SAND2017-12507PE

Disposal Engineering for HLW and Spent Nuclear Fuel

Ernest L. Hardin, Ph.D. (*ehardin@sandia.gov)*
Applied Systems Analysis & Research/8844
Sandia National Laboratories

Guest Lecture UNM ChNE 439/539
November, 2017

Sandia National Laboratories

Outline

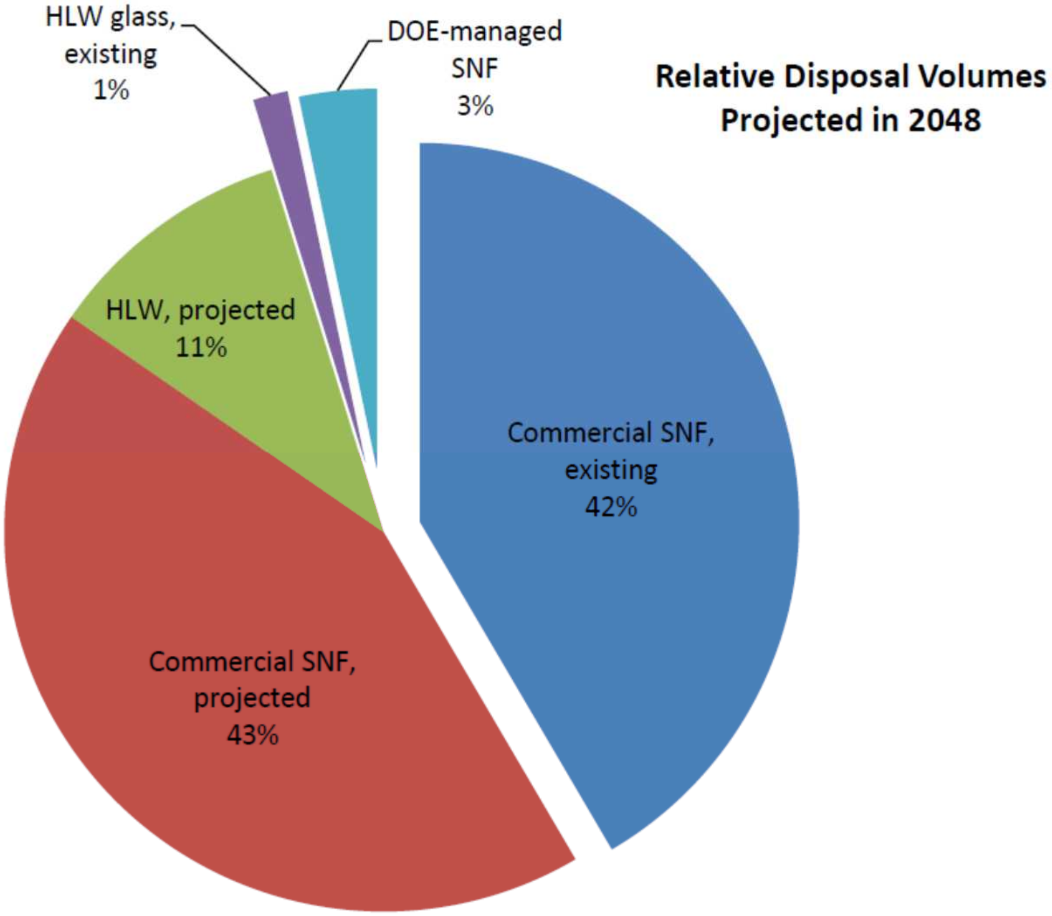
- U.S. defense waste inventory and commercial SNF projection
- Reference concepts for HLW/SNF disposal
- Temperature limits and thermal analysis
- Direct disposal of SNF in existing dual-purpose canisters
- Postclosure criticality control
- Summary

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)

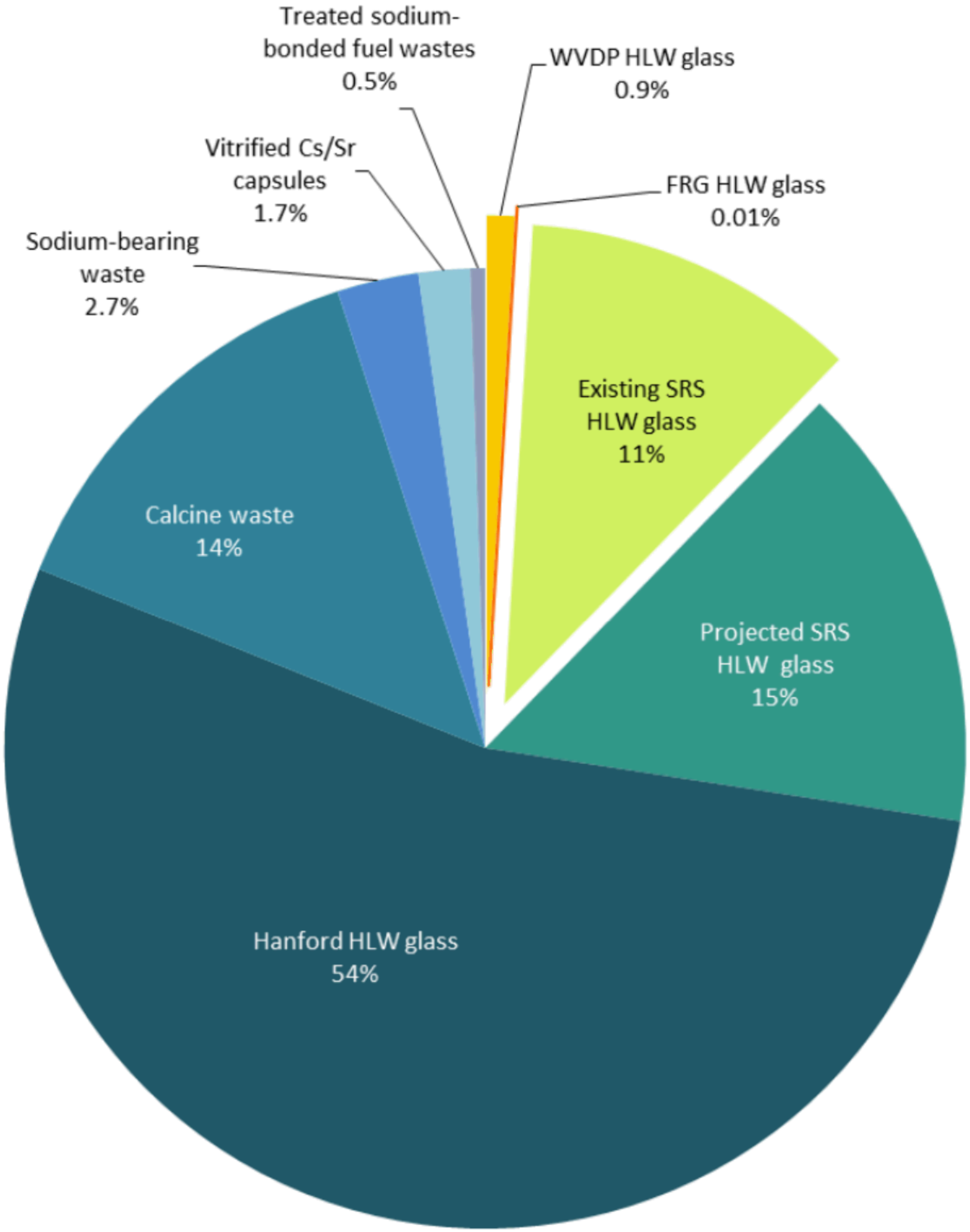
- Normalized based on estimated volume
- Assumptions
  - All commercial SNF disposed in DPC-based packages
  - Based on existing NPPs with 60-yr life extensions (140,000 MTU total)
  - Calcine waste is hot-isostatic pressed with RCRA additives
  - ~3,500 m^3 of naval SNF remains to be generated



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)

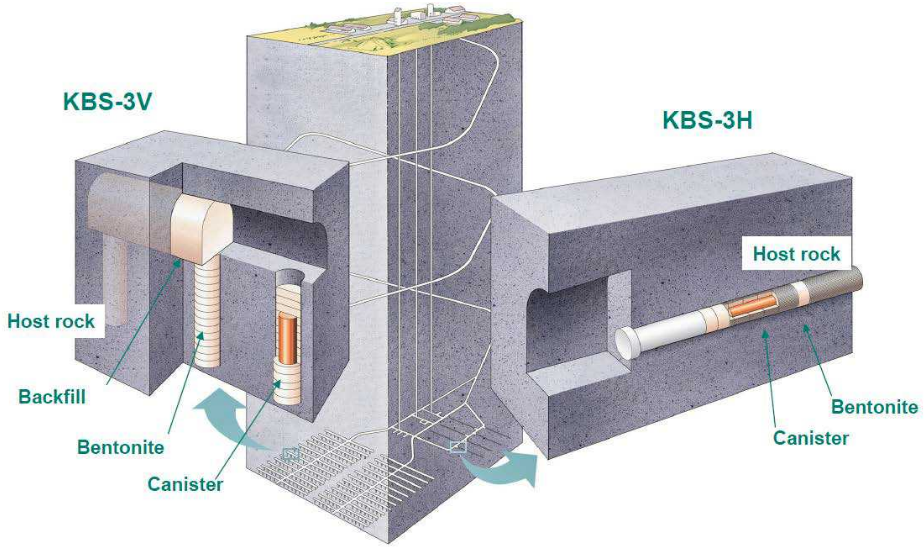


* Includes vitrified HLW of commercial origin, stored at the site of the West Valley Demonstration Project (WVDP) and managed by the U.S. government.

Reference Disposal Concepts Developed in the U.S. and Internationally, and Thermal Management Considerations

Mined Crystalline Rock with Vertical Borehole Emplacement (Sweden, Finland)

- 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



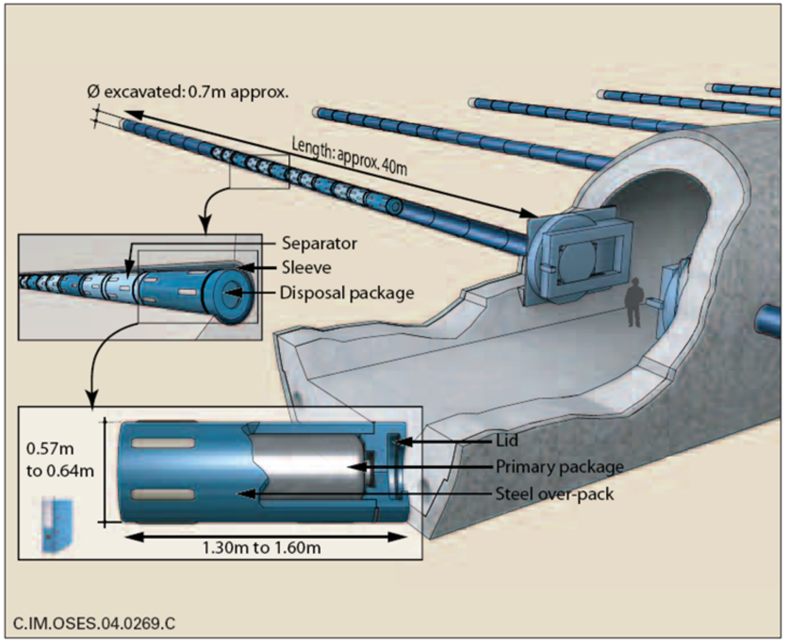
Disposal Characteristic	SNF	HLW
Emplacement mode	Vertical boreholes	Vertical boreholes
Overpack material	Copper or steel	Steel
Borehole spacing, m	10	10
Drift spacing, m	20	20
Borehole liner material	-	-
Buffer material	Bentonite clay	Bentonite clay
Backfill material	Clay/sand mixture	Clay/sand mixture

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.

Mined Clay/Shale with Horizontal Emplacement (France)

- 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.

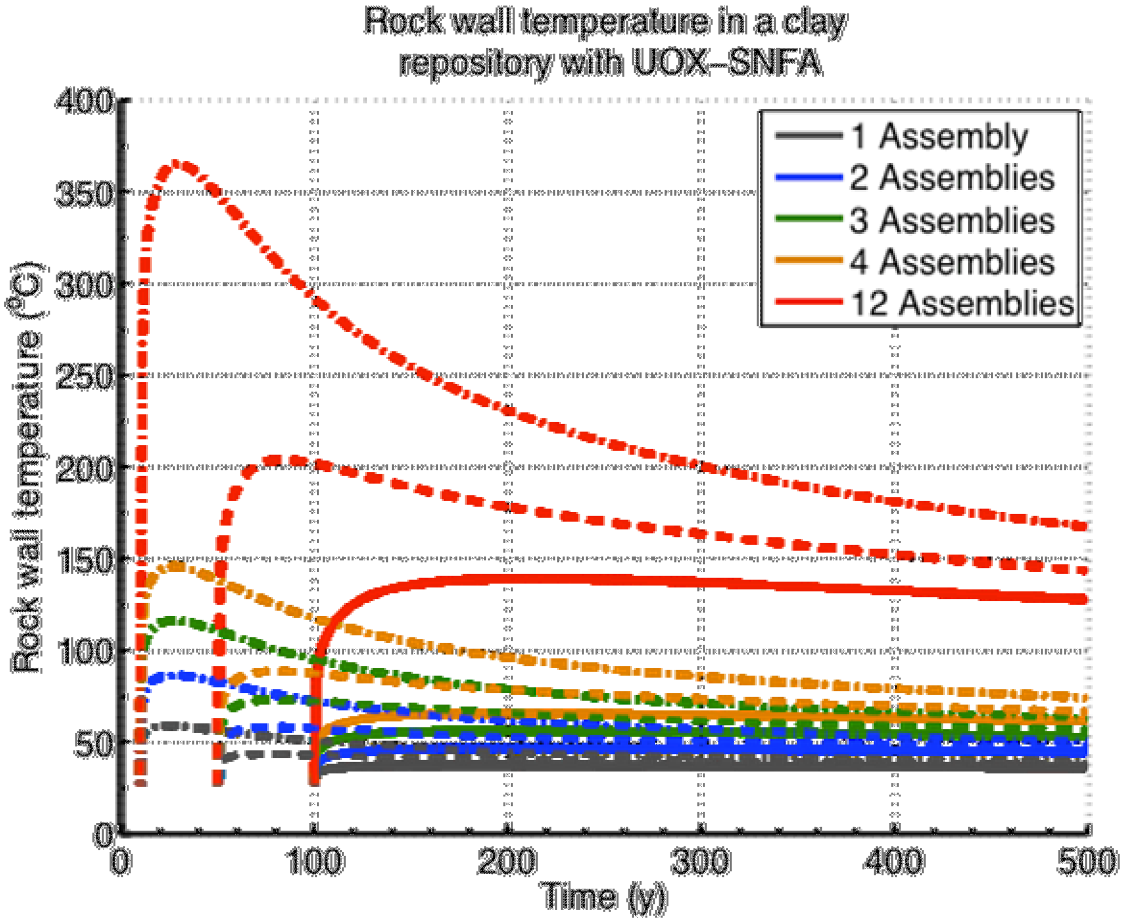
Hardin, E. & E. Kalinina 2016. *Cost Estimation Inputs for Spent Nuclear Fuel Geologic Disposal Concepts (Rev. 1).* SAND2016-0235. Sandia National Laboratories.

Reference (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

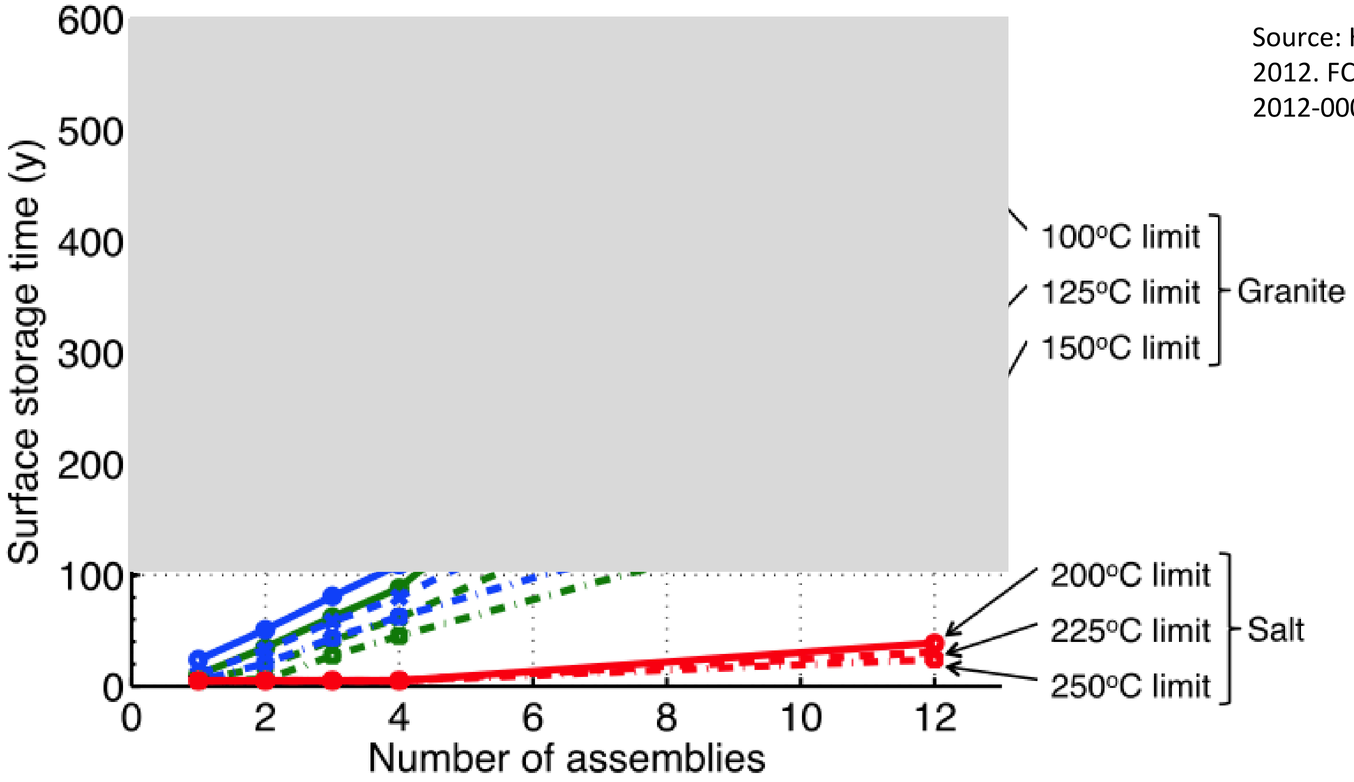
- **Example: clay/shale repository**
  - Host rock temperature (at rock wall)
  - LWR UOX SNF (60 GW-d/MTU)
  - Calculate for different package size/capacity



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-emplacement 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

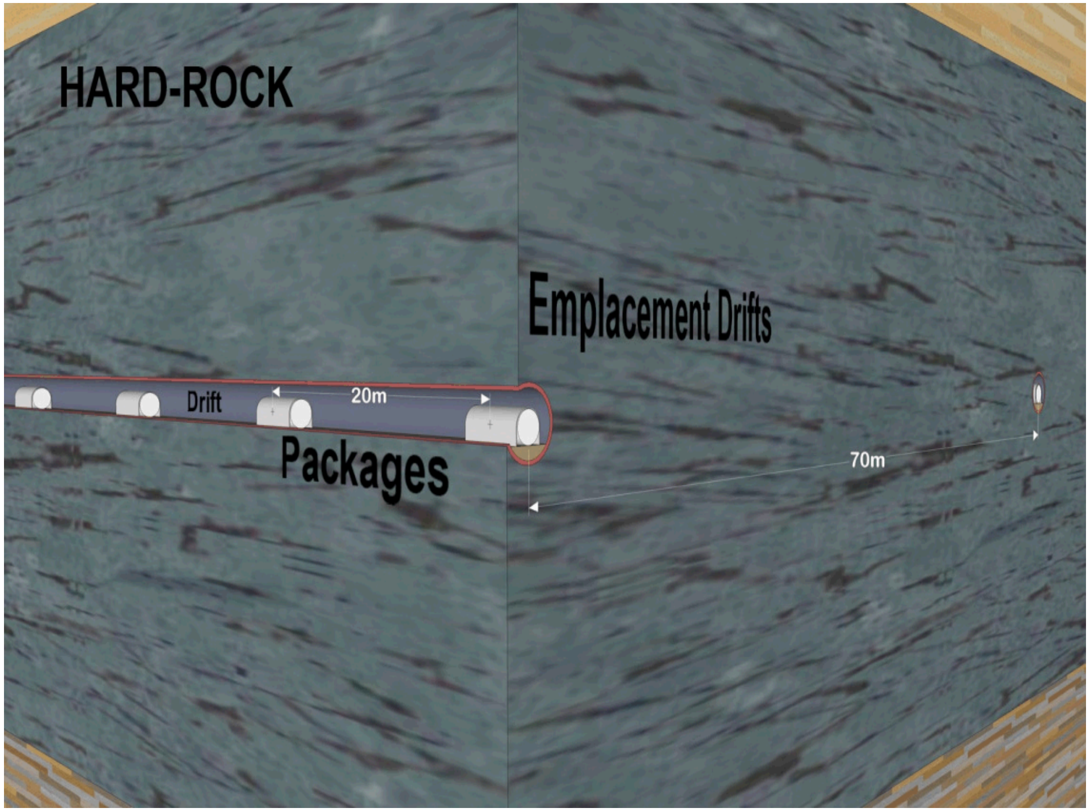
Reference Disposal Concepts for Heat-Generating SNF/HLW

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

** Concepts suitable for larger, hotter waste packages*

Hard-Rock Unbackfilled Open Concept

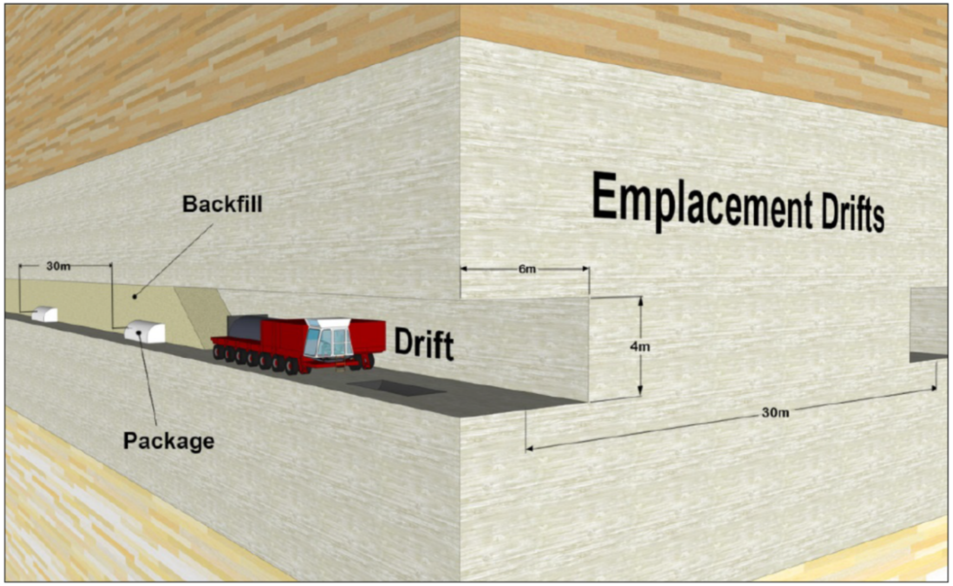
- Up to 32-PWR size or larger
- In-drift emplacement
- Emplace SNF at 50 to 100 years OoR
- Ventilate up to 50 years, closure at ≤150 years OoR
- Unbackfilled, for unsaturated settings
- Corrosion resistant waste packaging
- Additional engineered barriers may be installed at closure
- Long-term opening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



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

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

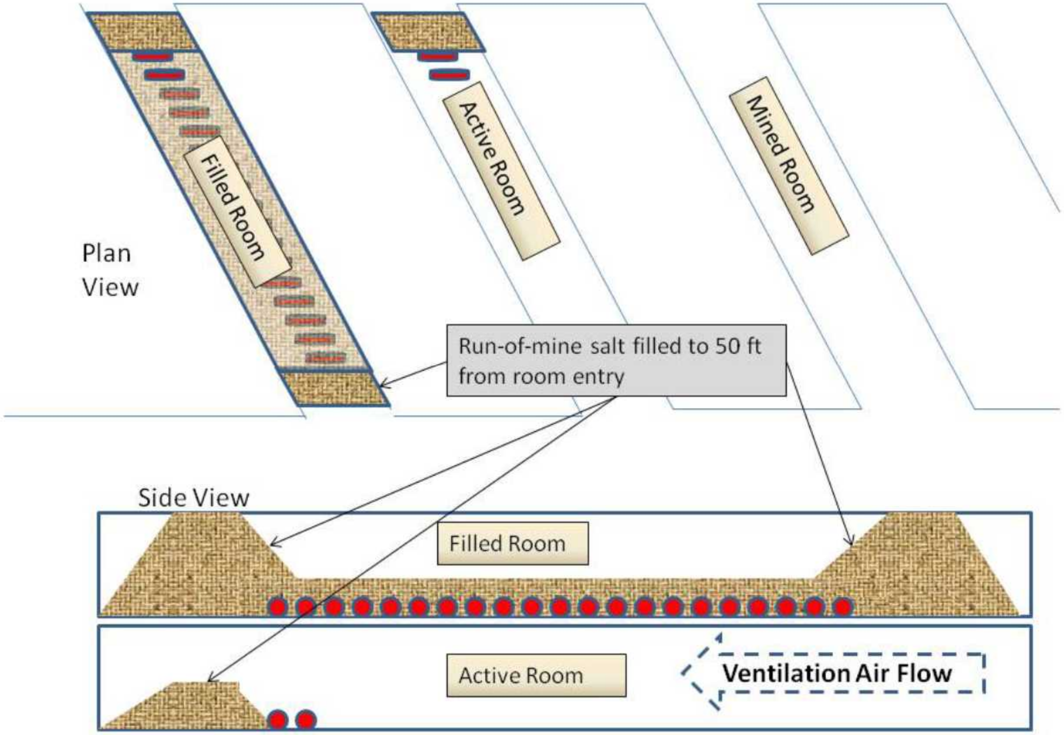
Carter et al. 2011. *A generic salt repository for disposal of waste from a spent nuclear fuel recycle facility*. SRNL-RP-2011-00149 Rev. 0.

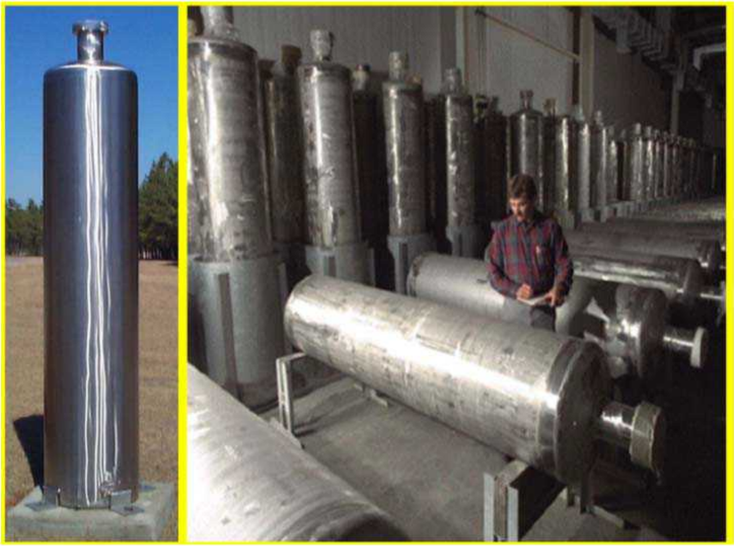
Hardin et al. 2013a. *Preliminary Report on Dual-Purpose Canister Disposal Alternatives*. FCRD-UFD-2013-000171 Rev. 0.

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:
Defense HLW and SNF in a Salt Repository

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

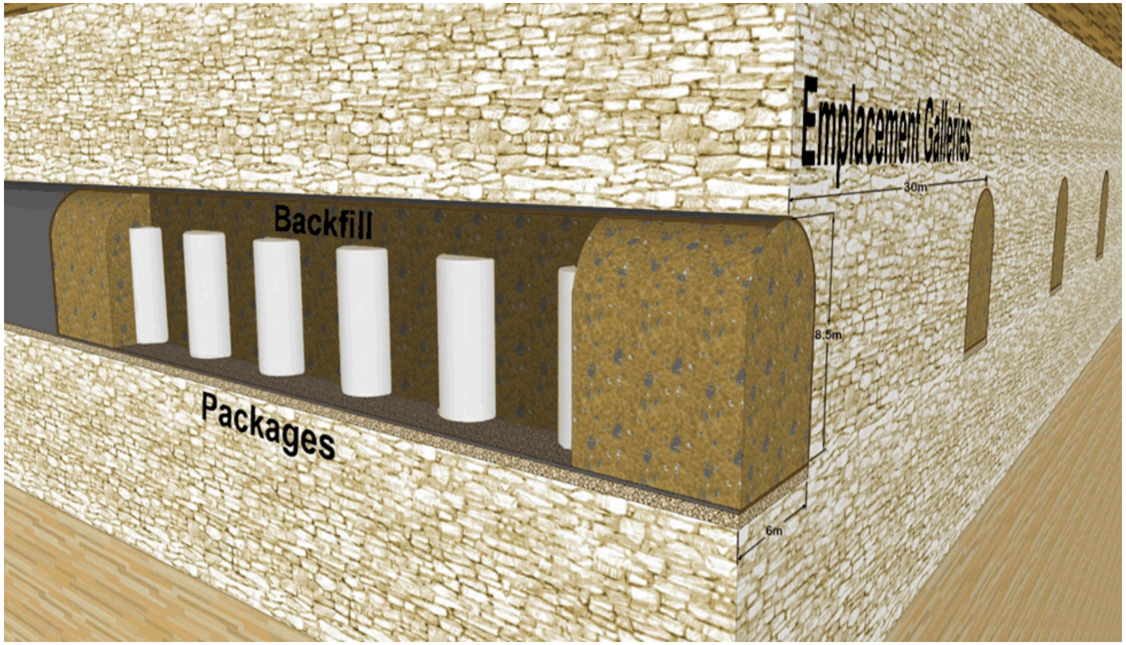




Source: Carter et al. 2012b. *Defense Waste Salt Repository Study*. FCRD-UFD-2012-000113.

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

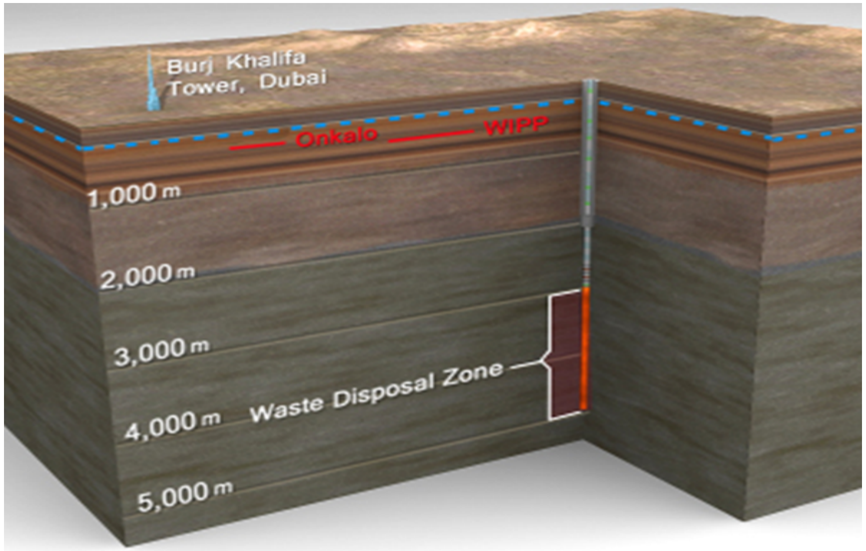


Concept from McKinley, Apted et al. 2008; figure from Hardin et al. 2013a.

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.

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

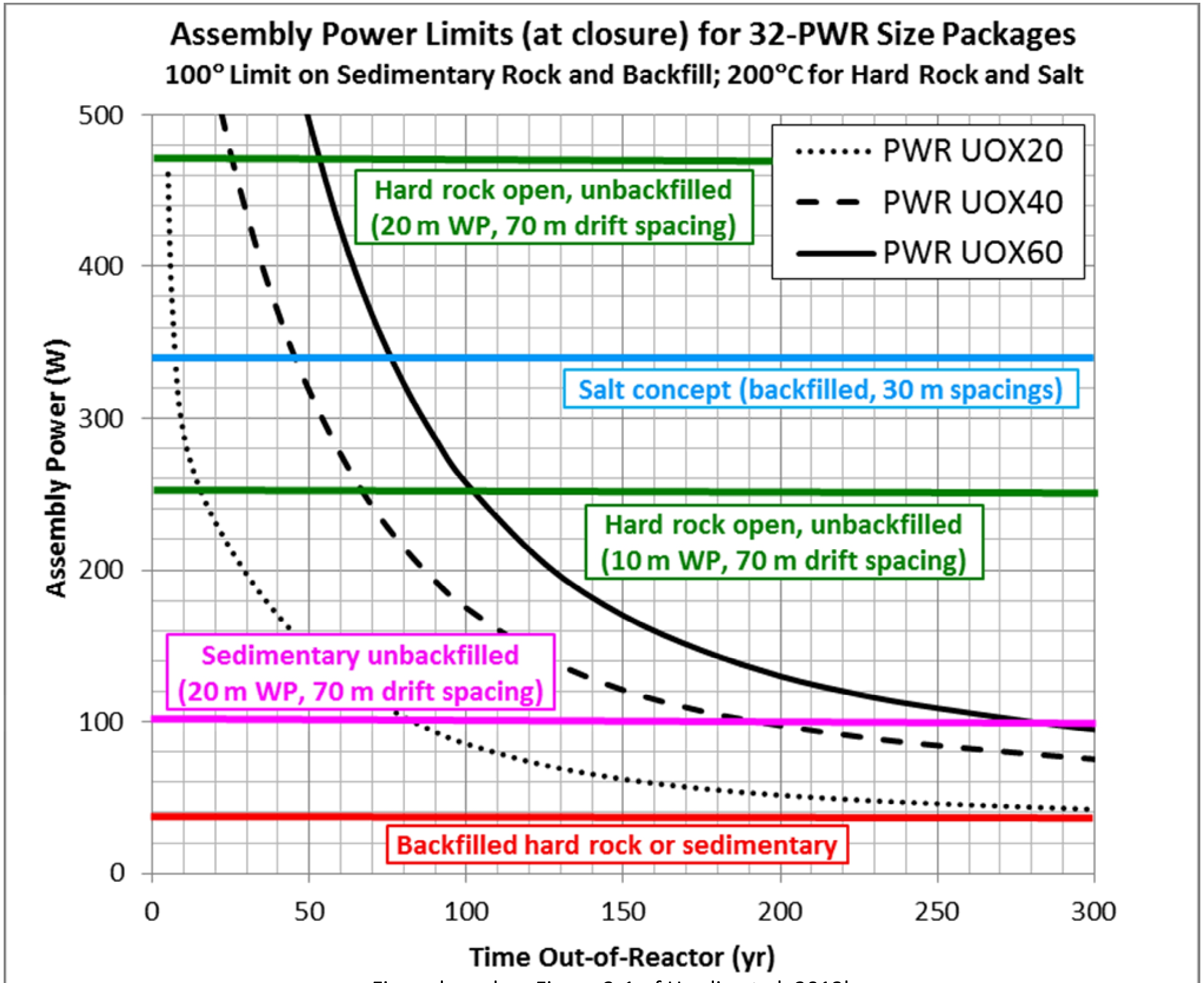
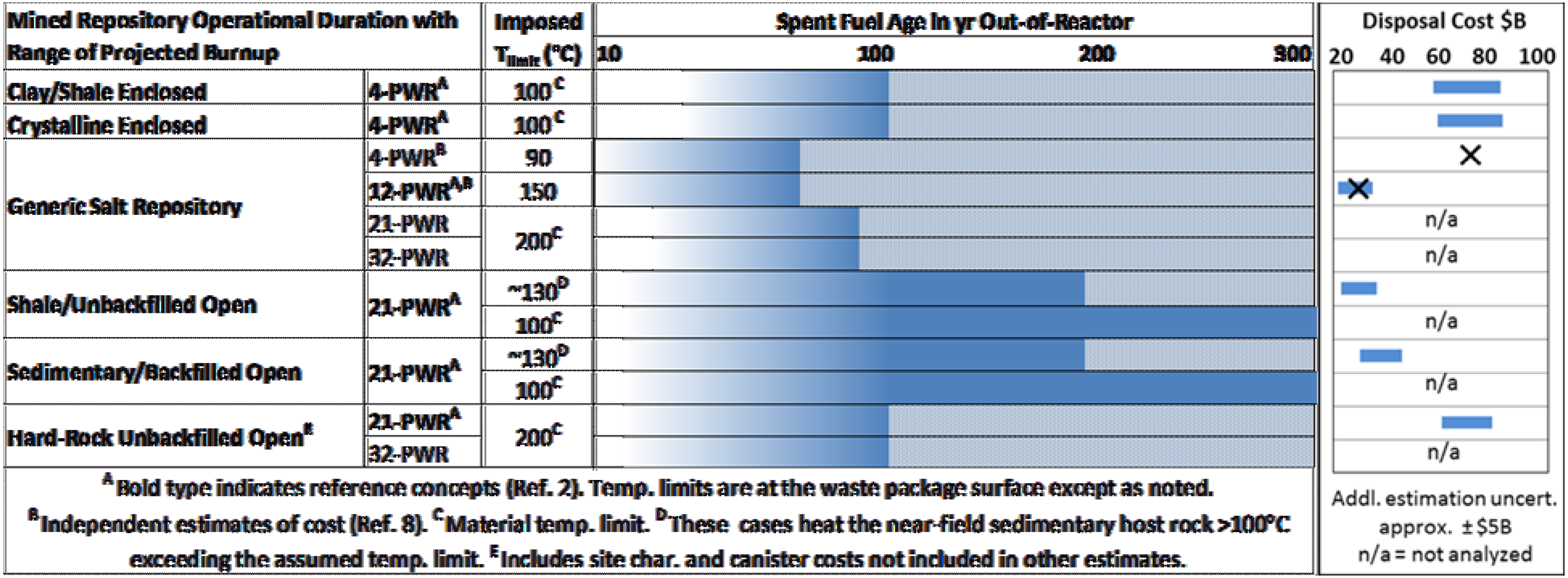


Figure based on Figure 2-1 of Hardin et al. 2013b.

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

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.

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

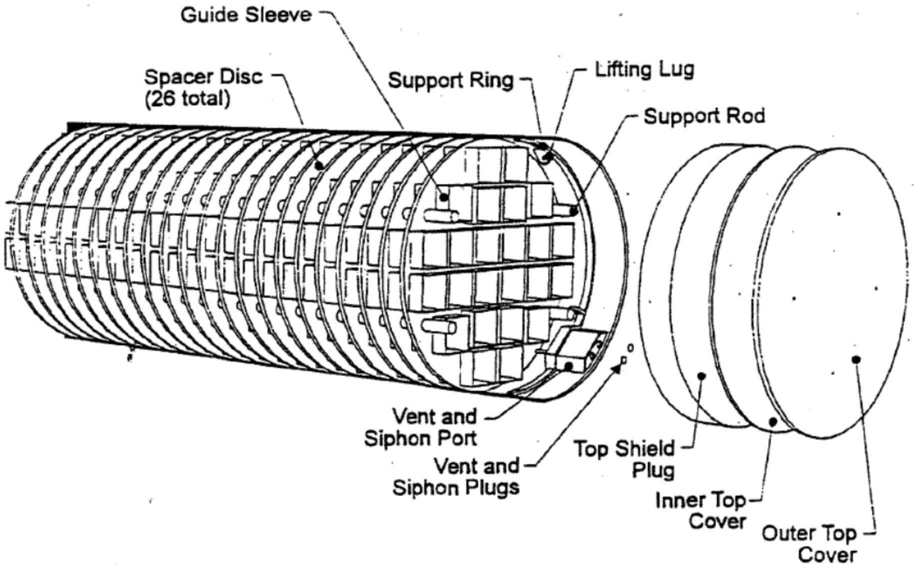
Technical Feasibility:

Thermal, Postclosure Criticality, Cost

Some Terminology

- **Canister** ≡ Sealed, unshielded vessel containing spent fuel (for use with various overpacks). Also, a sealed vessel containing HLW. Typically welded closure (Re: NRC annual inspection requirements for bolted closures). Three major vendors: Transnuclear/Areva, Holtec, and 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.
- **Dual-Purpose Canister** ≡ Dry storage canister that has been, or can be, licensed by the NRC for transportation also.
- **Multi-Purpose Canister** ≡ A canister that can be licensed for storage, transportation, and disposal (not the current range of vendor-designated "MPCs" which are DPCs)

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

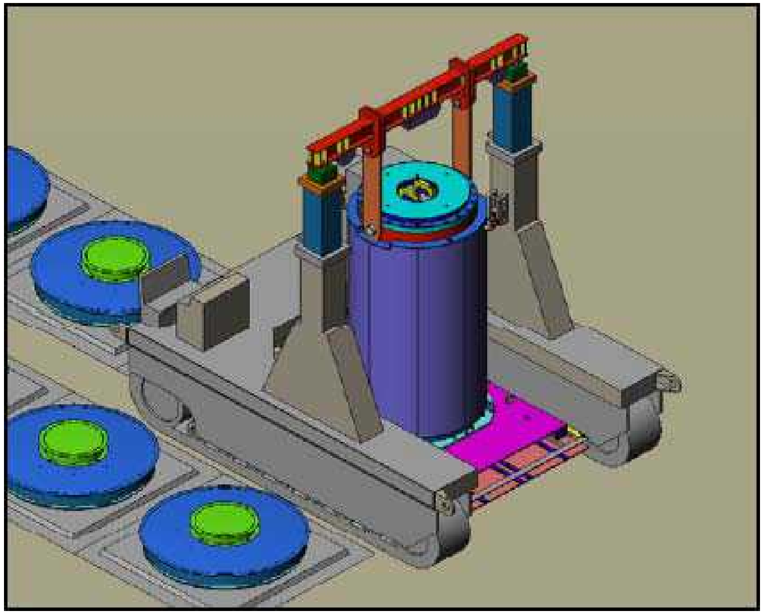
Largest, Recent DPC Designs

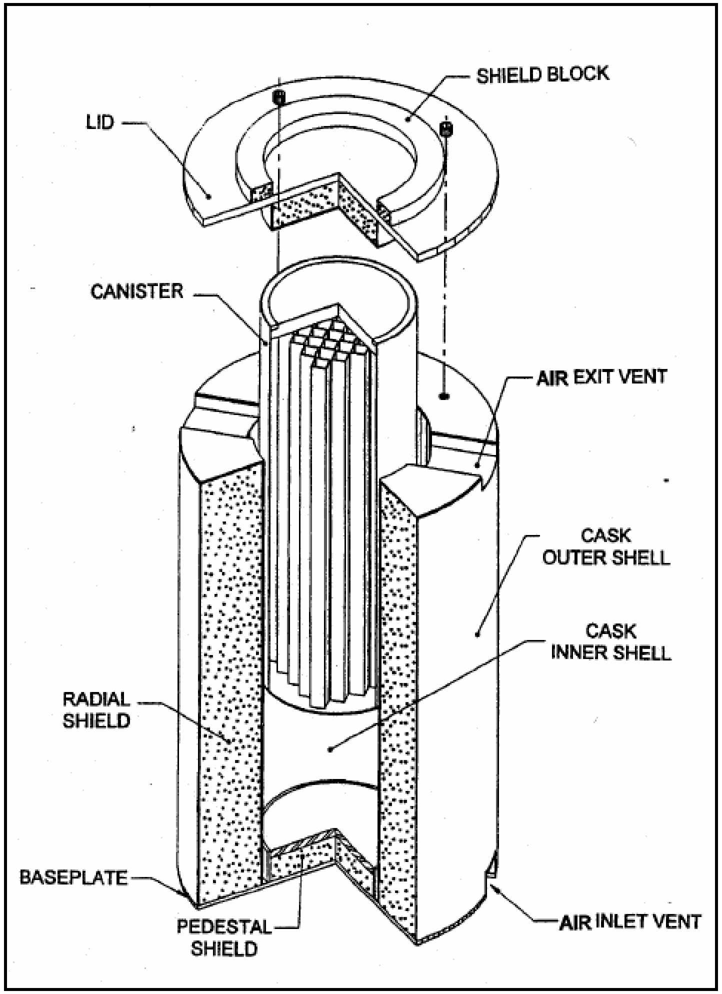
- Example: Magnastor DPC system (NAC International)
- Recently brought to market
- Capacity 37-PWR (equiv.)
- Thermal limits: 35.5 kW storage/24 kW transport
- Fuel cool time >4 yr OoR
- Size evolution (free market): burnup credit analysis, heat transfer features, transportation needs.

Pictures and data from NAC International website 31Mar2012

Dual-Purpose Canisters in Subterranean Storage

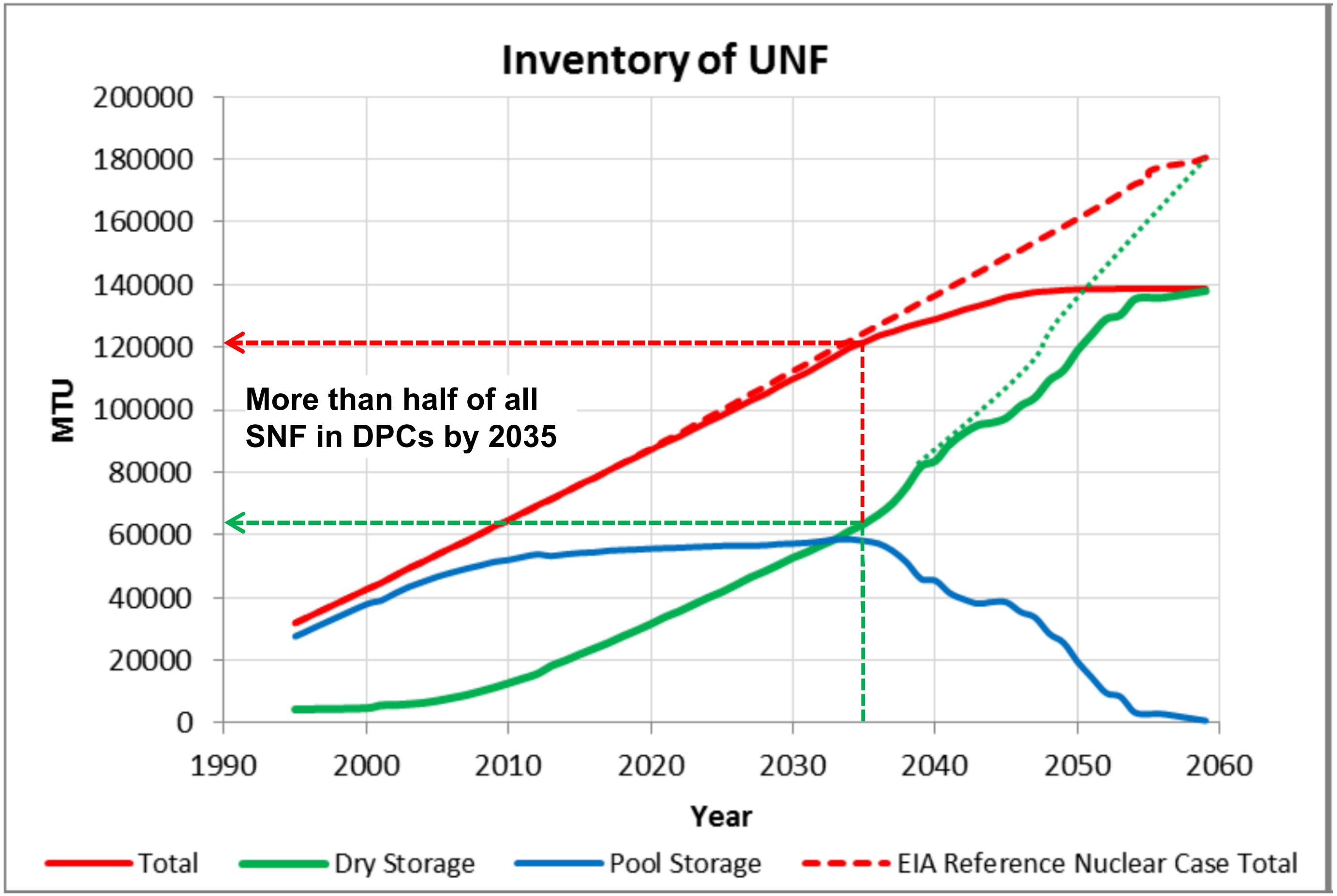
- **Holtec HI-STORM 100U subterranean canister overpack system (2 P/68 B)**
- **HI-STORM 100 shielded overpack with bolted closure, and welded stainless "multi-purpose" canister**
- **HI-TRAC (125 ton max.) transfer cask**
- **Mitigates aircraft crash hazard**





Pictures from EPRI Spent Fuel Storage Handbook

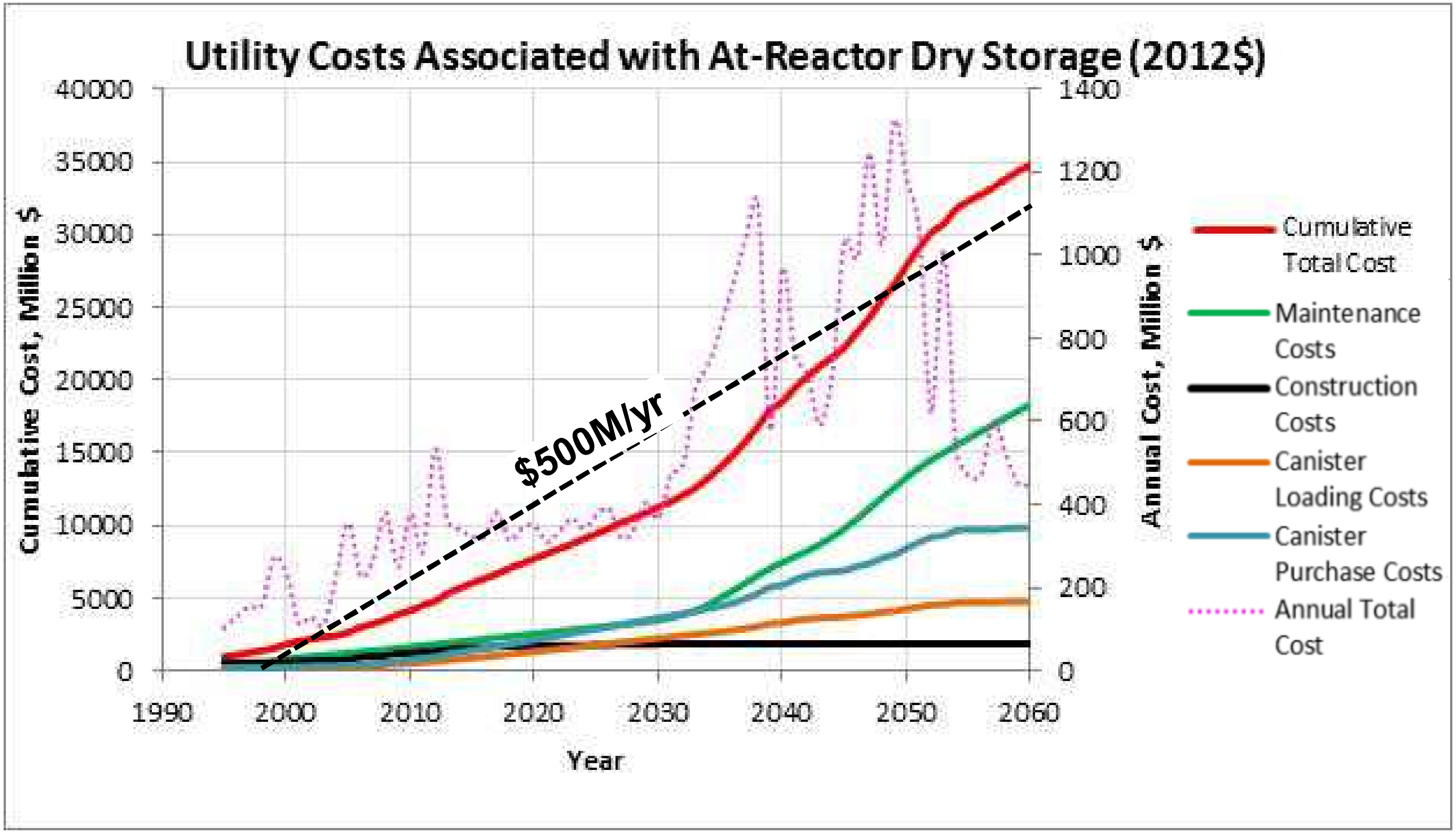
Spent Fuel Projection – TSL-CALVIN* Accumulation of Heavy Metal (MTU)



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.”

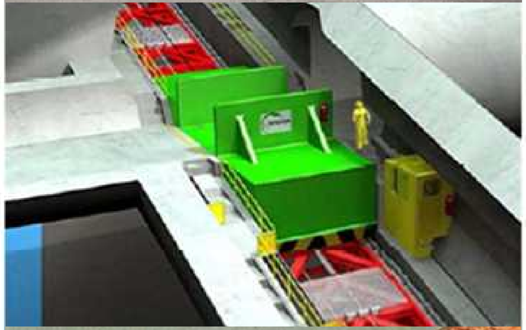
  Not necessarily, e.g., DPC package (70 MT) with shield (75 MT) + carriage < 175 MT (DBE TEC “DIREGT” conceptual hoist design)

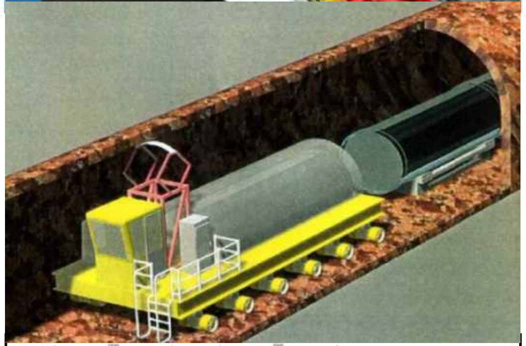
- “DPC-based packages would be too big/hot/heavy for a salt repository.”

  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.

Design Options for Engineering Challenges

- Handling/Packaging: Use Current Practices
- Surface-Underground Transport
  - Spiral ramp (10% grade)
  - Linear ramp (>10% grade)
  - Shallow ramp (≤ 2.5% grade)
  - Heavy shaft hoist
- Opening Stability Constraints
  - Salt (a few years with minimal maintenance)
  - Hard rock (50 years or longer)
  - Sedimentary (50 years may be feasible; longer may require special geologic settings)





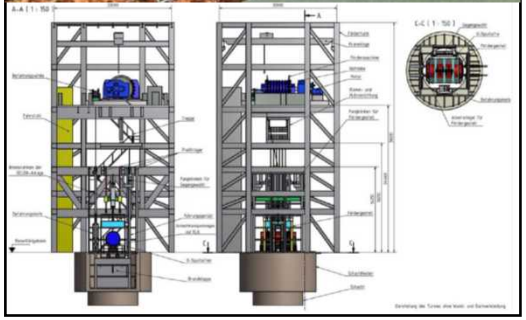
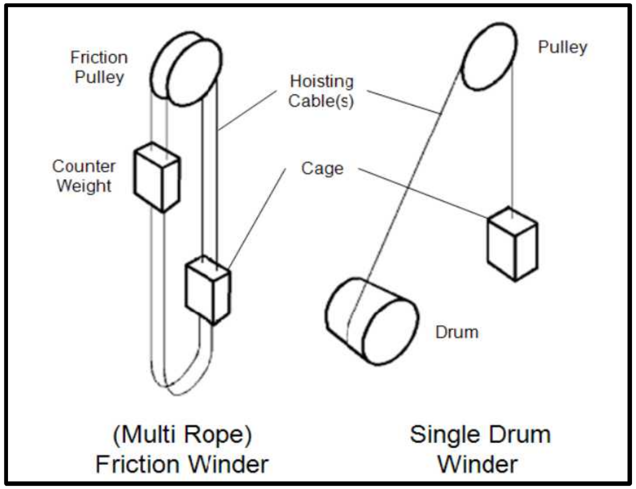
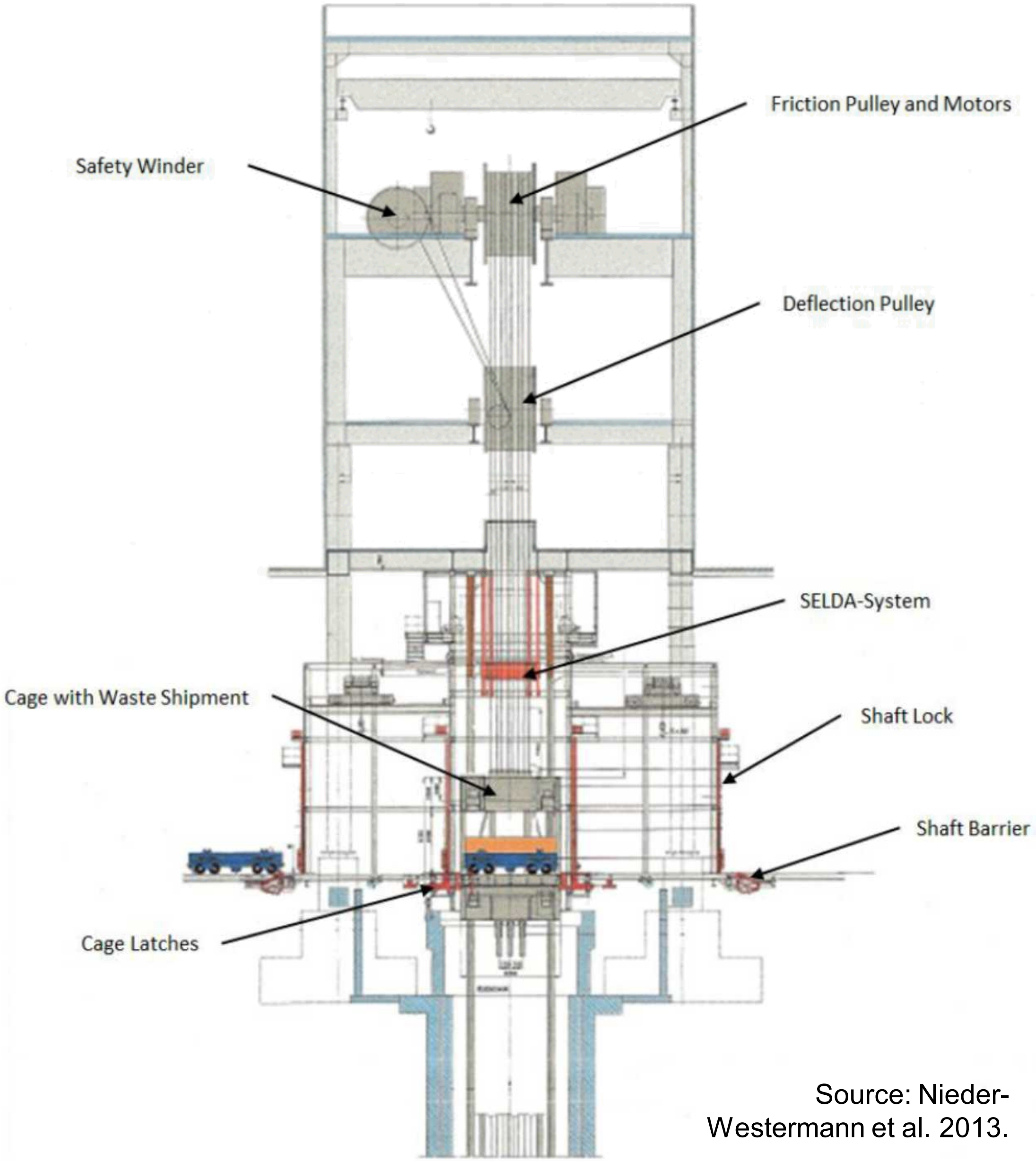


Image sources:
Fairhurst 2012
www.wheelift.com
Nieder-Westermann et al. 2013

Heavy Shaft Hoist Technology

- **Gorleben, Germany design and DEAB test (85 MT)**
- **Payload extension to 175 MT for DPC package, shielding & cart**
  - **Friction hoist, 6 cables (66 mm) plus 6 balance cables**
  - **Counterweight 133 MT**
  - **1 m/sec hoist speed**
  - **2.8 m drive pulley, 800 kW winder**
  - **Equipment cost ~$30M**

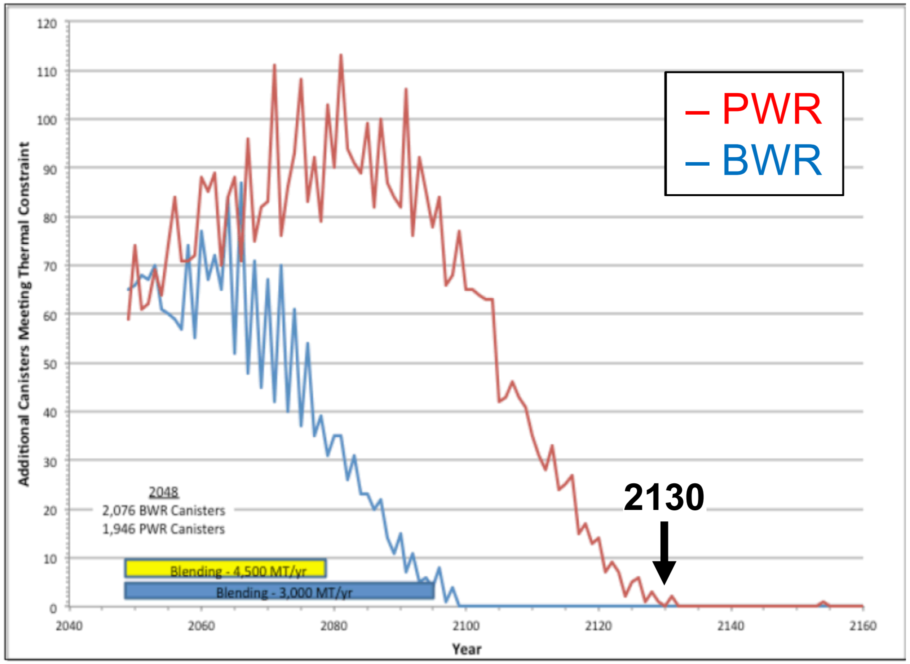




Source: Nieder-Westermann et al. 2013.

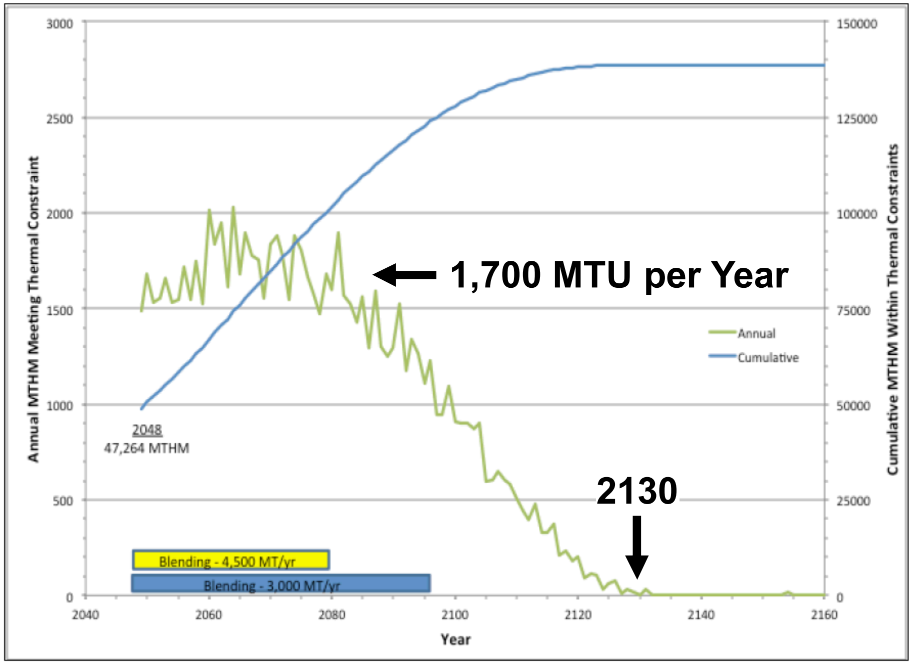
Cooling Time for DPC Direct Disposal

- **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



2130

# of Canisters per Year Cooling to 10 kW



1,700 MTU per Year

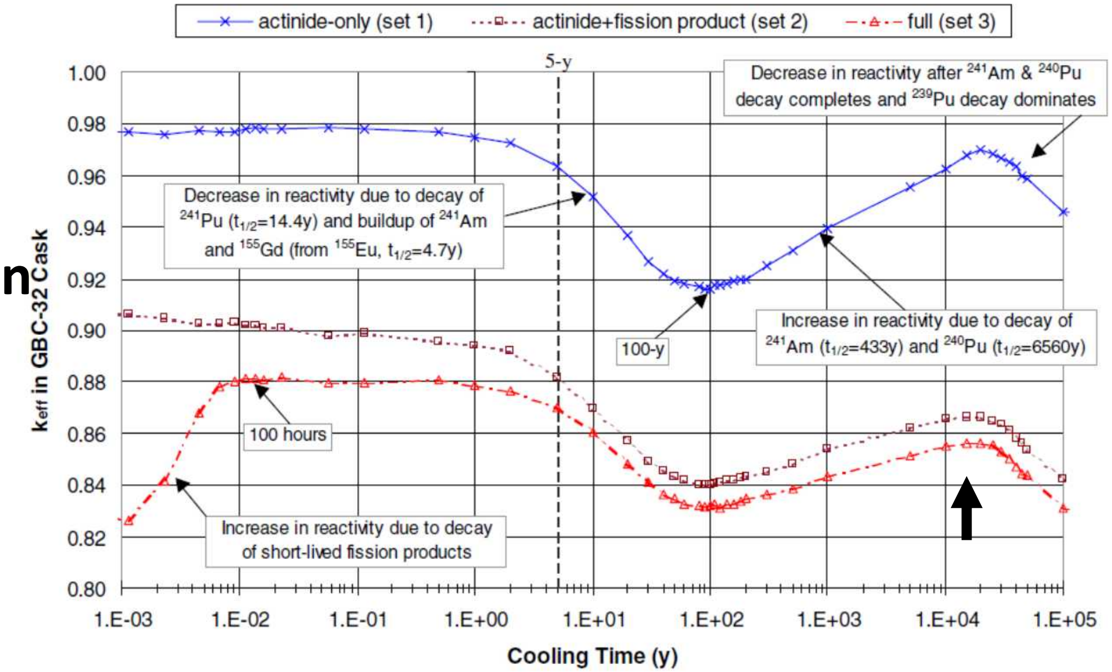
2130

SNF per Year (MTU) Cooling to 10 kW

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

Post-Closure SNF Criticality Control

- **Environment**
  - Groundwater availability
  - Water composition
  - Presence of chloride brine?
- **Option: moderator exclusion**
  - Package integrity
- **Option: moderator displacement**
  - Fillers (e.g., magnetite powder, cement, glass beads, B_4C?)
- **Option: as-loaded margin**
  - 3-D; axial burnup profiles (more difficult to characterize for BWRs)
  - Operation histories (from utilities)
  - Burnup credit
- **Ultimate fate: degradation of n-absorbers and fuel basket**



Decrease in reactivity after ^{241}Am & ^{240}Pu decay completes and ^{239}Pu decay dominates

Decrease in reactivity due to decay of ^{241}Pu ($t_{1/2}$=14.4y) and buildup of ^{241}Am and ^{155}Gd (from ^{155}Eu, $t_{1/2}$=4.7y)

Increase in reactivity due to decay of ^{241}Am ($t_{1/2}$=433y) and ^{240}Pu ($t_{1/2}$=6560y)

Increase in reactivity due to decay of short-lived fission products

32-PWR canister multiplication factor vs. time

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

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

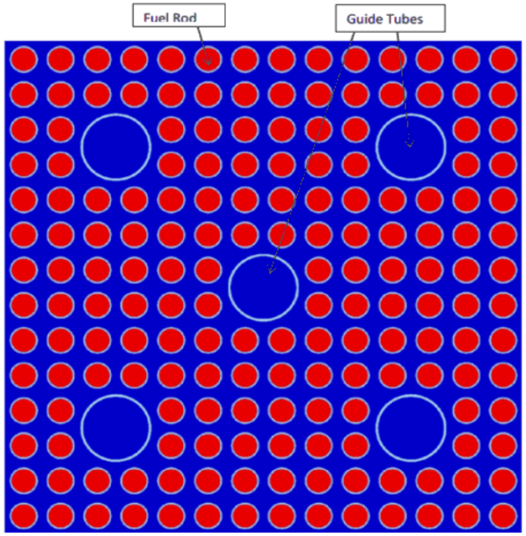
DPC Criticality Analysis (ORNL)

- Most DPCs use neutron absorbers that readily corrode in groundwater (e.g., Boral, Al-B_4C metal matrix composites)
- Legacy approach: YM topical report
  - Flooded (precedent in 10CFR71.55 analysis)
  - Degraded Case 1: Loss of absorber (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
  - Disposal environment (e.g., brine)
  - Burnup credit (best for early DPCs designed for fresh fuel, not "burnup credit" designs)

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

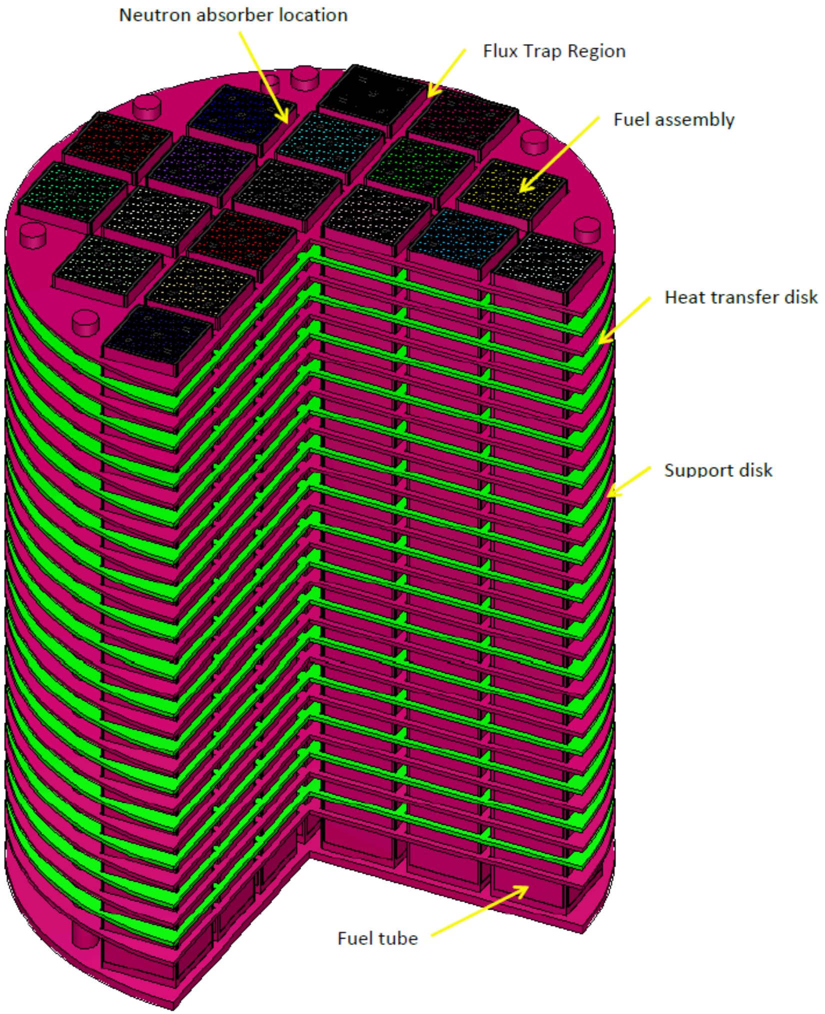
Clarity, J.B. and J.M Scaglione 2013. *Feasibility of Direct Disposal of Dual-Purpose Canisters-Criticality Evaluations*. ORNL/LTR-2013/213.

Reactivity Scoping Analysis, Example “Site A”



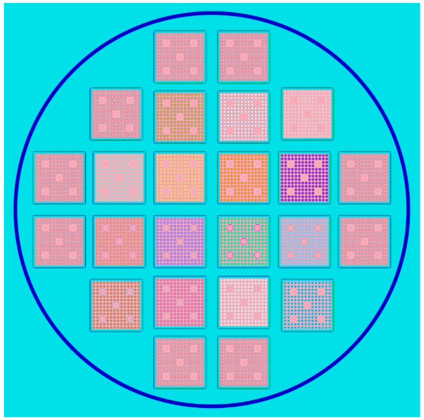
Model array representing a 14x14 standard PWR assembly in cross-section.

- 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: ~400 other PWR and BWR SNF DPCs

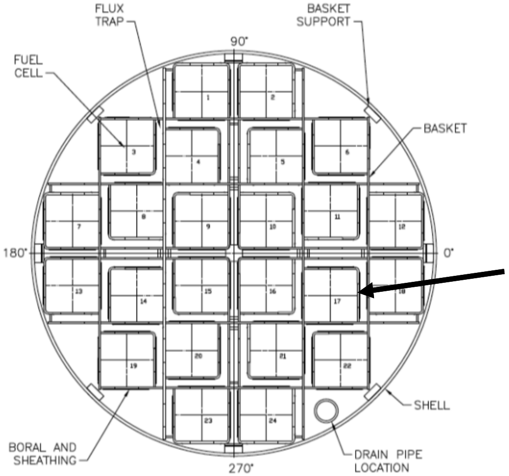


ORNL (Oak Ridge National Laboratory) 2011. ORNL/TM-2005/39 Version 6.1.
Also: Clarity, J.B. and J.M Scaglione 2013. ORNL/LTR-2013/213.

Basket Configurations for TSC-24 System: “Site A”

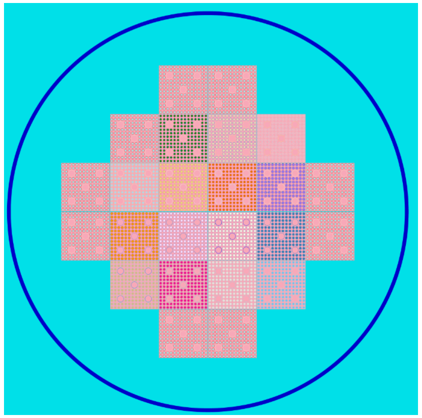


Intact Basket (as considered for preclosure safety analysis)

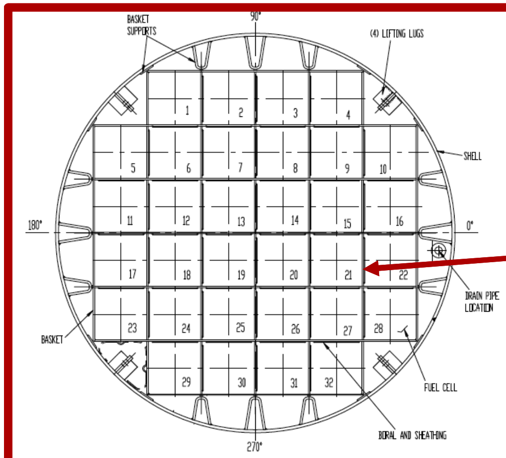


Fuel-tube type basket (e.g., TSC-24)

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



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



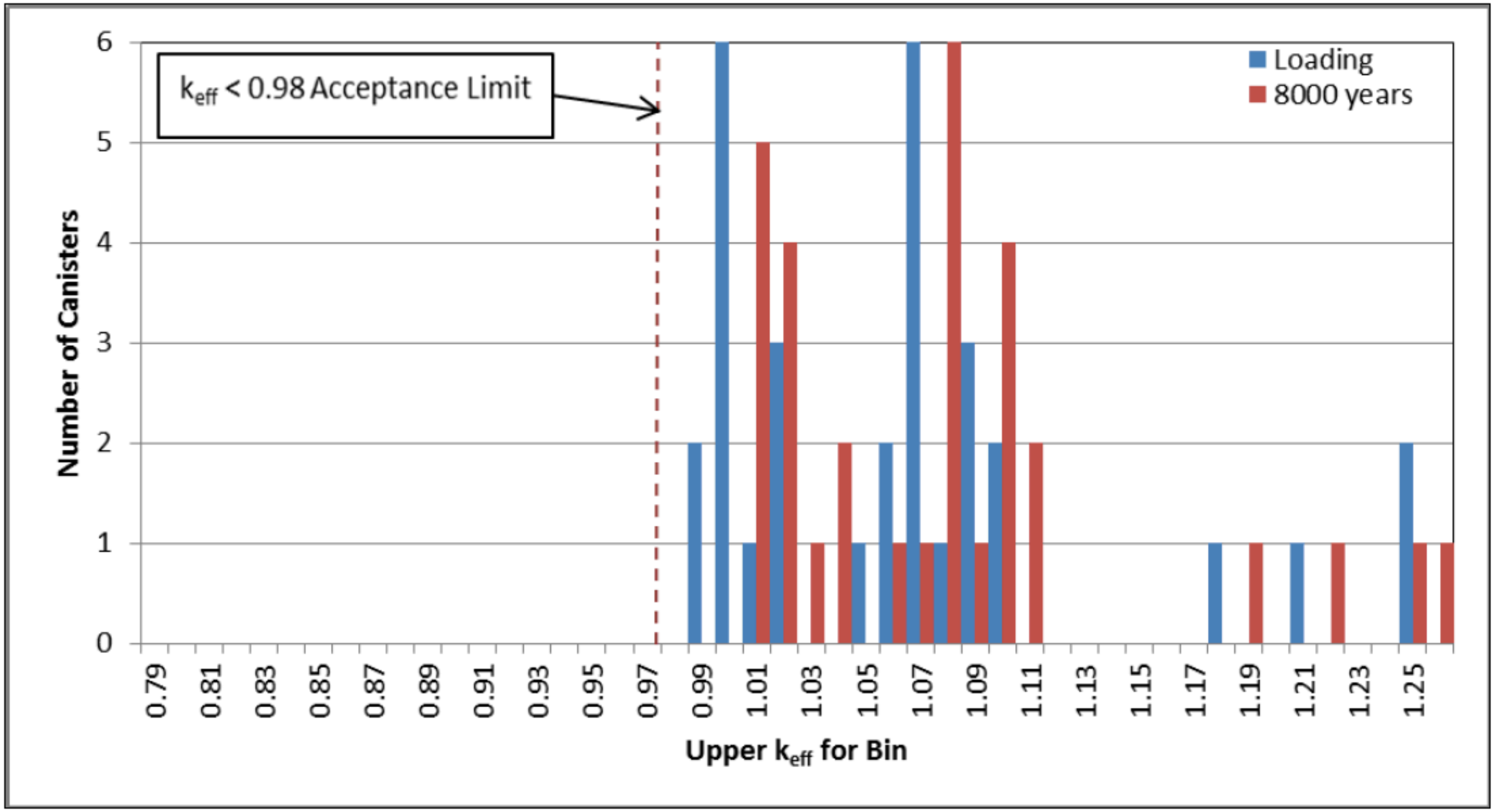
Egg-crate type basket (e.g., Holtec MPC-32)

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”

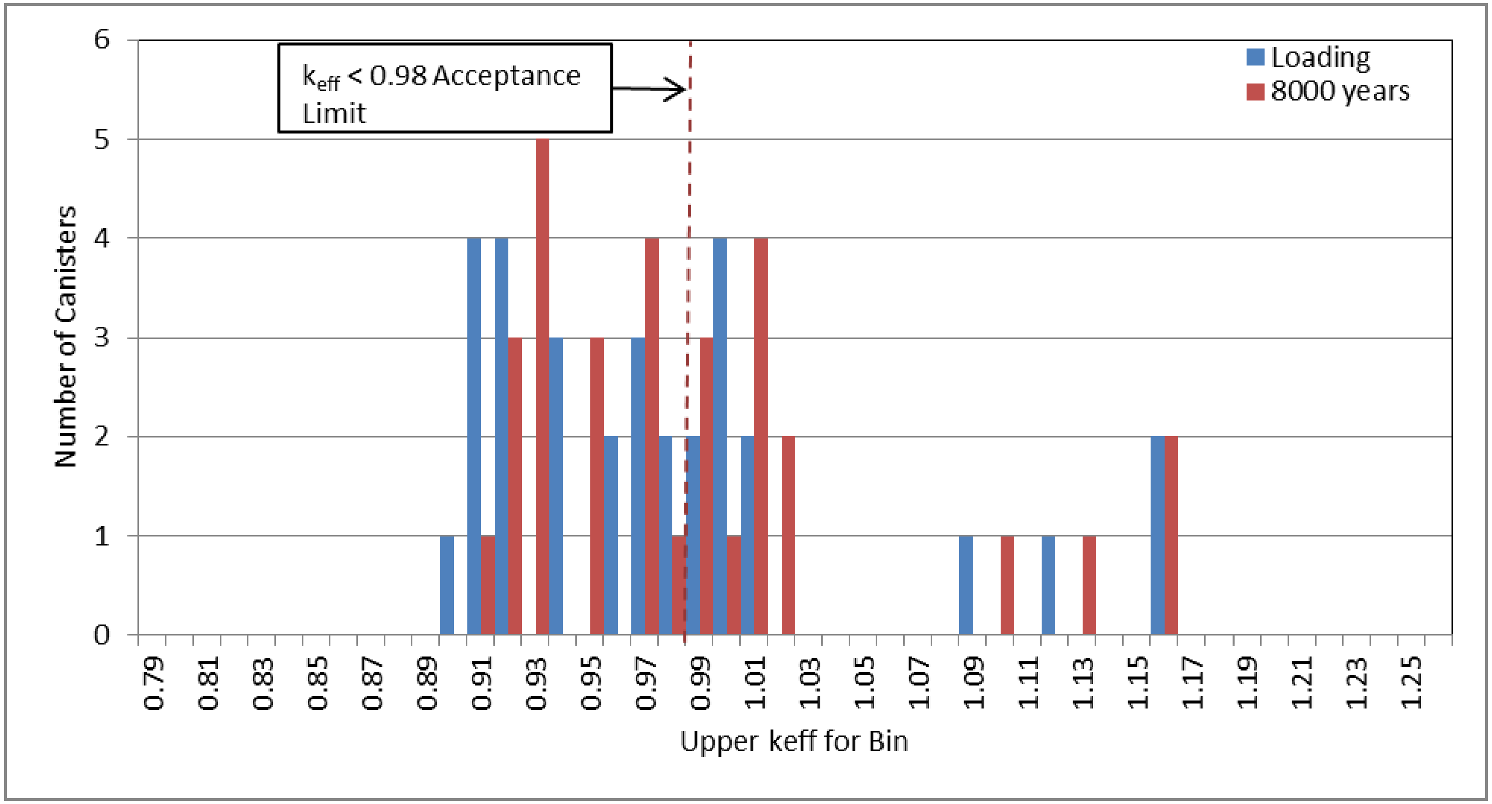
- **Degraded basket (worst) case** (and loss of B_4C absorber), <u>flooded with fresh water</u>
- Analyzed as-loaded with PWR SNF, with burnup credit (no mis-load)



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 $B
Projected costs to continue DPC status quo:					
Sunk cost for procuring, loading and storing existing DPCs ($/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					**38.7**
Potential cost savings from direct disposal of DPCs					**27.7**

Notes:

1. Estimates do not include new facility construction, maintenance, and some storage costs which could add $20B or more over the life of the current fleet.
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					**10.3**

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 "true 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*)

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)

References*

- 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.
- Arnold et al. 2011. *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2011-6749. Sandia National Laboratories.
- Brady, P.V. et al. 2009. *Deep borehole disposal of high-level radioactive waste*. SAND2009-4401. Sandia National Laboratories.
- 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. Savannah River National Laboratory.
- Carter, J. et al. 2012a. *Fuel Cycle Potential Waste Inventory for Disposition*. FCR&D-USED-2010-000031 Rev. 5.
- Carter. J. et al. 2012b. *Defense Waste Salt Repository Study*. FCRD-UFD-2012-000113.
- Clarity, J.B. and J.M Scaglione 2013. *Feasibility of Direct Disposal of Dual-Purpose Canisters-Criticality Evaluations*. ORNL/LTR-2013/213. Oak Ridge National Laboratory, Oak Ridge, TN. June, 2013.
- Hardin, E.L. et al. 2012. *Repository Reference Disposal Concepts and Thermal Management Analysis*. FCRD-USED-2012-000219 Rev. 2.
- Hardin, E.L. et al. 2013a. *Preliminary Report on Dual-Purpose Canister Disposal Alternatives*. FCRD-UFD-2013-000171 Rev. 0.
- Hardin, E.L. et al. 2013b. *Collaborative Report on Disposal Concepts.* FCRD-UFD-2013-000170 Rev. 0.
- Hardin, E. & E. Kalinina 2016. *Cost Estimation Inputs for Spent Nuclear Fuel Geologic Disposal Concepts (Rev. 1).* SAND2016-0235. Sandia National Laboratories.
- McKinley, I.G., M. Apted et al. 2008. “Cavern disposal concepts for HLW/SF: assuring operational practicality and safety with maximum programme flexibility.” *International Technical Conference on the Practical Aspects of Geological Disposal of Radioactive Waste*. June 16-18, 2008. Prague.
- Noss, P.W., J.C. Nichols, and S.R. Streutker 2000. “MCO Impact Absorbers Using Crushable Tubes.” WM 2000 Conference, Tucson, AZ.
- Nutt, M. et al. 2012. *Transportation Storage Logistics Model – CALVIN (TSL-CALVIN).* FCRD-NFST-2012-000424.
- Nutt, W.M. 2013. *Preliminary System Analysis of Direct Dual Purpose Canister Disposal*. FCRD-UFD-2013-000184 Rev. 0.
- ORNL (Oak Ridge National Laboratory) 2011. *SCALE: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design*. ORNL/TM-2005/39 Version 6.1. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-785. June, 2011.
- SNL (Sandia National Laboratories) 2016. *Deep Borehole Field Test Conceptual Design Report.* FCRD-UFD-2016-000070 Rev. 1.
- 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.
- SRNL (Savannah River National Lab) 2015. *Generic Repository Cost Estimates*. FCRD-UFD-2015-000740 Rev. 0.
- Wagner, J. and C. Parks 2001. *Recommendations on the Credit for Cooling Time in PWR Burnup Credit Analyses*. NUREG/CR-6781.
- Wagner, J. et al. 2012. *Categorization of Used Nuclear Fuel Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy*. FCRD-FCT-2012-000232.

* 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 (eventually) available at www.osti.gov.

Questions?