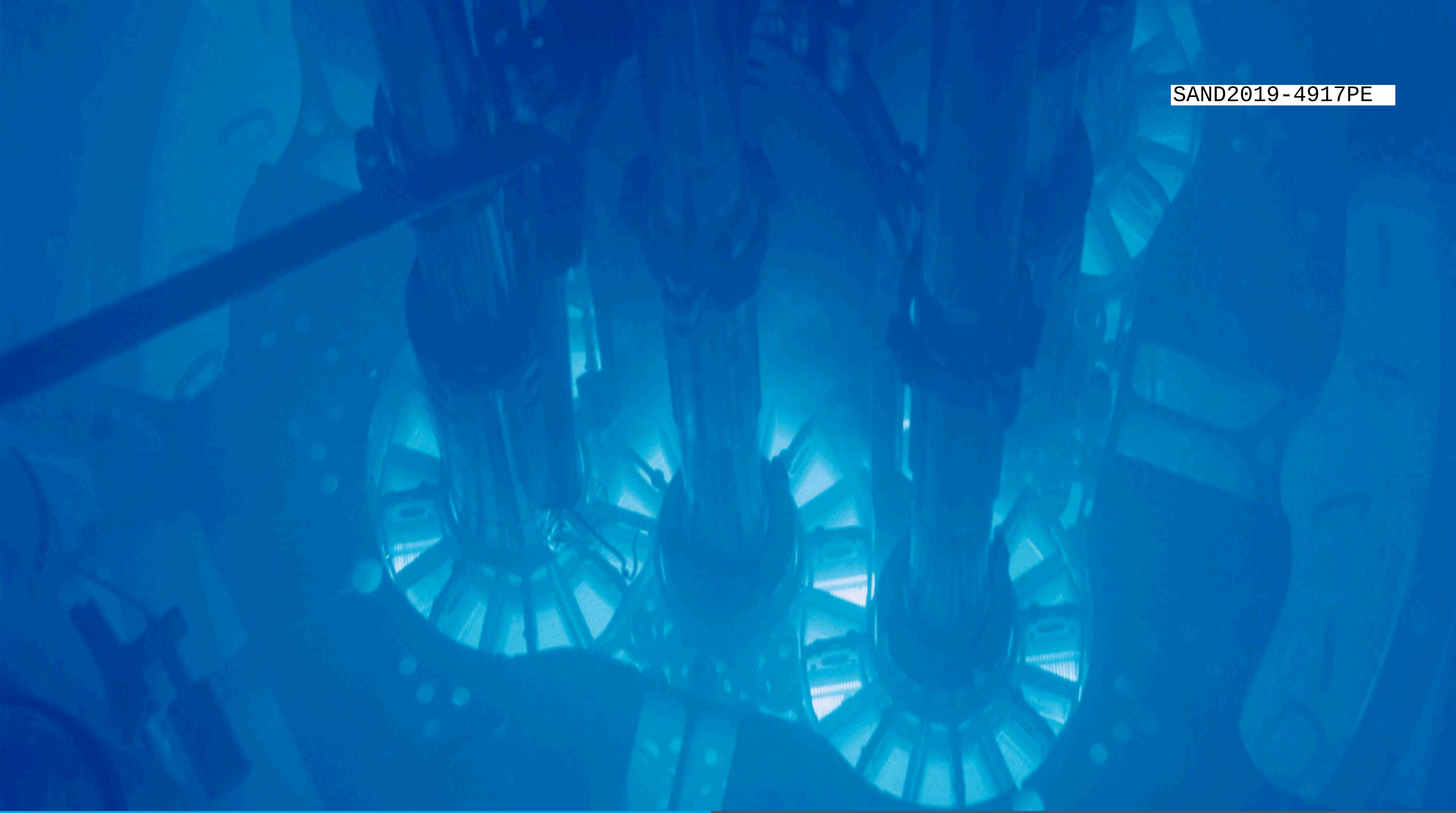


SAND2019-4917PE

# Overview of U.S. R&D Strategy for Disposition of Spent Fuel in DPCs

ENRESA – DOE/SNL Visit
May 9-10, 2019
Madrid, Spain

Ernest Hardin, Sandia National Laboratories

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. Approved for Unclassified, Unlimited Release (SAND2019-*****).

# Notices

This is a technical presentation that does not take into account the contractual limitations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). Under the provisions of the Standard Contract, DOE does not consider spent nuclear fuel in canisters to be an acceptable waste form, absent a mutually agreed-to contract amendment. To the extent discussions or recommendations in this presentation conflict with the provisions of the Standard Contract, the Standard Contract provisions prevail.

# Outline

- **Background on DPCs in the U.S.**
- **Previous DPC disposal feasibility studies**
- **DPC disposition R&D and implementation strategy**
- **Approach to injectable fillers**
- **Exclusion of postclosure criticality on low-consequence, background**

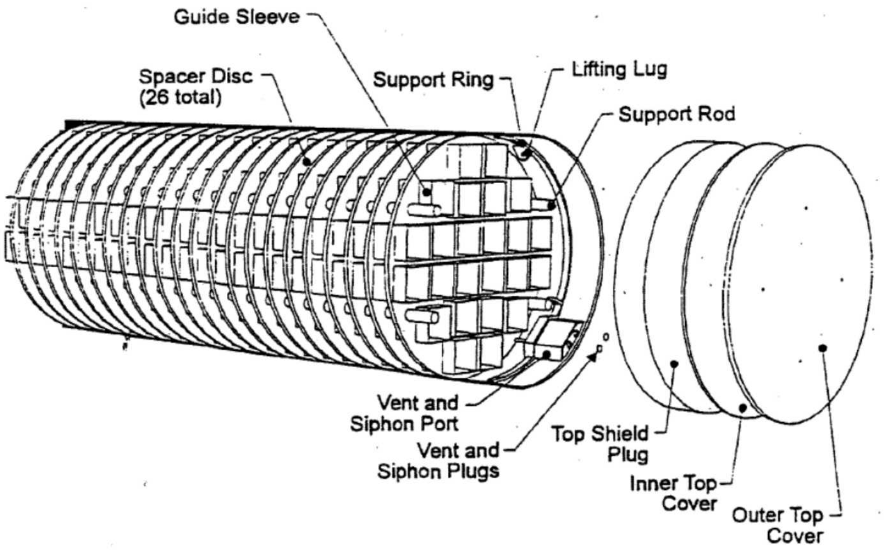
# Background on DPCs in the U.S.

# DPC Terminology

- **Canister** ≡ Sealed, unshielded vessel containing spent fuel, for use with various overpacks. Typically welded closure.
- **Dual-Purpose Canister** ≡ Dry storage canister that has been, or can be, licensed by the NRC for transportation also. Three major U.S. vendors: Transnuclear/Orano, Holtec, and NAC International.
- **Storage Cask** ≡ Shielded container for stationary storage. Typically stationary, with bolted closure.
- **Transportation Cask** ≡ Shielded container for transporting SNF in canisters (or as "bare" fuel assemblies). Bolted closure.
- **Transfer Cask** ≡ Used locally to transfer unshielded canisters from fuel pools to storage casks, or from storage casks to transport casks.
- **Multi-Purpose Canister** ≡ A canister that can be licensed for storage, transportation, and disposal.

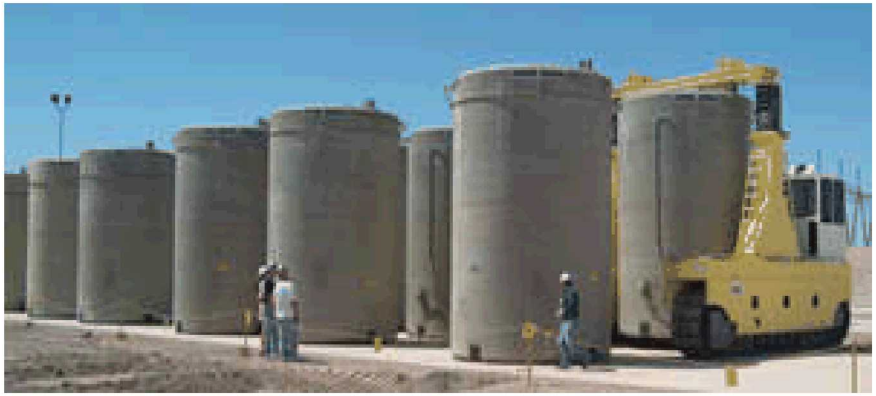
# Typical DPC Canister/Cask System – NUHOMS®

- NUHOMS® (TransNuclear/Orano) horizontal storage systems
- ~1/3 of existing U.S. DPC fleet
- NUHOMS line varies with capacity, PWR & BWR fuel types
- Shell is welded SS304; basket and plug materials vary



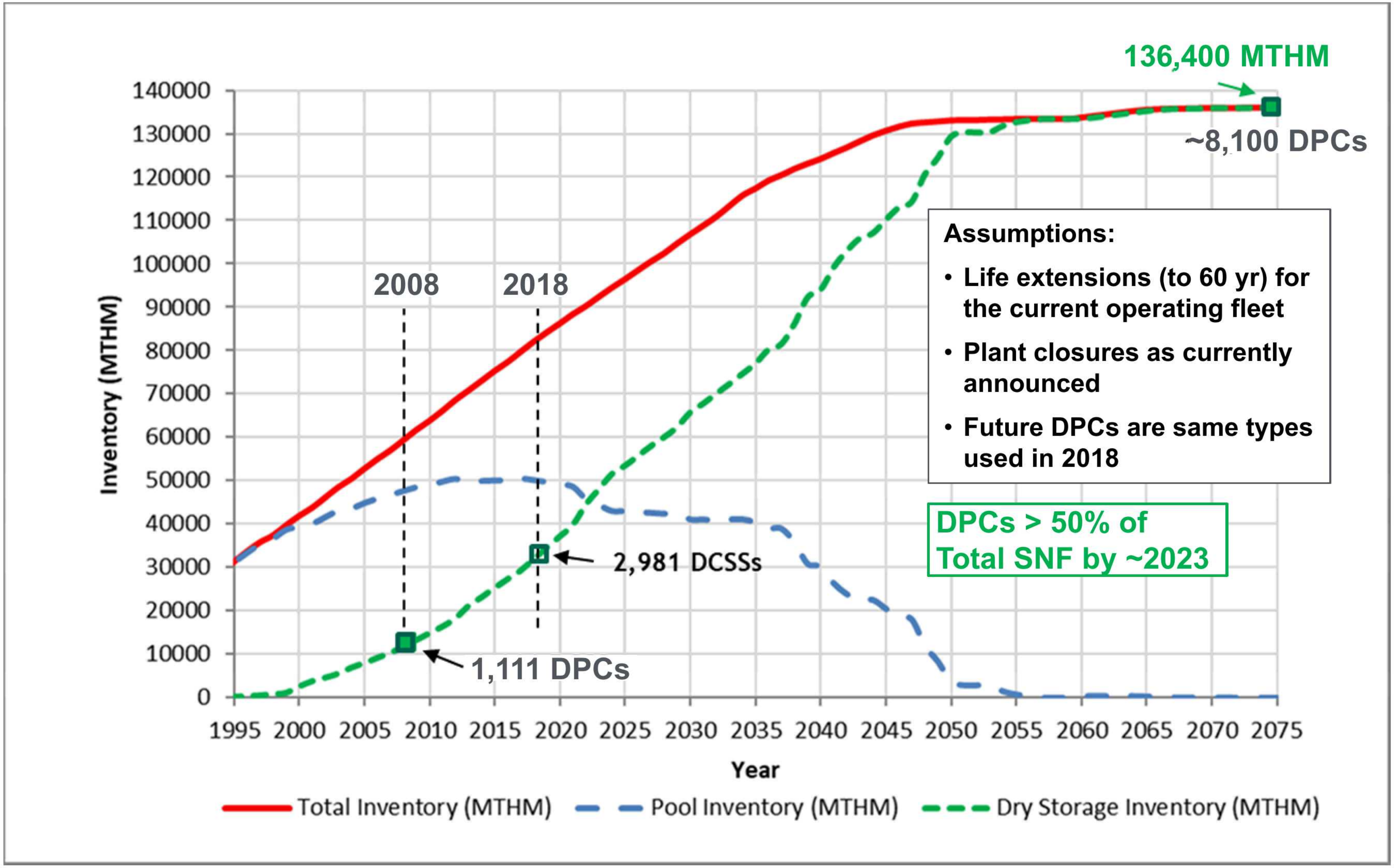
# Typical, Recent Large DPC System Designs – Magnastor®

- Magnastor® DPC system (NAC International)
- Capacity 37-PWR (or BWR equiv.)
- Thermal limits: 35.5 kW storage/24 kW transport
- Fuel cool time >4 yr out-of-reactor
- Design basis: burnup credit analysis, heat rejection features, transport needs.



Pictures and data from NAC International website

# TSL-CALVIN* Projection of SNF Accumulation in Pools and Dry Storage (MTU)




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

# Potential Benefits from Direct Disposal of SNF in DPCs of Existing Designs

- Less collective worker dose
  - Up to ~250 mrem/canister to load DPCs
  - Also re-packaging by analogy
- Less LLW produced (DPC hulls, ~12 $m^3$ each)
- Reduce the complexity of fuel management operations
  - Additional facilities
  - More transport
  - Staging and re-blending of spent fuel in new canisters
- Reduce risk from fuel damage after prolonged storage
- Significant financial savings up to $20B in the U.S.
  - 10 to 20% of overall geologic disposal cost for commercial SNF

# DPC Direct Disposal Cost Perspective (Rough-Order-of-Magnitude)

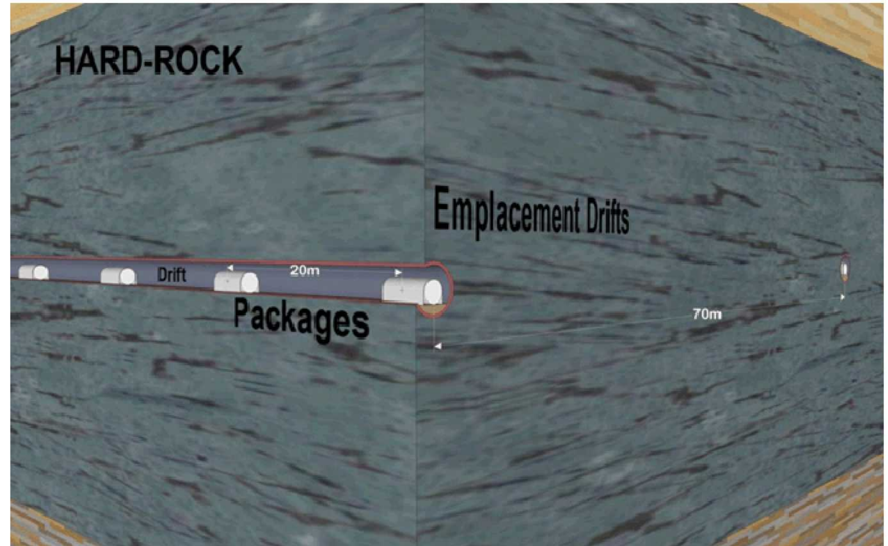
- **“Sunk” cost (present and future):**
  - Procure, load and store DPCs — $100,000/MTU
  - **Additional cost to continue through ~2055 — $11B**
- **Future costs for re-packaging all fuel:**
  - Unload DPCs — $10,000/MTU
  - Dispose of DPC hulls (~8,000 total) — $150,000 each
  - Re-canister for disposal (minimum) — $100,000/MTU
  - Disposal overpack savings (average) — $25,000/MTU
  - **Total for 140,000 MTU — ~$20B**

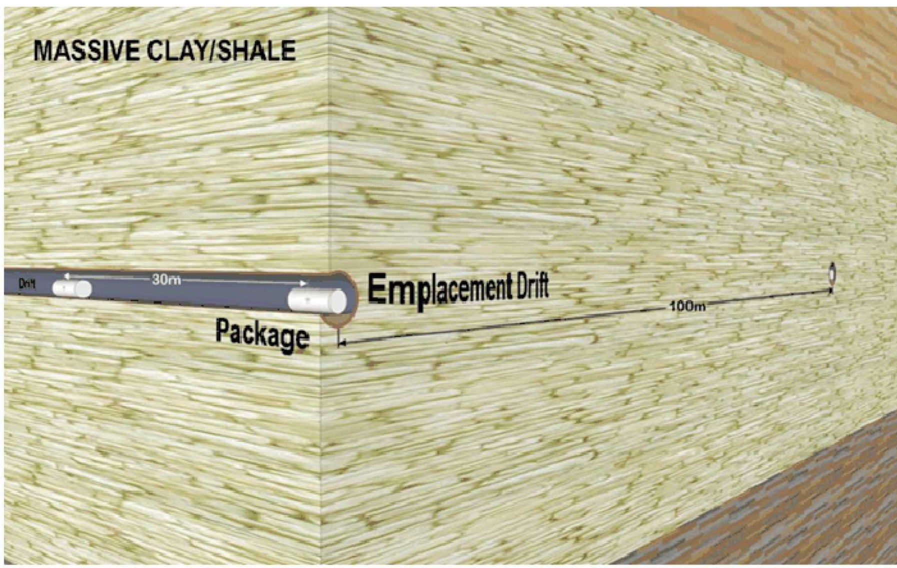
***Substantial cost savings could be achieved by: 1) direct disposal of all DPCs; or 2) direct disposal of some DPCs and early transition to <u>multi-purpose disposable canisters.</u>***

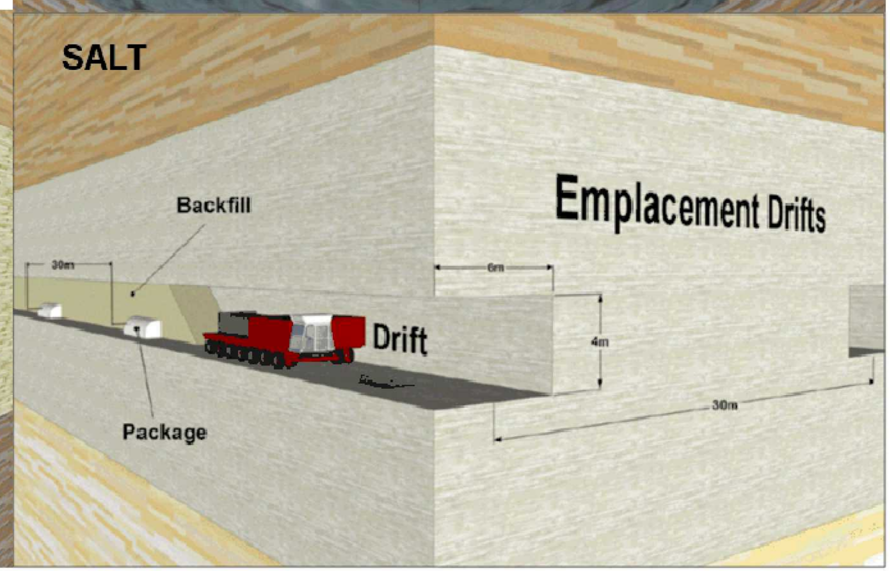
# Previous DPC Disposal Feasibility Studies

# DPC Direct Disposal Concepts

- Shaft or ramp transport
- In-drift emplacement
- Extended aging or repository ventilation (except salt)
- Backfill before closure (except hard rock unsaturated)
- Postclosure criticality control
- (not shown) Unsaturated hard rock



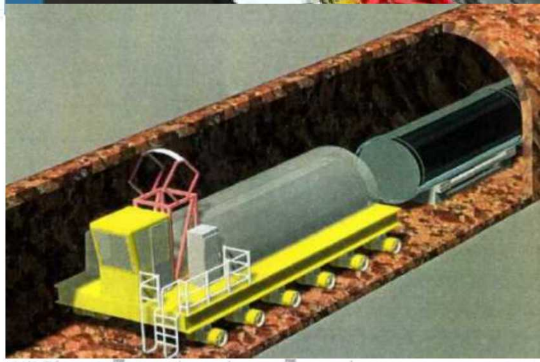
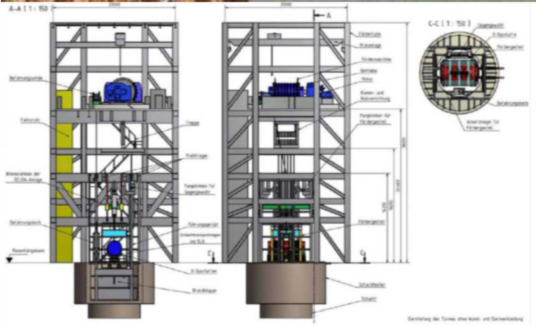




(Hardin et al. 2013. FCRD-UFD-2013-000171 Rev. 1)

# Engineering Challenges Can Be Met

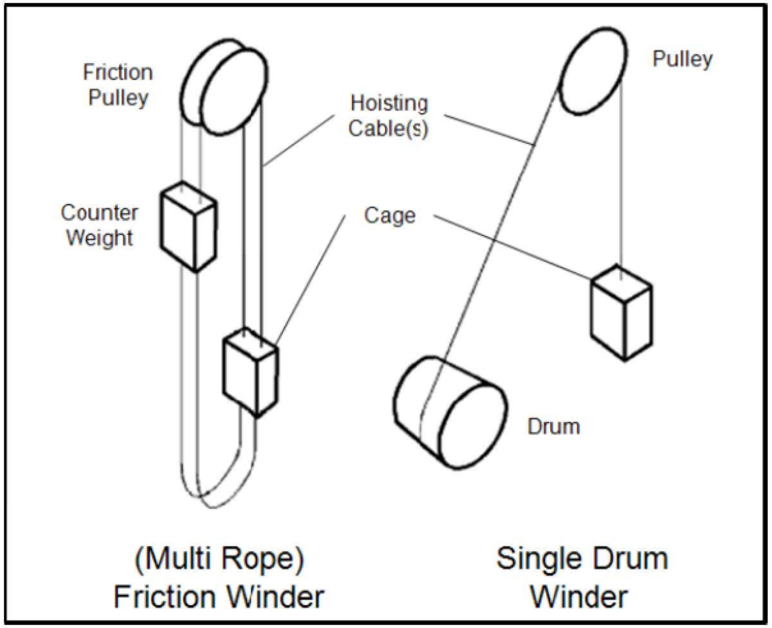
- Handling/Packaging: Use Current Practices
- Surface-Underground Transport
  - Spiral ramp (~10% grade, rubber-tire)
  - Linear ramp (>10% grade, funicular)
  - Shallow ramp (□ 3% grade, standard rail)
  - Heavy shaft hoist
- Drift Opening Stability Constraints
  - Salt (a few years, or longer with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



# Heavy Shaft Hoist Technology

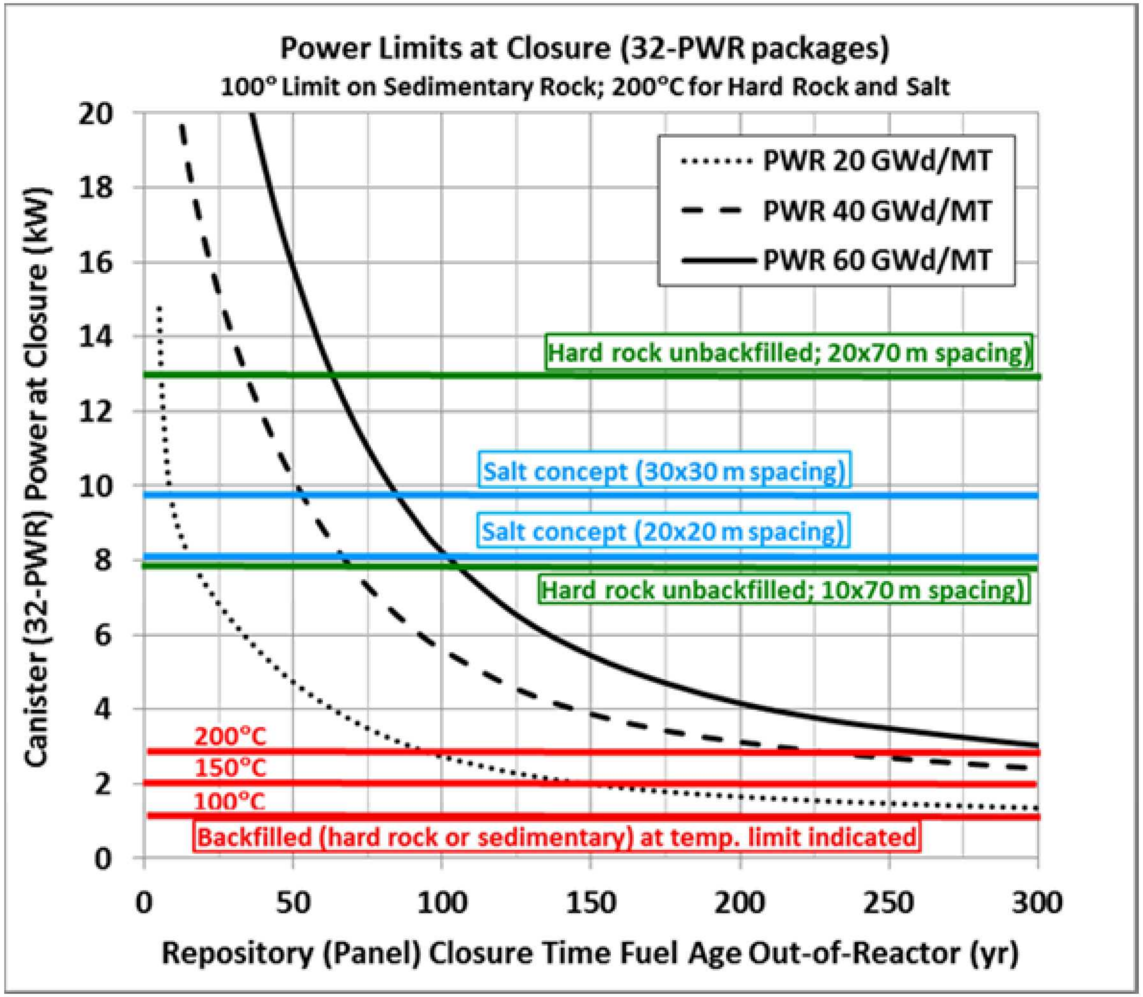
- Hoist R&D at Gorleben, Germany: Design and testing for 85 MT capacity (BGE Tec)
- Payload of 175 MT also studied for German “DIREGT” concept, similar to DPC + overpack + shielding + cart




  - Koepke friction hoist, 6 cables (each 66 mm ϕ)
  - Counterweight 133 MT
  - 1 m/sec hoist speed with 800 kW winder
  - Order-of-magnitude cost about $30M for equipment

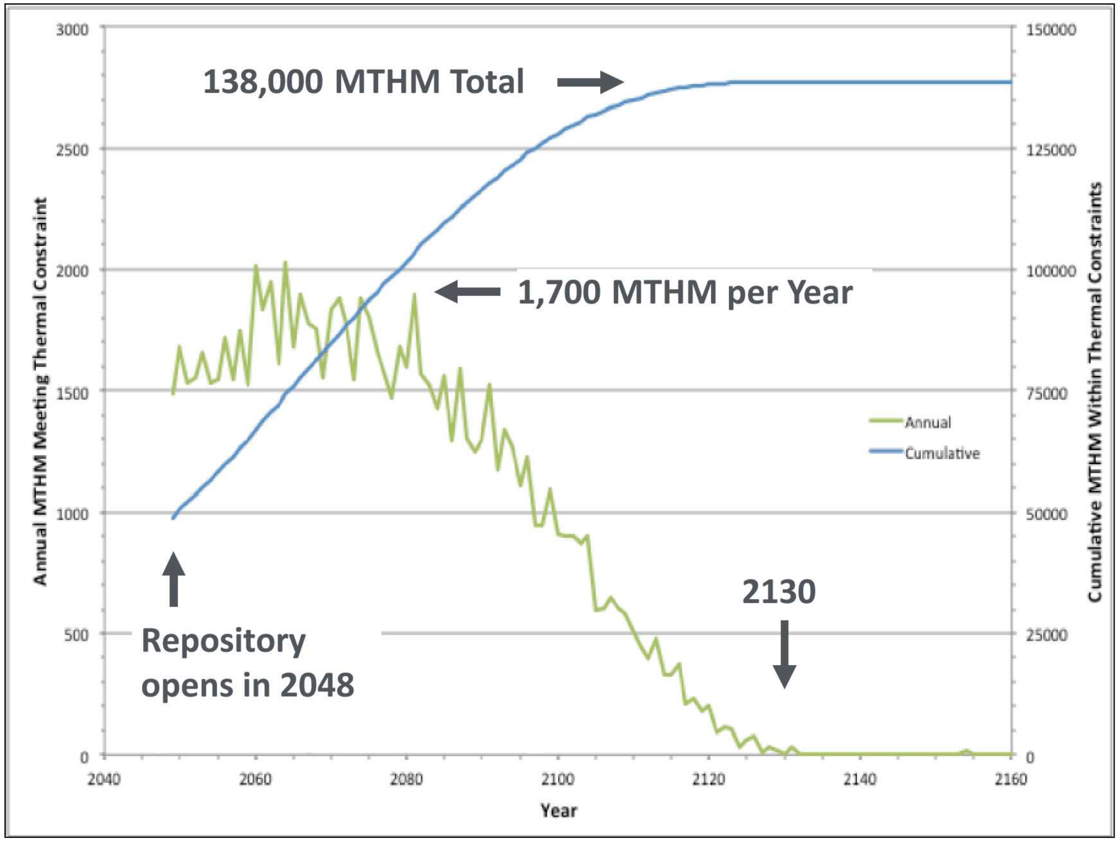
# Thermal Management for DPC Disposal Concepts

- SNF burnup (black curves) crossing points give aging time to meet peak temperature targets for 32-PWR size packages
- Heat dissipation is best for salt and unsaturated/ unbackfilled concepts
- Backfill constraints dominate (where backfill is used)



# AgingAnalysis for 10 kW Emplacement Power Limit

- TSL-CALVIN* logistics simulator
- 10 kW limit would be typical for salt and unbackfilled concepts
- 1,700 MTHM/yr throughput would keep pace with cooling to 10 kW
- Disposal of >98% of project SNF by 2130



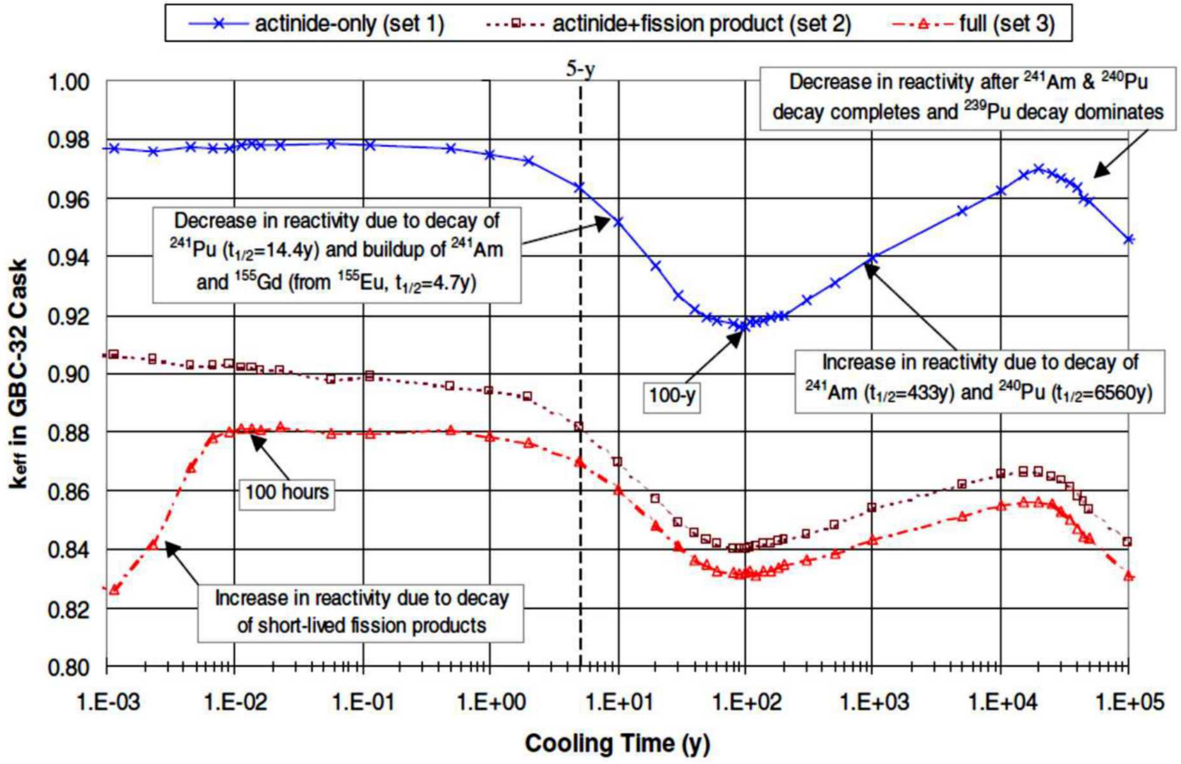

b) Amount of SNF

**SNF emplaced per year (MTHM) vs. calendar year**

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

# 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)
  - Disposal control rods (new DPCs only)
- Criticality Analysis Methodology
  - Burnup credit, as-loaded, stylized degradation cases
  - Peak reactivity occurs at ~25,000 years

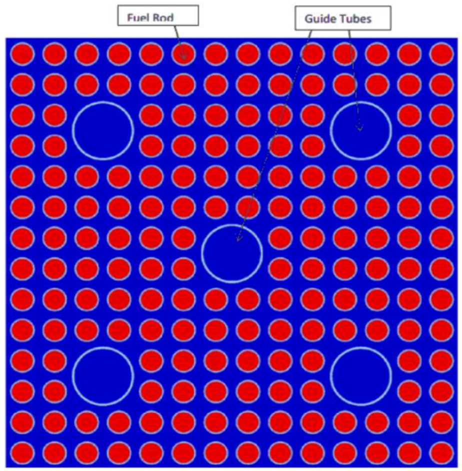



**Neutron multiplication factor ($k_{eff}$) vs. time**
Generic burnup-credit 32-PWR cask
PWR fuel (4% enriched, 40 GW-d/MT burnup)

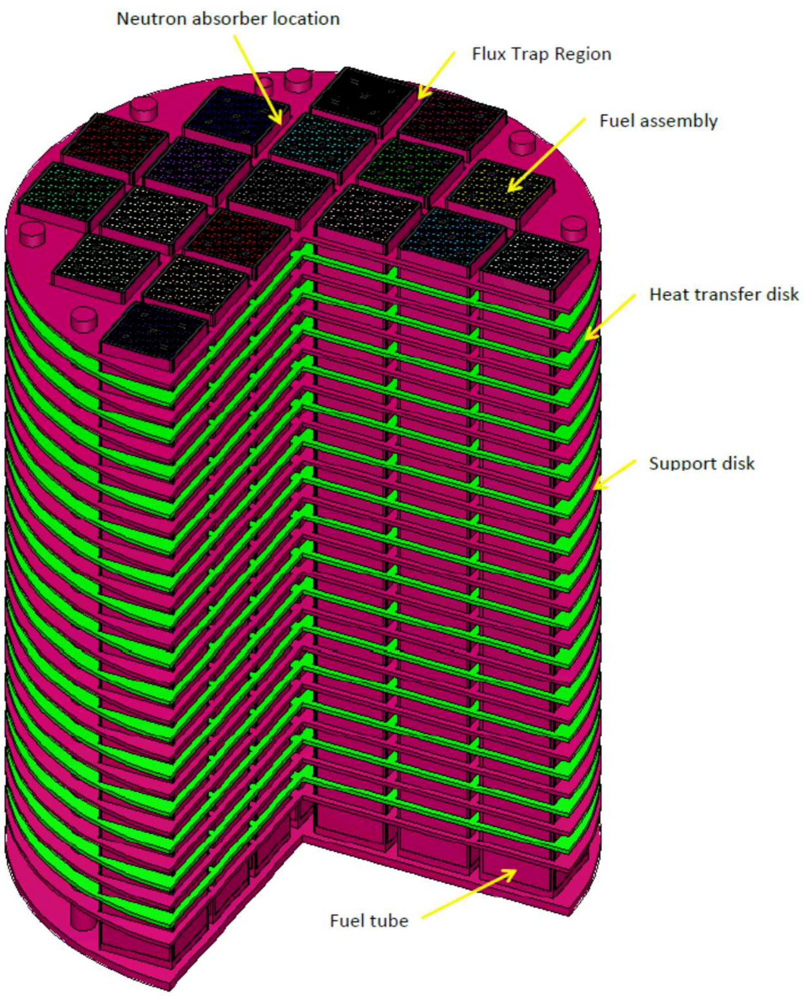
Wagner and Parks 2001 (NUREG/CR-6781, Fig. 3)

# Reactivity Scoping Analysis (Site "A")

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

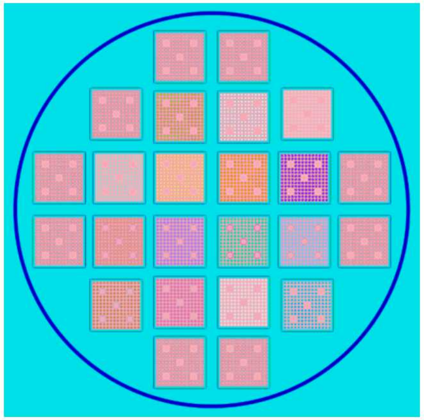



- Numerical Model of TSC-24 Canisters
- ORNL Database "UNF-ST&DRDS"
  - Software/Data
  - SCALE code system (ORNL 2011)
  - Details: Clarity and Scaglione (2013)

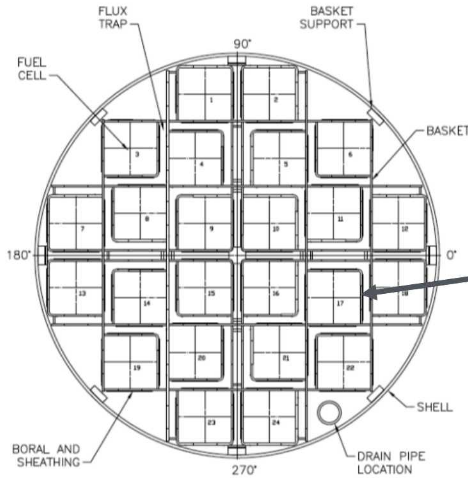



References:
ORNL (Oak Ridge National Laboratory) 2011. ORNL/TM-2005/39 Version 6.1.
Clarity, J.B. and J.M Scaglione 2013. ORNL/LTR-2013/213.

# Basket Configurations for TSC-24 System ("Site A")

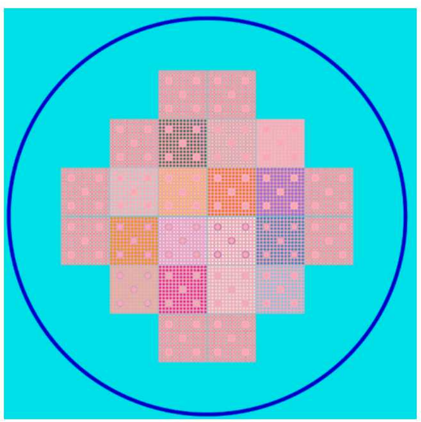


**Intact Basket With Loss of Neutron Absorber Plates**




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

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

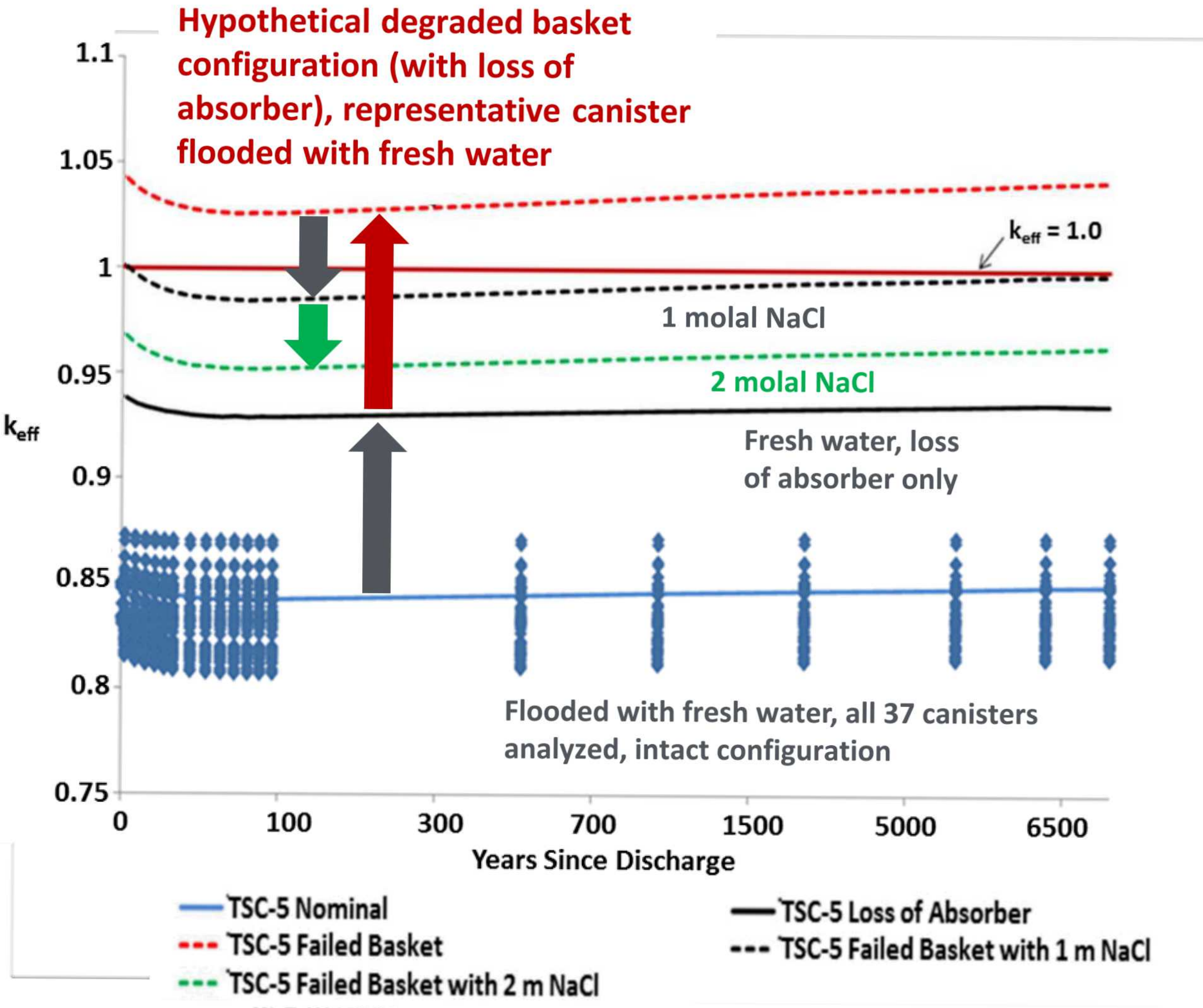


**Collapsed Basket, (with loss of neutron absorbers)**

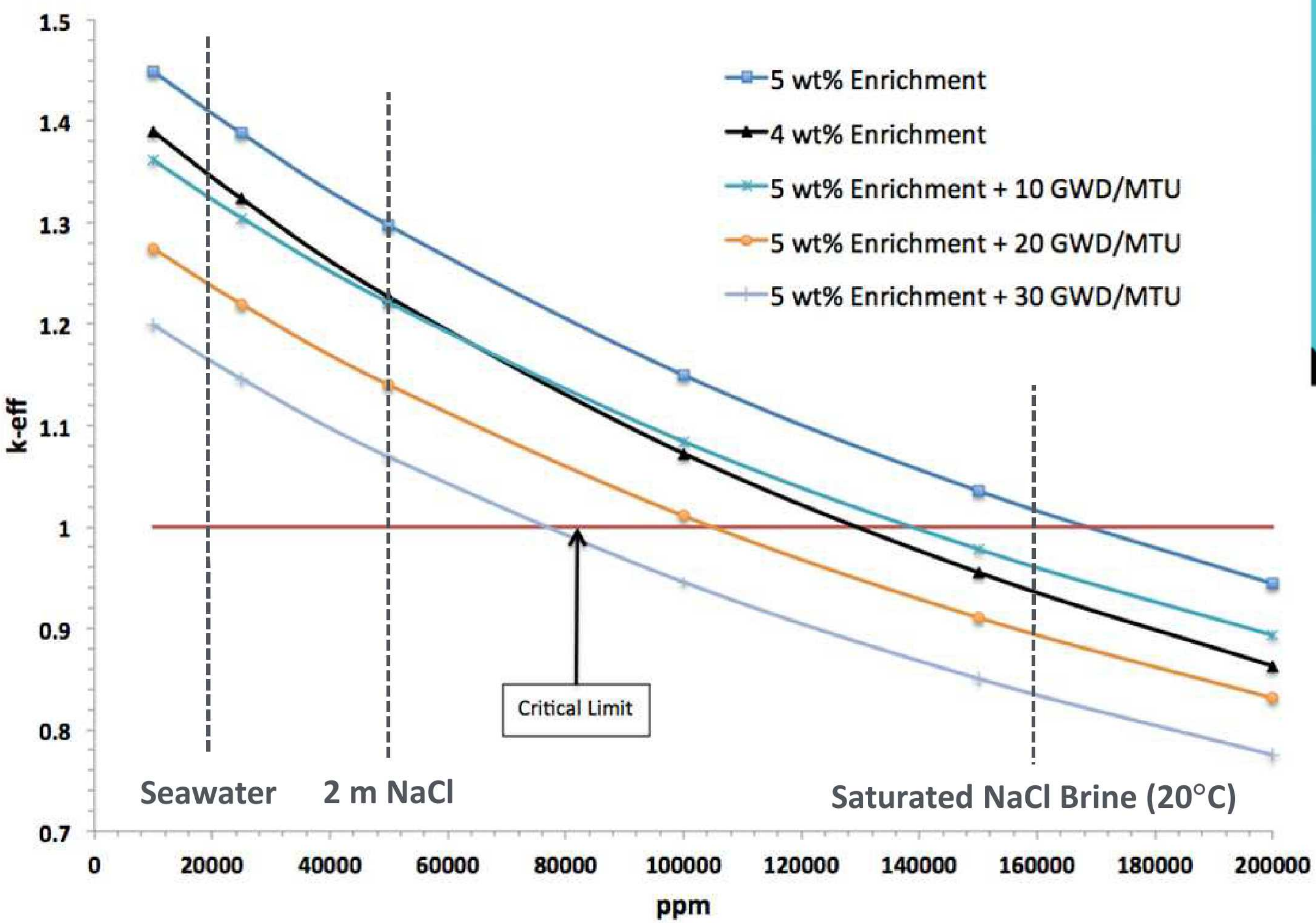
References:
Clarity, J.B. and J.M Scaglione 2013. ORNL/LTR-2013/213.
Hardin et al. 2012. FCRD-UFD-2012-000219 Rev. 2.

# Criticality Scoping Analysis Results ("Site A")

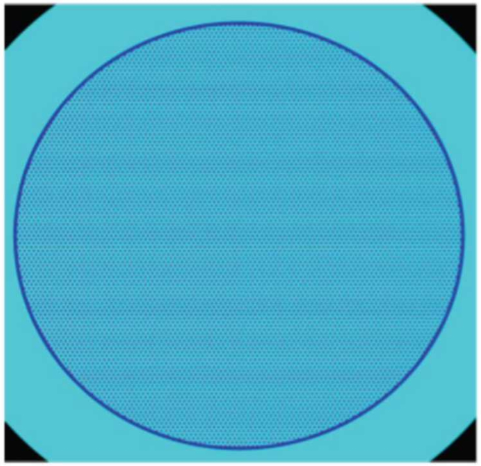
- Analyzed as-loaded, with burnup credit
- Higher chloride brine strength → less reactivity (saturated NaCl ≈ 6 molal)
- Note: $k_{eff}$>1 results signify DPCs for which additional control measures might be used, e.g., re-packaging



# Criticality Analysis for High-Reactivity Stylized Case – NaCl Brine




(Hardin et al. 2014. FCRD-UFD-2014-000069 Rev. 0)



High-reactivity case:

- Hexagonal array of 8617 PWR fuel rods (W17x17WL)
- Rods from slightly more than 32 assemblies, in a 32-PWR DPC

# Summary: Previous Studies (Low Probability)

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

***No implementation barriers although many existing DPCs could require treatment of repackaging***

- Most favorable concepts: salt and hard rock-unsaturated
  - **Mainly due to postclosure criticality control (thermal strategy for any medium can be developed)**
- Additional considerations important for direct disposal:
  - **Disposal overpack reliability estimates can be improved**
  - **DPC design features will impact structural longevity**
  - **Investigate DPC modifications for criticality control (e.g., fillers)**
  - **Investigate screening postclosure criticality on low consequence (instead of low probability)**

# DPC Disposition R&D and Implementation Strategy

# DPC Disposition Strategy

**N ≈ 8,100 U.S. DPCs (total) "as-loaded":**

**Low consequence?** → **Yes** → **IMPLEMENT FOR N**

**No (Abandon low-consequence approach FOR ALL N)** →

**For each DPC of *existing* design:**

**X: Reactivity margin* gets $k_{eff}$ « 1** OR

**Y: Fillers get $k_{eff}$ « 1** OR

**(N-X-Y): Repackage**

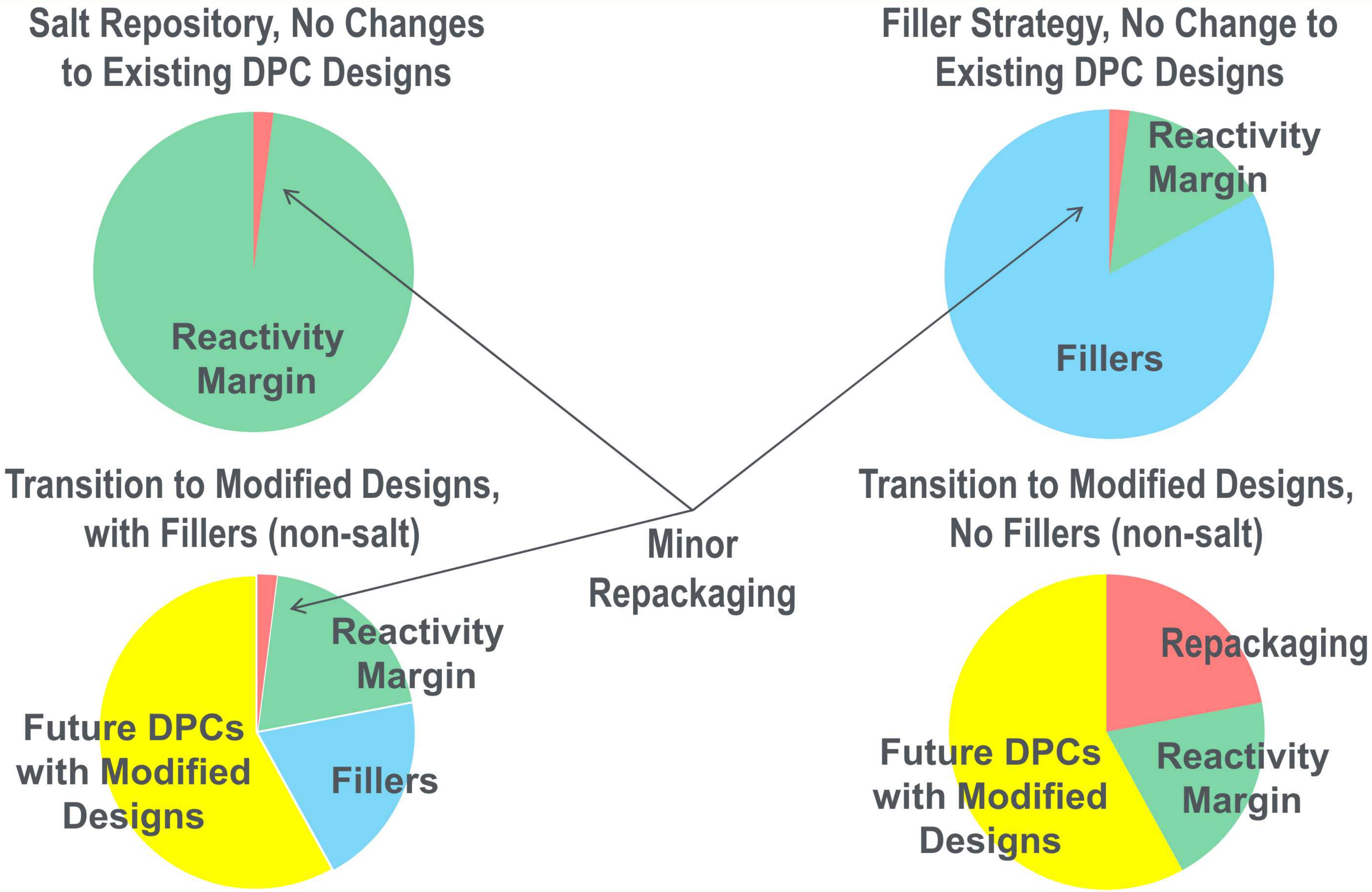
**For each future DPC of *modified* design:**

**Z: Modified DPC design gets $k_{eff}$ « 1** OR

**(N-X-Y-Z): Repackage**

*** Includes a repository in salt**

# Notional DPC Disposition System Endpoints for Low-Probability Screening Approach



# Approach to Injectable Fillers

# Perspective on Treatment Options for Existing (Sealed) DPCs

- Cut Lids Off Existing DPCs?
  - Skiving (wet) selected among various methods (DOE-ORNL study)
  - Could fill with steel shot (Cogar 1996), other particles such as glass beads (AECL; Forsberg 1997)
  - Could install disposal control rods (EPRI 2008) or rearrange assemblies (Alsaed 2019)
  - Filling must be done dry, and weld-resealing the canister must be dry
- Alternative: Injectable Fillers
  - Cut off small covers over existing DPC vent/drain ports

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.

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

Alsaed, H. 2019. Comparative Cost Evaluation of DPC Modifications for Direct Disposal. SAND2019-4070. Sandia National Laboratories, Albuquerque, NM.

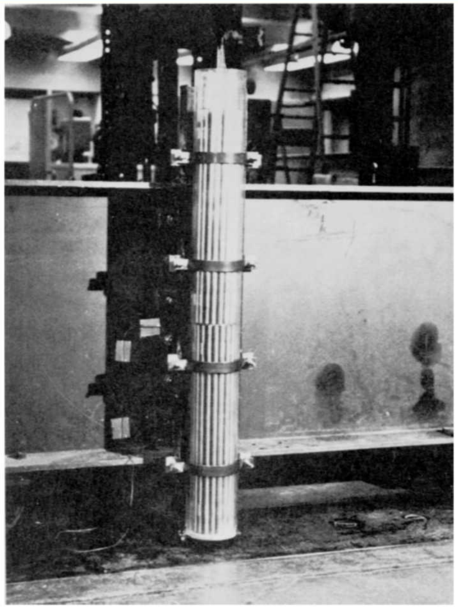
# Background: Yucca Mountain Project Steel-Shot Particulate Filler Test (Framatome-Cogema)

- **Steel-shot test: poured into open mockup fuel assemblies**
  - SAE S230 & S330 sizes; nom. 600-850 μm and 850-1,180 μm diameter
  - As-poured density ~4.6 g/cm$^3$
  - Thermal conductivity ~0.4 W/m•K
- **Basis for selecting steel shot:**
  - Ease of handling and placement ("flow")
  - Commercial availability and low cost
  - Cathodic protection of SNF
  - Chemical buffering
  - Moderator displacement
  - Thermal conductivity
- **Dummy PWR assemblies (15 × 15 and 17 × 17), polycarbonate cell**
- **Eight tests (2 assemblies, 2 shot sizes, with/without vibration)**
- **Results: 94% fill ratio (void space minus “excess” porosity)**

Cogar, J. 1996, *WASTE PACKAGE FILLER MATERIAL TESTING REPORT*, BBA000000-01717-2500-00008 REV 01

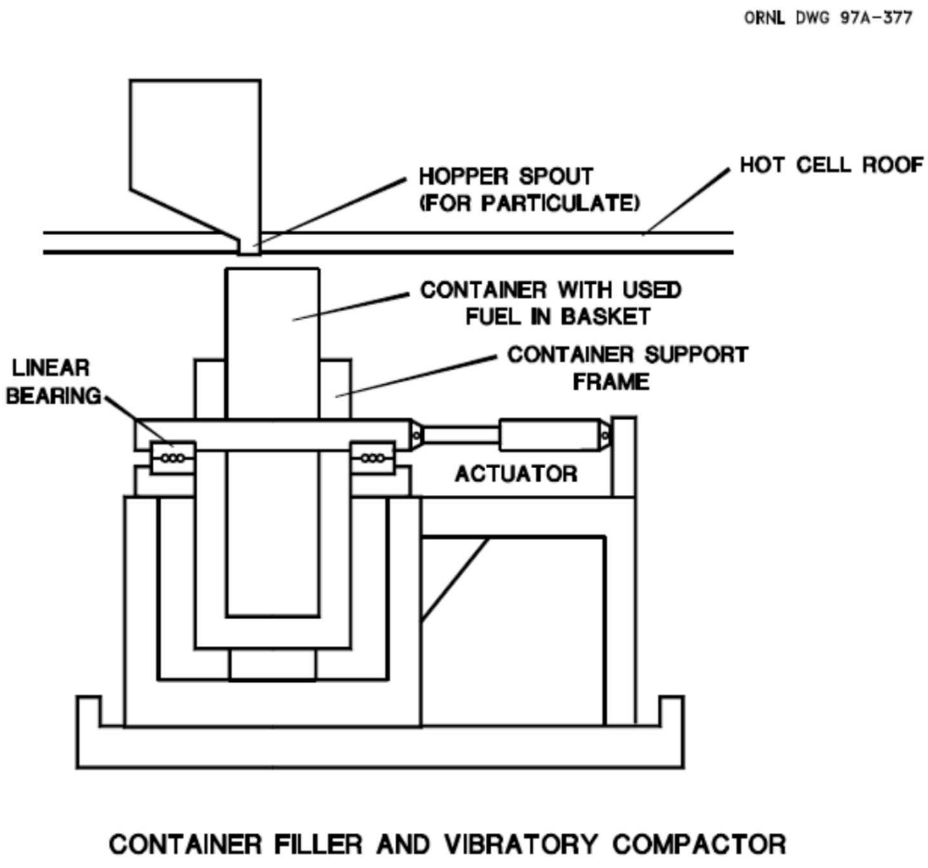
# Background: AECL Particulate Filler Tests (1/2)

- **Glass beads poured into open assemblies**
  - Industrial 20 to 300 µm and 0.8 to 1.2 mm dia.
  - Density 1.6 (small) to 1.9 (large) g/$cm^3$
  - Structural support (10 MPa hydrostatic)
  - Titanium-shell package
- **Single-cell filling test**
  - Two dummy CANDU assemblies
  - Shaker table
- **Mockup package test**
  - 19 × 2 ceramic basket
  - Vibratory compaction
  - Weld-sealed
  - Hydrostatic testing



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.

# Background: AECL Particulate Filler Tests (2/2)




**Vibratory compaction apparatus – full scale.**

**Hydrostatic testing vessel, AECL/Whiteshell**

**FIgures from Forsberg (1997)**

# Injectable Filler Needed Attributes (Liquid or Slurry Emplaced)

- **Injectable** – ~6,000 L through a 15 – 20 mm $\phi$ drain tube in a few hours
- **Void Filling** – Penetrate limber holes, assemblies, baskets
- **Compatible** – Limited gas generation or chemical attack (especially radiolysis of organics and moisture)
- **Durable** – 10,000+ yr chemical/physical lifetime befor after waste package breach (natural analogues)
- **Reactivity Control** – Displace ground water or incorporate neutron absorber, or both
- **Safe** – Does not endanger workers or members of the public (e.g., no additional Pb, Cd)
- **Practical** – Reasonable weight, possibility of retrieving fuel assemblies by removing filler
- **Low Cost** – Relative to other DPC disposition alternatives (e.g., repackaging)

# Background: Ordinary Portland Cement (OPC)

**Ordinary Portland Cement**

**= $CaCO_3$ + Clay + Gypsum + Heat = CaO-Silicates/Aluminates**

**The Good**

Reactions well understood
Many antique analogues
Inexpensive

**The Bad**

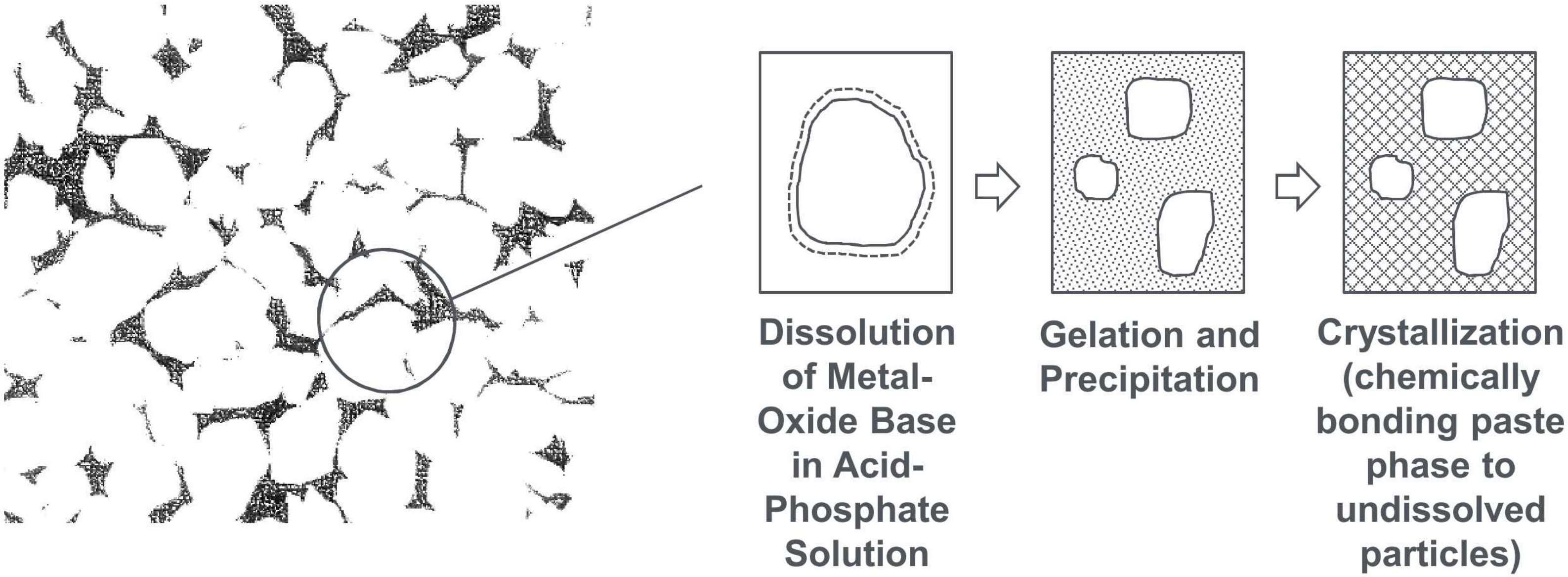
High pH bad for corrosion
High pH bad for RN solubility, sorption

**An Alternative – Phosphate Cements**

Lower pH decreases corrosion potential
Strong binder of RNs; used for reactive barriers, separations
Many natural analogues; fossil bone, teeth.

# Background: Chemically Bonded Ceramics

- Process and Nomenclature




Ceramic ← Crystalline
Cement ← Low temperature
Chemically Bonded ← Paste phase chemically bonded to remaining undissolved crystalline particles

# Nomenclature: Ceramic vs. Cement vs. Chemically Bonded Cement

| Attributes: | Ceramics | Cements | Chemically Bonded |
|---|---|---|---|
| **How they are commonly produced** | Fuse compacted powders at high-T | Hydraulic (water-based) | Acid-base reactions in slurries* |
| **Bonding** | Ionic or covalent | Hydrogen and van der Waals bonding | Mostly ionic or covalent |
| **Porosity** | Low (~1%, except sinters) | High (typ. 15 to 20%) | Moderate to high |
| **Service Temperature** | Very high T | Ambient to low T | Moderate |
| **Corrosion Resistance** | Wide pH range | Attack by strong acids and caustics; amorphous phases | Wide pH range, crystalline |
| **Cost** | Limiting | Bulk applications | Bulk and specialty |
| **Examples** | Porcelain | OPC | Phosphate-bonded cements (dental cements, Ceramicrete® & ThermaLock®) |

* Does not include chemical (liquid) grouts.

# Technical Questions
# Injectable Filler Behavior and Durability

- **Temperature**
  - Early time during filling, and during aging in a repository
- **Thermal Expansion**
  - Filler expansivity vs. canister, basket, and fuel
- **Radiolytic Gas Generation**
  - Gamma (fission products)
  - Neutron (spontaneous fission and (α, n) reactions)
  - Reactions with organics, moisture → gases
  - Removal of moisture from filler before sealing
- **Chemical Gas Generation**
  - Reaction of Al shunts and absorber plates with moisture → $H_2$ gas
- **Filler Cracking or Bond Failure**
  - Allow moisture penetration after package breach
- **Filler Dissolution and Alteration**
  - Before/after package breach (incl. wedging, galvanic corrosion)

# Exclusion of Postclosure Criticality on Low Consequence, Background

# Background – Criticality Onset Analysis for Low-Probability Screening

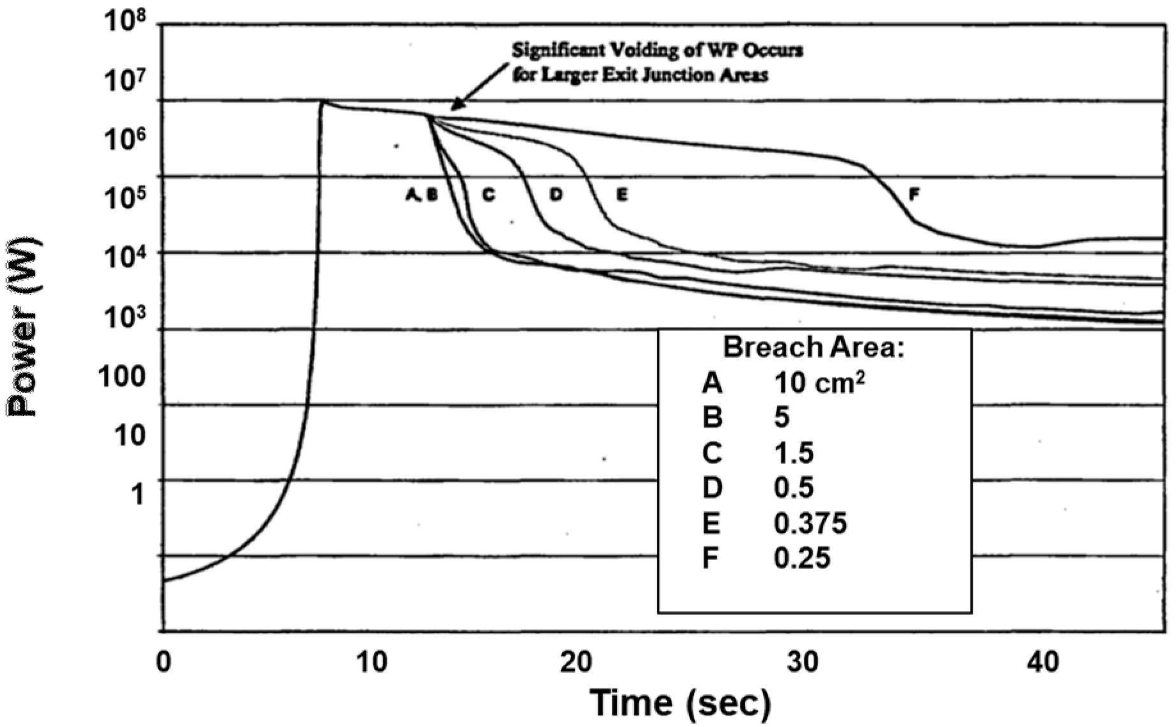
- **Electric Power Research Institute**
  - *YM Post-Closure Criticality – 2007 Progress Report* (EPRI 1015128)
  - *Feasibility of Direct Disposal of DPCs: Options for Assuring Criticality Control* (EPRI 1016629)
- **Yucca Mountain License Application**
  - *Screening of Criticality FEPs for LA* (ANL-DS0-NU-000001 REV00A)
  - *CSNF Waste Package Misload Analysis* (CAL-WHS-MD-00003 REV00A)
  - *CSNF Igneous Scenario Criticality* (ANL-EBS-NU-000009 REV00)
  - *CSNF Loading Curve Sensitivity Analysis* (ANL-EBS-NU-000010 REV 00)
- **Criticality Analysis for Direct Disposal of SNF in DPCs**
  - *Summary of Investigations on Technical Feasibility of Direct Disposal of DPCs* (SFWD-SFWST-2017-000045)

# Background: Previous Simulations of Waste Package Criticality

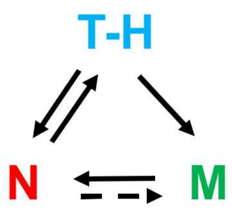
- Example Calculations:
  - *Criticality Consequence Analysis Involving Intact PWR SNF in a Degraded 21-PWR WP* (BBA000000-01717-0200-00057 REV 00)
  - *Sensitivity Study of Reactivity Consequences to Waste Package Egress Area* (CAL-EBS-NU-000001 REV00)

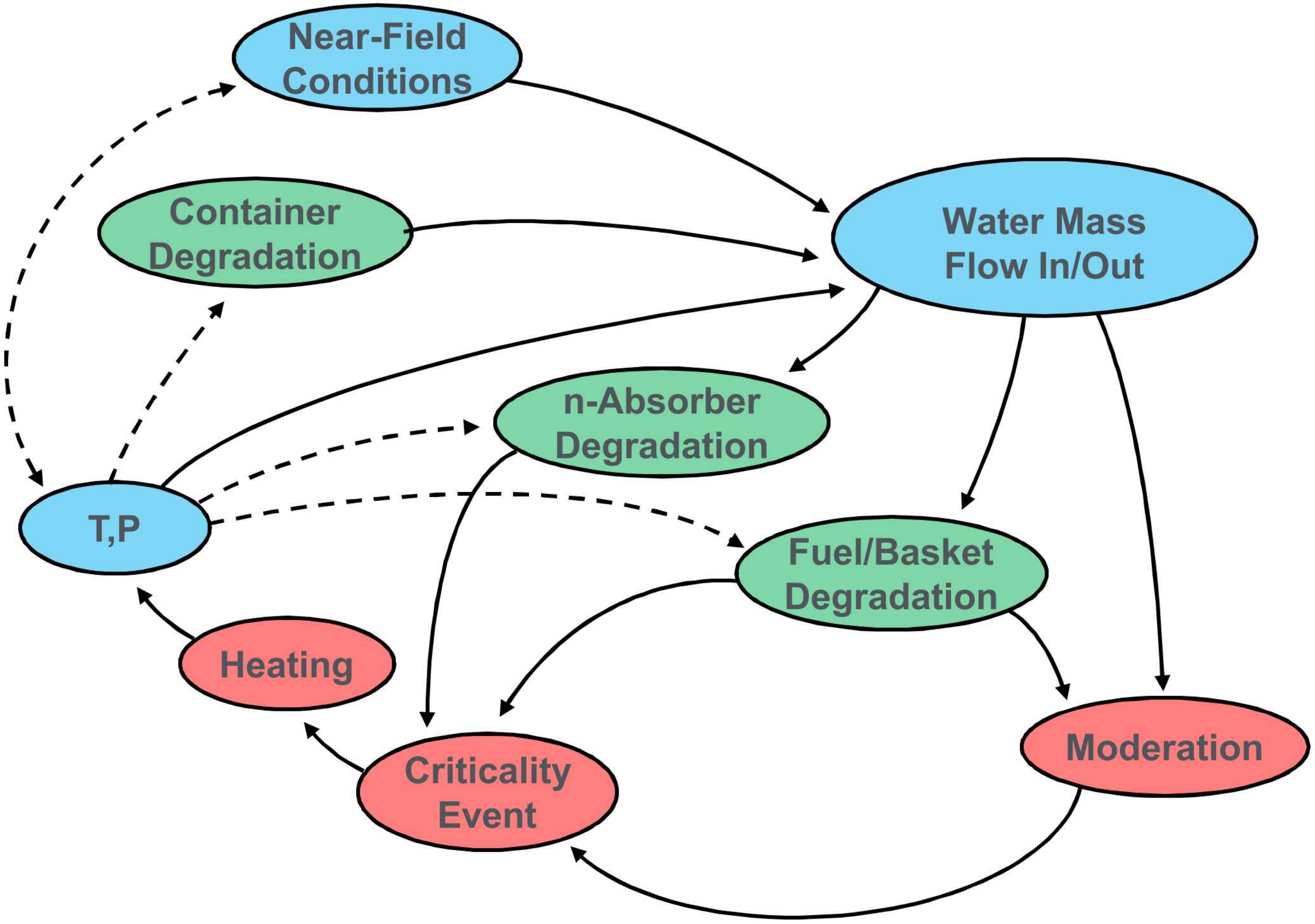
Waste Package Power vs. Time from RELAP5 Analysis of Fission Power Histories for Prompt Reactivity Insertion Rate (0.148 $/sec) Parameterized by Waste Package Breach Area

(CAL-EBS-NU-000001, Figure 6-5)



# Reference Coupling Scheme (Current State of the Art)




Dashed lines signify ad hoc input or loosely coupled processes