Integration of the Back-End of the Commercial Nuclear Fuel Cycle: Managing Commercial Spent Nuclear Fuel from Generation to Disposal

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Back End of Commercial Nuclear Fuel Cycle

- "Back End of NFC" starts when spent nuclear fuel is pulled out of reactor and ends with its permanent disposal in a deep geologic repository
- BENFC today not what was contemplated 10 years ago
- BENFC highly compartmentalized from the technical, operational and regulatory perspectives
- Current CSNF management practices might force technically possible, but sub-optimal solutions with considerable implications in terms of cost, schedule, and other issues, such as social and political acceptability

US CSNF Management System: Up to 2010

- **Geologic Disposal at Yucca Mountain, NV**
- **BENFC "integrated" primarily by use of Transportation, Aging and Disposal canister (TAD)**
  - **~90% of CSNF assemblies (~56K MTHM) loaded directly from pools into TADs at reactor sites, transported to YM, aged and disposed of without need to open TADs and repackage the fuel. TADs loaded to meet disposal regulatory requirements.**
  - **~10% of CSNF (~7K MTMH) transported to YM in dual-purpose (i.e., storage & transportation) casks (DPCs) or truck casks (uncanistered) loaded into TADs at the Waste Handling Facility.**

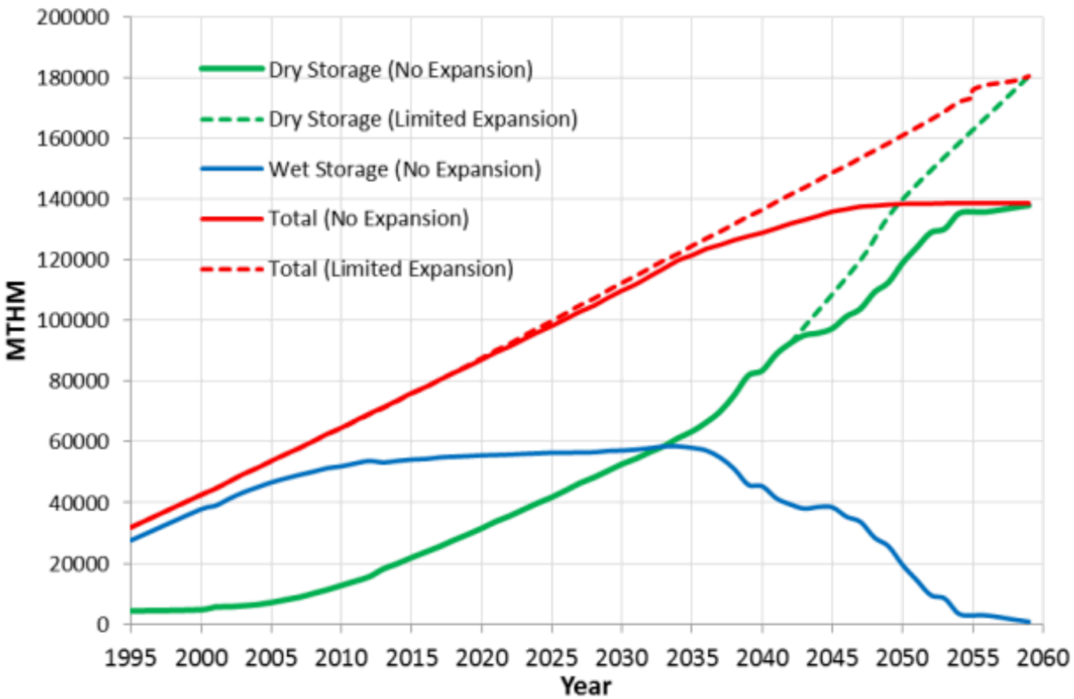
	TADs	DPCs	Truck Casks
Average Time out of Reactor	14 Years	41 Years	23 Years
Average Burn Up	48.4 GWD/MT	29.9 GWD/MT	41.9 GWD/MT
Total Number	6494	308	2,650
Total MTHM	55,565	2,992	4,442

US CSNF Management System: Now

- 99 operating reactors at 61 sites in 2015
  - 65 pressurized water reactors (PWR)
  - 34 boiling water reactors (BWR)
- Because of no final disposal site and continued safe at-reactor wet and dry storage, Independent Spent Fuel Storage Facilities (ISFSI's) at operating and shutdown reactor sites is the current practice
- At end of 2013, 71K MTHM in storage at reactor sites
  - 49K MTHM in wet storage & 22K MTHM in dry storage
- At mid 2015, ~ 78K MTHM in storage at reactor sites
  - ~53K MTHM in wet storage & >25K in dry storage
- ~140K MTMM by 2048 when a new CSNF repository is expected to be available (US DOE, January 2013)

Yucca Mountain repository statutory limit 70K MTHM total; 63K MTHM CSNF.

Future Projections



Source: Hardin, E., C.T. Stockman, E.A. Kalinina and E.J. Bonano 2013. "Integration of Long-Term Interim Storage of Spent Fuel with Disposal." ASTM Committee C26-Nuclear Fuel Cycle Workshop, Avignon, France. 17-21 June, 2013.

Approx. 71,000 MTHM (metric tons heavy metal) of SNF in storage in the U.S. (as of 2013)

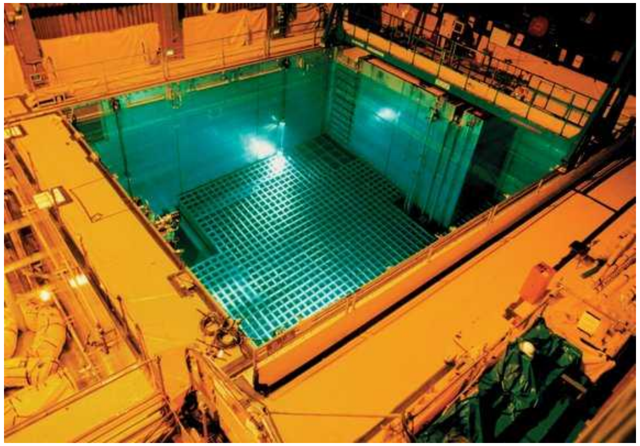
- **22,000 MTHM in dry storage at reactors, in approximately 1850 cask/canister systems**
- **Balance in pools, mainly at reactors**

Approx. 2000 MTHM of SNF generated nationwide each year

- **Approximately 200 new DPCs are loaded each year because reactor pools are essentially at capacity**

Standard Industry Practice

On-site storage of spent nuclear fuel is the only option available

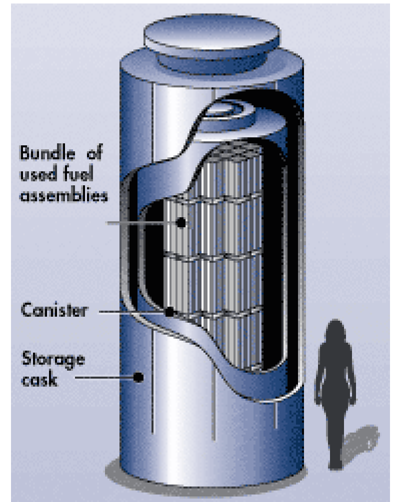


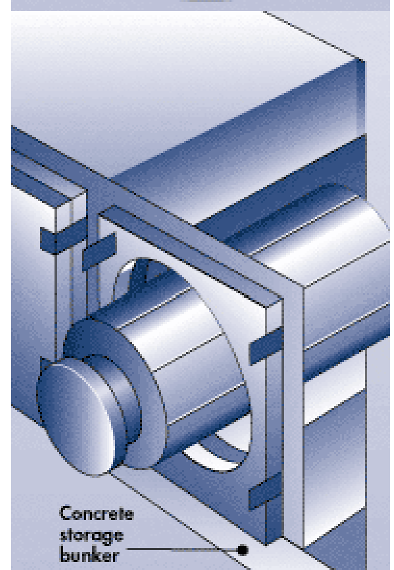
Pool Storage: essential to reactor operations, but nearing capacity, ~ 80% of existing US reactors have dry storage facilities on site

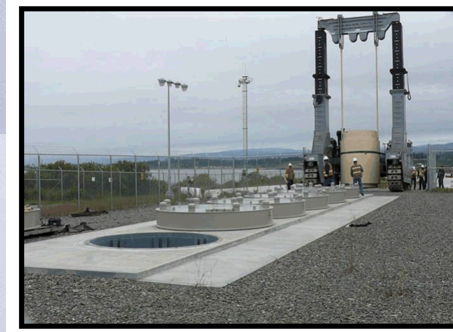
Dry Storage: horizontal and vertical concepts are in use. R&D in progress to support the technical basis for license extensions beyond original 20-yr period

Storage Terminology

- **Dual purpose canister (DPC)**
  - A canister that is certified for both storage and transportation of spent nuclear fuel
- **Dry cask/canister storage systems**
  - The most common type of dry storage cask system is the vertical cask/canister system shown above, in which the inner stainless steel canister is removed from the storage overpack before being placed in a shielded transportation cask for transport
    - Can be constructed both above and below grade
  - Horizontal bunker-type systems and vaults are also in use
  - Some older fuel is also stored as “bare fuel” in casks with bolted lids; few sites continue to load these systems
- **Multiple vendors provide NRC-certified dry storage systems to utilities**



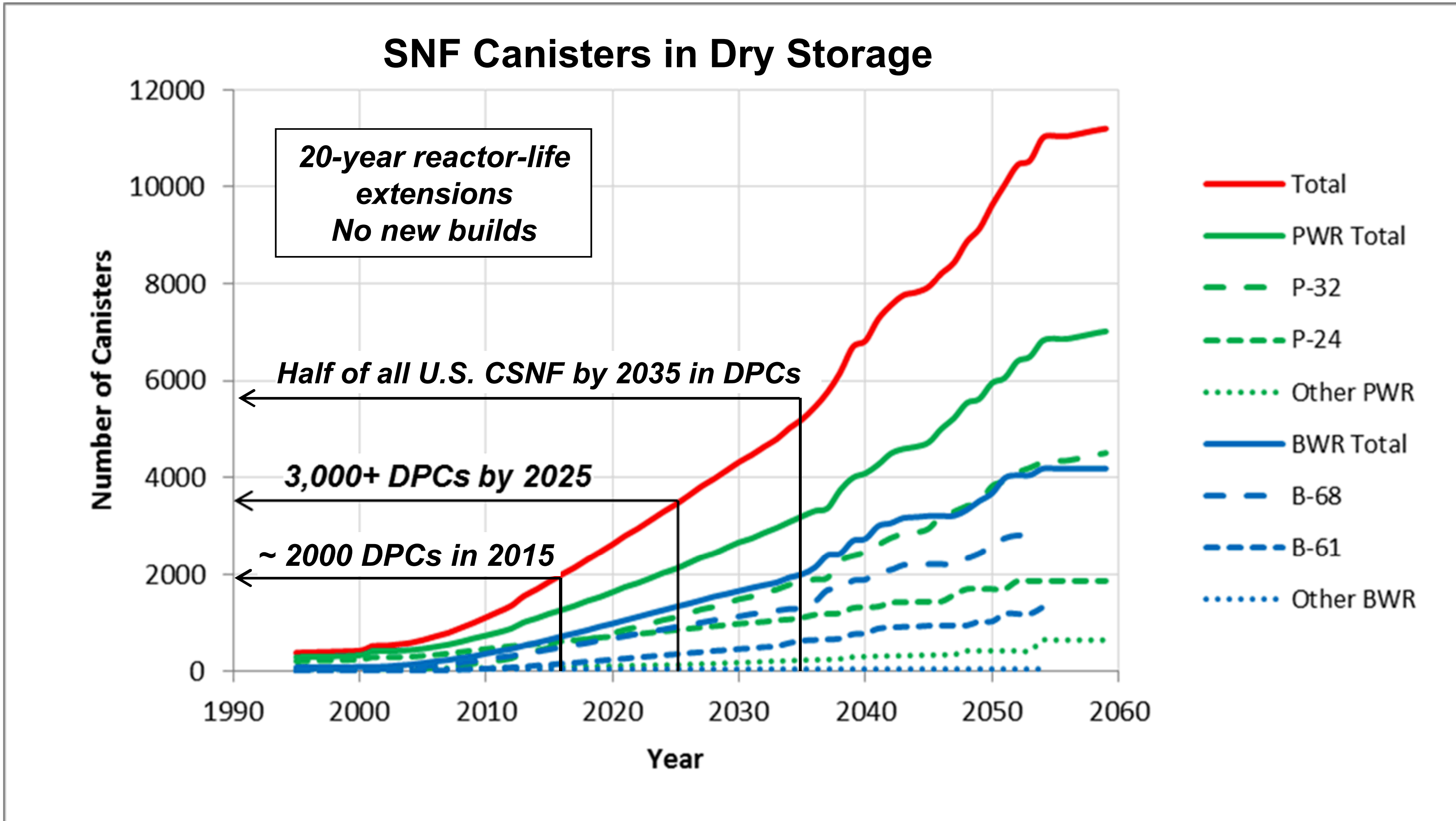




Dry Storage Dual-Purpose Canisters

- Large cylindrical canisters with passive cooling systems
- Can be loaded after 5 – 10 years of cooling in pool
- Incorporate criticality controls
- Can hold up to 37 PWR assemblies or 89 BWR assemblies
- Can accommodate SNF with burnup up to 66 GWd/mtU
- Weigh 58 tons when loaded with fuel (without cask)
- Most are designed to be used with transfer cask, storage cask, and transport cask (dual-purpose canister)
- Most are welded shut, although some are bolted
- Certificate of compliance is good for 20 years; extensions possible
- Each costs between $750,000 and $1,000,000

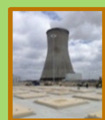
Current and Projected Accumulation of Used Commercial Reactor Fuel in Dry Storage (DPCs)



Current US CSNF Management System Components

UTILITY-OWNED

Spent Fuel Pools
(10 CFR Part 50)



ISFSIs
(10 CFR Part 72)

DOE-OWNED

Transportation:
(10 CFR Part 71)

DOE OR PRIVATELY-OWNED

Centralized Interim Storage
(10 CFR Part 72)

DOE-OWNED

Transportation:
(10 CFR Part 71)

DOE-OWNED

Unknown Disposal Site(s)
(10 CFR Part 60/63)

CSNF Path to Disposal

- Additional components in CSNF Management System
- Each component governed by different NRC regulation
- Hand-offs between different entities

Observations on Current Practice

- **Current practice is safe and secure**
  - **Extending current practice raises data needs; e.g., canister integrity, fuel integrity, aging management practices**
- **Current practice is optimized for reactor site operations**
  - **Occupational dose**
  - **Operational efficiency of the reactor**
  - **Cost effective on-site safety**
- **Current practice is not optimized for transportation or disposal**
  - **Thermal load, package size, and package design**

Placing spent fuel in dry storage in dual purpose canisters (DPCs) commits the US to some combination of three options

1) Repackaging spent fuel in the future
2) Constructing one or more repositories that can accommodate DPCs
3) Storing spent fuel at surface facilities indefinitely, repackaging as needed

Each option is technically feasible, but none is what was originally planned

Re-Packaging of CSNF for Disposal

- World-wide, no repositories have been designed to dispose of DPCs without repackaging
  - Yucca Mountain came closest, with TADs that held 21 PWR assemblies
    - Current DPC designs take up to 37 PWR assemblies
  - Most other nations limit disposal package size to 4 PWR assemblies, primarily for thermal load management
- ROM Cost of Repackaging for 140K MTHM > 2055: ~$36B*

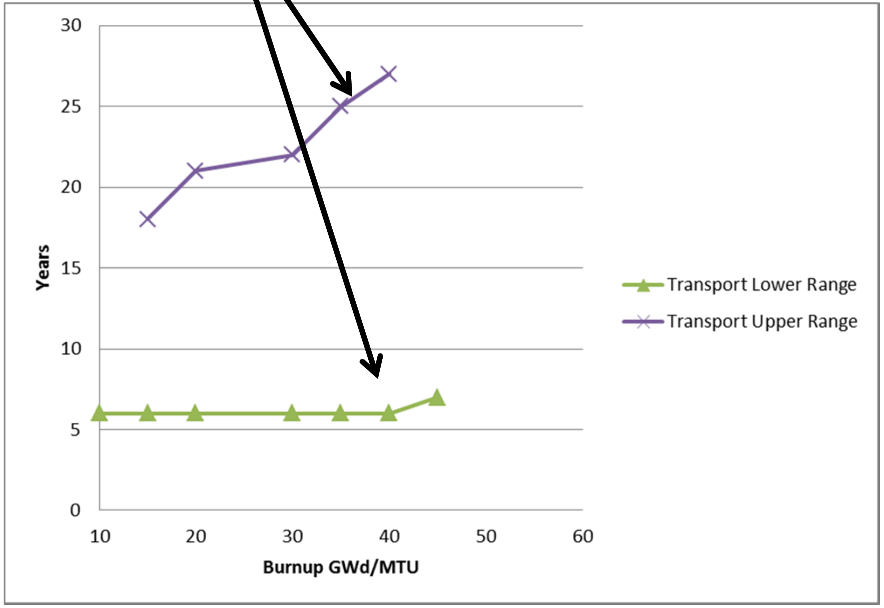
	Unit Cost	CSNF Qty. (MTMH)	Avg. DPC Capacity (MTHM)	# DPCs	Cost $B
Projected sunk costs based on DPC status quo:					
Procure, load and store existing DPCs ($/MTU)	100,000	25,000	12	2100	3
Cost to continue status quo through >2055 ($/MTU)	100,000	115,000	16.7	6895	11.5
Re-packaging costs for all fuel, current fleet estimate:					
Unload all DPCs ($/MTU)	10,000	140,000		8995	14
Transport and dispose of each DPC hull ($/DPC)	150,000			8995	1
Re-canister for disposal ($/MTU)	100,000	140,000			14
Re-packaging facility capital cost					5
Re-packaging facility operating cost for 30 years $/yr)	200,000,000				6
Total cost to make CSNF ready for disposal					36

*"Investigations of Dual-Purpose Canister Direct Disposal Feasibility", E. Hardin and E. Kalinina, Sandia National Laboratories; K. Banerjee, J. Clarity, R. Howard and J. Scaglione, Oak Ridge National Laboratory; J. Carter, Savannah River National Laboratory; SAND2015-1804 C, Waste Management 2015

Transportation Considerations

- Some DPCs may require decades of aging to cool spent fuel before they can be transported
  - High-burnup fuels may require longer aging
  - Cooling times are design-specific (in general, larger DPCs require longer cooling times)
- Transportation casks remain to be certified for some DPC systems

Range of aging times required before transport, shown as a function of burnup

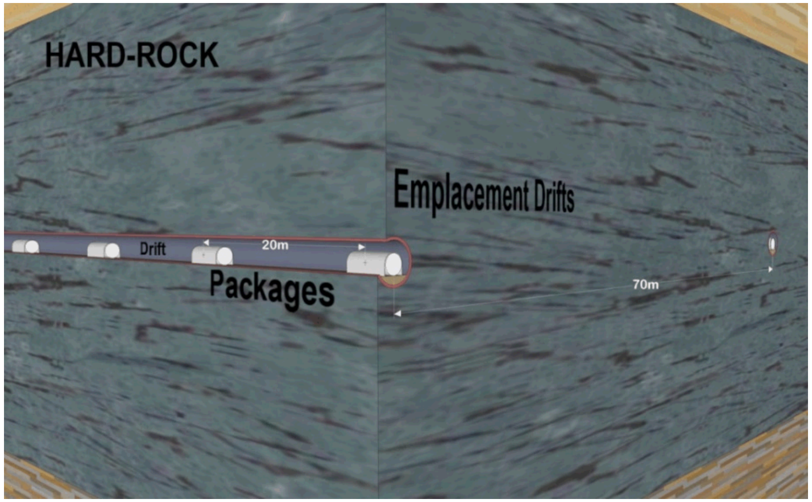


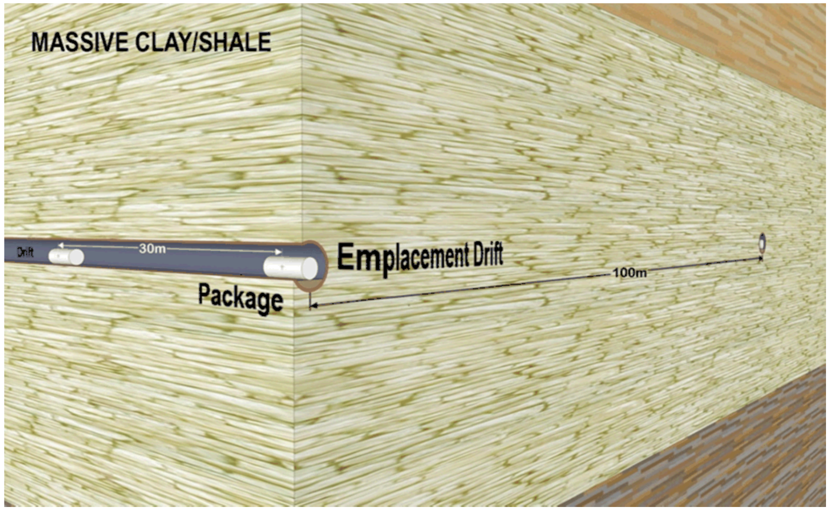
Source: Adapted from Stockman and Kalinina, SAND2013-2013P

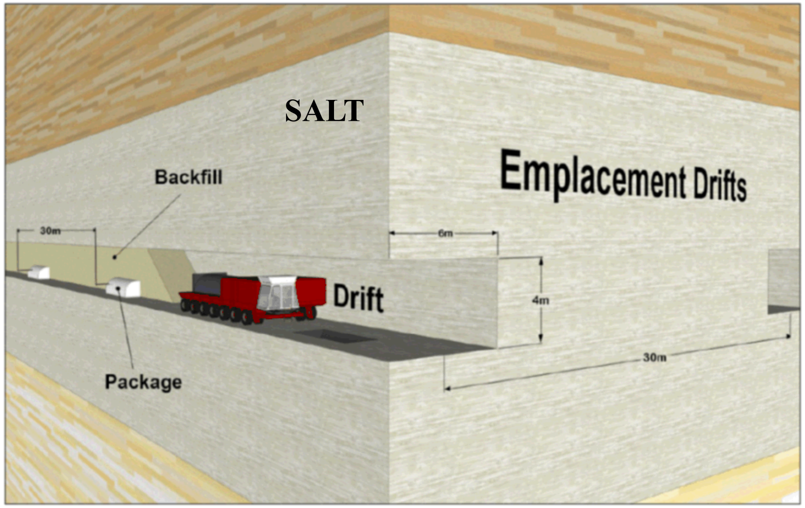
Minimum cooling times for multiple cask/canister systems, based on NRC certificates of compliance for specific designs as of 2013. Variation in times is due to the diversity of the current inventory, dominated by DPC size and heat transfer capabilities.

DPC Direct Disposal Concepts

- Engineering challenges (Shaft or ramp transport)
- In-drift emplacement
- Repository ventilation (except salt)
- Backfill prior to closure (except unsaturated)







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

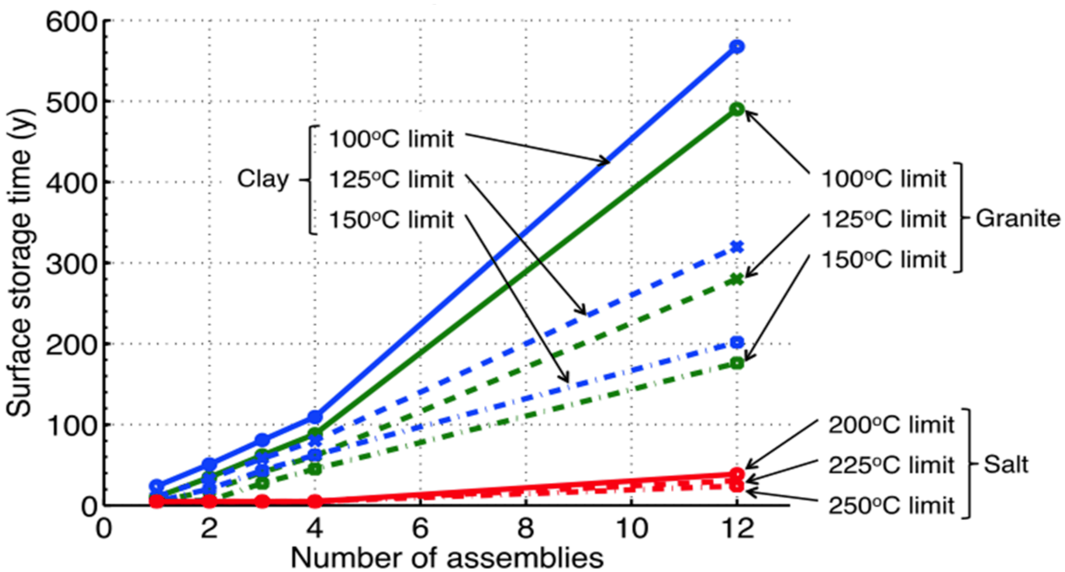
Repository Considerations: Thermal Management

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

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

Final temperature constraints will be site- and design-specific

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



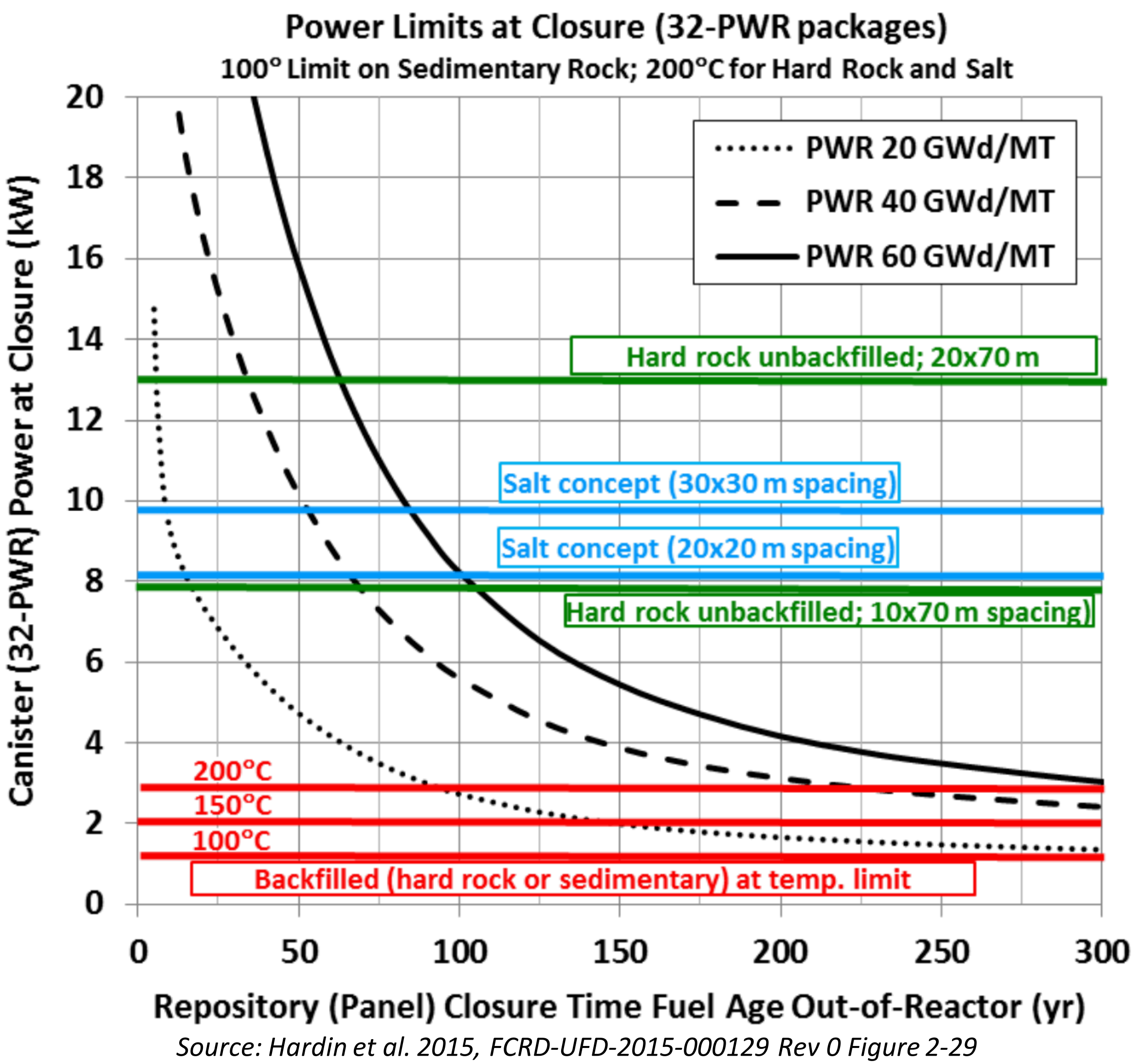
Thermal conductivity for all media selected at 100°C.

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

Repository thermal constraints can be met by

1) Aging
2) Ventilation in the repository
3) Decreasing package thermal output (size and burn-up)
4) Increasing package and drift spacing in the repository

Thermal Load Management (cont.)



Source: Hardin et al. 2015, FCRD-UFD-2015-000129 Rev 0 Figure 2-29

Higher burnup fuels require longer preclosure cooling times

Repository designs without backfill or in high-thermal-conductivity salt will need relatively shorter preclosure cooling times to accommodate large packages; underground spacing can have a large impact

Repository designs with thermal constraints on backfill will need long preclosure cooling times to accommodate large packages

Repository Considerations: Criticality Control

- Some already-loaded DPCs pose complications for licensing analyses of postclosure criticality control
  - Flooding by groundwater following canister degradation is a pre-requisite for criticality in any waste package
  - Al-based neutron absorbers used in some DPCs will degrade in water
  - Resulting reactivity increase can be offset by
    - High-reliability disposal overpacks
    - Uncredited margin in SNF configurations
    - High chloride content in groundwater (e.g., in salt)
  - Other options include
    - Open DPCs before disposal to add criticality controls
    - Include consequences of postclosure criticality in long-term performance estimates
  - Case-by-case analysis of individual DPCs may be needed for licensing (function of enrichment and burn-up)

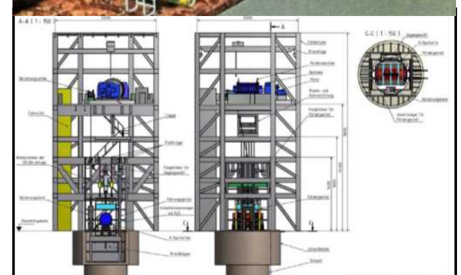
Other Considerations:
Waste Package Size

- **DPCs are massive, but not unprecedented**
  - Transportation, aging, and disposal canisters proposed for Yucca Mountain were in the range of sizes of existing DPCs
  - With disposal overpack and transport shielding, total mass could be on the order of 150 metric tons
- **Size poses engineering challenges for handling during both transportation and disposal, but options are available**

SKB Demo (90 MT), Äspö

Andra Funicular Concept

Wheelift® Transport-Emplacement Vehicle Concept



DBE Shaft Hoist Concept (85 MT)

Possible Options for an Integrated System

- **Introduce a standardized canister to be loaded at reactors in the future**
  - Selection of a standardized transportation, aging, and disposal (STAD) canister is repository-design and regulation specific
  - Loading STADs directly from reactor pools (as proposed for Yucca Mountain) is unlikely to happen before perhaps 2030, by which time more than 50,000 MTHM of SNF will be in DPCs
    - Later dates for repository and STAD selection will mean more fuel in DPCs
  - Lack of present incentive for utilities to use standardized canister
- **Repackaging of SNF from DPCs to STADs at a consolidated storage facility**
  - Cost and schedule of repackaging
  - Management of additional LLW stream (used DPCs)
- **Repository design options to handle multiple packaging systems**
  - Plan now for disposal of some DPCs, repackaging of others
- **Cost considerations–number of handling operations, number of packages, repository design, and complexity of licensing**

Note: the DOE has relevant work in progress in each of these areas

International Perspectives

- ***Potential Interface Issues in Spent Fuel*** **Management, IAEA- TECDOC 1774, 2015:**
  - **"A systems approach is needed to ensure that influences from and impacts on all phases of [the back end of nuclear] fuel cycle are taken into account when making decisions."**
  - **"The biggest uncertainty in successfully integrating the [back end of the nuclear fuel cycle] is the uncertainty relative to the end point." In the US, the "end point" is geologic disposal.**
  - **Successful integration requires an understanding of the full cycle and the willingness to make trade-offs [emphasis added] that assure success over all phases of the [back end of the nuclear fuel cycle] rather than optimizing for particular interfaces …"**
  - **"Effective integration begins early in the planning process. Opportunities are lost if interfaces are not identified and addressed in the early stages of each of the [back end of the nuclear fuel cycle] phases."**

Moving Forward

- **Factors to consider:**
  - **What would a better fuel management system look like?**
  - **What metrics should we use to judge a spent fuel management system? (e.g., cost, safety, security?)**
  - **What barriers prevent the US from implementing a better system?**
  - **Are the benefits of a better system worth the cost?**
  - **What can the nation do now that will impact future practice?**
  - **Can we plan for flexibility and contingency in case a stable national policy is not achieved?**
  - **What are the implications of doing nothing now?**

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