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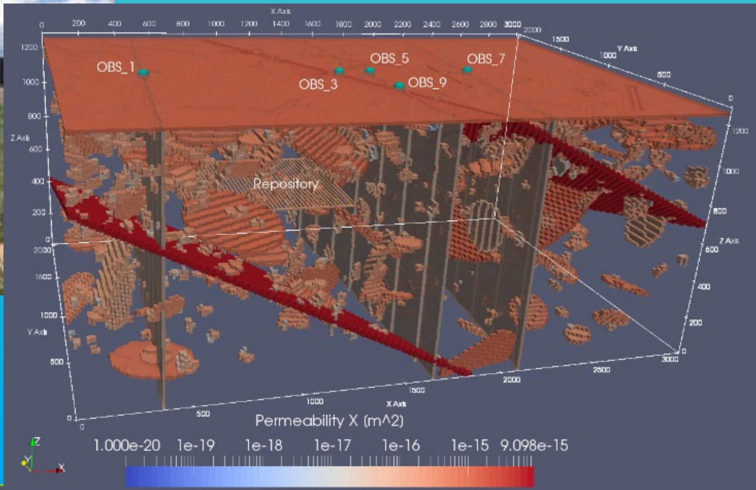

Technical Basis for Engineering Feasibility and Thermal Management

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Legal Notice

Outline

- Summary of Previous Technical Feasibility Studies
  - Safety
  - Engineering challenges
  - Thermal management
  - Postclosure criticality
- DPC dimensions and weights
- Emplacement concept
- Waste package handling, transport, emplacement
- Thermal management
  - Why temperature or thermal power limits
  - Disposal power limits are always less than transportation limits
  - Comparison of geologic settings on thermal criteria
  - Time required for DPCs to cool for disposal; fuel age at emplacement
- Postclosure internal criticality review
- Summary

Facts About Potential Direct Disposal of SNF in DPC-Based Waste Packages

- DPCs weigh about the same as Yucca Mountain (YM) canisters sized for 21-pressurized water reactor (PWR) assemblies.

  Loaded Magnastor® canister (NAC International) 37-PWR DPC (~50 MT) vs. loaded YM 21-PWR canister (≤ 49.3 MT)

- DPCs are about the same size as YM canisters for commercial SNF.

  Magnastor canister dimensional envelope (1.77 m D x 4.87 m L → 12.4 m^3) vs. YM canister (1.69 m D x 5.39 m L → 12.1 m^3).

- DPC-based waste packages could be lowered down a shaft with a large friction-winder type hoist.

  A DPC package (~70 MT) with shield (+75 MT) + carriage would compare to the 175 MT payload for the "DIREGT" conceptual hoist design (BGE Tec).

- Meeting thermal limits for disposal will require fuel aging

  Example 1: ~98% of projected DPCs will cool to 10 kW by 2130.

  Example 2: ~98% of projected **BWR** ***DPCs will cool to 4 kW by 2170.***

Summary of Previous (2013–2017) Technical Feasibility Study for DPC Direct Disposal

- **Direct disposal of spent fuel in DPCs is possible with all geologic settings evaluated**
  - Thermal management and postclosure criticality controls vary for geologic settings
  - Relative reliance on natural and engineered barriers also varies
- **Additional considerations**
  - Disposal overpack reliability estimates can be improved
  - DPC basket designs impact structural longevity after package breach
- **Major recommendations**
  - Investigate fillers for all DPCs
  - Investigate screening postclosure criticality on low consequence

Recommendations from Previous (2013-2017) Technical Feasibility Study (1/2)

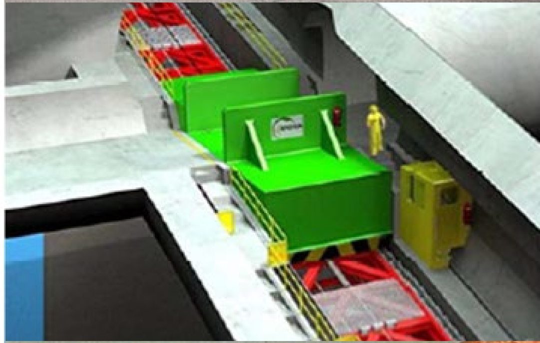
- **Safety**
  - General attributes of a safe repository also apply for DPCs
  - Performance assessment models need to discern differences
  - Likely need to use cementitious materials in repository construction
- **Engineering Feasibility**
  - Consider fuel and canister condition if extended aging is needed
  - Need to develop transporter and emplacement system concepts
  - Start corrosion testing for packaging materials
  - Update disposal overpack reliability
- **Thermal Management**
  - Continue R&D for high-temperature low-permeability buffer/backfill for crystalline and argillaceous host media (e.g.,150ºC or hotter)
  - Develop thermally driven process models (e.g., argillite repository)

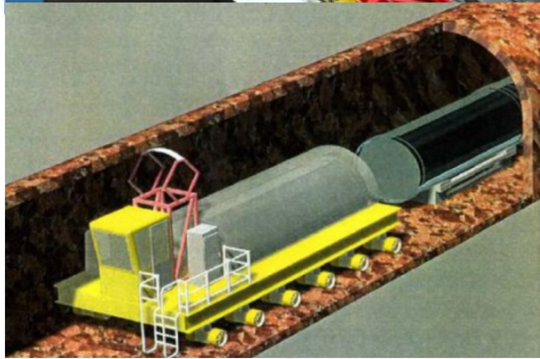
Recommendations from Previous (2013-2017) Technical Feasibility Study (2/2)

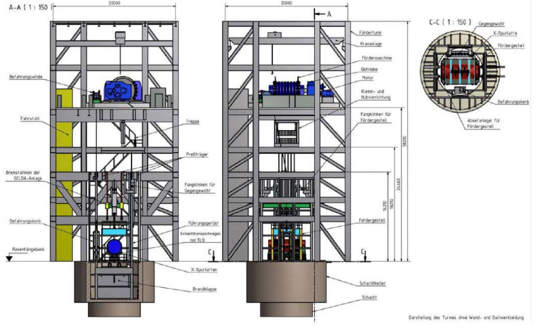
- **Postclosure Criticality Control**
  - Continue analysis of “as loaded” DPCs to estimate reactivity margin for degraded, flooded conditions
  - Document stylized degradation scenarios
  - Develop models of in-package (fuel, basket) degradation including effects from radiolysis
  - Develop advanced burnup credit methodology for BWR fuel
  - Conduct R&D on fillers for moderator exclusion and neutron absorption

Engineering Challenges Can Be Met

- **Handling/Packaging: Use Current Practices**
- **Surface-Underground Transport**
  - Spiral ramp (~10% grade, rubber-tire)
  - Linear ramp (>10% grade, funicular)
  - Shallow ramp (≤ 3% grade, standard rail)
  - Heavy shaft hoist (up to 175 MT payload)
- **Drift Opening Stability Constraints**
  - Salt (a few years with little attention or heating; longer with rock bolts and maintenance)
  - Hard rock (50 years or longer)
  - Sedimentary (50 years may be feasible, or longer depending on geologic setting)







Repository Concept of Operations

Aspects would be similar for DPC-based packages, as for purpose-designed canisters:

- Repository layout, construction method and sequence
- Shafts for worker access/materials, ventilation, and waste rock
- Waste transport ramp (or shaft, e.g., in evaporites)
- Ground support and invert options
  - Temporary vs. long-term; and use of cementitious materials
- Waste package handling, transport and emplacement
  - Heavy-haul equipment, with shielding and remote operation
- Backfill emplacement drifts to:
  - Hasten reconsolidation (salt)
  - Limit ground water flow (clay/shale and crystalline)
  - Limit EBS damage from rockfall and seismic motion (unsaturated, and other concepts)
- Use plugs/seals as appropriate

DPC Overpack Functional Description

- Preclosure functions assigned to overpack:
  - Containment for > 100 yr or until repository closure
  - Structurally robust to withstand handling and drops
  - Unshielded (saving 40+ MT in weight per waste package)
- Postclosure function assigned to overpack:
  - Containment consistent with disposal concept (100 yr to >10,000 yr)
    - Corrosion allowance or resistance
    - Resist impact from rockfall, and crushing from ground water and rock pressures, during containment period

DPC Canister Size and Weight (1/2)

- Example DPC dimensions, weights (Greene et al. 2013)

S&T DPC System	Cap.	Wt. Loaded	Canister		Storage	Transport
		MT	Diameter, m	Length, m	Cask System	Cask System
MPC-24 series	24 PWR	**40.9**	**1.74**	**4.83**	HI-STORM 100/100U HI-STAR 100	HI-STAR 100
MPC-32 series	32 PWR	**40.9**	**1.74**	**4.83**	HI-STORM 100/100U HI-STAR 100	HI-STAR 100
MPC-68 series	68 BWR	**40.9**	**1.74**	**4.83**	HI-STORM 100/100U	HI-STAR 100
MPC-37	37 PWR	**52.9**	**1.92**	**4.60**	HI-STORM FW/UMAX	HI STAR 190
MPC-68 series	68 BWR	**52.9**	**1.92**	**4.83**	HI-STORM FW/UMAX	HI STAR 190
TSC Class 1-3	24 PWR	**33.1**	**1.71**	**4.45 – 4.87**	VCC Class 1-3	UTC
TSC Class 4-5	56 BWR	**34.4**	**1.71**	**4.72 – 4.84**	VCC Class 4-5	UTC
Magnastor PWR	37 PWR	**46.6**	**1.80**	**4.70**	VCC	MAGNATRAN
Magnastor BWR	87 BWR	**47.0**	**1.80**	**4.87**	VCC	MAGNATRAN
NUHOMS 24 series	24 PWR	**37.3 - 43.0**	**1.71**	**4.73 – 4.99**	HSM-H	MP187/MP197 MP197HB
NUHOMS 32 series	32 PWR	**40.1 - 50.0**	**1.71 – 1.77**	**4.72 – 5.04**	HSM 80 or 102 HSM-H or 102 HSM "Advanced"	MP197HB MP187/MP197
NUHOMS 37 series	37 PWR	**49.1 - 49.7**	**1.77**	**4.62 – 4.81**	HSM-H	MP197HB
NUHOMS 61 series	61 BWR	**40.2 - 42.3**	**1.71**	**4.98**	HSM 80 or 120 HSM-H or -HS HSM "advanced"	MP197/MP197HB
NUHOMS 69BTH	69 BWR	**48.2**	**1.77**	**4.98**	HSM-H/HS	MP197/MP197HB

Greene et al. 2013. *Storage and Transport Cask Data for Used Commercial Nuclear Fuel*. ATI-TR-13047. Energx. Oak Ridge, TN.

DPC Canister Size and Weight (2/2)

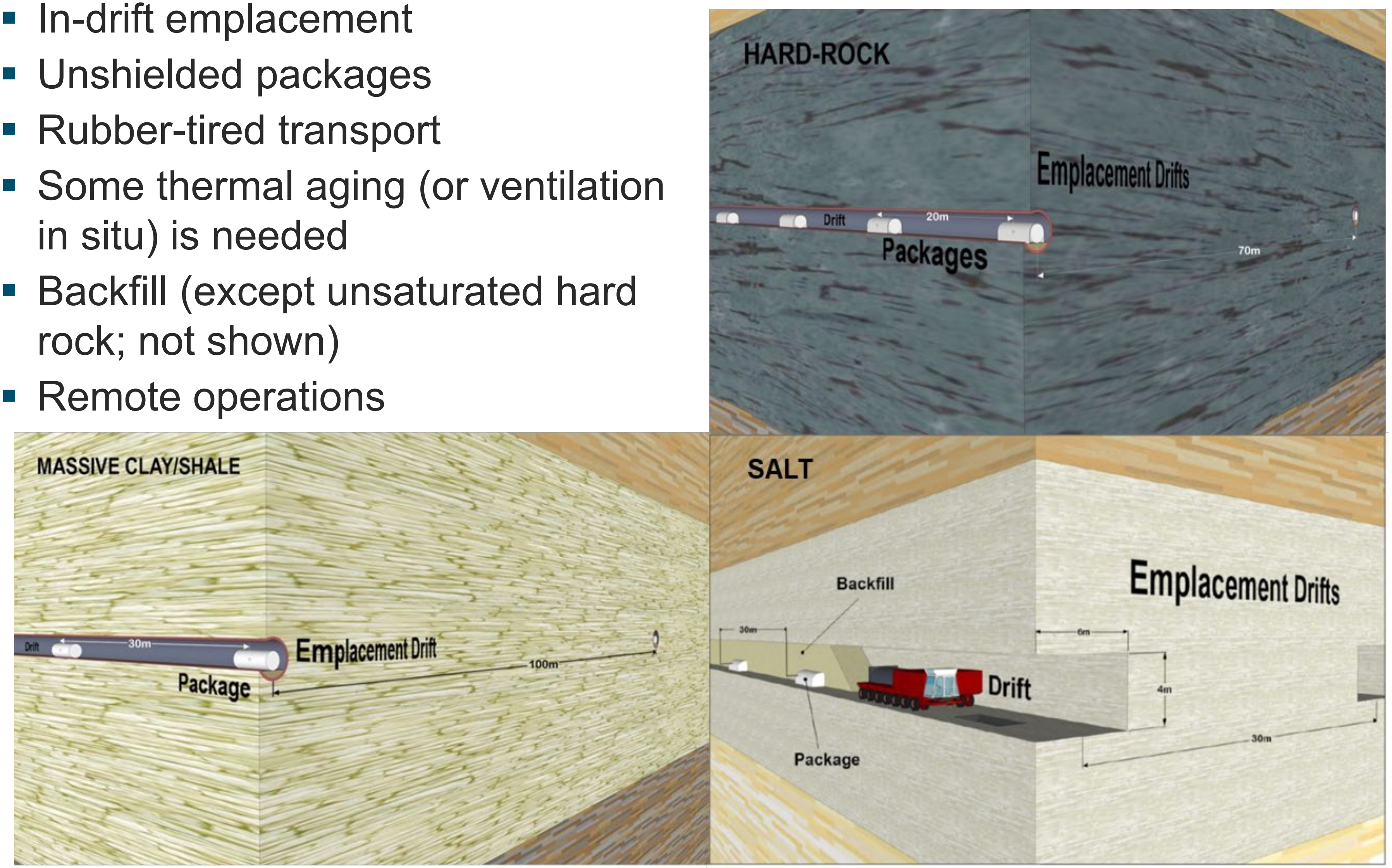
	Yucca Mountain Transport-Aging-Disposal (TAD) Canister	Largest DPC (3 major vendors) *
Capacity	**21-PWR/44-BWR**	**37-PWR/89-BWR**
Diameter	**1.69 m**	**1.92 m**
Length	**5.39 m**	**4.87 m**
Weight	**49.3 MT (loaded)**	**52.9 MT (loaded)**

- Conclusions:
  - Handling and packaging of DPCs for disposal is within the industrial state of practice
  - TAD canisters would be robust

* See example DPC dimensions, previous slide

DPC Direct Disposal Concepts

- In-drift emplacement
- Unshielded packages
- Rubber-tired transport
- Some thermal aging (or ventilation in situ) is needed
- Backfill (except unsaturated hard rock; not shown)
- Remote operations



(Hardin et al. 2013. FCRD-UFD-2013-000171 Rev. 1)

Why Thermal Limits for Disposal?

- Cladding protection (ISG-3 Rev. 3 limits adapted to postclosure, e.g., max. 350ºC)
- Packaging material limits (de-alloying/sensitization, e.g., 300ºC for Alloy 22)
- Repository temperature limits
  - Buffer/backfill alteration (100 to 200ºC)
  - Microcracking of siliceous rock (~200ºC)
  - Salt decrepitation (~270ºC)
- Injectable fillers (limit internal pressure during filling operations)
- Waste package handling (e.g., 18 kW/package for YM transport-emplacement-vehicle)

DPC Thermal Power Limits for Storage and Transportation

- Example thermal limits for licensed DPC storage/transport systems (Greene et al. 2013)

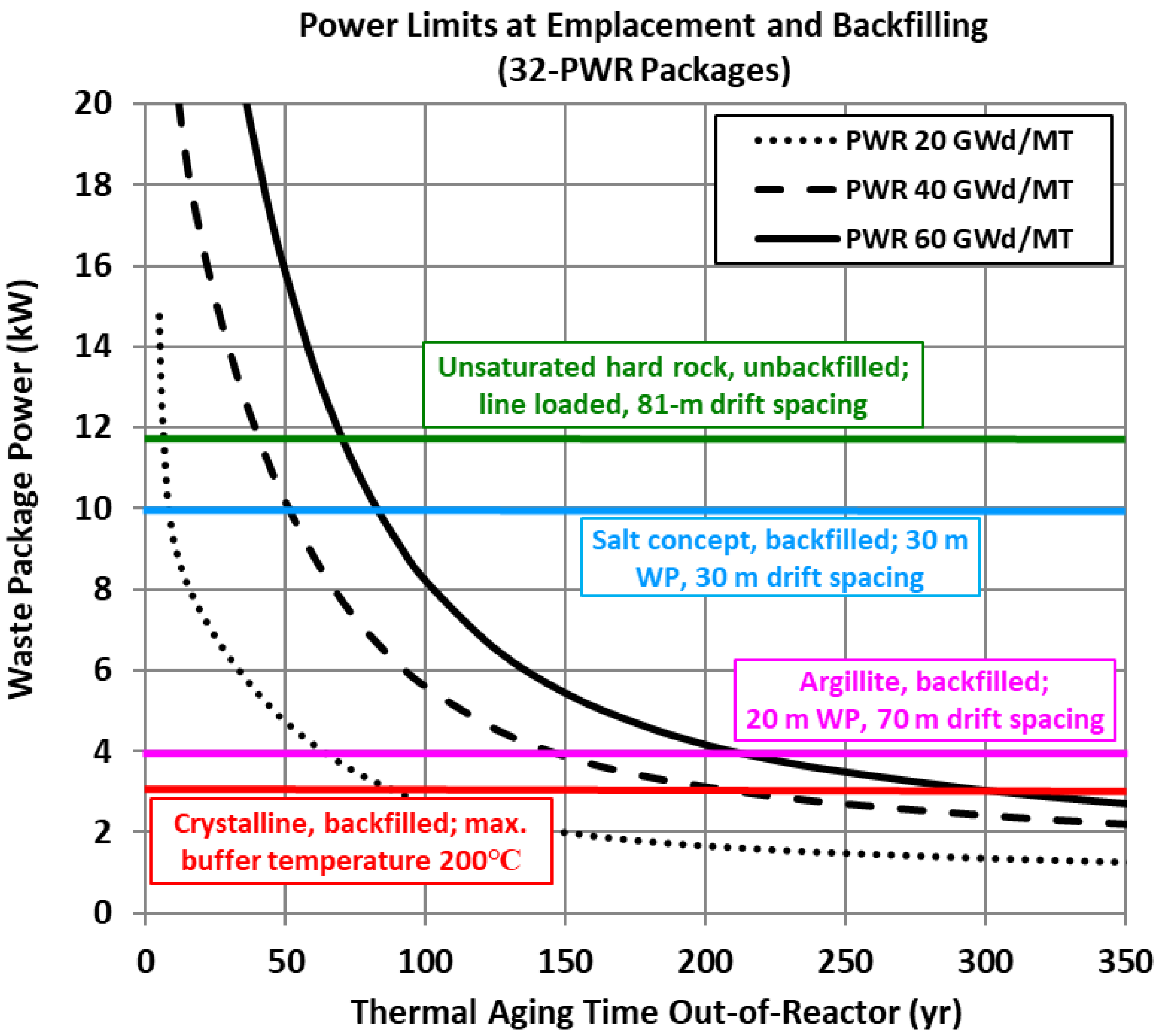
S&T DPC System	Cap.	Wt. Loaded	Heat Rejection	Licensing	Storage	Transport
		MT	**Storage/Transport., kW**	Status (2013)	Cask System	Cask System
MPC-24 series	24 PWR	40.9	**36.9 / 20.0** **19.0 / 20.0**	S&T	HI-STORM 100/100U HI-STAR 100	HI-STAR 100
MPC-32 series	32 PWR	40.9	**36.9 / 20.0**	S&T	HI-STORM 100/100U HI-STAR 100	HI-STAR 100
MPC-68 series	68 BWR	40.9	**36.9 / 18.5** **18.5 / 18.5**	S&T	HI-STORM 100/100U	HI-STAR 100
MPC-37	37 PWR	52.9	**47.0 / 38.0**	S	HI-STORM FW/UMAX	HI STAR 190
MPC-68 series	68 BWR	52.9	**46.3 / 38.0**	S	HI-STORM FW/UMAX	HI STAR 190
TSC Class 1-3	24 PWR	33.1	**23.0 / 20.0**	S&T	VCC Class 1-3	UTC
TSC Class 4-5	56 BWR	34.4	**23.0 / 16.0**	S&T	VCC Class 4-5	UTC
Magnastor PWR	37 PWR	46.6	**35.5 / 33.0**	S&T	VCC	MAGNATRAN
Magnastor BWR	87 BWR	47.0	**35.5 / 33.0**	S&T	VCC	MAGNATRAN
NUHOMS 24 series	24 PWR	37.3 - 43.0	**24.0 - 40.8 / 24.0 - 32.0**	S	HSM-H	MP187/MP197 MP197HB
NUHOMS 32 series	32 PWR	40.1 - 50.0	**24.0 - 40.8 / 24.0 - 32.0**	S	HSM 80 or 102 HSM-H or 102 HSM "Advanced"	MP197HB MP187/MP197
NUHOMS 37 series	37 PWR	49.1 - 49.7	**30.0 / 30.0**	S&T	HSM-H	MP197HB
NUHOMS 61 series	61 BWR	40.2 - 42.3	**18.3 - 31.2 / 15.9 - 31.2**	S&T	HSM 80 or 120 HSM-H or -HS HSM "advanced"	MP197/MP197HB
NUHOMS 69BTH	69 BWR	48.2	**26.0 - 32.0 / 26.0 to 32.0**	T	HSM-H/HS	MP197/MP197HB

Greene et al. 2013. *Storage and Transport Cask Data for Used Commercial Nuclear Fuel*. ATI-TR-13047. Energx. Oak Ridge, TN.

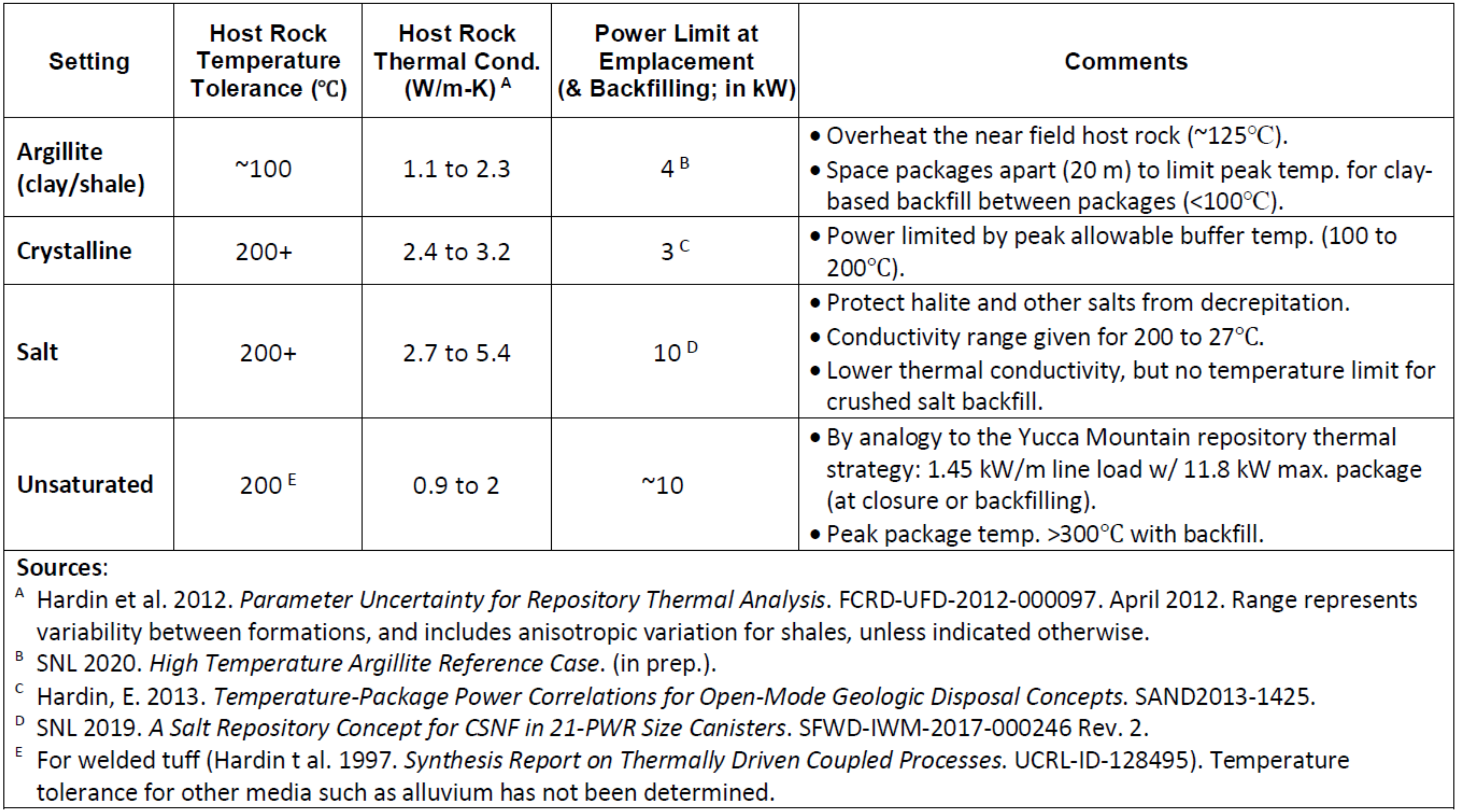
DPC Thermal Power Limits for Transportation vs. Disposal

- Typical disposal power limits:
  - Yucca Mountain License Application: ≤ 18 kW/package at emplacement; ≤ 11.8 kW/package at closure
  - Emplacement power limits of 10 kW/package or less, for generic disposal concepts in various media
- Conclusions:
  1) Thermal power limits for storage and transport are greater than limits for disposal, and
  2) Thermal aging (or ventilation in situ) will be needed for DPC direct disposal, with duration depending on EBS and host rock temperature limits

DPC Thermal Power Limits for Different Disposal Concepts



DPC Direct Disposal Concepts: Thermal Comparison



Setting	Host Rock Temperature Tolerance (°C)	Host Rock Thermal Cond. (W/m-K)[A]	Power Limit at Emplacement (& Backfilling; in kW)	Comments
Argillite (clay/shale)	~100	1.1 to 2.3	4[B]	- Overheat the near field host rock (~125°C). - Space packages apart (20 m) to limit peak temp. for clay-based backfill between packages (<100°C).
Crystalline	200+	2.4 to 3.2	3[C]	- Power limited by peak allowable buffer temp. (100 to 200°C).
Salt	200+	2.7 to 5.4	10[D]	- Protect halite and other salts from decrepitation. - Conductivity range given for 200 to 27°C. - Lower thermal conductivity, but no temperature limit for crushed salt backfill.
Unsaturated	200[E]	0.9 to 2	~10	- By analogy to the Yucca Mountain repository thermal strategy: 1.45 kW/m line load w/ 11.8 kW max. package (at closure or backfilling). - Peak package temp. >300°C with backfill.

Sources:

[A] Hardin et al. 2012. *Parameter Uncertainty for Repository Thermal Analysis*. FCRD-UFD-2012-000097. April 2012. Range represents variability between formations, and includes anisotropic variation for shales, unless indicated otherwise.

[B] SNL 2020. *High Temperature Argillite Reference Case*. (in prep.).

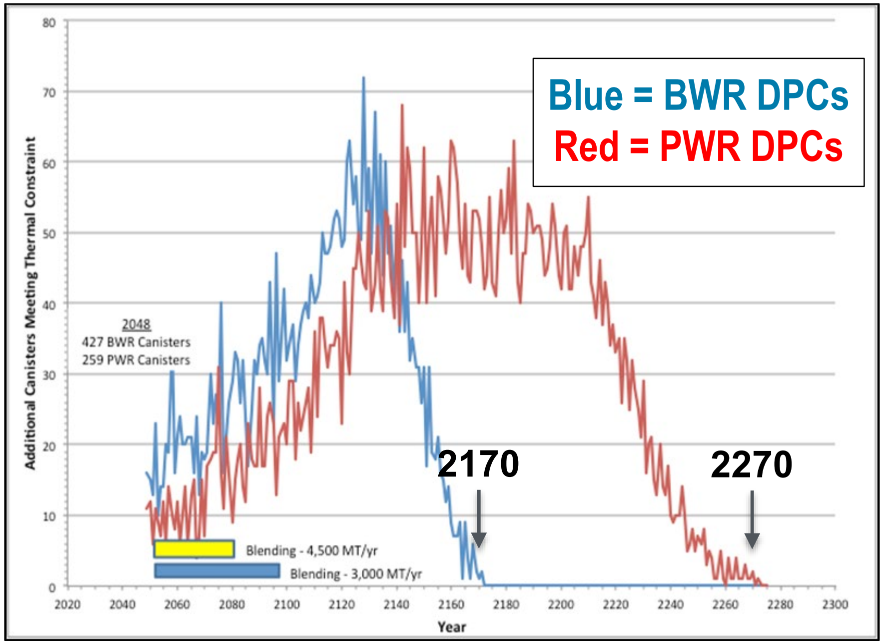
[C] Hardin, E. 2013. *Temperature-Package Power Correlations for Open-Mode Geologic Disposal Concepts*. SAND2013-1425.

[D] SNL 2019. *A Salt Repository Concept for CSNF in 21-PWR Size Canisters*. SFWD-IWM-2017-000246 Rev. 2.

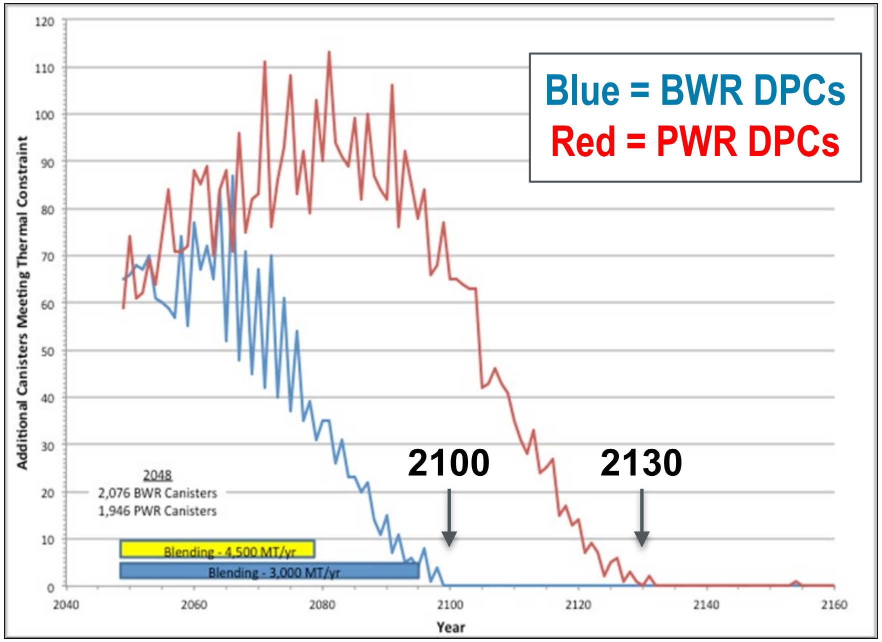
[E] For welded tuff (Hardin t al. 1997. *Synthesis Report on Thermally Driven Coupled Processes*. UCRL-ID-128495). Temperature tolerance for other media such as alluvium has not been determined.

(Hardin et al. 2013. FCRD-UFD-2013-000171 Rev. 1)

Projections of All DPCs to be Loaded Cooling: to Meet Disposal Thermal Power Limits



Number of DPCs that cool to **4 kW** each year (argillite or crystalline disposal concepts with clay-based buffer/backfill.



Number of DPCs that cool to **10 kW** each year (salt, unsaturated hard rock disposal concepts.

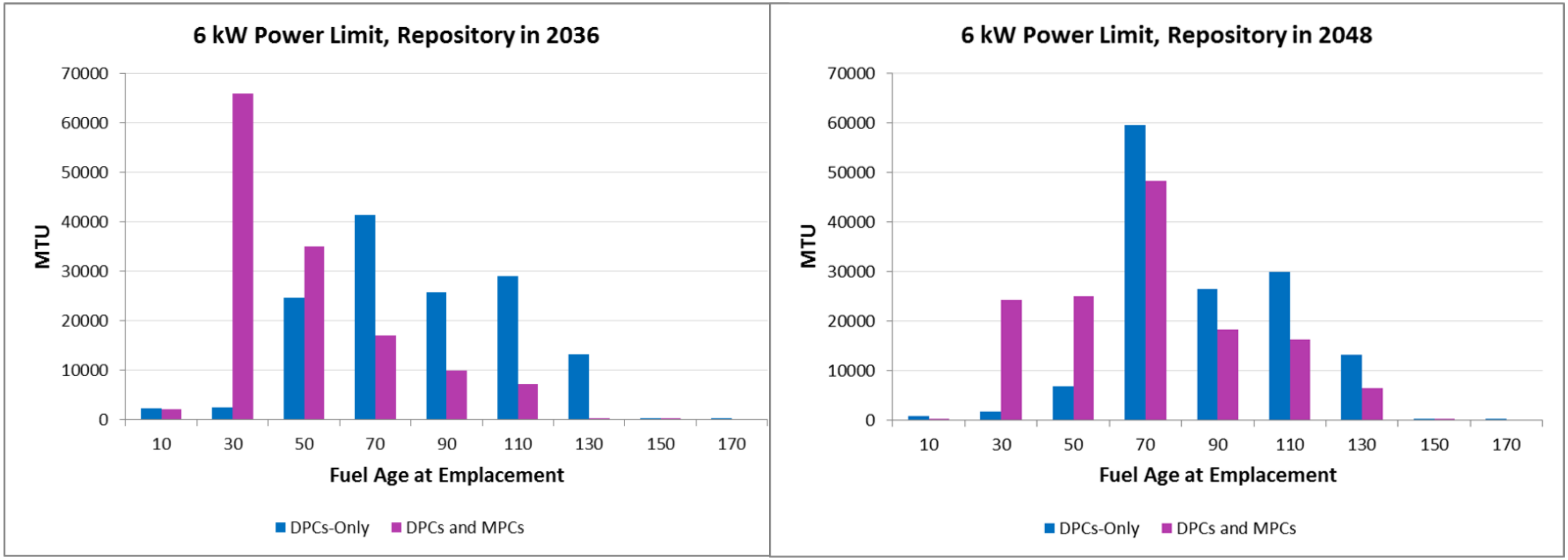
FCRD-UFD-2014-000069 Rev. 0 Investigations of Dual-Purpose Canister Direct Disposal Feasibility (FY14)

Fuel Age Out-of-Reactor at Disposal

Fuel age at emplacement is potentially important if constraints on canister or fuel condition are related to aging time.

- Minimum fuel age at emplacement is obtained by re-packaging all DPCs into smaller canisters (e.g., 4-PWR), thus decreasing thermal aging time.
- For a future transition from DPCs to smaller canisters, without re-packaging the DPCs, fuel age at emplacement is comparable to repackaging if the emplacement power limit is high enough (≥ 10 kW).
- To maintain comparable fuel age at emplacement for a lower emplacement power limit (6 kW) two changes would be needed:
  - Transition to smaller canisters, and
  - Early repository start (e.g., 2048 or sooner).

Fuel Age (out-of-reactor) at Emplacement: Example TSL-CALVIN Projection

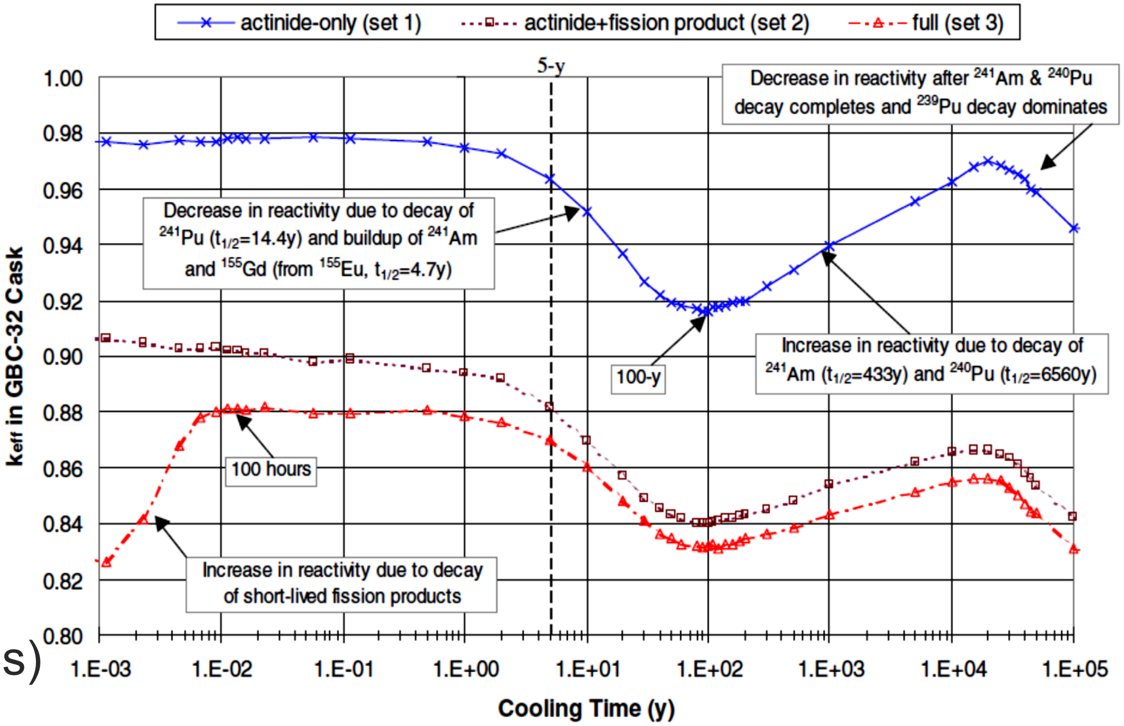


- DPC direct disposal compared to repackaging all fuel into purpose-designed 4 PWR/9 BWR packages (MPCs).
- Repackaging starts 5 years before repository opening.
- DPC case produces the oldest fuel at disposal because of thermal aging.
- MPC case produces the youngest because no thermal aging is needed after repackaging.

FCRD-UFD-2014-000069 Rev. 0 Investigations of Dual-Purpose Canister Direct Disposal Feasibility (FY14)

Postclosure Nuclear Criticality Control

- **Disposal Environment**
  - Groundwater availability
  - Chloride in groundwater
- **Moderator Exclusion**
  - Overpack integrity
- **Moderator Displacement**
  - Fillers
- **Add Neutron Absorbers**
  - Fillers (e.g., B_4C loaded)
  - Control hardware (future DPCs)
- **Zone Loading**
- **Criticality Analysis Methodology**
  - Burnup credit, as-loaded, stylized degradation cases
  - Peak reactivity occurs at >10,000 years
  - Reactivity margin (many DPCs)



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

Neutron multiplication factor (k_{eff}) vs. time
Generic burnup-credit 32-PWR cask
PWR fuel (4% enriched, 40 GW-d/MT burnup)

Wagner and Parks 2001 (NUREG/CR-6781)

Postclosure Criticality Control Measures (1/2)

- **Alternative: Reactivity Margin**
  - Many (not all) DPCs are subcritical in stylized degradation cases.
- **Alternative: Criticality Control Features**
  - PWR or BWR fuel assembly disposal control rods (EPRI 2008)
  - BWR fuel rechanneling *
  - Chevron inserts (patents extant) *
  - Zone loading (future DPCs; EPRI 2008)

* Requires corrosion resistant neutron absorber material

- **Alternative: Injectable Fillers**
  - Cut off covers over existing DPC vent/drain ports
- **Alternative: High-Performance Disposal Overpack**
  - May not be sufficiently reliability for low-probability exclusion of internal criticality

EPRI (Electric Power Research Institute) 2008. *Feasibility of Direct Disposal of Dual-Purpose Canisters: Options for Assuring Criticality Control*. #1016629.

Postclosure Criticality Control Measures (2/2)

- **Cut DPC Lids Off?**
  - Skiving (wet or dry)
  - Dry filler tests: steel shot (Cogar 1996); glass beads (Forsberg 1997)
  - Particle filling would be done dry (inert gas cover)
  - Criticality control hardware installation (e.g., disposal control rods, rechanneling) could be done wet
  - Requires re-welding

Cogar, J. 1996. *Waste Package Filler Material Testing Report*. BBA000000-01717-2500-00008 Rev 01. OCRWM.

Forsberg, C.W. 1997. *Description of the Canadian Particulate-Fill Waste Package (WP) System for Spent Nuclear Fuel (SNF) and its Applicability to Light-Water Reactor SNF WPs with Depleted Uranium Dioxide Fill.* ORNL/TM-13502.

Summary (1/3)

Technical feasibility investigations for direct disposal of commercial SNF in DPCs established:

- ***At least some DPCs are disposable for all of the generic geologic settings evaluated (and excluding postclosure criticality from PA on low probability).***
- **Preclosure operational safety:** Similar to the current state-of-the-practice in fuel handling and packaging
- **Postclosure waste isolation:** No substantial difference compared to site-specific, purpose-designed, possibly smaller canisters.
- **Engineering challenges:** Can be met (including a first-of-a-kind heavy shaft hoist if needed)

Summary (2/3)

- **Postclosure internal criticality:**
  - Unlikely for disposal concepts that don’t allow package flooding
  - A fraction of existing DPCs have sufficient reactivity margin to remain subcritical if degraded and flooded
  - There are many types of DPCs (50 or more) with various types of degradation on exposure to ground water, and different fuel characteristics
- **Thermal management:**
  - Disposal power limit of 10 kW allows 98% of projected DPCs to cool by 2130 (6 kW DPCs by 2170, 4 kW BWR DPCs by 2170)
  - Favors disposal concepts with ≥ 200ºC temperature tolerance (e.g., at package surface) and greater thermal conductivity
  - BWR DPCs cool significantly faster (e.g., 4 kW BWR DPCs cool ~100 yr sooner than PWR DPCs)

Summary (3/3)

Review of Recommendations from Technical Feasibility Study through 2017

- Information needs analyzed (SNL 2015)
- Continue to collect and analyze information on existing DPCs
- Develop burnup credit approach for BWR fuel
- Ensure DPC service lifetime (≥100 yr) needed for thermal aging
- Investigate disposal concepts with greater host-medium thermal conductivity and temperature tolerance
- Research injectable fillers for postclosure criticality control in DPCs by moderator displacement
- Perform consequence analysis for criticality event exclusion from, or inclusion in performance assessment

SNL 2015. *Summary of Investigations on Technical Feasibility of Direct Disposal of Dual-Purpose Canisters*. FCRD-UFD-2015-000129 Rev. 0

Liljenfeldt, H. et al. 2016. Sum*mary of Investigations on Technical Feasibility of Direct Disposal of Dual-Purpose Canisters*. SFWD-SFWST-2017-000045 (calculations update to SNL 2015).

Questions?