

Spent Fuel and Waste Science and Technology SAND2018-5437PE

Direct Disposal of Spent Nuclear Fuel in Dual-Purpose Canisters: R&D Path Forward

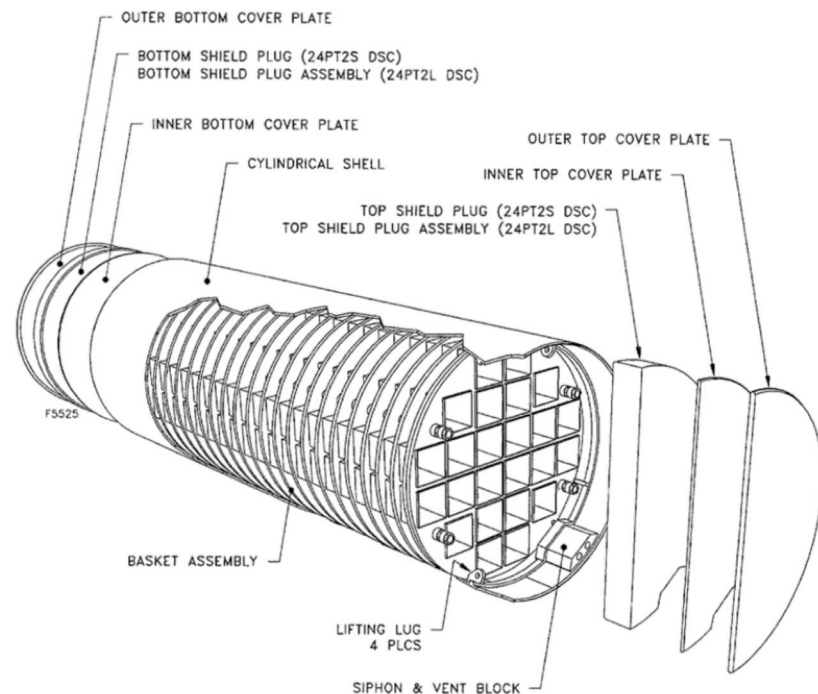
**Prepared by Sandia National Laboratories technical staff,
with input from consultants and other laboratories**

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- DPC Direct Disposal Concepts
- Worker Safety and Economic Drivers
- Goals for DPC Direct Disposal R&D Activities
- Planned Technical and Programmatic Thrusts



Top view of MPC-68 shell and basket (Greene et al. 2013).

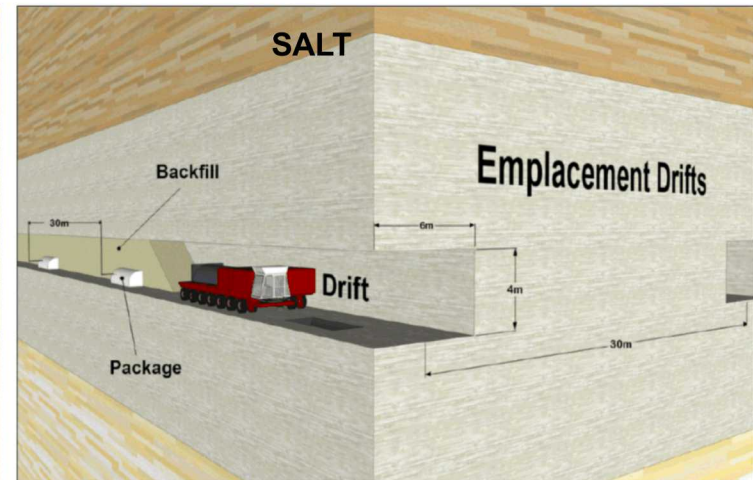
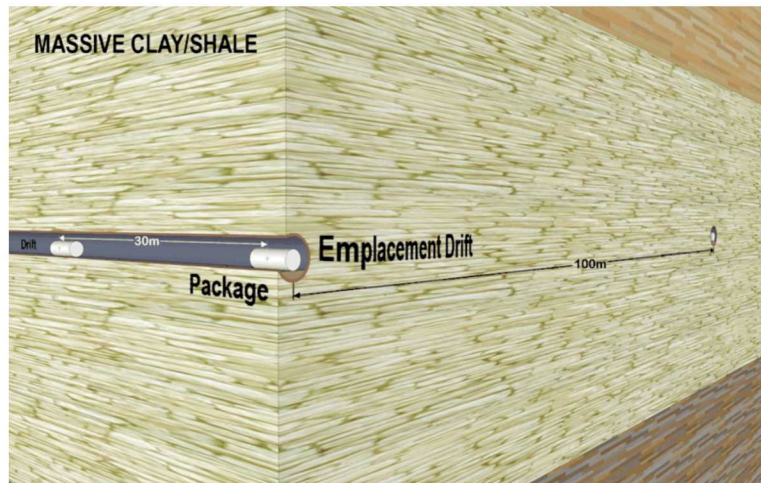
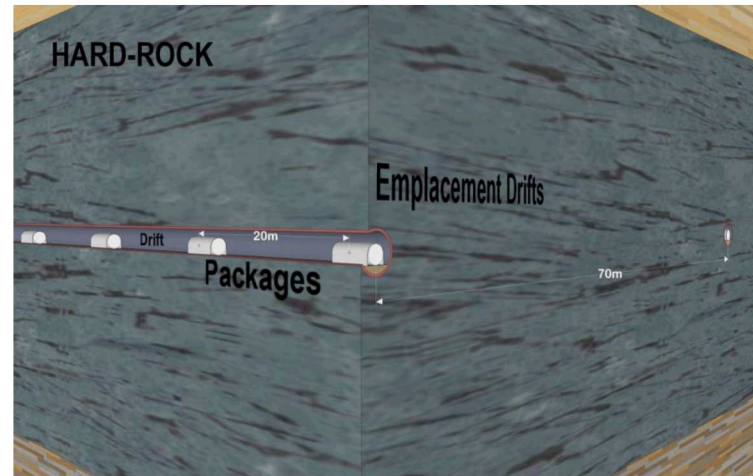


NUHOMS® 24-PT2 basket, shell, and lids (Greene et al. 2013)

Two basic types of DPC
baskets: tube/spacer-plate
and egg-crate

DPC Direct Disposal Concepts: Repository Engineering

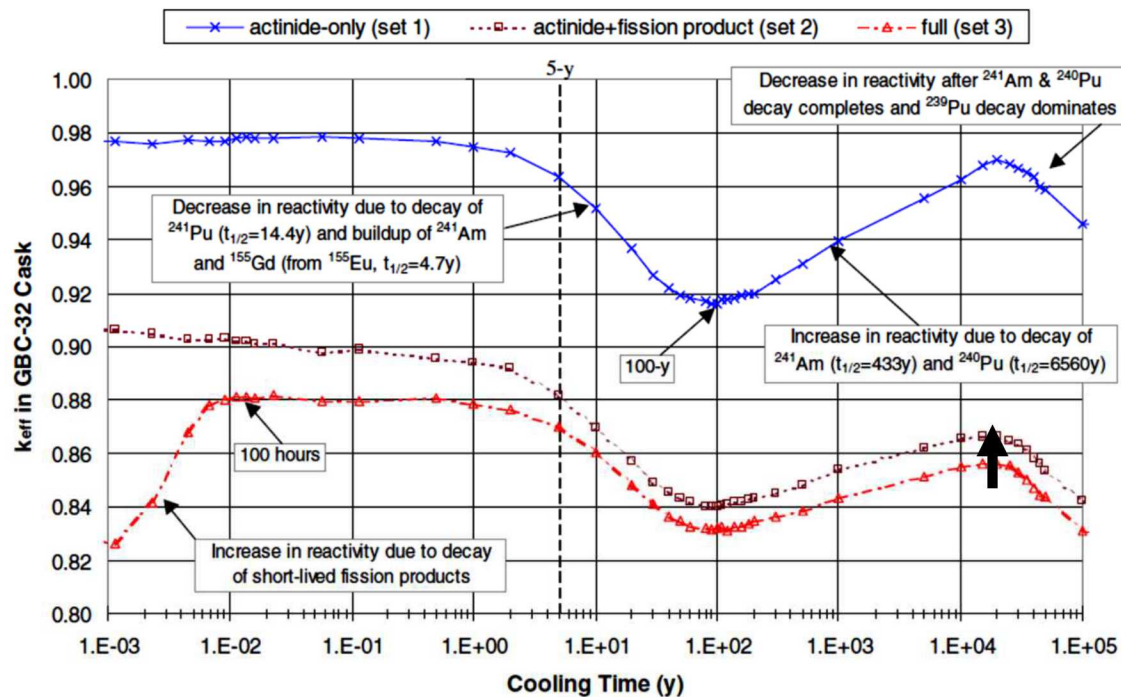
- Engineering challenges are technically feasible
- Shaft or ramp transport
- In-drift emplacement
- Repository ventilation (except salt)
- Backfill prior to closure (except unsaturated)



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

Spent Fuel Disposal: Postclosure Nuclear Criticality Control Concepts

- **Disposal Environment**
 - Groundwater availability
 - Chloride in groundwater
- **Moderator Exclusion**
 - Overpack integrity
- **Moderator Displacement**
 - Fillers
 - Impervious DPC fillers
- **Add Neutron Absorbers**
 - Fillers (e.g., B₄C loaded)
 - Disposal control rods
- **Criticality Analysis Methodology**
 - Burnup credit, as-loaded, stylized degradation cases
 - Peak reactivity occurs at ~25,000 years



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

Wagner and Parks 2001 9NUREG/CR-6781, Fig. 3)

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Summary: SFWST Study on Technical Feasibility of DPC Direct Disposal

■ Technical evaluation results:

- Safety of workers and the public
- Engineering feasibility
- Thermal management
- Postclosure criticality control

No implementation barriers although all existing DPCs may not be disposable depending on the disposal concept *

■ Most favorable concepts: salt and hard rock-unsaturated

- Mainly due to postclosure criticality control (thermal strategy for any medium can be developed)

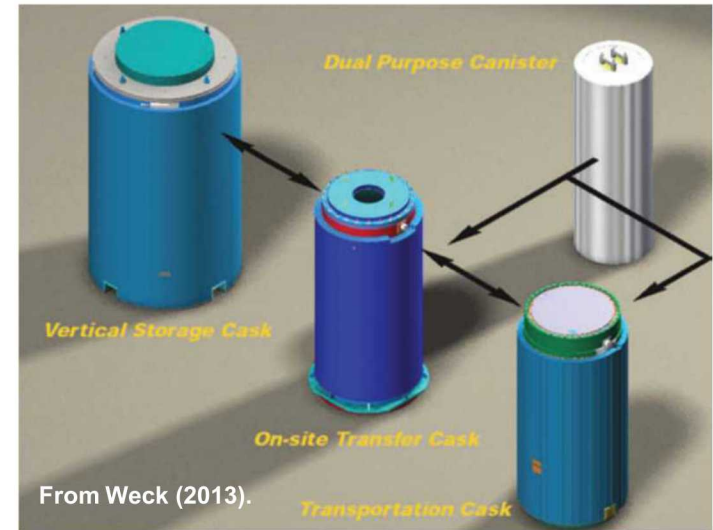
■ Additional considerations important for direct disposal:

- 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 risk (instead of low probability)

Worker Dose Associated with Re-Packaging

- **DPC unloading/re-packaging in fuel pools would increase collective radiation exposure by ~250 mRem/canister¹**

- NUHOMS® system (Dominion)¹
- Worker doses for re-packaging DPCs stored vertically are expected to be similar or slightly less¹

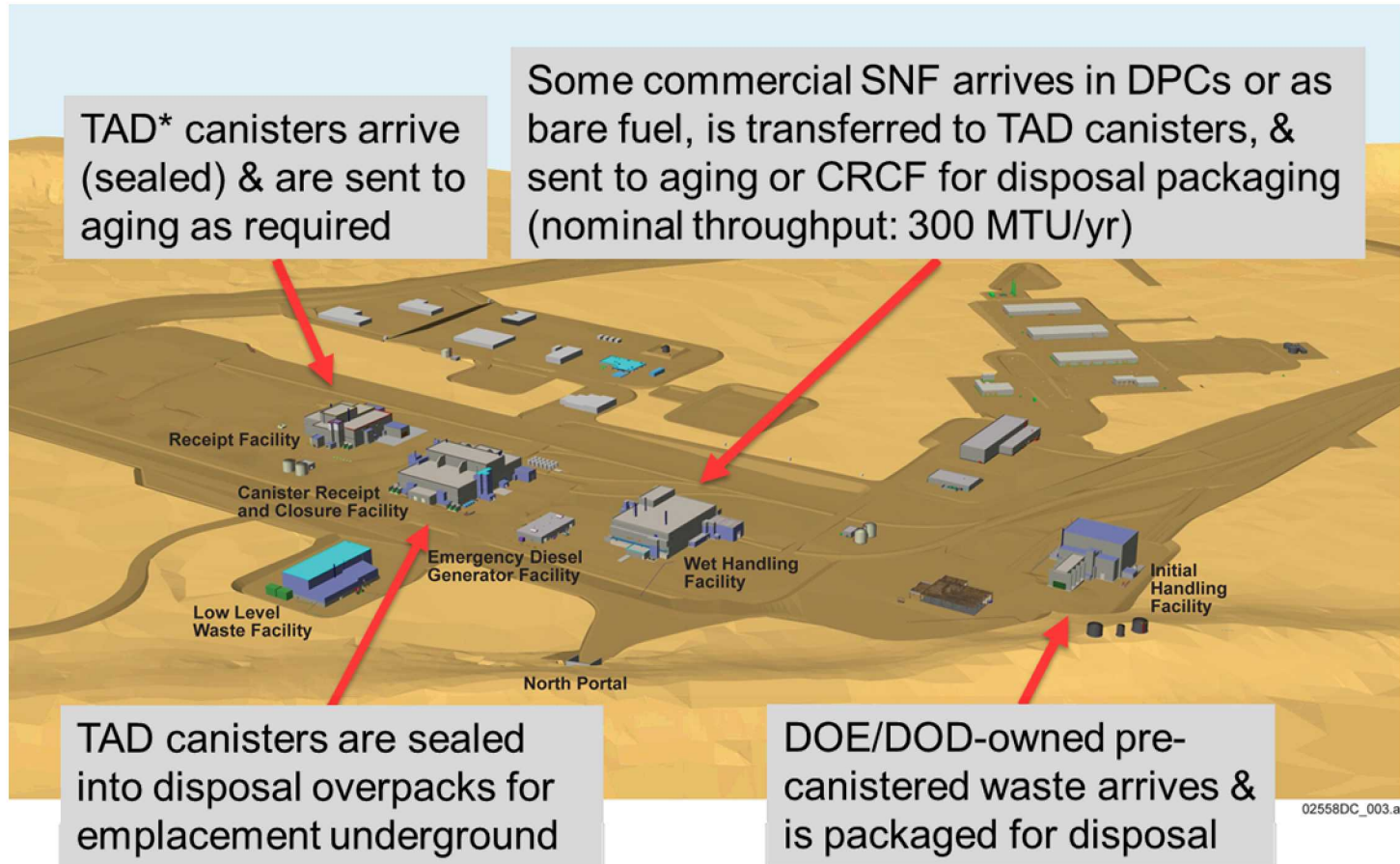


- **Dry unloading and loading would increase collective radiation exposure by 220 to 393 mRem/canister¹**

- Confinement hazard with off-normal fuel breach (e.g., fuel drop)²
- Over-heating and release hazards with certain off-normal events (e.g., seismic ground motion caused canister tip-over)²

Sources 1. Weck, P.F. 2013. *Radiation Protection Dosimetry*, Vol. 156, No. 3, pp. 386–393.
2. Hanson, B.D., et al. 2008. *Fuel-In-Air FY07 Summary Report*. PNNL-17275, Rev. 1.

Yucca Mtn Surface Facilities (proposed)



* TAD = Transport, aging and disposal

Throughput analysis reference: Spradley et al. 2010. Nuclear Technology, 169(2), pp. 180-194.

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**ROM Cost Analysis:
Re-Packaging of All Projected U.S.
Commercial SNF for Disposal**

Scenario: Load All CSNF into DPCs and Re-package All for Disposal (most costly)		CSNF Qty., MTUs	Avg. DPC Capacity, MTUs		
Total SNF in DPCs: 140,000 MTU (all to be re-packaged)	Unit Cost			# DPCs	Cost \$B
Sunk cost to procure, load and store existing DPCs (\$/MTU)	\$100,000	25,000	12.0	2100	\$ 2.5
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	\$ 1.4
Transport and dispose of each DPC hull (\$/DPC)	\$ 150,000	140,000		8995	\$ 1.3
Re-canister for disposal (\$/MTU)	\$ 100,000	140,000			\$ 14.0
Re-packaging facility capital cost					\$ 2.0
Total cost to make CSNF ready in canisters for disposal (re-packaging all)					\$ 32.7
Maximum potential savings from direct disposal of all CSNF in DPCs					\$ 18.7
Notes:					
1. \$100k/MTU canisterization cost is for hardware and labor to load/seal/store, and not for facilities.					
2. Estimate does not include the repository, CSNF storage, disposal overpacks, or disposal of obsolescent casks.					
3. Estimate does not include an interim storage facility that could be needed to support the repository.					
4. Re-packaging facility operating cost does not include transportation to/from storage.					

- **Potential stakeholder and decision-maker interests:**
 - **Low worker dose and dose to members of the public**
 - **Low economic cost**
 - **Low technical risk (available materials, proven technology, intrinsic safety)**
 - **Low schedule risk**
 - **Timely disposition of fuel from shutdown sites**
 - **Expedite disposal of all spent fuel**
 - **Acquire technical data to support program decisions and regulatory analysis**
 - **Limit fuel management costs to utilities and increase economic benefits to host entities**
 - **Solutions that are workable to canister/system vendors**
 - **Implement widely acceptable policy decisions**
 - **Excellent program performance**

Criticality Screening Requirements – 10CFR63

	Individual Protection Standard		Individual Protection Standard for Human Intrusion		Groundwater Protection Standard: <ul style="list-style-type: none"> • $^{226}\text{Ra} + ^{228}\text{Ra}$ activity • Gross α activity • Dose from β + photon-emitting radionuclides
Dose Limit	15 mrem	100 mrem	15 mrem	100 mrem	
Performance Period	$\leq 10,000$ yr	$> 10,000$ yr	$\leq 10,000$ yr	$> 10,000$ yr	$\leq 10,000$ yr
Title 10 CFR Reference	63.311(a)(1)	63.311(a)(2) (note 2)	63.321(b)(1)	63.321(b)(2) (note 2)	63.331
Probability of Occurrence of FEP (per yr) ↓					
$< 10^{-8}$ (see note 1)	Not Included 63.342(a)	Not included 63.342(c)	Not included 63.342(a)	Not included 63.342(c)(1)	Not included 63.342(a)
$10^{-8} \leq p < 10^{-5}$	Included	Included	Not included 63.342(b)	Not included 63.342(c)(1)	Not included 63.342(b)
$> 10^{-4}$	Included	Included	Included	Included	Included
Notes:					
<ol style="list-style-type: none"> 1. A FEP can also be excluded if its effect on repository performance (risk) is shown to be insignificant (10 CFR 63.342(a)). 2. For these two standards, 10 CFR 63.342(c) requires the inclusion of seismic and igneous activity, subject to probability limits, and also requires inclusion of the effects of climate change (with prescribed limits on the effects of climate change) as well as inclusion of the effects of general corrosion. 					

- **Criticality risk = probability (i.e., incidence) × consequence**
 - ⇒ System-wide assessment w/ aleatory and epistemic uncertainties
- **How will criticality be affected by repository conditions?**
 - Spatial frequency and timing of waste package containment failures
 - Groundwater composition and rate of influx in to waste packages
 - Seismic hazard
- **How will the waste form and canister affect the incidence of criticality?**
 - Fuel enrichment & burnup
 - SNF degradation rate vs. basket
 - Gradual vs. episodic degradation (sediment, collapse, ground motion effects)
- **How can internal criticality affect the repository as a system?**
 - Heating rate and duration (T,P damage to SNF, WP, and near field)
 - Thermal, chemical (e.g., radiolytic), and groundwater transport effects on WP/WF degradation and radionuclide release

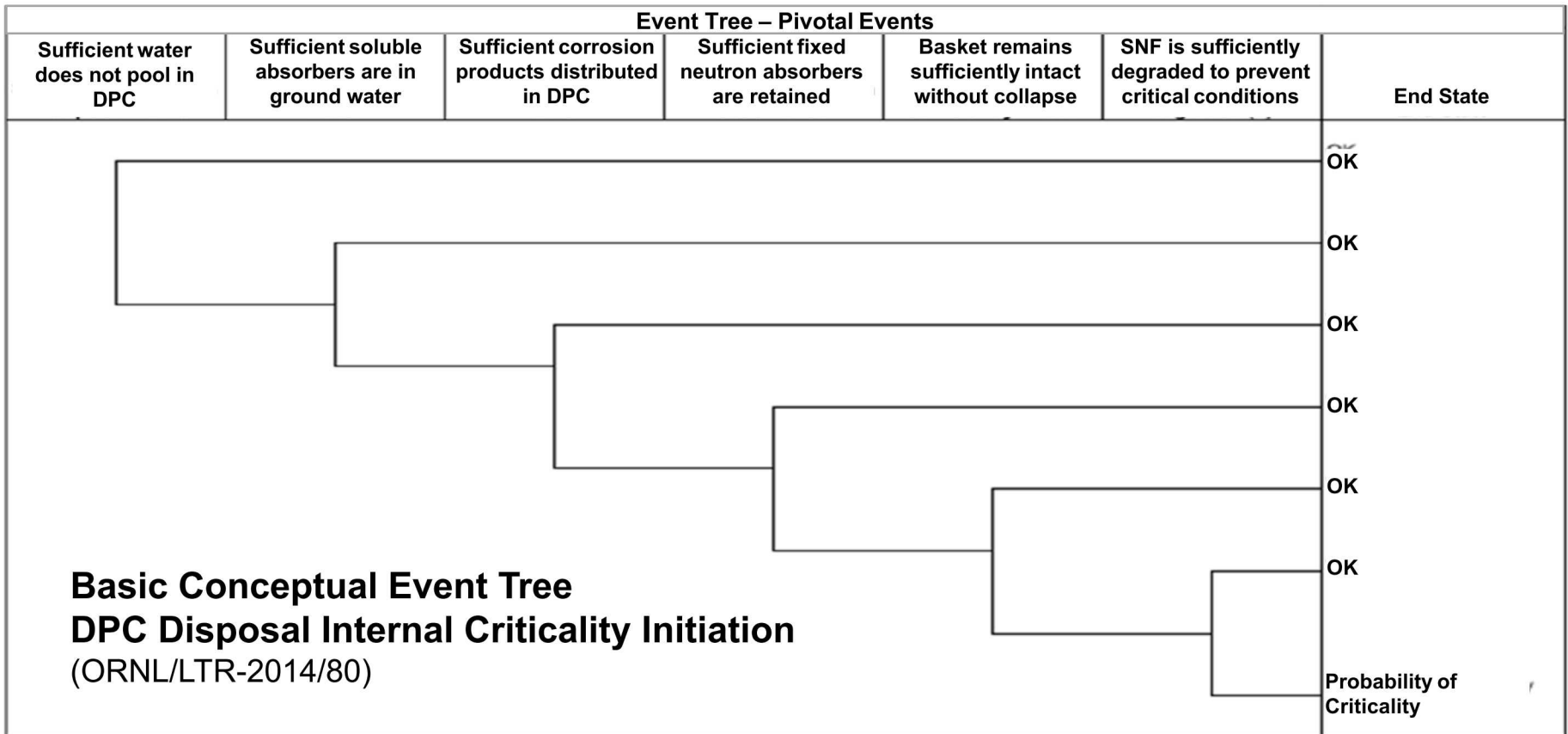
System-Level Criticality Risk Screening Questions 2018 Independent Review*

- What is the threshold of mechanical energy that would impact repository performance?
- What is the threshold of concentration increase for radionuclides already considered in the PA that would impact the regulatory dose estimate?
- What is the threshold of significant concentration increase for radionuclides not already considered in the PA (e.g., short-lived fission products)?
- What is the threshold of temperature increase that would impact repository performance?
- What is the radiolysis threshold (mainly from neutrons) that would impact waste package chemistry?

* Alsaed, A. 2018. Review of Criticality Evaluations for Direct Disposal of DPCs and Recommendations. SFWD-SFWST-2018-000491 (EnviroNuclear Services ENS-2018-SNL001)

DPC Disposal Criticality Analysis Plans

- Postclosure Criticality Analysis Approach for Disposal of DPCs (Wagner 2013, Draft)
- Feasibility of Direct Disposal of Dual Purpose Canisters-Criticality (ORNL/LTR-2013/213)
- Criticality Analysis Process for Direct Disposal of Dual Purpose Canisters (ORNL/LTR-2014/80)

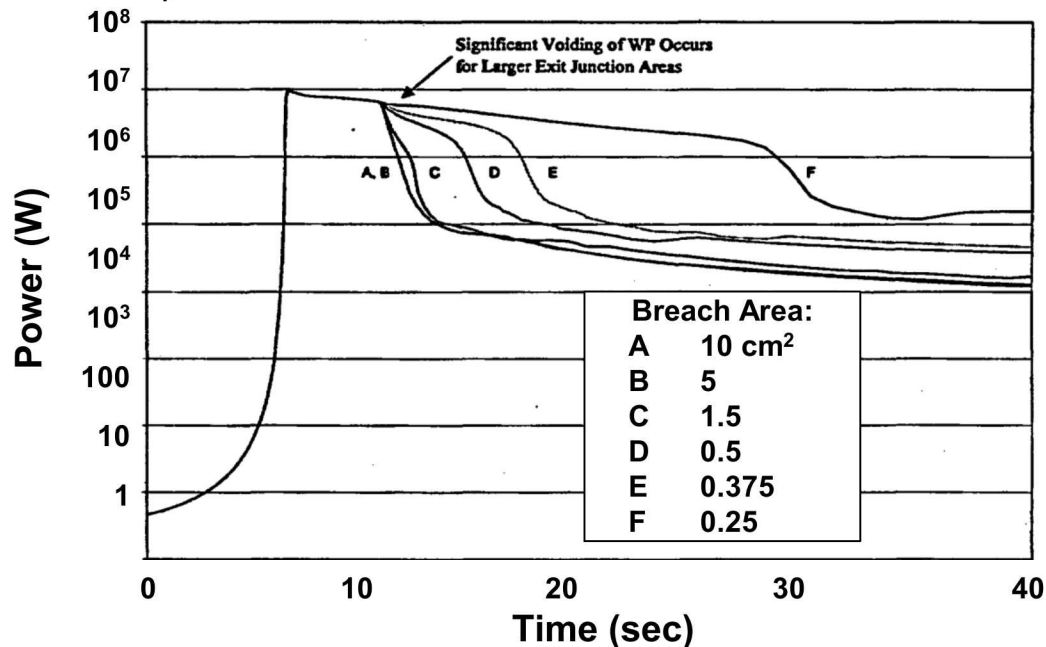


Background - SNF Internal Waste Package Disposal Criticality Simulations

- Probabilistic Criticality Consequence Evaluation (BBA000000-01717-0200-00021 Rev00)
- 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 0.158- $\$/\text{sec}$
(prompt) Reactivity Insertion
Rate Parameterized by Waste
Package Breach Area

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



Background - Analysis of Conditions for Possible Internal Disposal Criticality

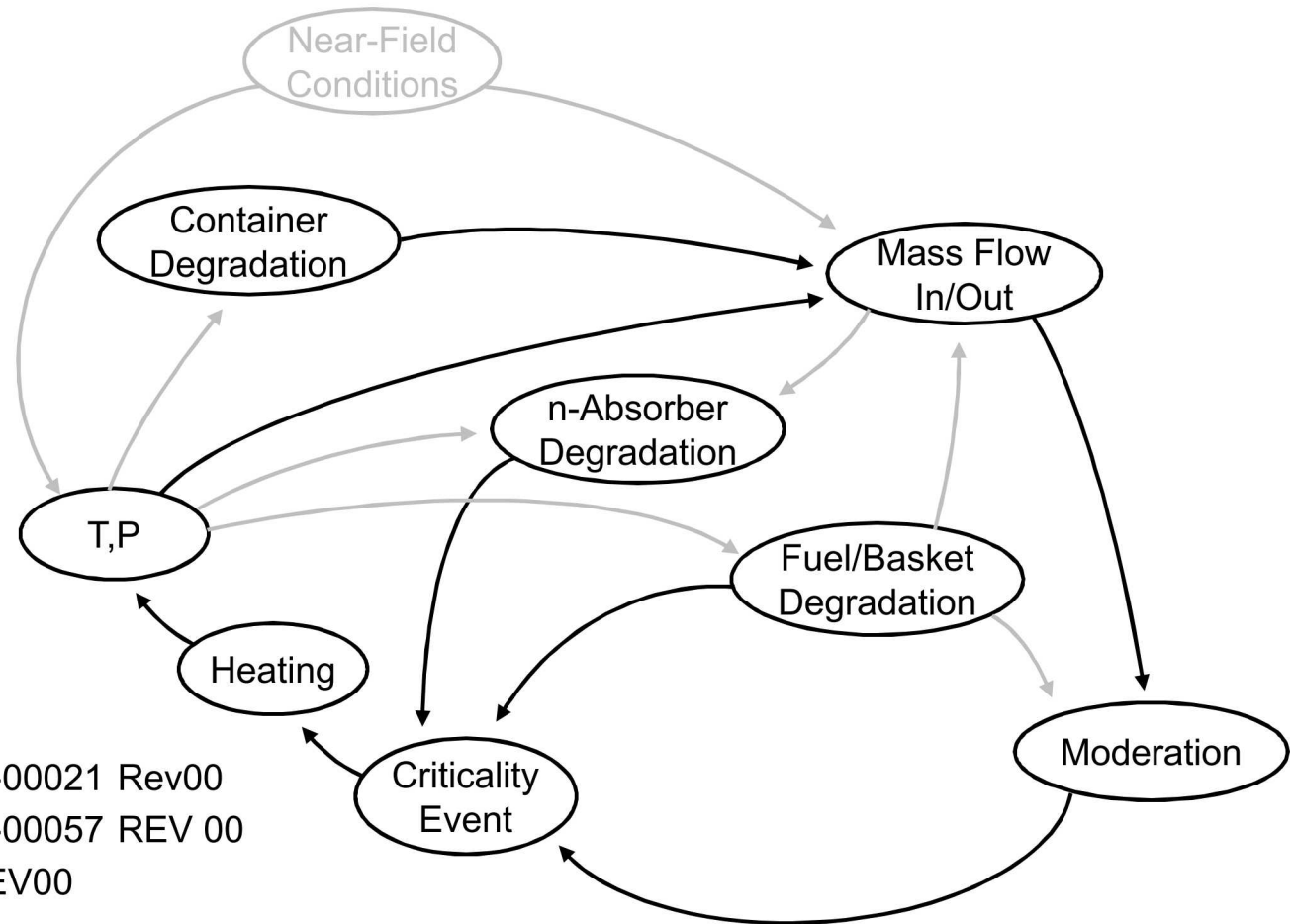
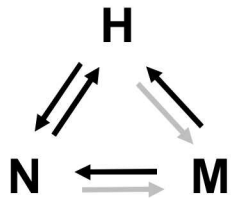
- **YM Post-Closure Criticality–2007 Progress Report** (EPRI 1015128)
- **Feasibility of Direct Disposal of DPCs: Options for Assuring Criticality Control** (EPRI 1016629)
- **Screening of Criticality FEPs for LA** (ANL-DS0-NU-000001 REV00A)
- **CSNF Waste Package Misload Analysis** (CAL-WHS-MD-00003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

- **Potentially important effects from criticality on repository performance:**
 - Change in radionuclide inventory (burnup)
 - Other effects on radionuclide transport, including
 - Increased temperature
 - EBS **degradation** (over-pressure, accelerated corrosion, radionuclide release)
- **WF/WP degradation will likely shorten duration**
- **Consider steady state and transient events**
 - Low-power events may be steady-state or pulsing
 - Transient events may be due to slow or rapid reactivity insertion
- **Context (Rev. 02): One basic CSNF canister design**

- **Disposal overpack reliability**
 - Analyzed in 2014 (FCRD-UFD-2015-000714)
 - **Waste package early-failure abstraction is conservative, e.g., “No credit was allowed for engineered measures designed to prevent or mitigate the effects of human errors.”**
- **Canister structural longevity**
 - Many designs, sizes, materials complicate description of degraded configurations
- **Evaluate DPC modifications for criticality control**
 - Fillers and other measures (separate presentation)
- **Screen postclosure criticality on low risk (not low probability)**
 - System-level PRA for generic saturated and unsaturated repositories
 - Integrated with performance assessment
 - Supported by mechanistic simulations

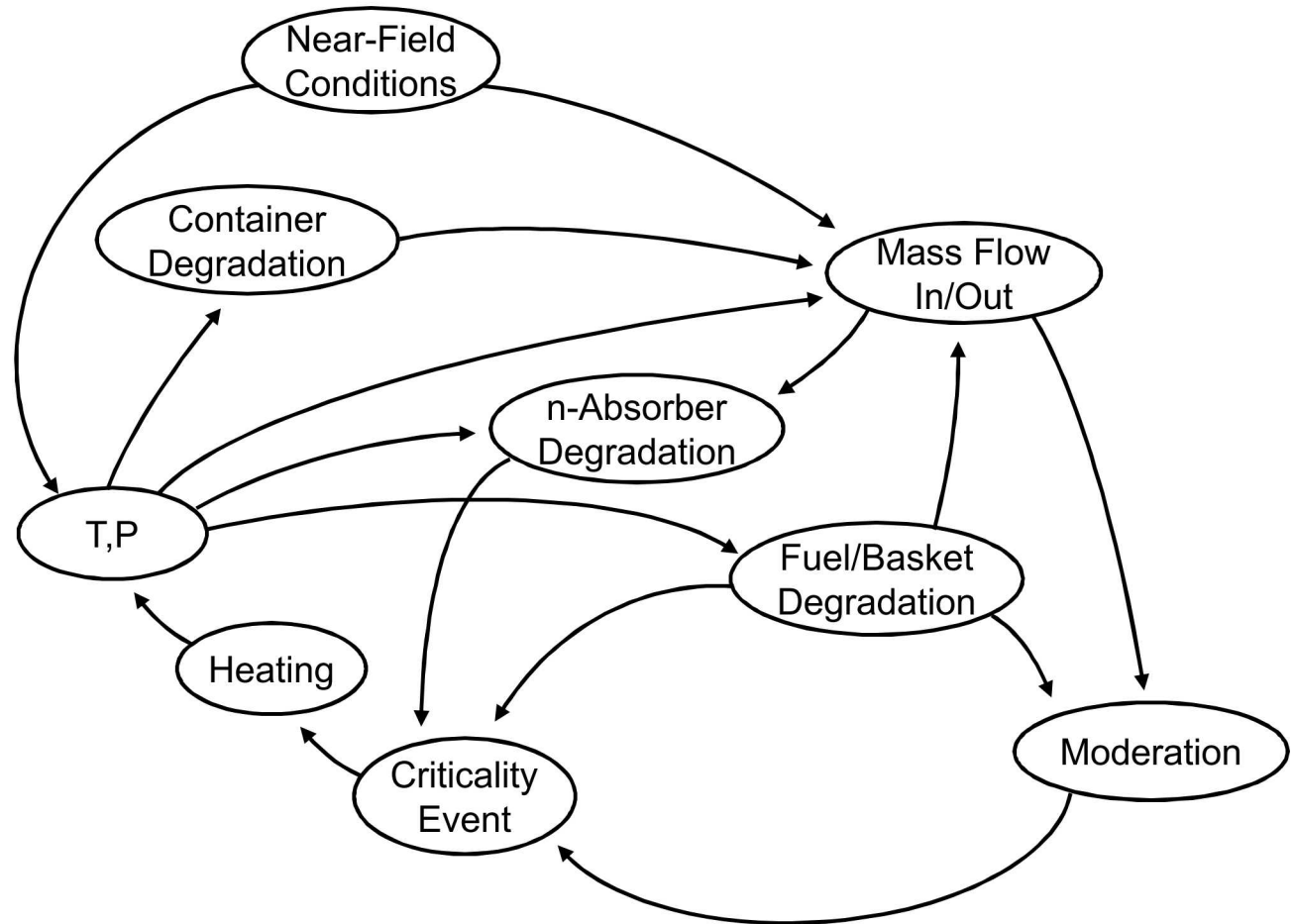
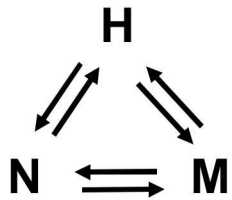
- **Technical/Programmatic Solutions for Direct Disposal of SNF in DPCs**
 - Analysis effort
 - Stakeholder engagement
 - Engineering and resource analysis support
- **Probabilistic Post-Closure DPC Criticality Consequence Analysis**
 - Scoping phase
 - Preliminary analysis phase
- **DPC Filler and Neutron Absorber Degradation R&D**
- **Multi-Physics Simulation of DPC Criticality**
 - Scoping phase
 - Preliminary analysis phase

Coupling Scheme YM Simulations 1996-1999

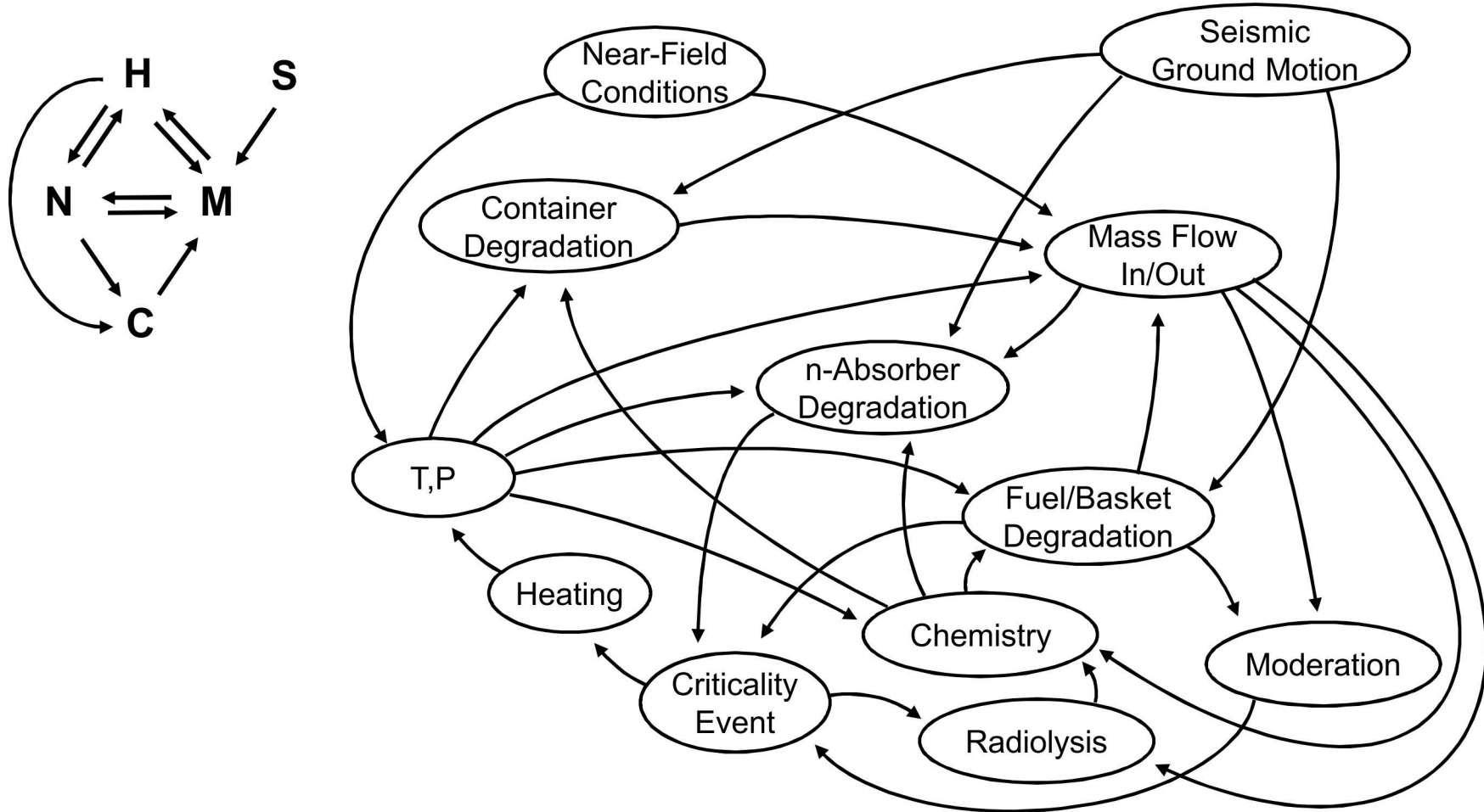


- BBA000000-01717-0200-00021 Rev00
- BBA000000-01717-0200-00057 REV 00
- CAL-EBS-NU-000001 REV00

Multi-Physics Mechanistic Modeling Reference Coupling Scheme (DRAFT)



Example Complex Coupling Scheme w/ Chemical Degradation, Radiolysis, and Seismic Ground Motion (DRAFT)



Summary

- **Scope for FY18-19 probabilistic and mechanistic modeling for criticality risk analysis**
 - Programmatic and Technical Analysis for DPC Disposition
 - Probabilistic post-closure DPC criticality consequence analyses
 - Multi-Physics Simulation of DPC Criticality
 - Fillers R&D
- **Collaboration of SNL, LANL, LBNL and ORNL**
- **Expected Outcomes**
 - DPC disposition alternatives, R&D and resource needs
 - Generic (non-site specific) preliminary PRA
 - Preliminary multi-physics coupled models
 - Feasibility of thermal-setting phosphate cement as filler

Backup Slides

SNF Canister Background

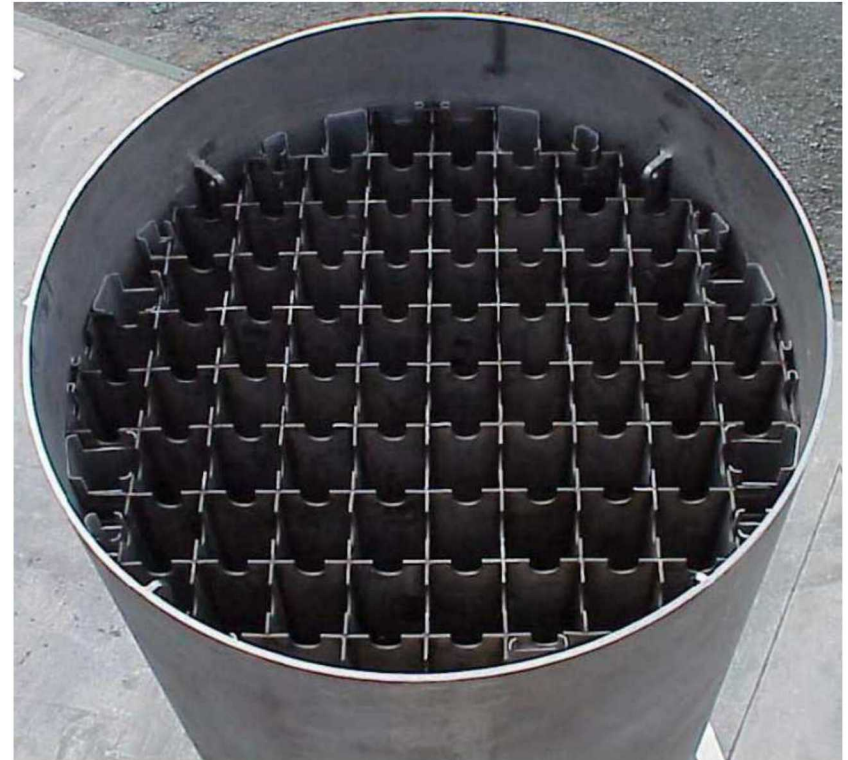
- **Dry storage is a low-cost solution for storage**
 - Loaded in fuel pools, then dewatered and weld-sealed, using a transfer cask for shielding
 - Transfer into fixed, shielded storage casks or vaults
- **Canisters can be moved in shielded transportation casks**
 - Only DPC systems with licensed transport functionality
 - ~15%* of total existing canisters (about 2,500) are storage-only
- **~2,500 DPCs have been loaded with ~30,000 MTU SNF**
- **DPCs are not licensed for geologic disposal of spent fuel**
 - After disposal, waste packages will eventually breach and fill (or partially fill) with water to some extent
 - DPC fuel baskets are not designed for criticality control for thousands of years after package breach

* Including 58 VSC-24, 200 NUHOMS-24Pxx, and 27 NUHOMS-52B canisters (Greene et al. 2013)

- **Trends in DPC Design:**
 - **Larger capacity**
 - **Greater thermal limits**
 - **Burnup credit basis for criticality control when flooded**
 - **Aluminum-composite materials**

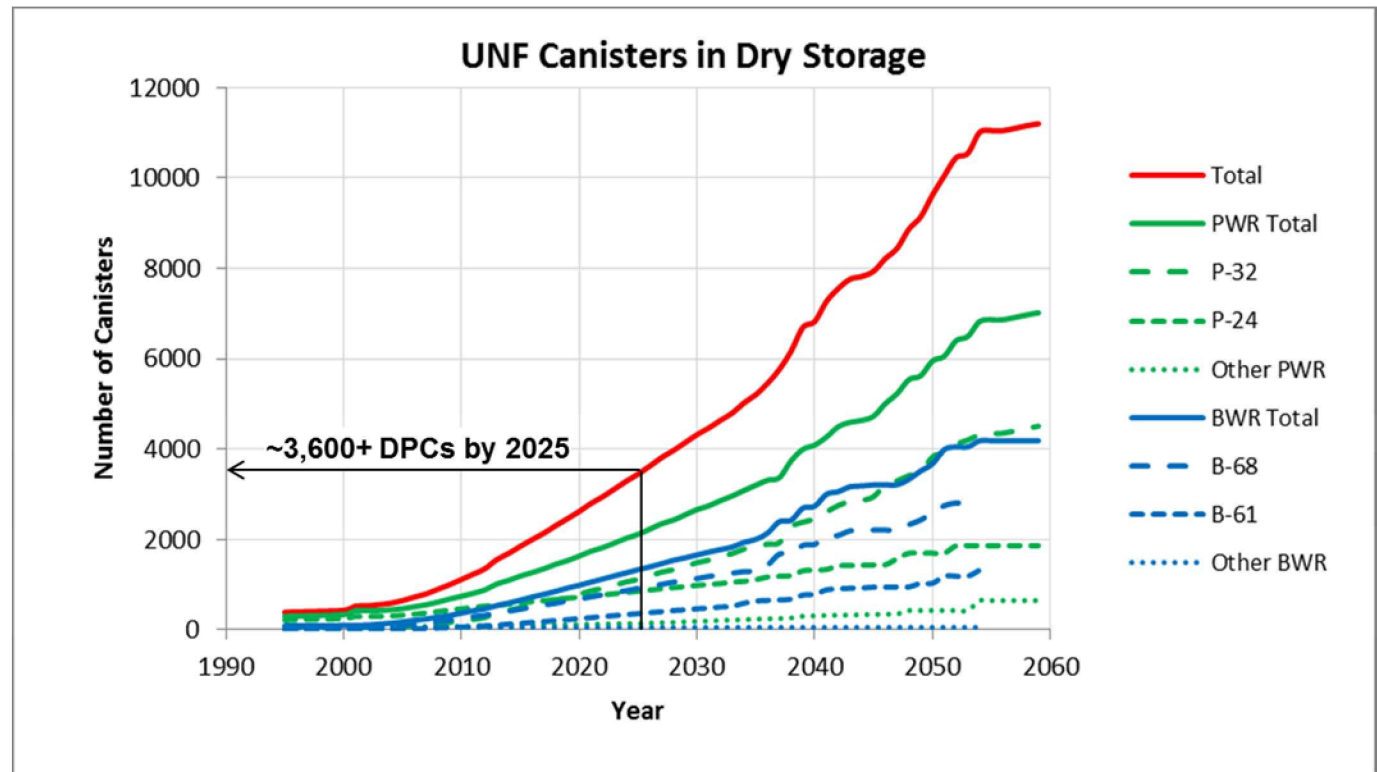
Top view of MPC-68 shell and basket
(Greene et al. 2013).

This design uses an aluminum composite material (in lieu of stainless steel or other materials) for basket plates that are both structural and serve as neutron absorbers.

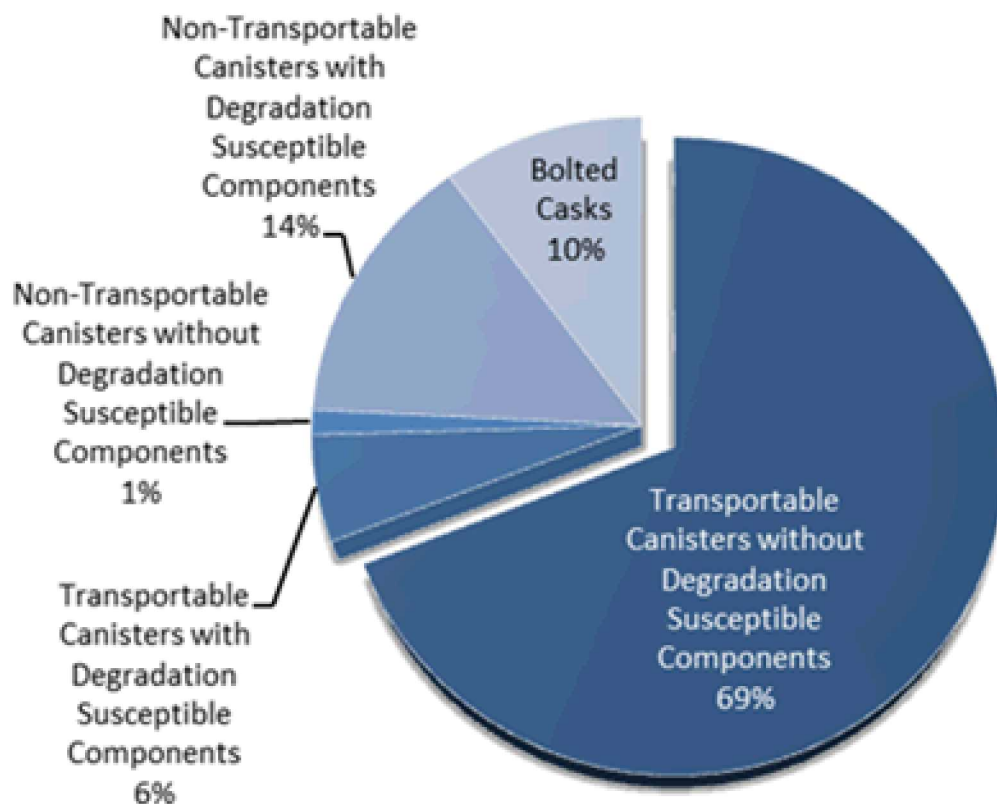


- Transition from fresh-fuel to burnup-credit canister basket designs for criticality control (1990's to 2000's)
- Fuel pool safety + 10CFR71 accident analysis → reactivity control (short term)

Figure from Hardin et al. (2013).
Preliminary Report on Dual-Purpose Canister Disposal Alternatives (FY13). FCRD-UFD-2013-000171 Rev. 1.



DPC Construction Affects Potential for Postclosure Criticality



Hardin et al. 2014. *Investigations of Dual-Purpose Canister Direct Disposal Feasibility (FY14)*. FCRD-UFD-2014-000069 Rev. 1.

- Fresh-water disposal environment, flooding possible
- Reliance on uncredited margin (as-loaded, full burnup credit)
- After package breach, degradation of neutron absorbers
- Basket structural integrity maintains assembly fuel rod pitch
- Stainless steel has the longest corrosion lifetime

- **International Studies**

- **Criticality Safety Computations for Spent CANDU Fuel in a DGR (NWMO TR-2014-08)**
- **Criticality effects of long-term changes in material compositions and geometry in disposal canisters (SKB TR-16-06)**
- **Geological Disposal Criticality Safety Status Report (NDA/RWMD/038)**
- **Status of the safety concept and safety demonstration for an HLW repository in salt – Summary Report (VSG) (DBE TEC-15-2013-AB)**