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Dual-Purpose Spent Fuel Canister Cement Fillers Program

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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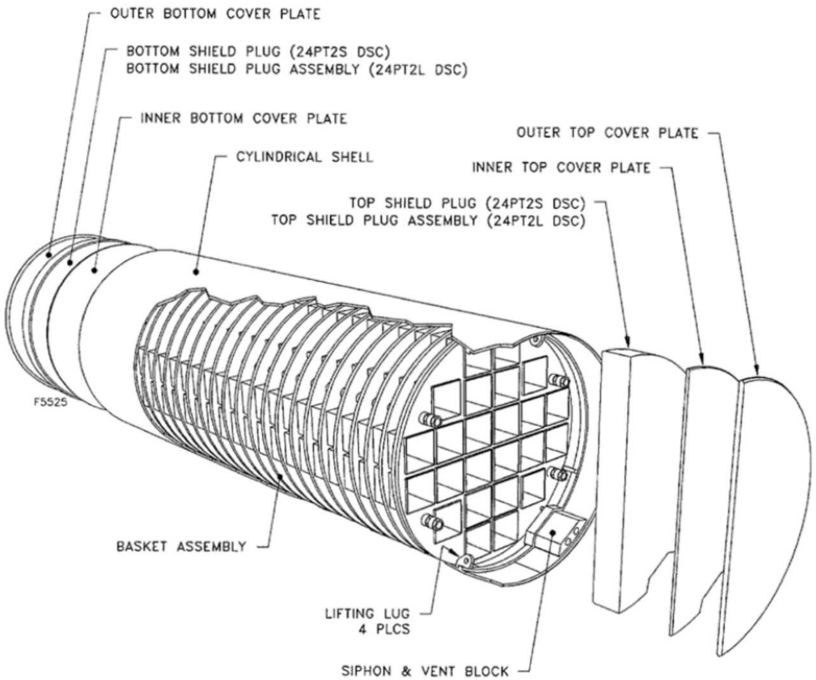
Outline

- Dual-Purpose Canister Background
- DPC Disposability Issues
- History of Dry Particle Filler Demos
- Filler Attributes (liquid emplacement)
- Cement Slurry Fillers
  - Background
  - Selected Cement Types
  - Technical Questions
  - Testing Strategy
  - Workplan



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

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

Two basic types of DPC baskets: tube/plate and eggcrate

U.S. Spent Fuel Inventory

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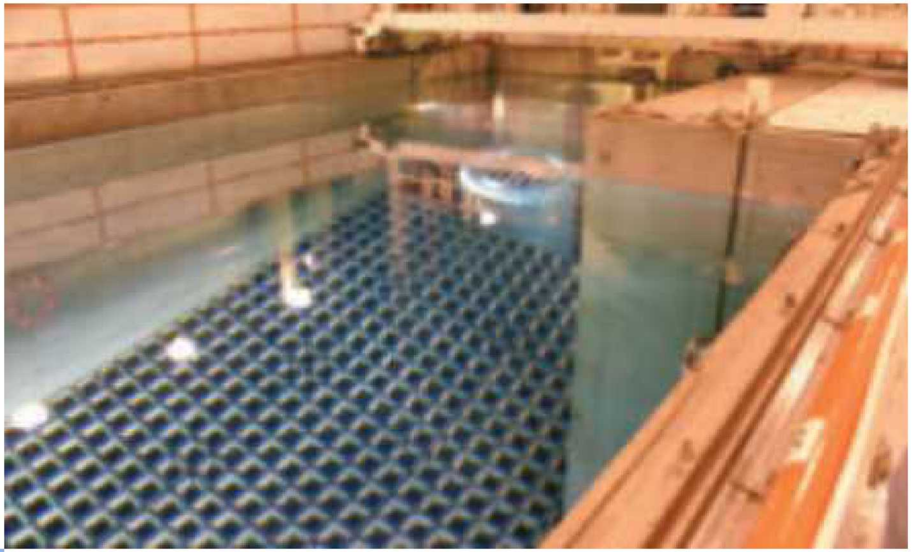
- CSNF Projection
  - Extend all operating reactors → 60 yr
  - Last shutdown ~2055 (140,000 MTHM total)
  - Avg. burnup ~45 GWd/MT



- Pool Storage for SNF
  - ~60,000 MTHM system-wide capacity
- Dry Cask Storage
  - ~20,000 MTHM current
  - +2,000 MTHM/yr
  - 1/2 of all U.S. SNF by ~2035

Recent DPC Designs

- Example: Magnastor® DPC system (NAC International)
- Capacity 37-PWR assemblies (or BWR equiv.)
- Thermal limits: 35.5 kW storage/ 24 kW transport
- Size evolution: fresh fuel → burnup credit → heat transfer features → more efficient storage and transport

Pictures and data from NAC International website 31Mar2012

ROM Cost Analysis for DPC Direct Disposal vs. Re-Packaging of All Commercial SNF

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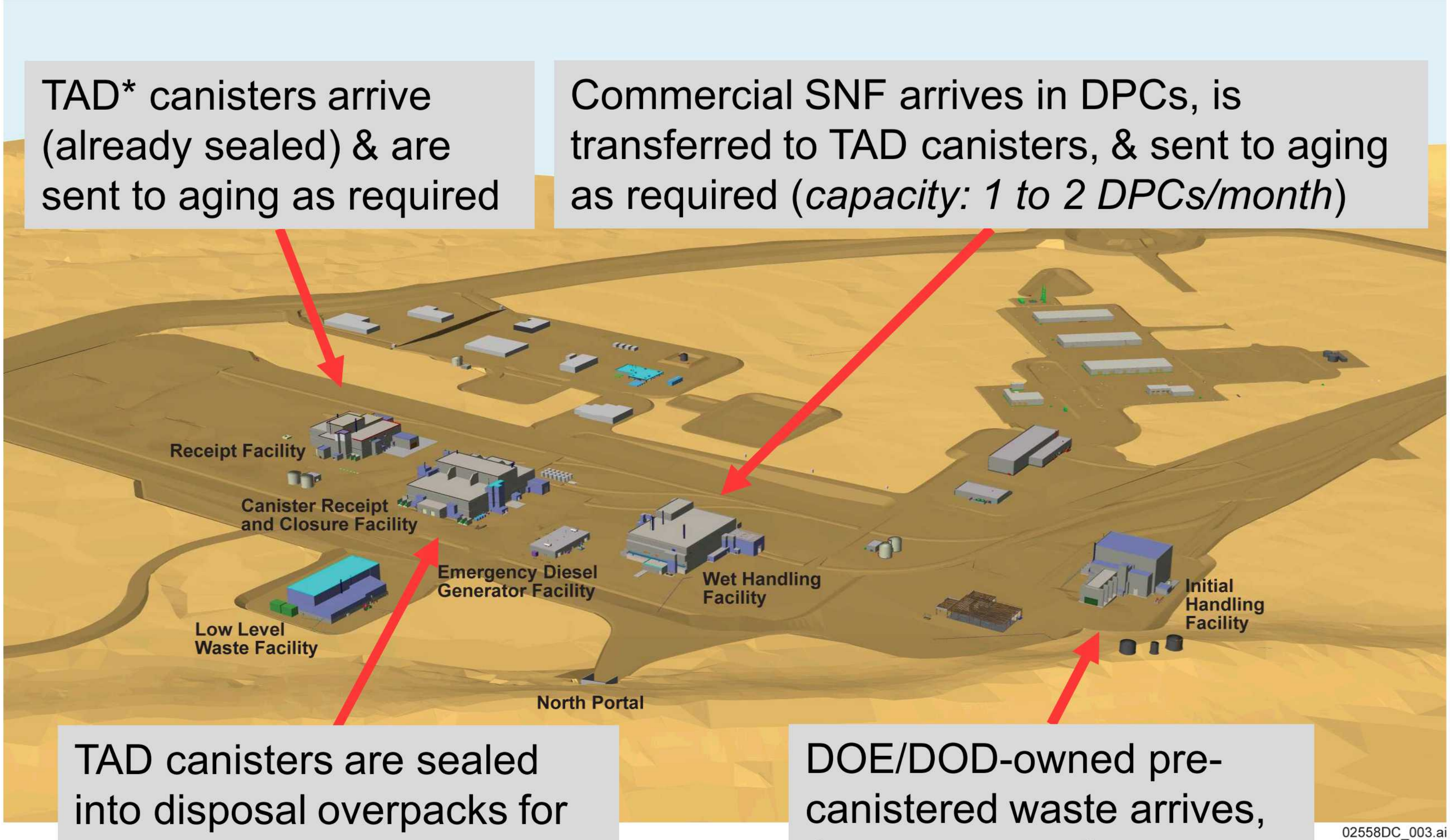
Scenario 1: Estimated Most Costly Case, Loading All CSNF into DPCs and Re-packaging All of Them for Disposal Total DPCs 140,000 MTU (all re-packaged)	Unit Cost	CSNF Qty. (MTU)	Avg. DPC Capacity, MTUs	# DPCs	Cost $B
Sunk cost to procure, load and store existing DPCs ($/MTU)	$ 100,000	25,000	12.0	2100	$ 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 for disposal					**$ 32.7**
Maximum potential savings from direct disposal of DPCs, not including filler implementation					**$ 18.7**
Notes:					
1. $100k/MTU canisterization cost is for hardware and labor to load/seal/store, and not for facilities.					
2. Does not include costs for the repository, storage of re-packaged CSNF, or disposal of storage and transportation 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.					

Yucca Mtn Surface Facilities (LA Design)

TAD* canisters arrive (already sealed) & are sent to aging as required

Commercial SNF arrives in DPCs, is transferred to TAD canisters, & sent to aging as required (*capacity: 1 to 2 DPCs/month*)



TAD canisters are sealed into disposal overpacks for emplacement underground

DOE/DOD-owned pre-canistered waste arrives, & is packaged for disposal

* TAD = Transport, aging and disposal

Postclosure Criticality of SNF in Breached and Flooded DPC-Based Waste Packages

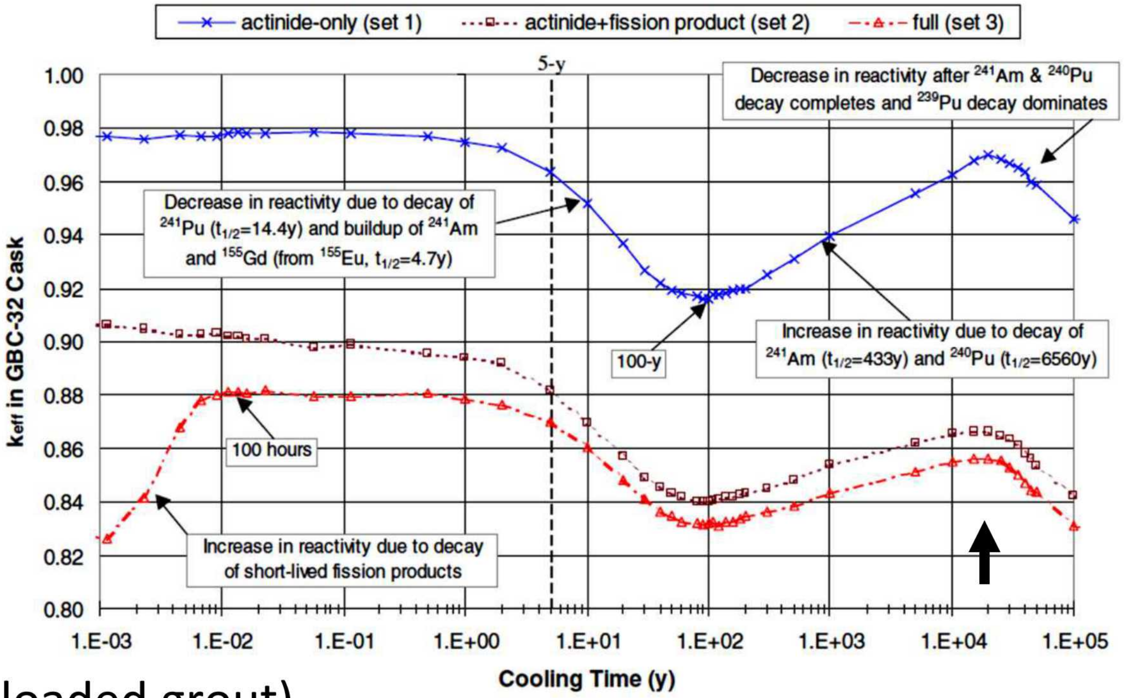
- **Postclosure criticality is particular to SNF in large canisters (e.g., >4 PWR fuel assemblies)**
- **Package breach from external corrosion leads to flooding with ground water (criticality cannot occur without at least partial flooding)**
- **Neutron absorbers readily corrode in water (Boral®, Al-B4C, and Metamic® are all aluminum-based)**
- **Stylized fuel basket degradation cases for criticality analsyis:**
  - Loss of Al-based neutron absorbers
  - Basket collapse (and loss of absorbers)
- **Apply reactivity margin to degradation cases for individual DPCs**
  - Burnup credit analysis, with as-loaded fuel and configurations,
  - Investigate disposal environments (e.g., brine)

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

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

Spent Fuel Disposal: Postclosure Nuclear Criticality Control

- **Disposal Environment**
  - Groundwater availability
  - Chloride in groundwater
  - Overpack integrity
- **Moderator Exclusion**
  - Overpack integrity
- **Moderator Displacement**
  - Fillers (e.g., boron carbide loaded grout)
- **Criticality Analysis Methodology**
  - Burnup credit, as-loaded, degradation cases
  - Peak reactivity occurs at ~25,000 years

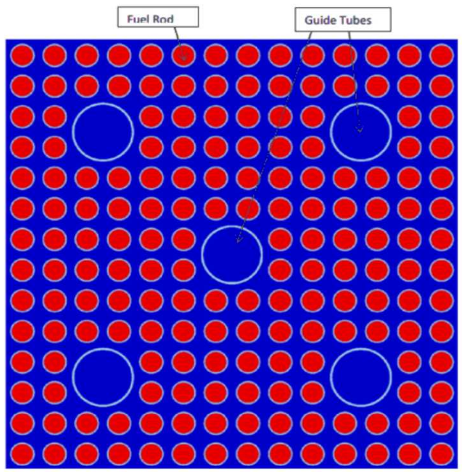


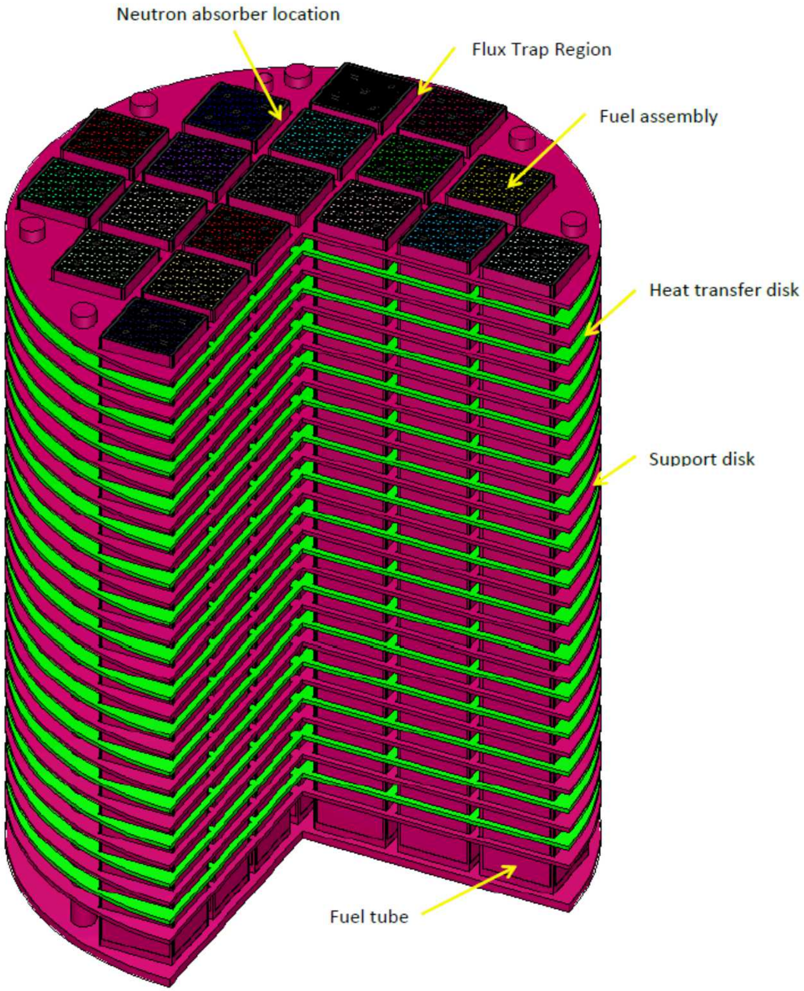
k_{eff} vs. time
Generic burnup credit 32-PWR cask
PWR fuel (4% enriched, 40 GW-d/MT burnup)

Wagner and Parks 2001 9NUREG/CR-6781, Fig. 3)
Note: Set #2 burnup credit reactivity results correspond to criticality scoping analysis of Clarity & Scaglione (2013).

Reactivity Scoping Analysis (Site "A")

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

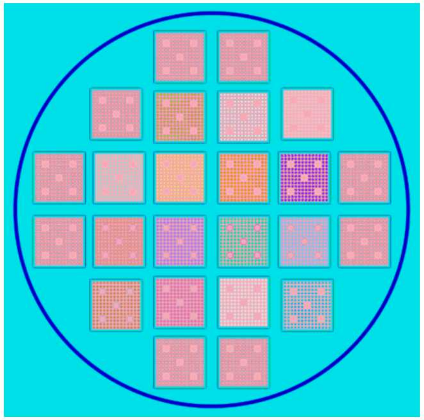




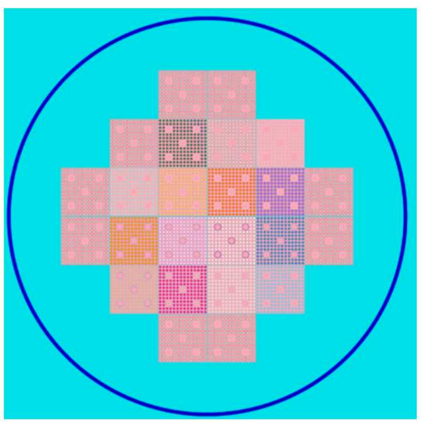
- Numerical Model of TSC-24 Canisters
- ORNL Database "UNF-ST&DRDS"
  - Software/Data
  - SCALE code system (ORNL 2011)
  - Details: Clarity and Scaglione (2013)

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.

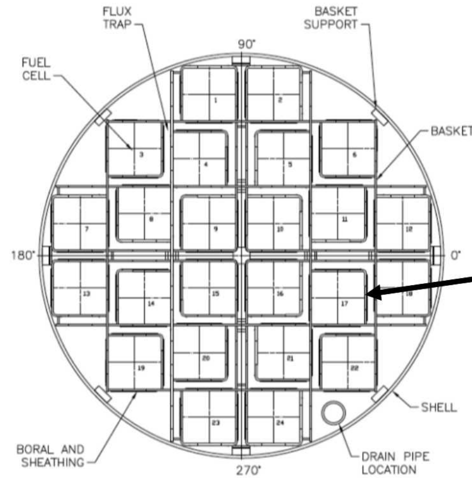
Basket Configurations for TSC-24 System ("Site A")



Intact Basket With Loss of Neutron Absorber Plates



Collapsed Basket, (with loss of neutron absorbers)



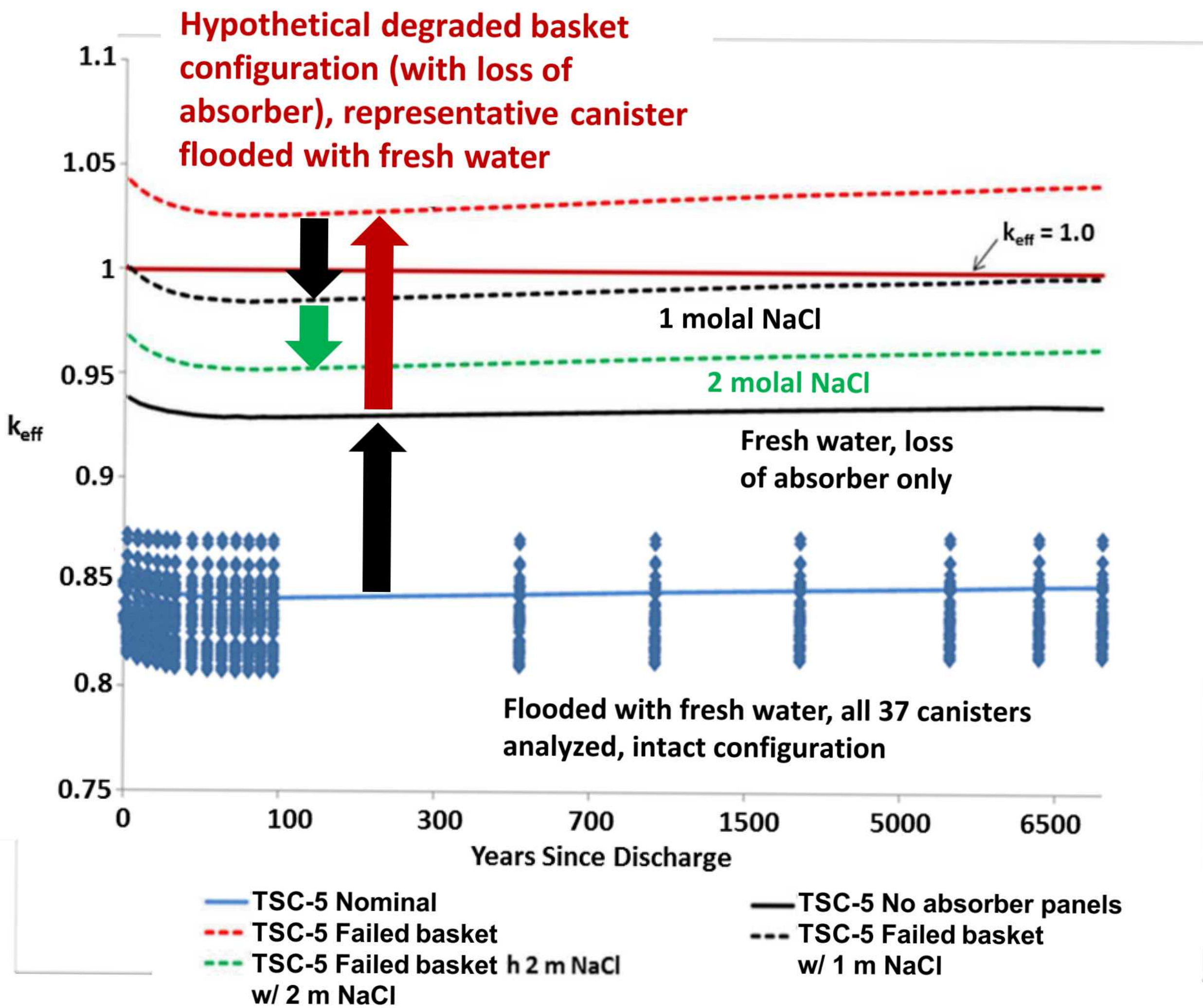
Fuel-tube type basket (e.g., TSC-24)

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

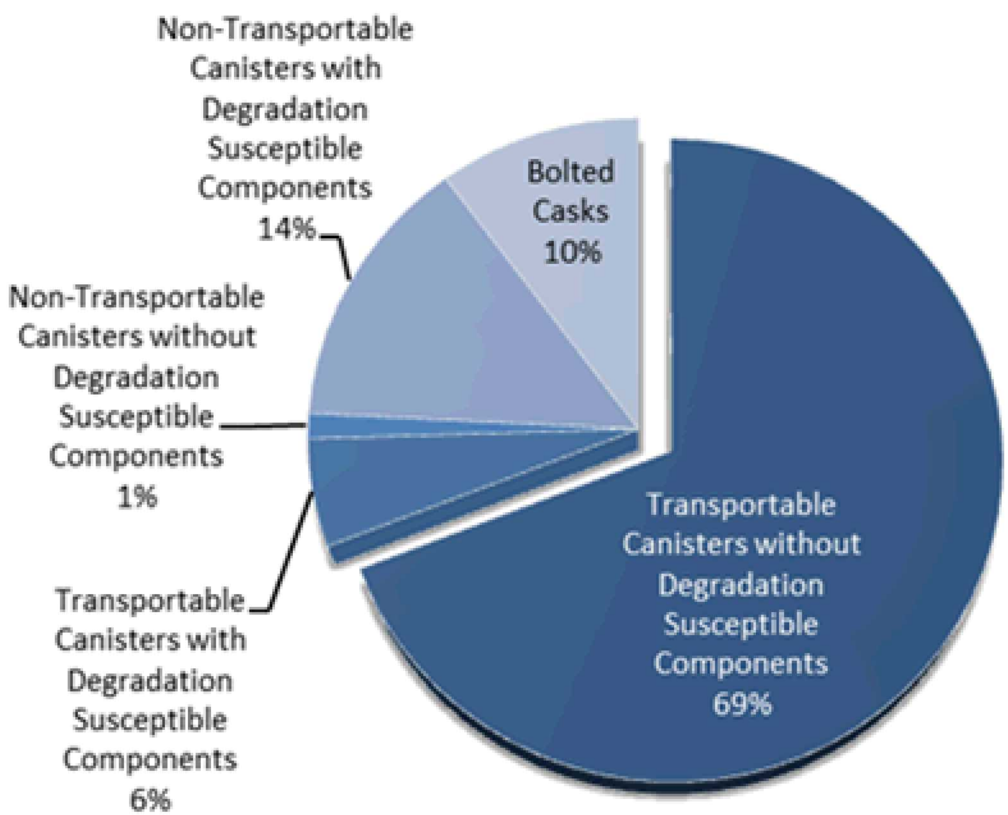
References:
Clarity, J.B. and J.M Scaglione 2013. ORNL/LTR-2013/213.
Hardin et al. 2012. FCRD-UFD-2012-000219 Rev. 2.

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



DPC Construction Affects Potential for Postclosure Criticality and Thus, Disposability

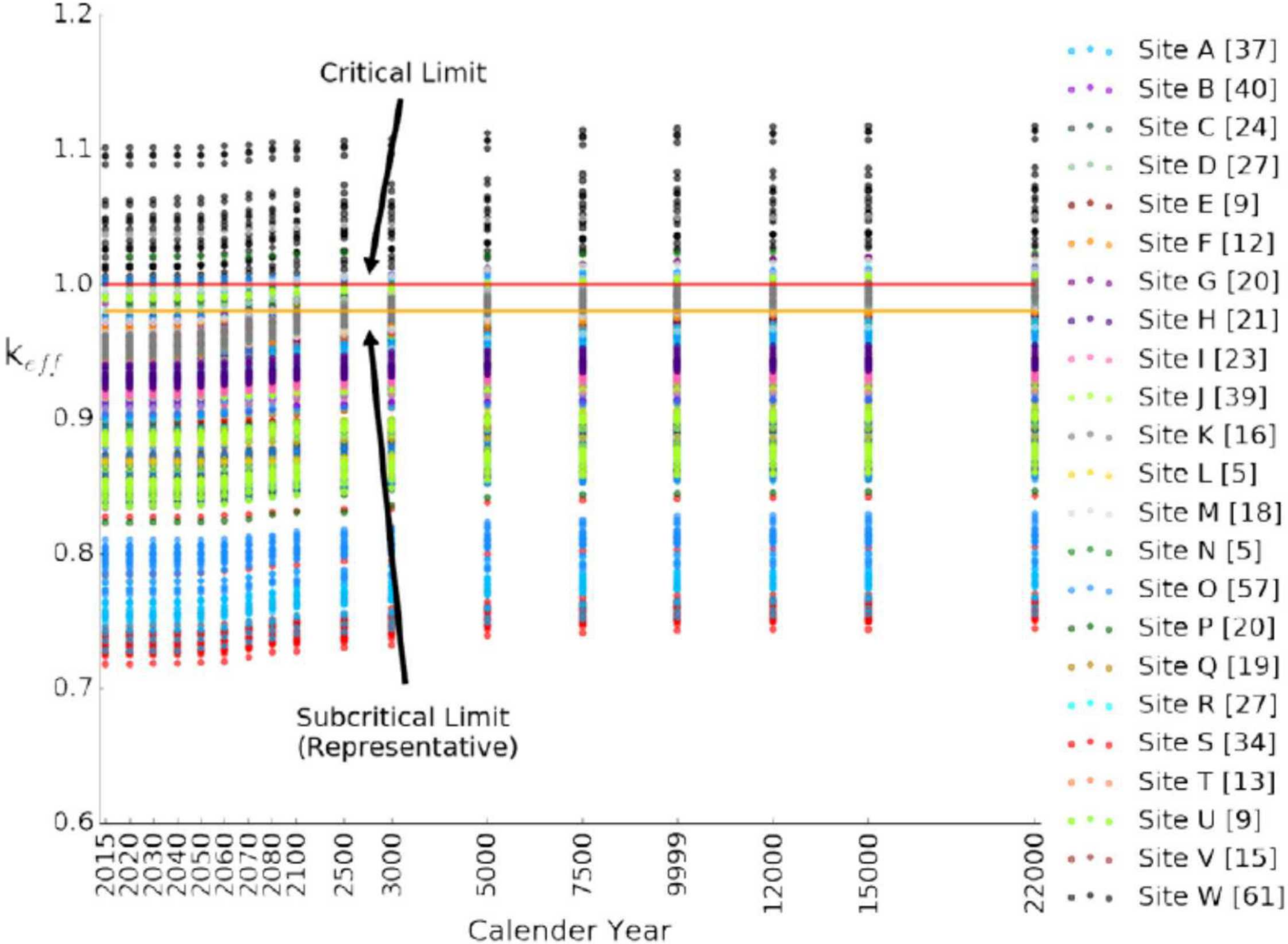


Based on Greene et al. 2013. *Storage and Transport Cask Data For Used Commercial Nuclear Fuel – 2013 U.S. Edition*. ATI-TR-13047.

- 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

k_{eff} vs. Time for DPCs Flooded with Fresh Water

All DPCs from 23 sites, loss-of-absorber (except P & W)



Selected sites include most decommissioned power plants, and both PWR and BWR plants

Liljenfeldt et al. 2017. *Summary of Investigations on Technical Feasibility of Direct Disposal of Dual-Purpose Canisters*. SFWD-SFWST-2017-000045.

Canister Disposability Framework

Group	Postclosure Criticality Design Alternative
Group 1 – Small canisters (up to 4 PWR assemblies or BWR equiv.) with no neutron absorbers	1.A Small capacity waste package
	1.B Small capacity waste package combined with heavy insert
Group 2 – Larger canisters with bolted closures or bolted/welded combinations	2.A Bolted closures (both inner and outer canister lids)
	2.B Bolted closure combined with welded closure
	2.C Can-within-can arrangements using bolted or welded closures
DPC Direct Disposal Ideas (Existing Canisters)	3.A High reliability (~10^{-12}/year/package) overpack performance
	3.C Flooding possible only with chloride brine
	This study
Group 4 – Existing DPC designs (welded closure) used for disposal with modifications	4.A Reactivity control improvements
	4.B Fillers for reactivity control
Group 5 – Multi-purpose canisters with long-lived baskets and neutron absorbers	
	5.B Larger canisters, with basket and absorber materials selected for longevity in a range of chemically reducing and oxidizing environments

Source: Hardin, E. 2013. Spent Fuel Canister Disposability Baseline Report. FCRD-UFD-2014-000330 Rev. 0.

Proposed Goals - DPC Filler Program

- **Develop technological filler solutions**
  - Maturity sufficient for decision making
  - Provide information to scope program and select one or more approaches
- **Involve stakeholders (utilities, vendors, and regulators) for program review and to build acceptance**
  - Develop wide consensus on:

    1) which types of canisters and baskets, with

    2) which fuel characteristics, are disposable in

    3) which repository environments, and

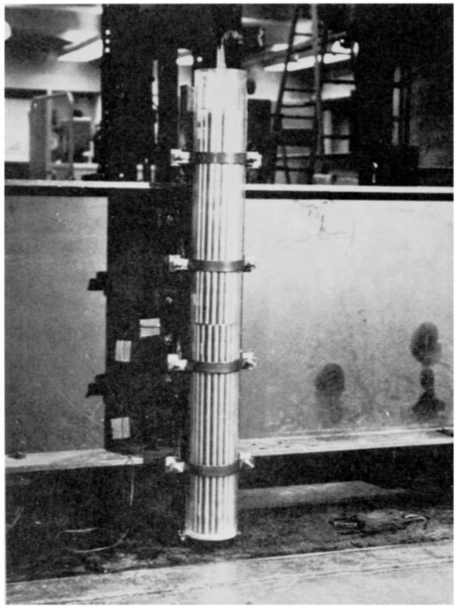
    4) what modifications can be made to DPCs to expand disposability

R&D History: YMP Steel Shot Filler Test (Framatome-Cogema)

- **Steel shot**
  - 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
- **Selection (judgement based)**
  - Ease of handling and placement ("flow")
  - Commercial availability
  - Low cost
  - Cathodic protection
  - Chemical buffering
  - Moderator displacement
  - Thermal conductivity
- **Dummy PWR assemblies (15 × 15 and 17 × 17) in polycarbonate cells**
- **Eight tests (2 assemblies, 2 shot sizes, w/without vibration)**
- **Test successful: 94% fill ratio (void space minus “excess” porosity)**

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

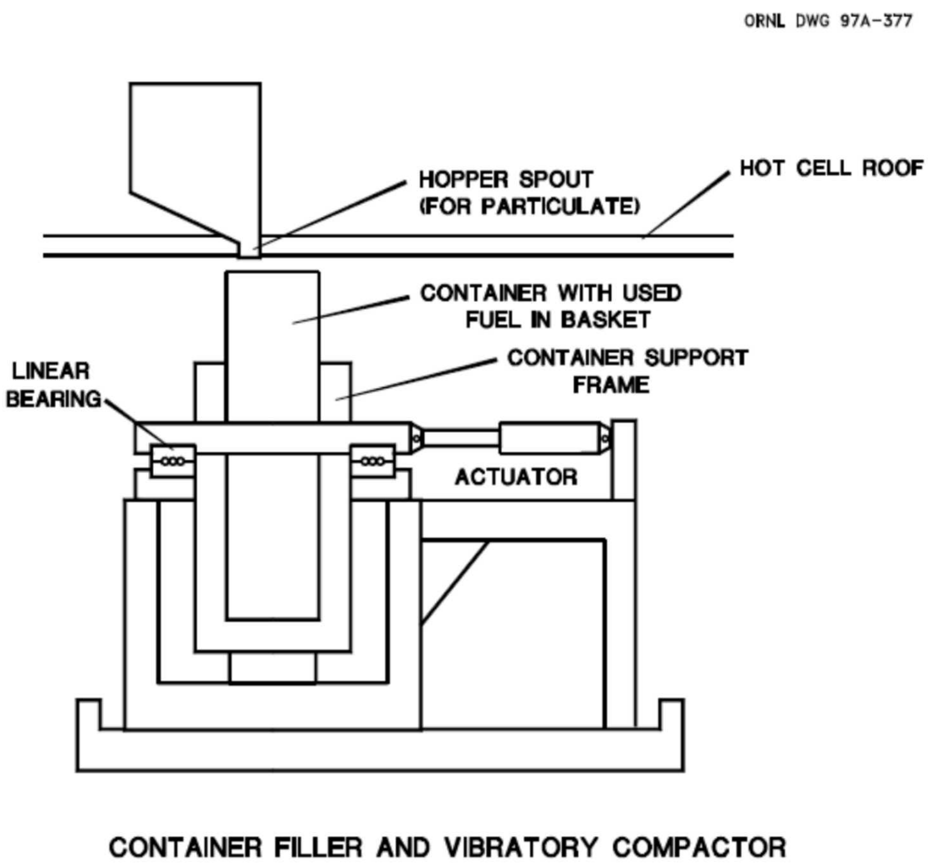
R&D History: Particle Filler Tests (1/2)
Atomic Energy of Canada, Ltd.



- **Glass Beads**
  - 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 fuel 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.

AECL Filler Tests (2/2)



Vibratory compaction apparatus – full scale.

Hydrostatic testing vessel, AECL/Whiteshell

FIgures from Forsberg (1997)

Perspective on Dry Particulate Filler Options for Existing U.S. DPCs

- **Cut DPC Lids Off**
  - Skiving selected among various methods (DOE IWM/NFST investigation)
  - Wet is possible but what about dry operations? Cut lids off dry?
- **Particulate Filling → Dry**
  - Dewatering after filling is impractical
  - Moisture → Corrosion & radiolysis, gas generation, internal pressure
- **Alternative: Criticality Control Features (EPRI 2008)**
  - Open DPCs, insert “disposal control rods”
  - Rearrange fuel assemblies and/or de-rate capacity

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

Liquid or Slurries Fillers Pumped In: Attributes

Injectable – ~6,000 L through a 0.5-in ID fill (drain) tube in reasonable time (e.g., a few hours)

Void Filling – Penetrate limber holes, fuel end blocks, spacer grids, and fuel-rod gaps (voids may be less than 1 mm, may be >8,000 fuel pins)

Compatible – Limited gas generation, no chemical attack of fuel or canister internals, limited water content

Durable – 10,000+ yr chemical/physical lifetime before or after waste package breach (natural analogues)

Reactivity Control – By displacing groundwater that may flood a package, or incorporating neutron absorbing material, or both

Safe – Handling and implementation does not endanger workers or members of the public (e.g., RCRA metals)

Practical – Reasonable weight, possibility of retrieving fuel

Low Cost (relative to alternative disposal alternatives)

Background: Ordinary Portland Cement (OPC)

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

The Good

Reactions well understood
Many antique analogues
Inexpensive

The Bad

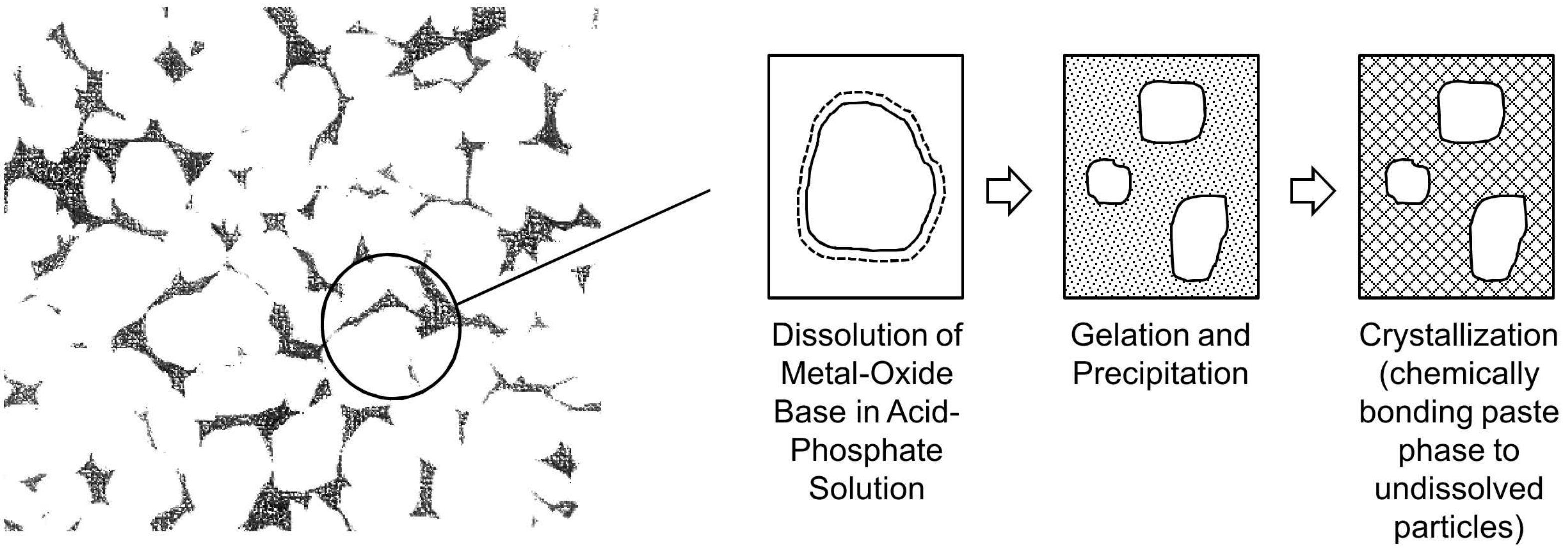
High pH bad for corrosion
High pH bad for RN solubility, sorption

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



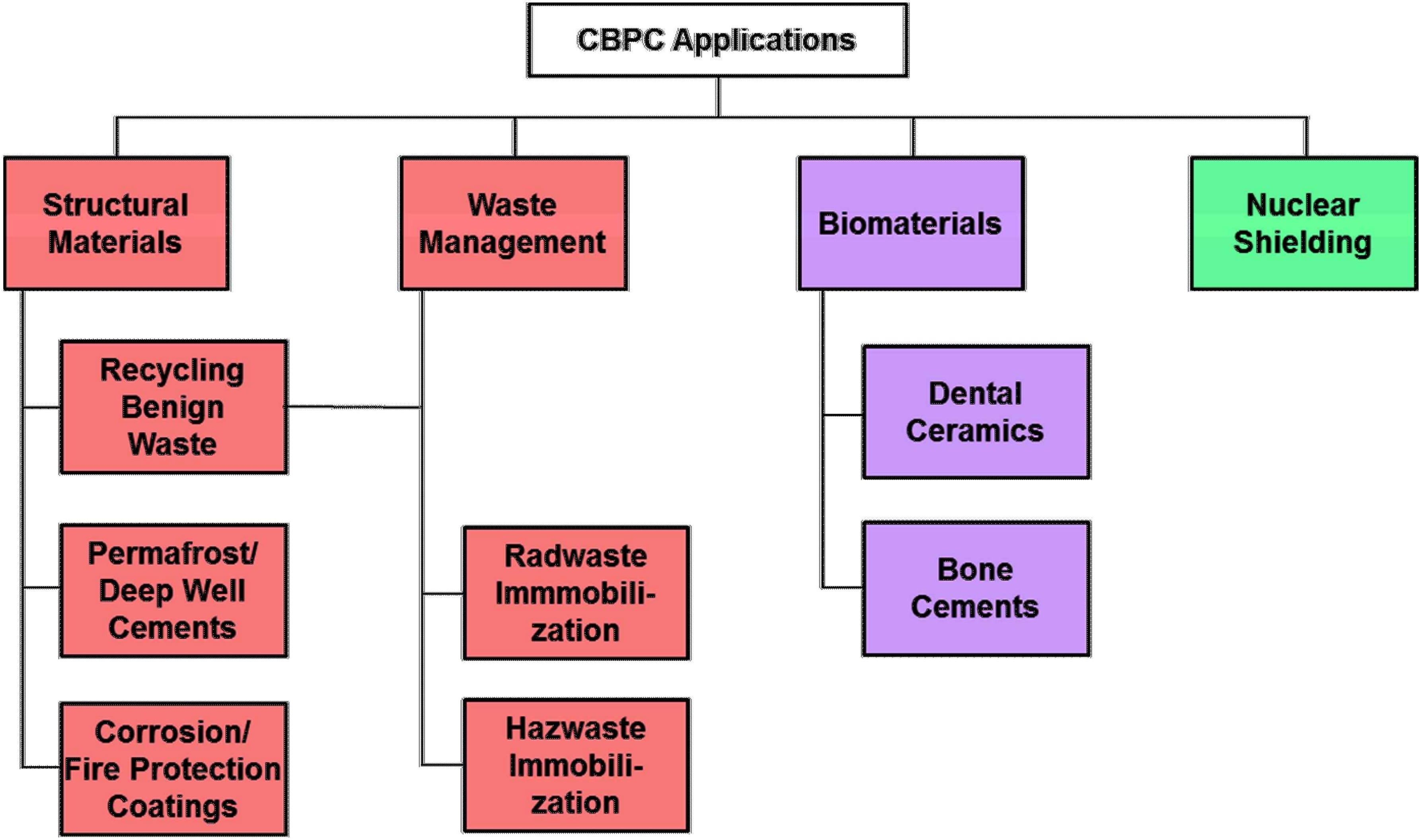
Ceramic ← Crystalline
Cement ← Low temperature
Chemically Bonded ← Paste phase chemically bonds to undissolved particles or aggregates (instead of hydrogen bonds)

Background 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, or organics.

How are Phosphate Cements Being Used?



Example Cement Types: Ceramicrete® Mg-K-PO_4 Chemically Bonded Phosphate Ceramic Binder

A. Wagh* and D. Singh, Argonne National Laboratory

$$MgO + KH_2PO_4 + 5H_2O \rightarrow MgKPO_4 \cdot 6H_2O$$

MKP binder: Density 1.7 g/cm^3 Porosity 2.9% (Cantrell & Westsik 2011; PNNL)
Admixtures: Fly ash, sand, zeolite, wollastonite ($CaSiO_3$), boric or citric acid as retarder

Slurry pH 5 to 8; Final pH slightly alkaline; Working time 20 min to 2+ hours;
Comp. strength >> 500 psi; Adiabatic temp. rise 50 to 80°C (Stefanko & Langton 2011).

Waste immobilization (Hanford secondary waste studies)
Waste encapsulation (SRNL P-Reactor cement study)
Nuclear material storage (Borobond® – Ceradyne/3M with ORNL, ANL)
Casting and patching (rapid setting/early strength and permafrost)

Ceramicrete: R&D 100 awards in 1996 and 2004 (*R&D Magazine*)

GRANCRETE YouTube URL: https://www.youtube.com/watch?v=p7foDkuQi7U
Ceramicrete YouTube URL: https://www.youtube.com/watch?v=KxidwoJaC1c

* Inorganic Polymer Solutions, Inc.

Example Cement Types: ThermaLock® Ca-Al-Phosphate Geothermal Wellbore Cement

Haliburton, Unocal, and Brookhaven National Laboratory;
Sugama (1996 and various other publications); Wagh (2016, Section 16)

$(CA + CA_2 + \ldots) + m(NaPO_3)_n(aq) + CO_2 + H_2O \rightarrow$

$a \times Ca_5(PO_4)_3 \cdot OH)$ (hydroxyapatite) +
$b \times Na_6Ca(CO_3)AlSiO_4 \cdot H_2O$ (cancrinite) +
$c \times Al_2O_3(s) + \ldots$

Tested CO_2 resistant in geothermal wells

Strength, pumping time, and temperature tolerance suitable for deep well cementing

May have high porosity (e.g., >20%); boric acid may not function as retarder at higher temp.

Probable admixtures: fly ash, sulfonate plasticizer, betaine stabilizer

A visual comparison of ThermaLock cement (right) and Portland cement (left) shows how CO2 deteriorates Portland cement over time, while leaving ThermaLock cement virtually unaffected (HAL1343).

Alternative formulation (Wagh 2016, Table 16.3):

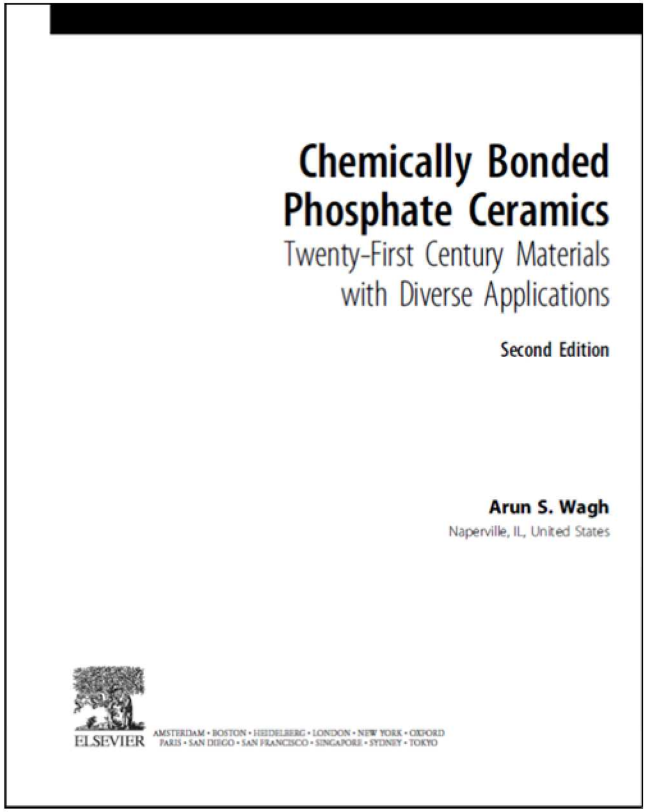
$Al_2O_3 + 2H_3PO_4(aq) \rightarrow$

$2AlPO_4$ (berlinite) + $3H_2O$

Forms $AlH_3(PO_4))$ gel at low temperature (but converts to crystalline berlinite at 150°C

Recommended Cement Types for Filler Investigation

- **Al-phosphate** (end-product berlinite, $AlPO_4$, as thermally setting binder, possibly with fly ash)
- **Mg-K-phosphate** (Ceramicrete® binder with fly ash, fine silica sand, retarder)
- **Ca-phosphate** (esp. dental cements that form hydroxyapatite, with retarders and fly ash)
- **Ca-aluminate-phosphate**
  - ThermaLock® as received from Halliburton
- **Generic OPC Class G Oilwell Cement** (with plasticizer/retarder, fly ash, fine sand)
- Defer testing of
  - Ca-aluminate cements (alkaline)
  - Ca-sulphoaluminate cements (less alkaline, but forms thermally unstable ettringite)

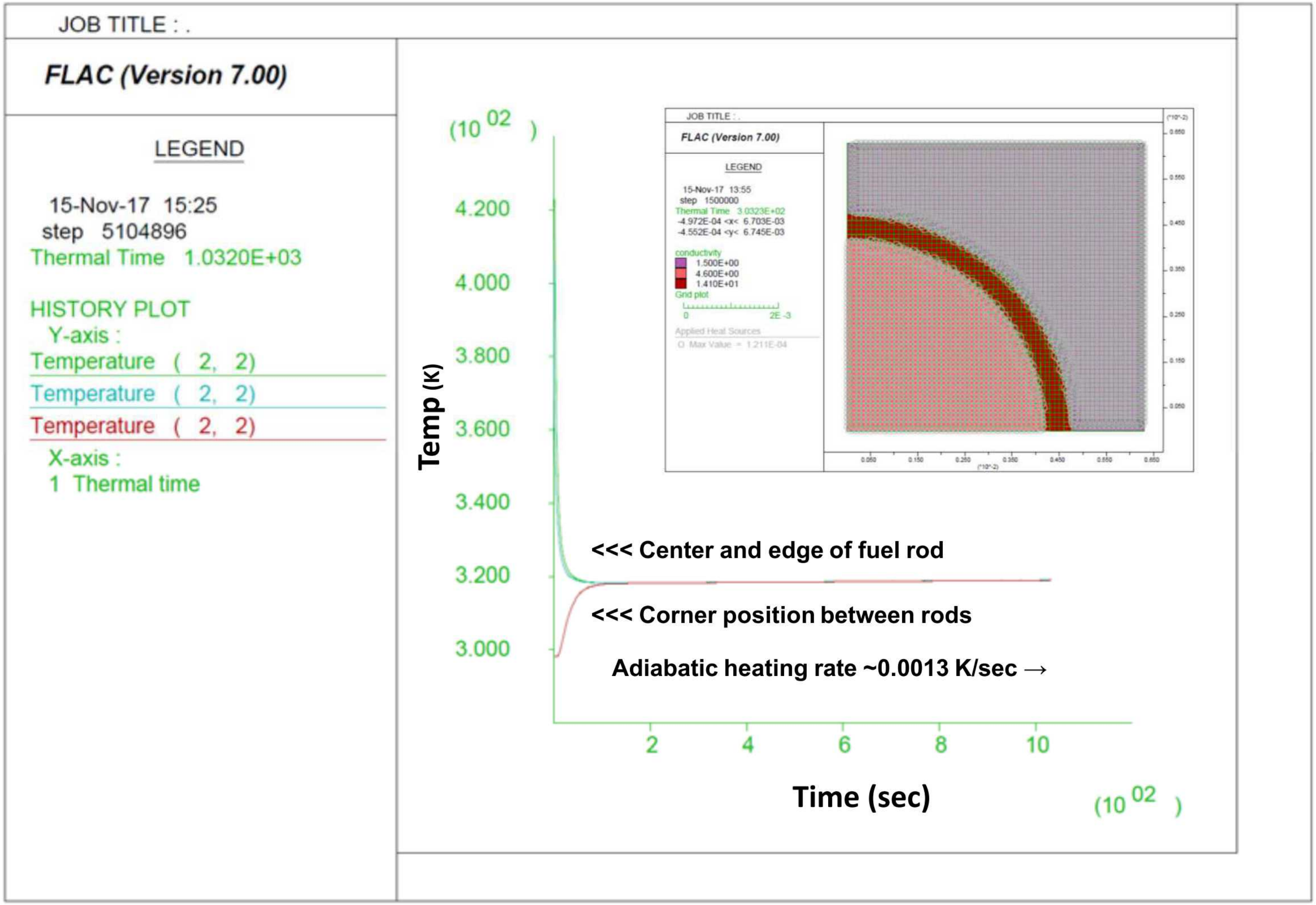


Technical Questions

Filler Behavior and Durability in the Canister Environment

- Curing behavior and intermediate complexes and solids
- Temperature during filling and cure (heat generation, heat of reaction)
- Thermal Expansion
  - Filler expansivity vs. canister internals, during initial set and cooling
  - Contraction on dewatering after set
- Dewatering Effectiveness
  - After set, self-heated and vented canister → 200°C
- Radiolytic Gas Generation
  - Gamma: ^{137}Cs and ^{90}Sr-^{90}Y ($t_{1/2}$ ~30 yr)
  - Neutron: Spontaneous fission of ^{242}Cm ($t_{1/2}$ < 1 yr), ^{244}Cm ($t_{1/2}$ = 18 yr)
  - ^{238}Pu (α, n) (target $t_{1/2}$ = 88 yr)
  - Other possible reactions, include decay ingrowth
  - Interaction with filler materials
- Filler Cracking or Bond Failure
  - Before/after package breach (cracks allow groundwater penetration)
- Filler Dissolution and Alteration
  - Long-term leaching tests
  - Mainly after package breach (incl. wedging, galvanic corrosion effects)

Early-Time Fuel and Filler Temperature from Scoping Adiabatic Model



Zero heat flow through model boundaries, heat generation in fuel and filler ($10\ kW/m^3$), initial fuel/filler temps. 150/25°C

Cement Slurry Testing Strategy (1/2)

1. **Initial Screening: Eliminate candidate cements that are non-injectable, produce liquid separation, or exhibit rapid exothermic reaction.**

   Screening tests applied together or selectively:

   – Pseudo-viscosity at time intervals, e.g., 30, 60 and 120 minutes after mixing.
   – Separation (bleed) test (ASTM C-940)
   – Adiabatic curing temperature history
   – Slurry pH (test paper)
   – Curing expansivity (in simple molds)
   – Pre-rinse ingredients (e.g., fly ash)

Ford cup (ASTM D-1200) and flow cone (ASTM C-939) testing apparatus:

Cement Slurry Testing Strategy (2/2)

2. **Heat Treat Selected Samples (especially $AlPO_4$):**
   - Follow approximate DPC temperature-time trajectory

Down-select 4-5 cement mixes

3. **Additional Screening:**
   - Modify/improve candidate cements, and add fillers like B_4C

Down-select 2-3 cement mixes

4. **Characterization:**
   - Powder XRD (mineral identification)
   - TGA (release of moisture and gases; mineral identification)
   - Radiolysis (exposure to gamma dose; gas generation)
   - Autoclave/geochemical bomb aging studies (leaching effects)
   - Cured pH (leaching effects)
   - Compressive strength (compare internal cement structure)
   - Viscometry (multi-process simulation)
   - Physical/thermal properties (multi-process simulation)
   - Unsaturated permeability/contact angle (multi-process simulation)
   - Calorimetry (multi-process simulation)
   - Acid dissolution (retrieval scenario)

Testing Final Goal: Filler Demonstration

- Scaled
- Simulated Basket and Fuel
- Filler Handling/Emplacement Equipment (mixing, heating/ cooling)
- Environmental Exposure (heat, moisture)
- Pre-Test Predictions
- Post-Test Examination
- Final Documentation

Weld-test mock-ups from ORNL standardized canister test program.

Backup Slides

Background: Mg-phosphate Phases

Phases found in Mg-phosphate cements (Wagh 2016)		
$MgHPO_4 \cdot H_2O$, $MgHPO_4 \cdot 2H_2O$	Haysite	
$MgHPO_4 \cdot 3H_2O$	Newberyite	Secondary; lava tube caves
$Mg(NH_4HPO_4)_2 \cdot 4H_2O$	Schertelite	Converts to struvite
$MgNH_4PO_4 \cdot 6H_2O$	Struvite	Found in guano, bioliths, wastewater scales; endpoint phase = struvite
$MgNH_4PO_4 \cdot 4H_2O$	Stercolite	
$MgNH_4PO_4 \cdot H_2O$	Dittmarite	
$MgK(PO_4)_2 \cdot 6H_2O$	Mg potassium phosphate	
$Mg_3(PO_4)_2 \cdot 4H_2O$	Mg phosphate	
$Mg(H_2PO_4)_2 \cdot 2H_2O$	Mg dihydrogen phosphate	
$Mg(H_2PO_4)_2 \cdot 4H_2O$		
Some other Mg-phosphate minerals		
$Mg_3(PO_4)_2$	Farringtonite	Meteorites
$Mg_3(PO_4)_2 \cdot 8H_2O$	Bobierrite	Found in guano, elephant tusks
$(Mg,Fe)_2PO_4F$	Wagnerite	Pegmatite
$Mg_2(PO_4)(OH)$	Hydroxylwagnerite	Hydrated form
$Mg_2(PO_4)(OH,F)$	Althausite	With serpentine, magnesite
$Mg_3B_2(PO_4)_2(OH)_6 \cdot 6H_2O$	Lünebergite	
$Mg_{14}(PO_4)_6(PO_3,OH,CO_3)_2(OH)_6$	Phosphoellenbergerite	With serpentine, magnesite; high-P assemblages
Does not include phosphates containing Mg with transition metals, Li, Sr, U, Pb, As, etc. Based on Wagh (2016) Table 2.2: Phases found in Mg-phosphate ceramics.		

Background: Ca-phosphate Phases

Ca-phosphate phases found in nature and in phosphate cements		
$Ca_5(PO_4)_3{\cdot}OH$	Hydroxyapatite	Bone, dental enamel
$Ca_5(PO_4)_3F$	Fluorapatite	Most common natural phosphate; igneous, metamorphic and sedimentary occurrences; a major component of phosphorite rock
$Ca_5(PO_4)_3Cl$	Chlorapatite	Igneous and metamorphic; forms in fluorine-deficient solutions
$Ca_5(PO_4{\cdot}CO_3)_3{\cdot}(OH,F)$	Dahllite	Carbonated apatite
$CaHPO_4{\cdot}2H_2O$	Brushite	Cave minerals, bioliths, coal ash
$CaAl_3(PO_4)(PO_3OH)(OH)_6$	Crandallite	Phosphatic aluminous sedimentary rock, some carbonatites, pegmatites and metamorphics, anoxic marine sediments, clay-rich tropical soils
$Ca_4O(PO_4)_2$	Hilgenstockite	Artificial tetracalcium phosphate; alters to hydroxyapatite
$Ca_3(PO_4)_2$	Whitlockite	Tricalcium phosphate; kilning of bone
Does not include phosphates containing Ca with transition metals, Li, Sr, U, Pb, As, etc.		

Background: Al-phosphate Phases

Al-phosphate phases found in nature and in phosphate cements		
$AlPO_4$	Berlinite	High temperature
$AlPO_4 \cdot 2H_2O$	Variscite	Hydrated form
$KAl_2(PO_4)_2(OH,F) \cdot 4H_2O$	Minyulite	Secondary product from phosphate minerals
$Al_4PO_4(OH)_3$	Trolleite	Metamorphic, exceptionally hard
$Al_3(PO_4)_2(OH)_3$	Wavellite	Pegmatite mineral alteration
Al_2O_3	Alumina	Occurs naturally as corundum, in bauxite, etc.
$Al(OH)_3$	Gibbsite	Common secondary mineral
$Al_2O_3 \cdot 3H_2O$	Bayerite	Polymorph of gibbsite (with doyleite and nordstrandite)
γ-AlOOH	Boehmite	Dimorphic with diaspore; component of bauxite
$Ca_2Al_2SiO_7$	Gehlenite	Naturally occurring weathering product; constituent of Ca-aluminate cements
Does not include phosphates containing Al with transition metals, Li, Sr, U, Pb, As, etc.		

Cement Testing – Phases 2 and 3

- **Examples of Unit Cell Tests**
  - Flow studies to compare mixes (Bingham fluids)
  - Slurry separation and homogeneity of set cement at scale
  - Hydraulics of tube-and-plate baskets vs. egg-crate designs
- **Examples of Separate Effects Tests**
  - Heating during injection
  - Agitation/vibration during injection
  - Variations in basket configurations