPC Capacity, MTU	# DPCs	Cost $B
Alternative: Implement disposable MPCs for half of all commercial SNF (starting ~2030)					
Sunk cost on DPCs for first half of CSNF	100,000	70,000	14.4	4,861	7.0
Unload DPCs ($/MTU)	10,000	70,000		4,861	0.7
Transport and dispose of each DPC hull ($/DPC)	150,000			4,861	0.7
Re-canister for disposal ($/MTU)	100,000	70,000			7.0
Re-packaging facility capital cost					3.0
Re-packaging facility operating cost for 30 years ($/yr)	100,000,000				3.0
MPC canisterization for second half ($/MTU)	100,000	70,000	16.7	6,592	7.0
Total cost to re-package commercial SNF for disposal					**28.4**
Potential savings compared to status quo					**7.3**

DPC Direct Disposal Technical Feasibility Summary

- **Technical feasibility evaluation results for:**
  - **Safety of workers and the public**
  - **Engineering feasibility**
  - **Thermal management**
  - **Postclosure criticality control**

Feasible based on generic (non-site specific) evaluation

- **Most favorable disposal concepts: salt and hard rock unsaturated/unbackfilled**
- **Transition to MPCs could facilitate earlier repository loading/closure**
  - Begin disposal with MPCs; DPCs cool 20 to 50 years later
- **Other considerations could be important for DPC disposability:**
  - Basket structural longevity
  - Disposal overpack reliability (better than 4.5×10^{-5} /each for Yucca Mtn LA)
  - UNF-ST&DRDS unified database (ORNL) capabilities (model post-closure criticality when DPCs *are loaded*)

Cost Estimates for Disposal of U.S. Commercial SNF

Estimated Life-Cycle Repository Cost (2016 $B)		**4-PWR/9- or 12-BWR**	**12-PWR/ 21-BWR**	**21-PWR/ 44-BWR**	**DPC Direct**
“Enclosed”					
Crystalline	Based on KBS-3V (SKB 2011)	**$63 – 85B**			
Argillaceous	Based on ANDRA (2005) (for SNF in horiz. boreholes)	**$83 – 116B**			
	Based on NAGRA (2002, 2003) (for in-drift, self-shielded pkgs, with immediate backfilling)		**$51 – 69B**		
Salt	U.S. reference (in-drift)	**$44 – 60B**	**$30 – 42B**	**$25 – 34B**	**$32 – 44B**
“Open”					
Hard Rock (e.g., Crystalline)	Unsaturated, unbackfilled, open (YM concept, DOE 2008)		**$60 – 80B**	**$44 – 59B**	**$44 – 59B**
	Saturated, backfilled, open		**$57 – 76B**	**$42 – 57B**	**$40 – 54B**
Argillaceous	Backfilled, open		**$60 – 81B**	**$46 – 62B**	**$44 – 60B**

Sources:

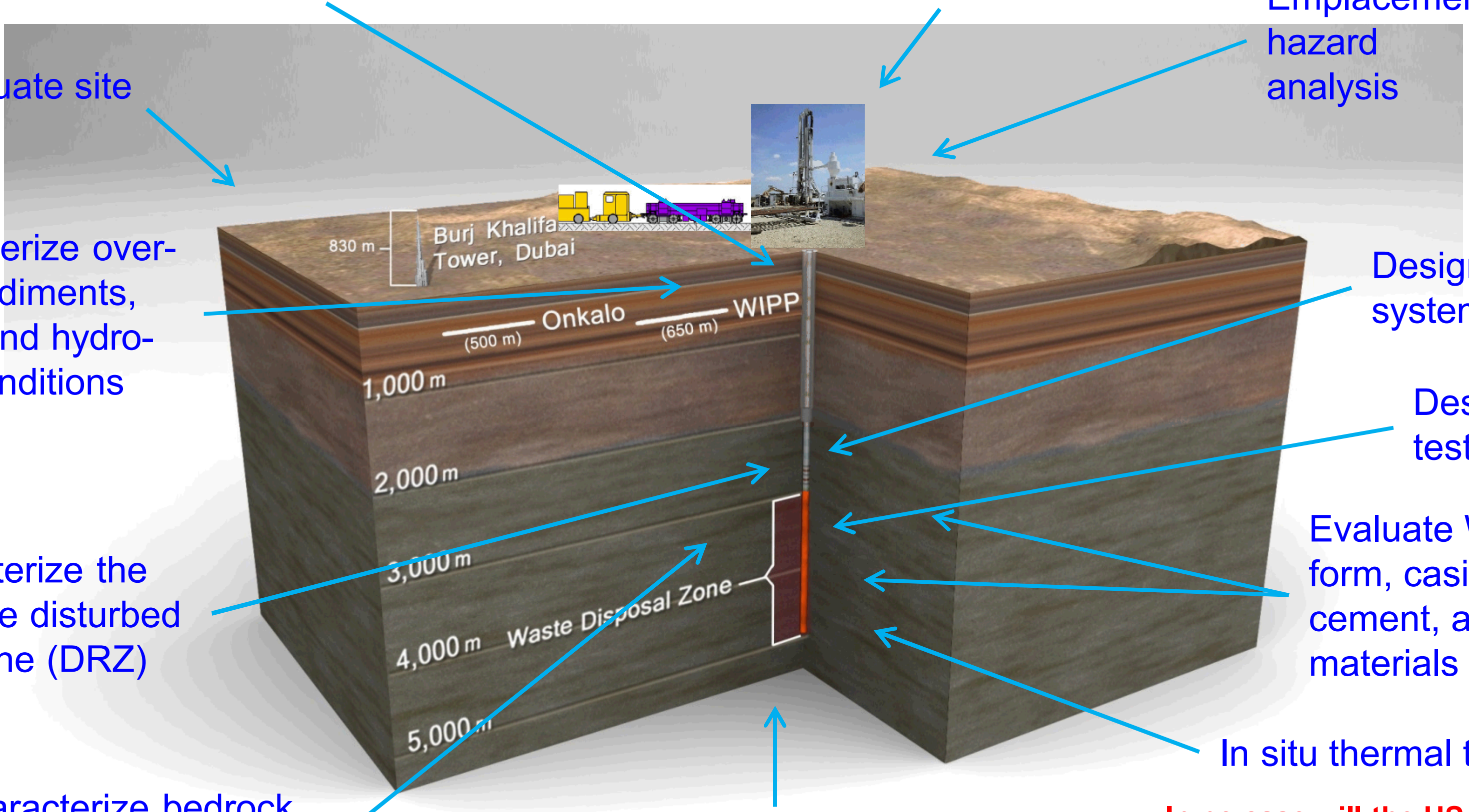
Hardin, E. & E. Kalinina 2016. *Cost Estimation Inputs for Spent Nuclear Fuel Geologic Disposal Concepts (Rev. 1)*. SAND2016-0235.

SRNL (Savannah River National Lab) 2015. *Generic Repository Cost Estimates.* FCRD-UFD-2015-000740 Rev. 0.

Deep Borehole Field Test

Objectives of the Deep Borehole Field Test

Synthesize field test activities, test results, and analyses into a comprehensive evaluation of concept feasibility



Design and construct characterization borehole then field test borehole

Develop and test systems for handling, emplacing, and retrieving waste packages (WPs)

Emplacement hazard analysis

Evaluate site

Characterize over-lying sediments, fluids, and hydro-logic conditions

Design seal system

Design and test WPs

Characterize the borehole disturbed rock zone (DRZ)

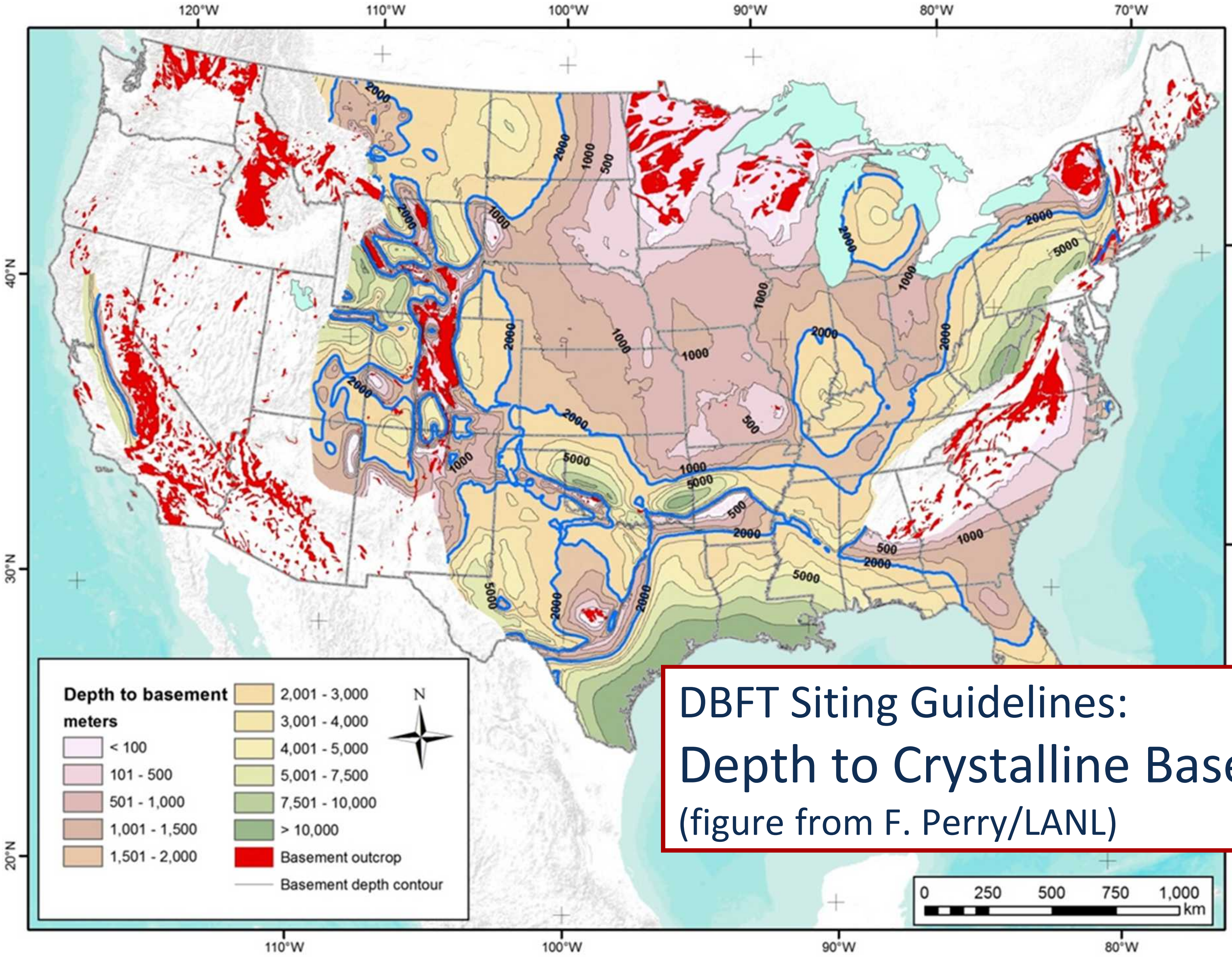
Evaluate WP, waste form, casing, cement, and seal materials

In situ thermal test

Characterize bedrock, fluids, and hydrologic conditions

Assess post-closure safety

In no case will the US Government place or otherwise have nuclear material, nuclear waste, or other waste material on the property.



DBFT Siting Guidelines:

Depth to Crystalline Basement

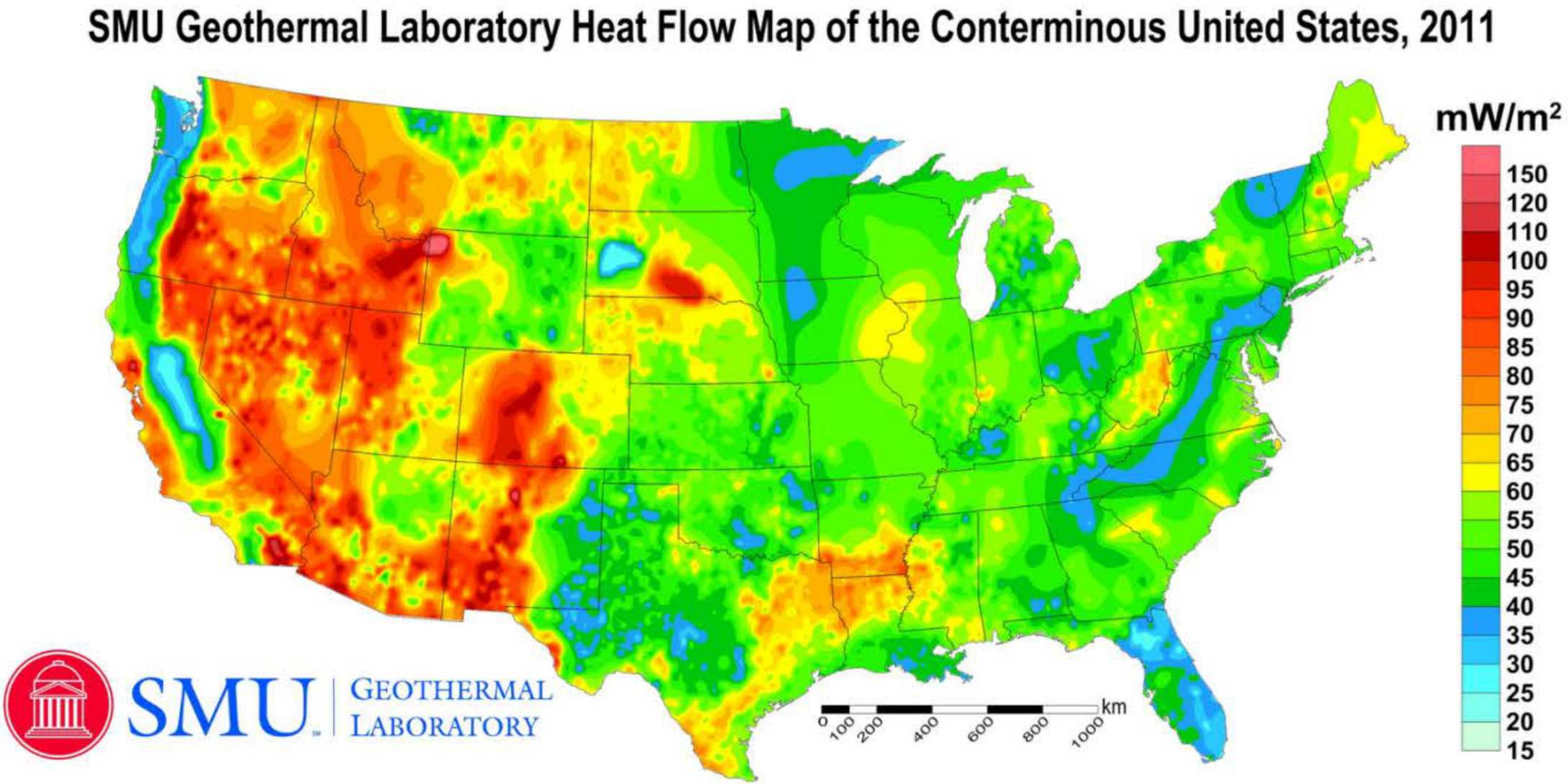
(figure from F. Perry/LANL)

DBFT Siting Guidelines:
Brine Origin and Apparent Age

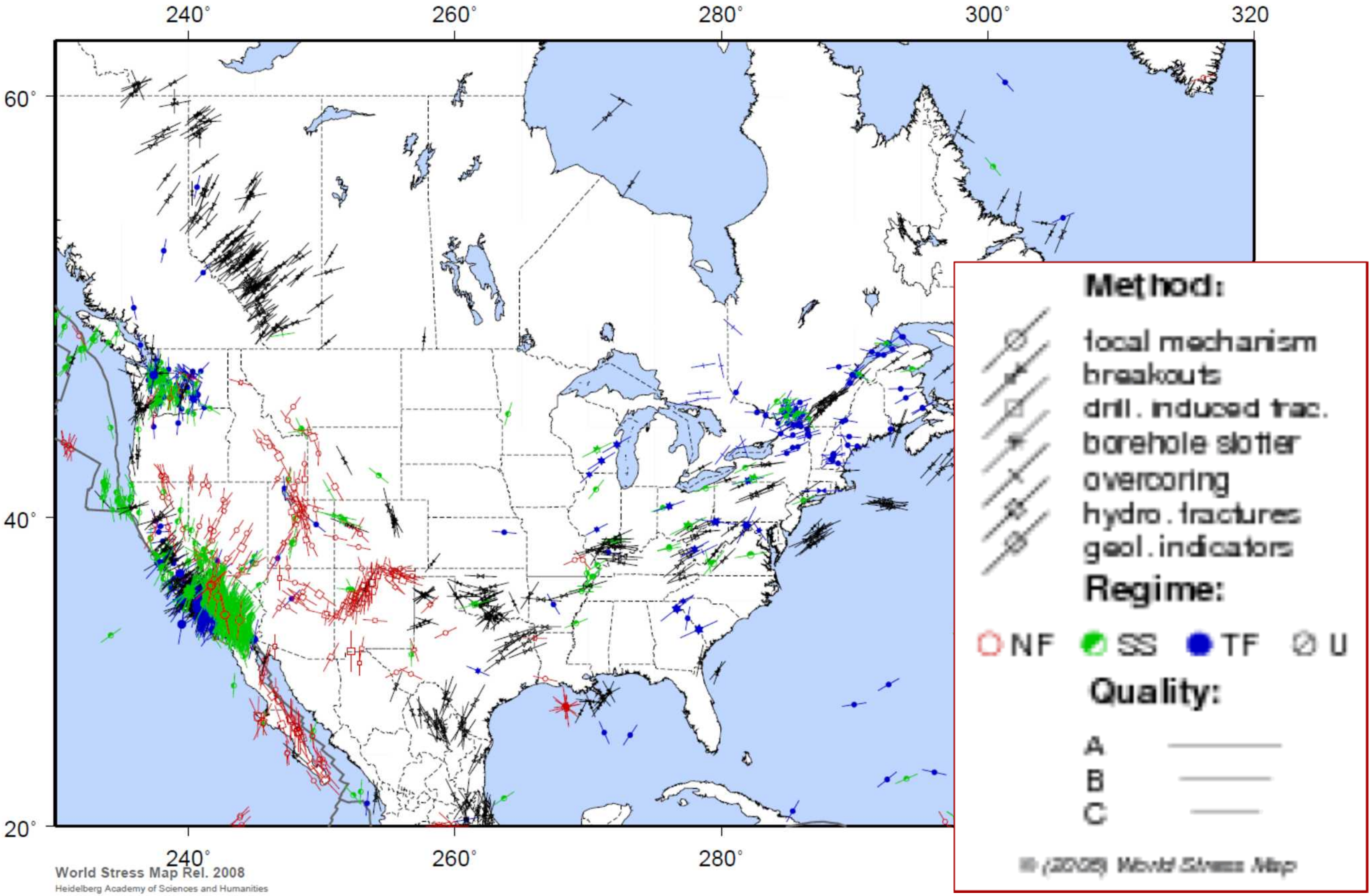
> *"…evidence for the absence* of recharge at depth…"

- **Brine Origin Hypotheses**
  - Cryogenic
  - Dissolution of evaporites
  - Rock-water interaction
  - Evaporative concentration of modern or ancient seawater
- **Chloride/Bromide Mass Ratio:**
  - Atmospheric precipitation: 50 to 100
  - Seawater: 290
  - Groundwater: 100 to 200 (water-rock interaction)
  - Evaporite minerals: 1000 to 10,000
- **Chemical & Isotopic Signatures**
  - Ca/Na, Sr/Ca, Li/Br (seawater and rock-derived)
  - δ^{6}Li, δ^{18}O, δ^{10}B, ^{86}Sr/^{87}Sr (seawater and rock-derived)
  - Noble gas abundance (radiogenic $\alpha \rightarrow {}^{4}$He, ^{40}K$\rightarrow{}^{40}$Ar)
  - Nucleogenic tracers (from spontaneous fission, mainly natural U)
  - Cosmogenic tracers (^{14}C, ^{81}Kr, etc.)

DBFT Siting Guidelines: Heat Flux



DBFT Siting Guidelines: World Stress Map (2008)



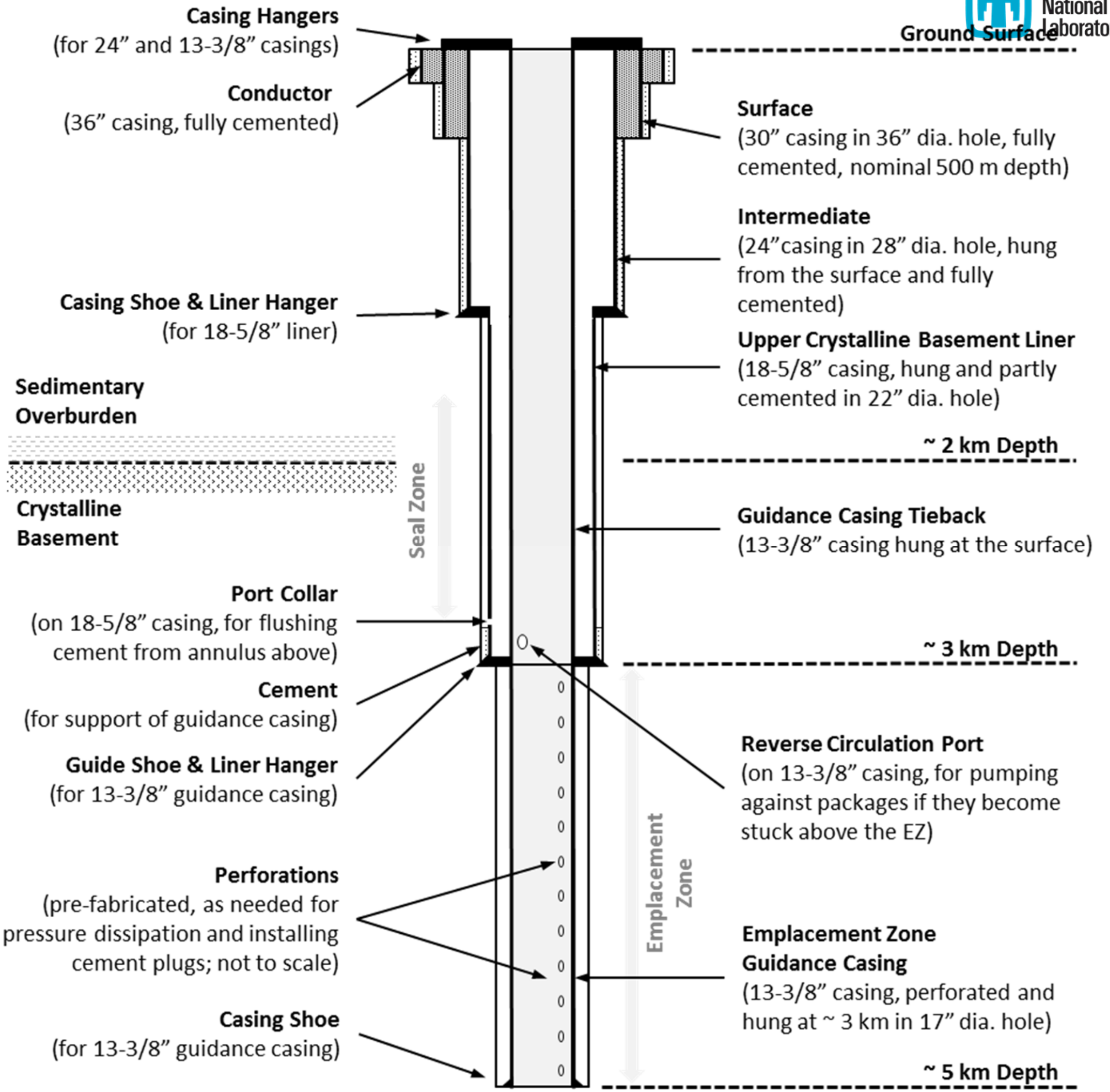
World Stress Map Rel. 2008
Heidelberg Academy of Sciences and Humanities
Geophysical Institute, University of Karlsruhe

http://dc-app3-14.gfz-potsdam.de/pub/casmo/casmo_frame.html

Prior Work: Spent Fuel Test–Climax, Nevada Test Site 1978-83
Eleven irradiated PWR assemblies stored 3 years

Large Diameter Test Borehole

- 17” Dia. @ 16,400 ft.
- 13-3/8” Guidance Casing
- 22” Dia. Seal Zone
- Modeled After Reference Disposal Concept (Arnold et al. 2011)



Casing Hangers
(for 24” and 13-3/8” casings)

Conductor
(36” casing, fully cemented)

Casing Shoe & Liner Hanger
(for 18-5/8” liner)

Sedimentary Overburden

Crystalline Basement

Port Collar
(on 18-5/8” casing, for flushing cement from annulus above)

Cement
(for support of guidance casing)

Guide Shoe & Liner Hanger
(for 13-3/8” guidance casing)

Perforations
(pre-fabricated, as needed for pressure dissipation and installing cement plugs; not to scale)

Casing Shoe
(for 13-3/8” guidance casing)

Seal Zone

Emplacement Zone

Ground Surface

Surface
(30” casing in 36” dia. hole, fully cemented, nominal 500 m depth)

Intermediate
(24”casing in 28” dia. hole, hung from the surface and fully cemented)

Upper Crystalline Basement Liner
(18-5/8” casing, hung and partly cemented in 22” dia. hole)

~ 2 km Depth

Guidance Casing Tieback
(13-3/8” casing hung at the surface)

~ 3 km Depth

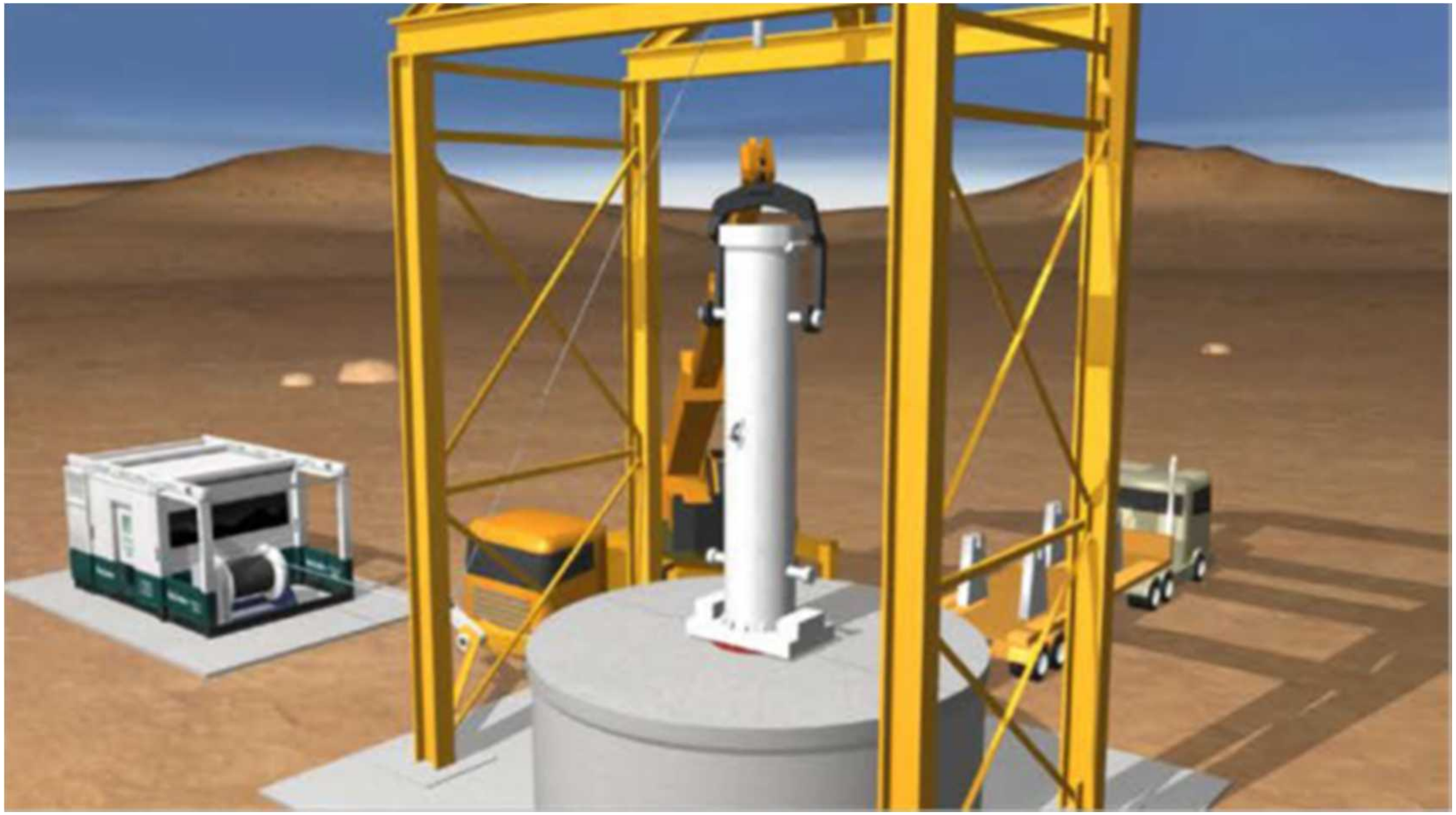
Reverse Circulation Port
(on 13-3/8” casing, for pumping against packages if they become stuck above the EZ)

Emplacement Zone Guidance Casing
(13-3/8” casing, perforated and hung at ~ 3 km in 17” dia. hole)

~ 5 km Depth

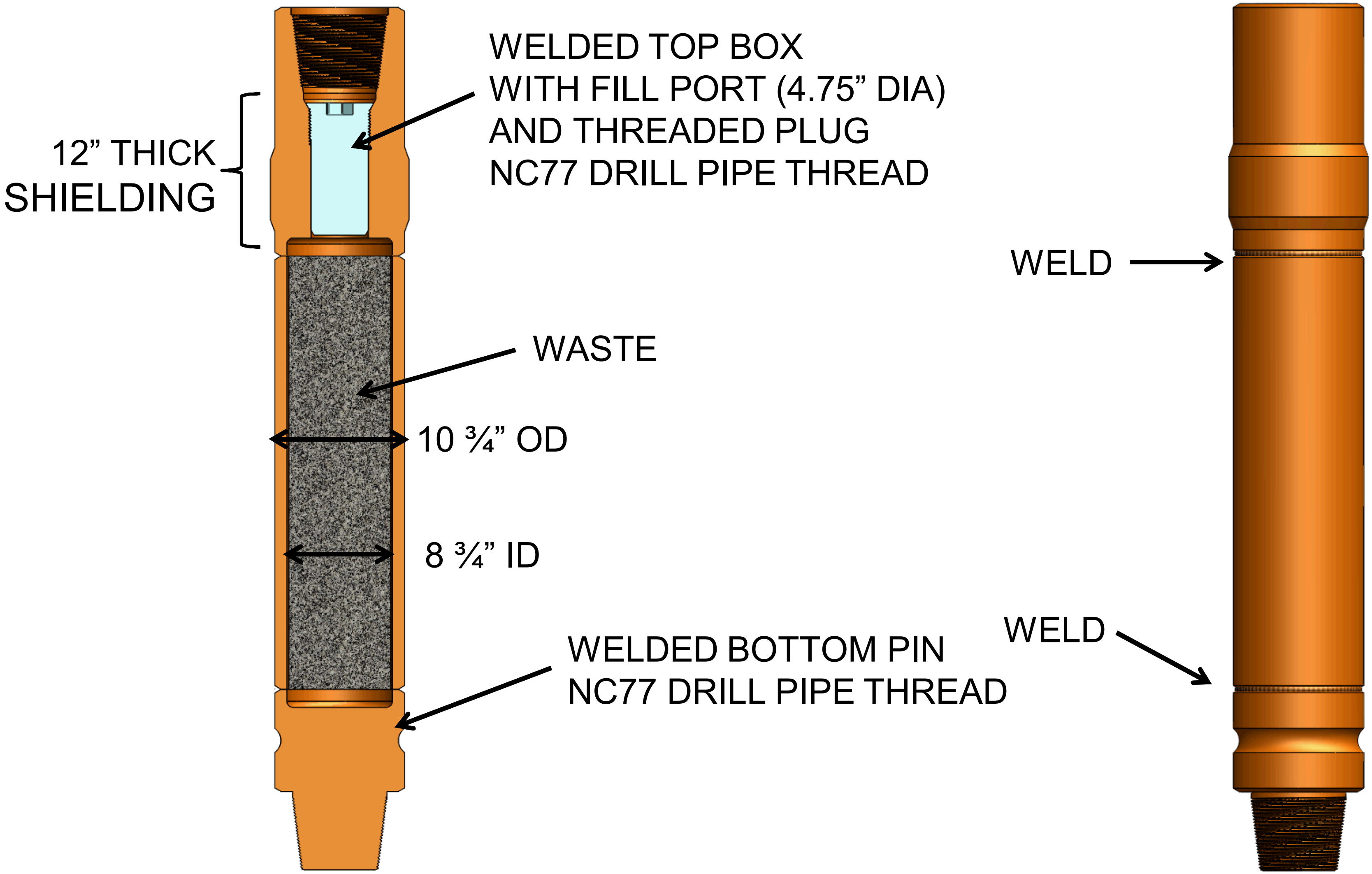
Wireline Emplacement Concept

- Transfer Cask Installed on Wellhead, Over a Shielded "Pit"
- Modern Wireline Cable and Tools (e.g., SLB Tuffline®)
- Fixed Headframe (avoids crane reliability issues)



Crane placing loaded transfer cask on wellhead (SNL 2016).

Deep Borehole Disposal Engineering: Packaging Concept for Bulk Waste



12” THICK SHIELDING

WELDED TOP BOX
WITH FILL PORT (4.75” DIA)
AND THREADED PLUG
NC77 DRILL PIPE THREAD

WELD

WASTE

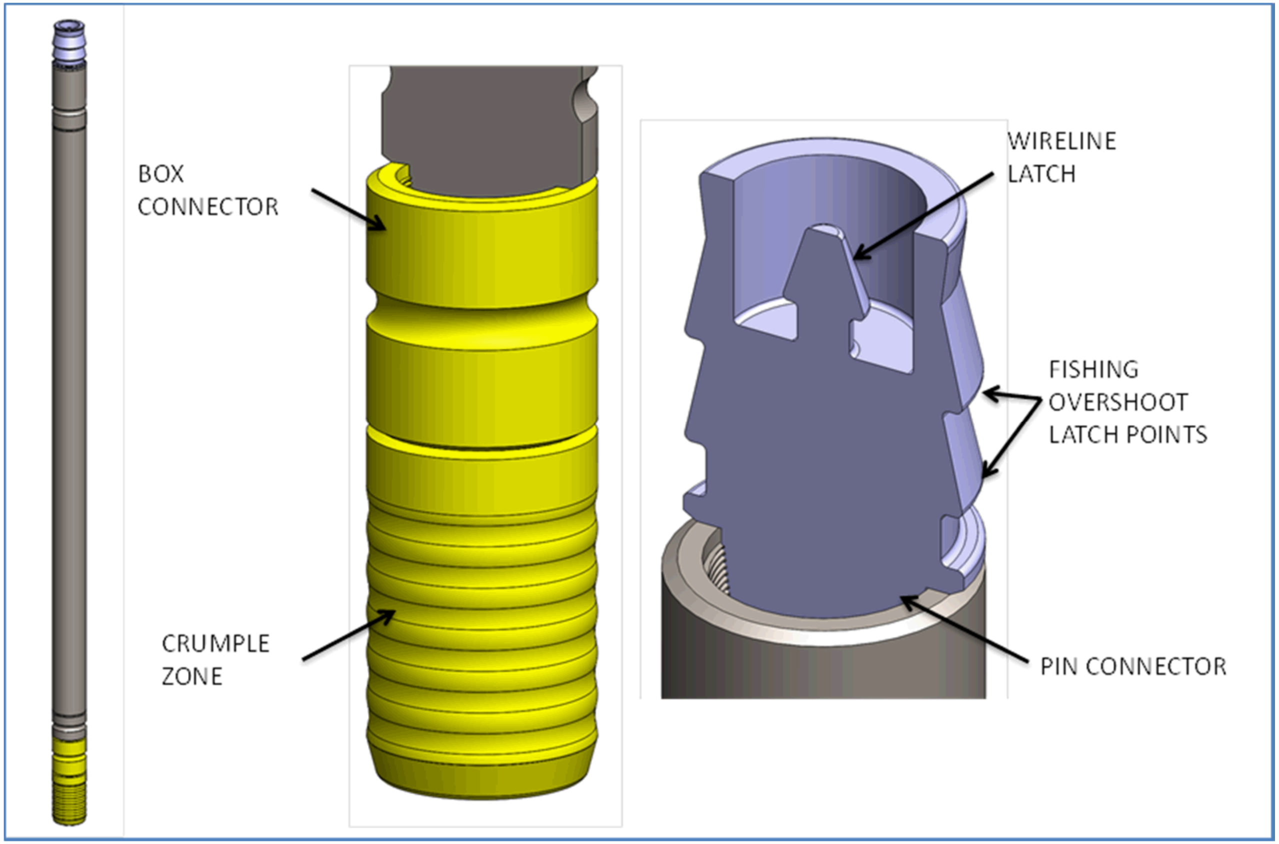
10 ¾” OD

8 ¾” ID

WELDED BOTTOM PIN
NC77 DRILL PIPE THREAD

WELD

Deep Borehole Disposal Engineering: Top and Bottom Attachments on Waste Packages

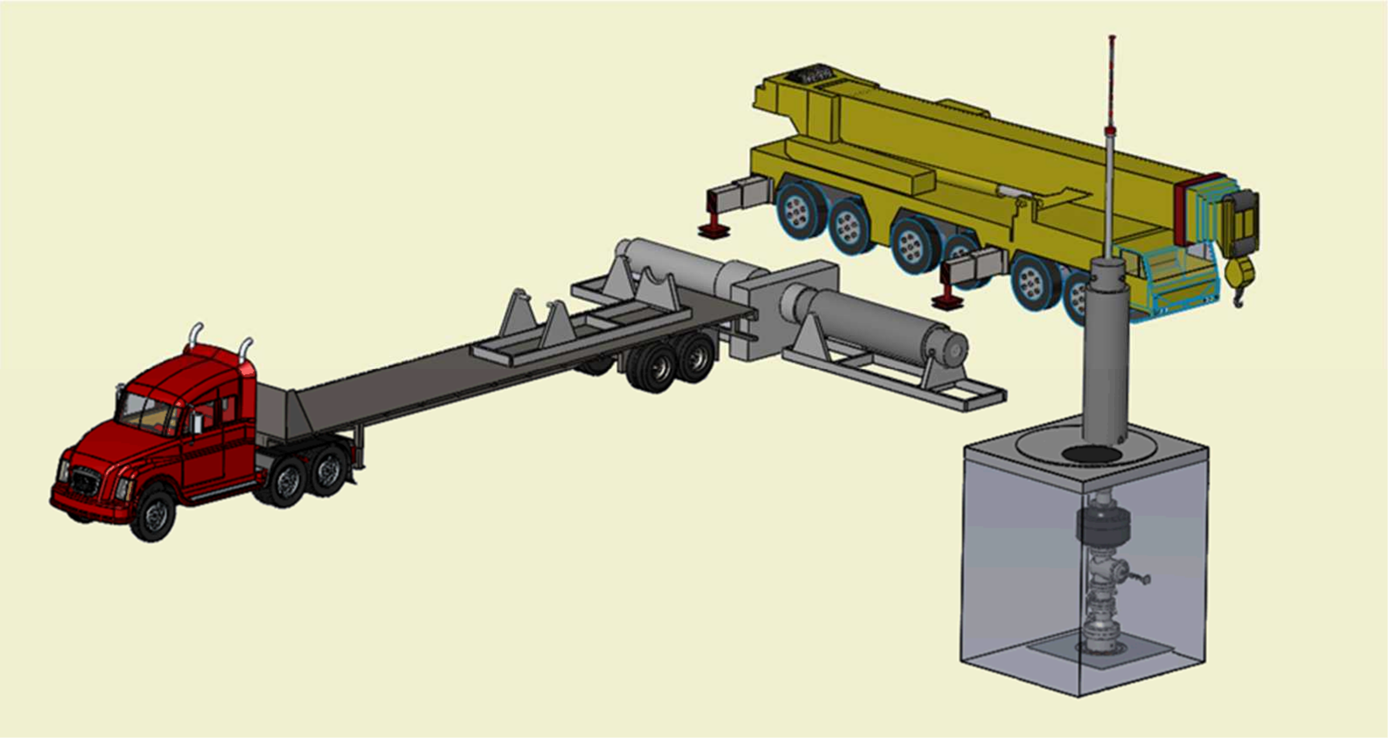


SNL 2016. *Deep Borehole Field Test Conceptual Design Report.* FCRD-UFD-2016-000070 Rev. 1.

Source: photos from Brad Day/SNL, based on work of Noss, et al. (2000).

Surface Handling/Emplacement Concept

- Transportation cask
- Transfer cask (double ended)
- Shielded "pit" with rotating shield plate
- Wellhead (oilfield-type equipment and interface to transfer cask)



55 Hardin, E.L., Geologic Disposal Concepts for HLW and Spent Nuclear Fuel

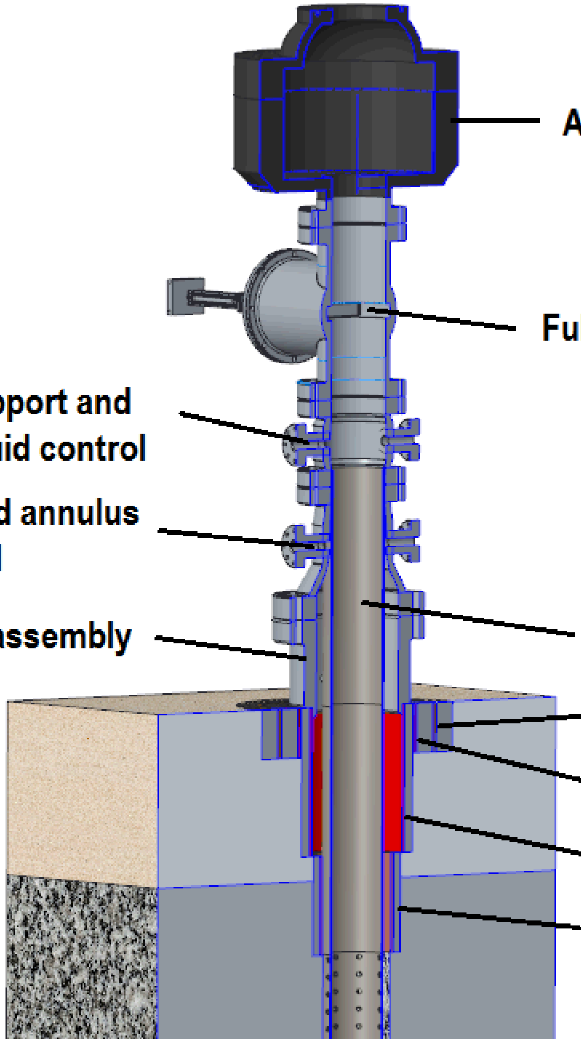
Transportation Cask Availability

- **Existing Type B cask**
- **Legal-weight truck**
- **NAC-LWT as example**
  - 178 inch cavity length
  - 13.4 inch cavity ID
- **(used for transporting single fuel assemblies)**

Wellhead Configuration

Oilfield Equipment in a Shielded "Pit"

Transfer Cask Will Be Part of Wellbore Pressure Control Envelope



Annular BOP

Full-bore gate valve

Tieback support and borehole fluid control

Reducer and annulus fluid control

Baseplate assembly

Guidance tieback casing

Conductor

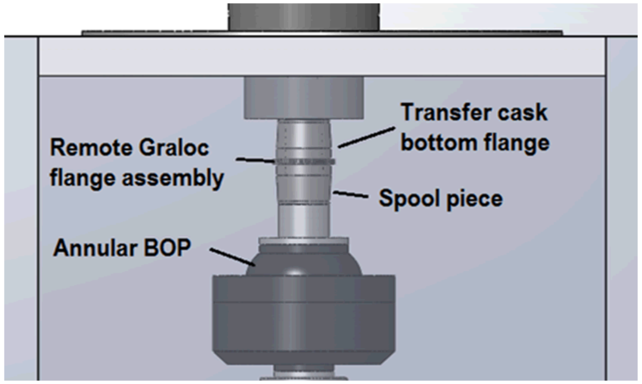
Surface casing

Upper intermediate casing

Lower intermediate casing

(casing vertical scale highly exaggerated)

Shield plate, transfer cask lower plug, and mating flange detail



Deep Borehole Field Test Schedule (Notional)

	FY#1	FY#2	FY#3	FY#4	FY#5
Site & Characterization Borehole – Issue Final RFP	◆	08/05/16 (superseded previous)			
Site & Characterization Borehole – Proposals Due		◆			
Site & Characterization Borehole – Award Contract in Phases		◆→◆			
Characterization Borehole – Start Drilling			◆		
Field Test Engineering – Award Task Order			◆		
Field Test Borehole – Award Drilling Contract			◆		
Characterization Borehole – Complete			◆		
Field Test Borehole – Start Drilling				◆	
Field Test Borehole – Complete				◆	
Field Test – Start Emplacement Demonstration				◆	
Field Test – Complete Emplacement Demonstration					◆
Documentation – Field Test Analyses and Evaluation					◆

Topics Reviewed:

- U.S. defense waste inventory and commercial SNF projection (waste is accumulating in storage)
- Reference concepts for HLW/SNF disposal (international, multiple disposal media)
- Temperature limits and thermal analysis (clay, granite, salt)
- "Open-mode" disposal concepts (using ventilation in situ, particular to U.S. program)
- Direct disposal of SNF in existing dual-purpose canisters (could be safe and cost effective, but media-specific)
- Postclosure criticality control (significant challenge for disposal of existing DPCs)
- Deep borehole disposal R&D (focus on engineering)

Questions?

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* Documents referenced to a document number (e.g., FCRD-UFD-2013-000170) were developed by the U.S. Department of Energy, Office of Spent Fuel Waste, Science and Technology, and are available at www.osti.gov.