

# Fillers Program Goals and Plans

DPC Fillers Review Meeting, Las Vegas NV  
January 24, 2018



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

<b>Scenario 1: Estimated Most Costly Case, Loading All CSNF into DPCs and Re-packaging All of Them for Disposal</b>	<b>Unit Cost</b>	<b>CSNF Qty. (MTU)</b>	<b>Avg. DPC Capacity, MTUs</b>	<b># DPCs</b>	<b>Cost \$B</b>
<b>Total DPCs 140,000 MTU (all re-packaged)</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
<b>Re-packaging costs for all fuel, current fleet estimate:</b>					
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
<b>Total cost to make CSNF ready for disposal</b>					<b>\$ 32.7</b>
<b>Maximum potential savings from direct disposal of DPCs, not including filler implementation</b>					<b>\$ 18.7</b>
<b>Notes:</b>					

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.

# Alternative ROM Cost Analysis: Switch to Disposable MPCs for Half of CSNF & Use Fillers for Half of the DPCs

<b>Scenario 2: Estimated Best Case with Direct Disposal and Use of Fillers</b>					
<b>Total DPCs 70,000 MTU</b>					
DPCs for direct disposal 35,000 MTU					
DPCs for fillers & disposal 35,000 MTU					
<b>MPCs loaded at reactor or storage facility 70,000 MTU (direct disposal)</b>	<b>Unit Cost</b>	<b>CSNF Qty. (MTU)</b>	<b>Avg. DPC Capacity, MTUs</b>	<b># DPCs</b>	<b>Cost \$B</b>
Sunk cost to procure, load and store 35,000 MTU in DPCs (\$/MTU)	\$ 100,000	35,000	16.7	2102	\$ -
<b>Re-packaging costs for CSNF in half of DPCs:</b>					
Unload all DPCs (\$/MTU)	\$ 10,000	35,000			\$ 0.4
Transport and dispose of each DPC hull (\$/DPC)	\$ 150,000	35,000		2102	\$ 0.3
Re-canister for disposal (\$/MTU)	\$ 100,000	35,000			\$ 3.5
Re-packaging facility capital cost					\$ 1.0
<b>Maximum savings from use of fillers to prevent re-packaging 35,000 MTU (not including filler implementation)</b>					<b>\$ 5.2</b>

# 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**
  - Review safety, engineering feasibility, and cost
  - Form a consortium of industry and R&D organizations
  - Work with a standards organization (e.g., ASTM International) to develop a standard for disposability that works for all vendors

# Proposed Plans - DPC Filler Program

- **Develop consensus strategies for postclosure criticality control for a range of geologic conditions**
  - Direct disposal with/without fillers
  - Removal/rewelding of DPC lids for filler emplacement
  - Include possible re-packaging
- **Plan and implement a multi-year campaign to acquire RD&D information that can be used for licensing**
- **Maintain current as-loaded information for DPC fleet**

# DPC Fillers: Cement Slurry Approach

E. Hardin and P. Brady  
Sandia National Laboratories

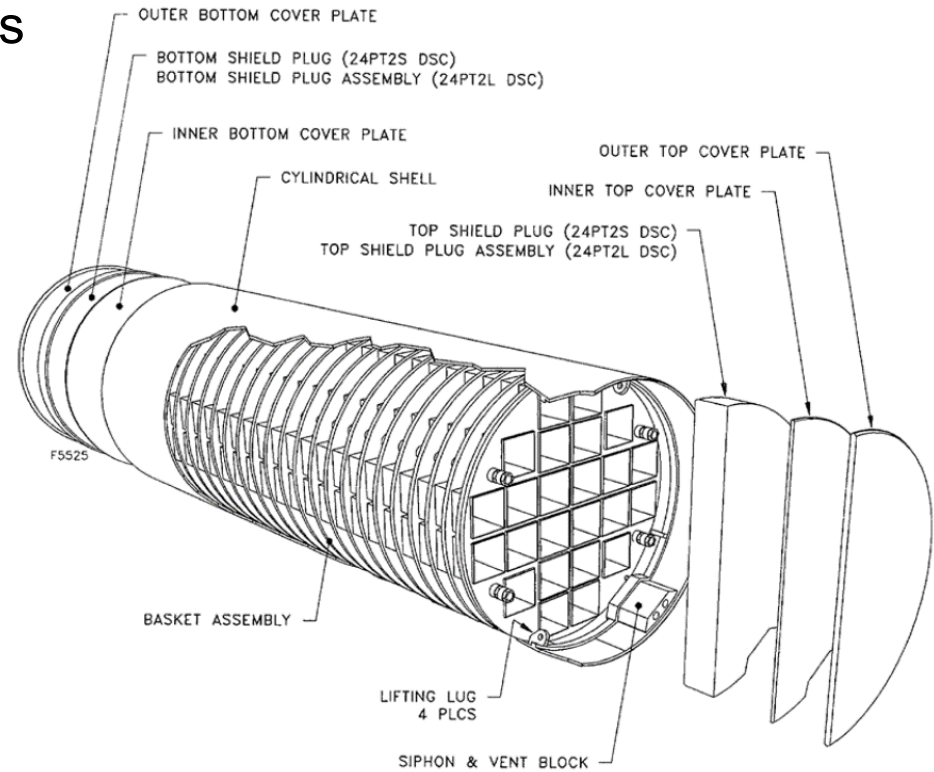
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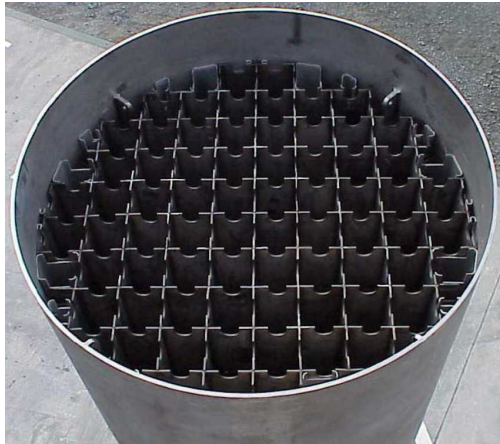
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# Outline

- Filler Attributes (liquid emplacement)
- Review Dry Particle Filler Demos
- 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).

# YMP Steel Shot Filler Test

## Framatome-Cogema

- **Steel shot**
  - SAE S230 & S330 sizes; nom. 600-850  $\mu\text{m}$  and 850-1,180  $\mu\text{m}$  diameter
  - As-poured density  $\sim 4.6 \text{ g/cm}^3$
  - Thermal conductivity  $\sim 0.4 \text{ W/m}\cdot\text{K}$
- **Selection (judgement based)**
  - Ease of handling and placement ("flow")
  - Commercial availability
  - Low cost
  - Cathodic protection
  - Chemical buffering
  - Moderator displacement
  - Thermal conductivity
- **Dummy PWR assemblies ( $15 \times 15$  and  $17 \times 17$ ) in a polycarbonate cell**
- **Eight tests (2 assemblies, 2 shot sizes, with/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

# AECL Filler Tests (1/2)

- **Glass Beads**

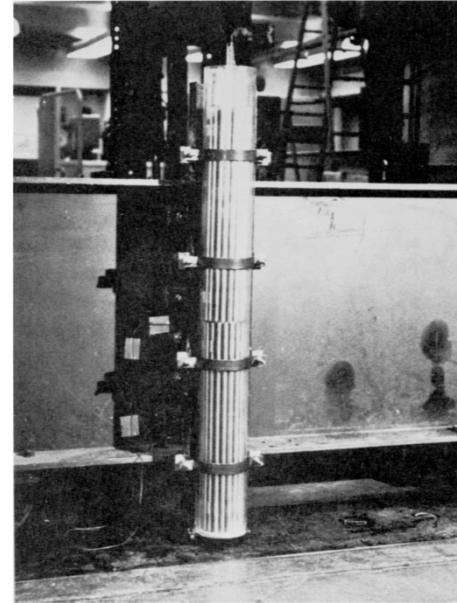
- Industrial 20 to 300  $\mu\text{m}$  and 0.8 to 1.2 mm dia.
- Density 1.6 (small) to 1.9 (large)  $\text{g}/\text{cm}^3$
- Structural support (10 MPa hydrostatic)
- Titanium-shell package

- **Single-Cell Filling Test**

- Two dummy CANDU assemblies
- Shaker table

- **Mockup Package Test**

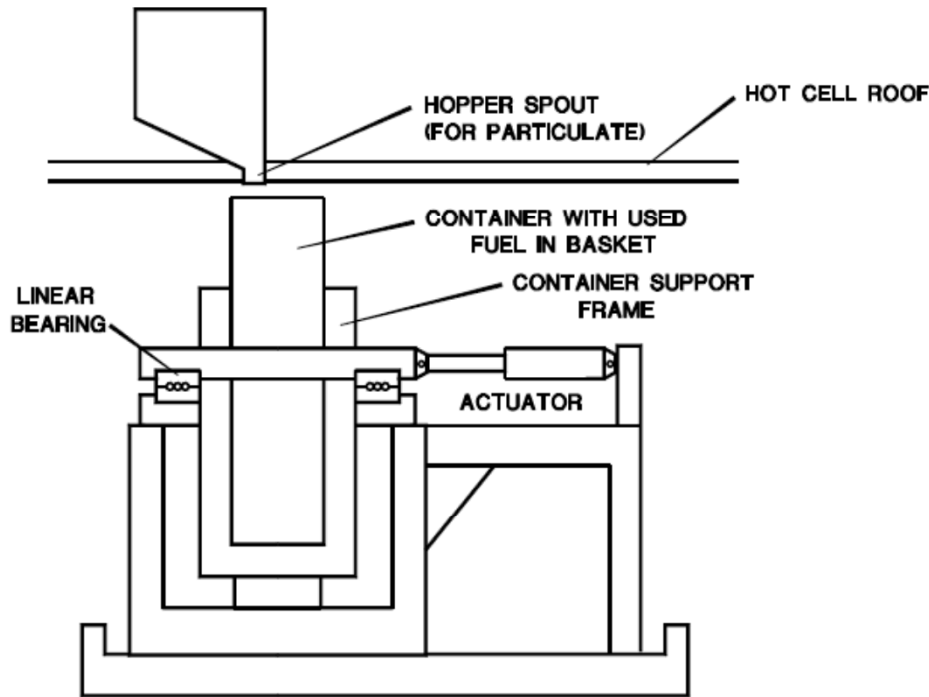
- 19  $\times$  2 ceramic basket
- Vibratory compaction
- Weld-sealed
- Hydrostatic testing



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)

ORNL DWG 97A-377



CONTAINER FILLER AND VIBRATORY COMPACTOR

Vibratory compaction apparatus – full scale.



Hydrostatic testing vessel, AECL/Whiteshell

Figures from Forsberg (1997)

# Perspective on Dry Particulate Fillers for U.S. DPCs

- **Cut DPC Lids Off**
  - Skiving selected among various methods (DOE IWM/NFST investigation)
  - Wet or dry?
- **Particulate Filling → Dry**
  - Dewatering after filling is impractical
  - Moisture → Corrosion, internal pressure, radiolysis
- **Alternative: Criticality Control Features (EPRI 2008)**
  - Disposal control rods
  - Re-loading
  - De-rating
- **Cut Lids Off Dry?**

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

# (Liquid) Filler 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 fittings, spacer blocks, and fuel-rod gaps (voids may be less than 1 mm)

**Compatible** – Limited gas generation, no 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)

**Low Cost** (relative to alternative disposal alternatives)

**Practical** – Reasonable weight, possibility of retrieving fuel

# Background: Ordinary Portland Cement (OPC)

**OPC =  $\text{CaCO}_3$  + 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

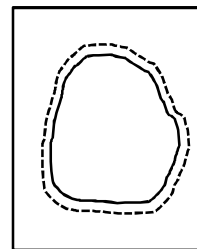
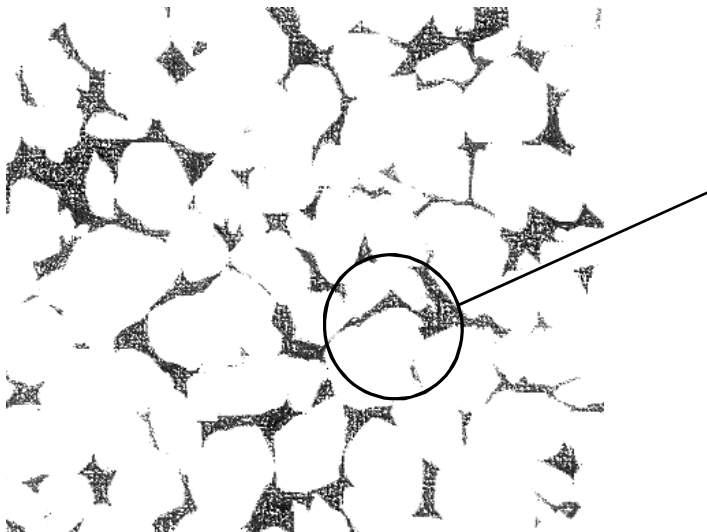
## An Alternative – Phosphate Cements

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

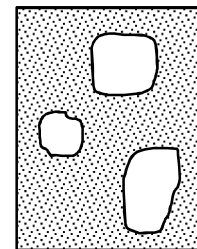


# Background: Chemically Bonded Ceramics

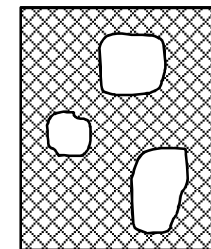
- Process and Nomenclature



Dissolution of Metal-Oxide Base in Acid-Phosphate Solution



Gelation and Precipitation



Crystallization (chemically bonding paste phase to undissolved particles)

Ceramic ← Crystalline

Cement ← Low temperature

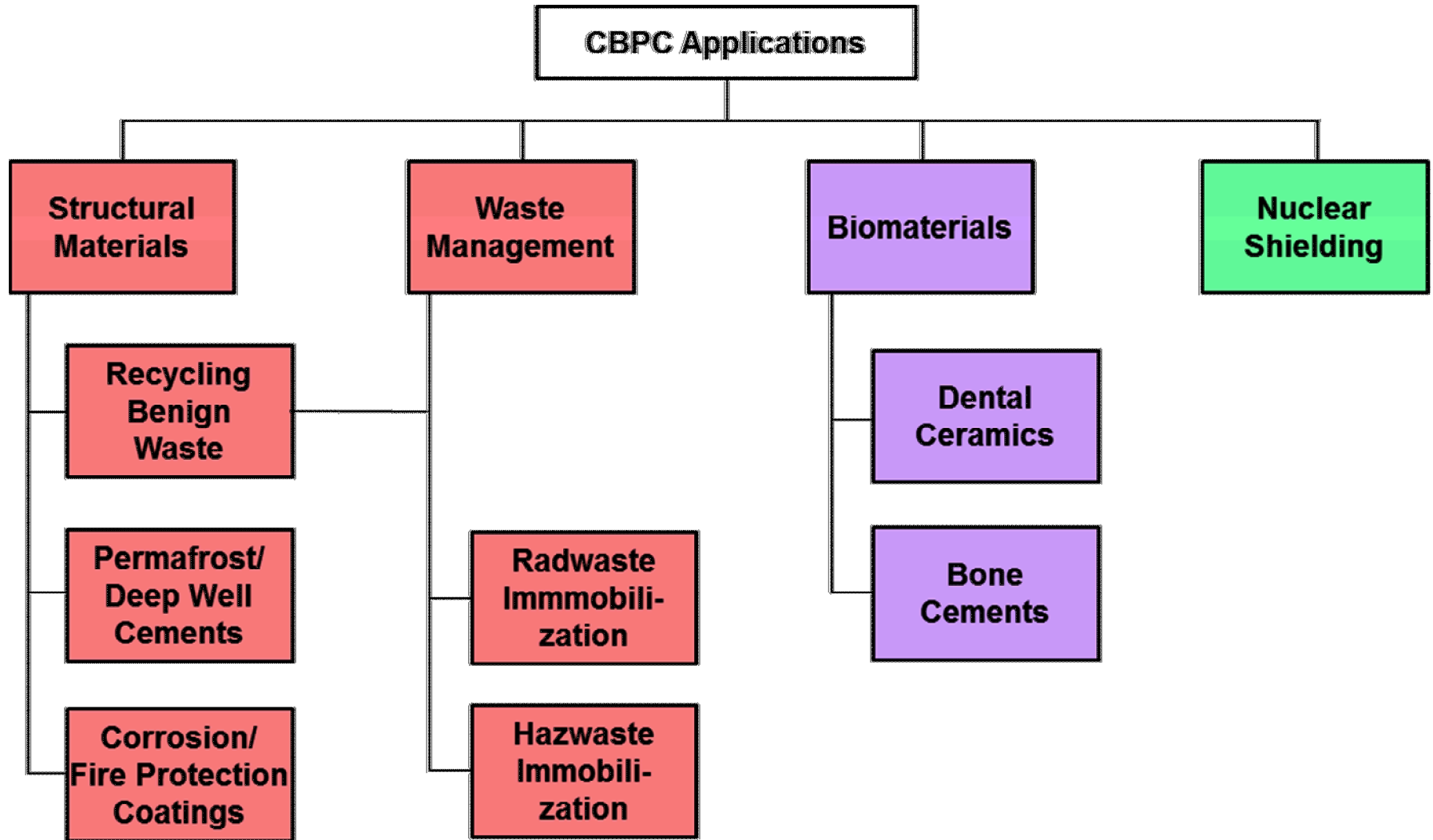
Chemically Bonded ← Paste phase chemically bonded to remaining undissolved crystalline particles

# Background Nomenclature:

## Ceramic vs. Cement vs. Chemically Bonded Cement

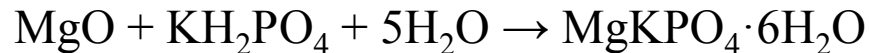
<b>Attributes:</b>	<b>Ceramics</b>	<b>Cements</b>	<b>Chemically Bonded</b>
<b>How they are commonly produced</b>	Fuse compacted powders at high-T	Hydraulic (water-based)	Acid-base reactions in slurries*
<b>Bonding</b>	Ionic or covalent	Hydrogen and van der Waals bonding	Mostly ionic or covalent
<b>Porosity</b>	Low (~1%, except sinters)	High (typ. 15 to 20%)	Moderate to high
<b>Service Temperature</b>	Very high T	Ambient to low T	Moderate
<b>Corrosion Resistance</b>	Wide pH range	Attack by strong acids and caustics; amorphous phases	Wide pH range, crystalline
<b>Cost</b>	Limiting	Bulk applications	Bulk and specialty
<b>Examples</b>	Porcelain	OPC	Phosphate-bonded cements (dental cements, Ceramicrete® & ThermaLock®)
* Does not include chemical (liquid) grouts.			

# How are Phosphate Cements Being Used?



# Cement Types: Ceramicrete® Mg-K-PO<sub>4</sub> Chemically Bonded Phosphate Ceramic Binder

A. Wagh\* and D. Singh  
Argonne National Laboratory  
\* Inorganic Polymer Solutions, Inc.



MKP binder: Density 1.7 g/cm<sup>3</sup> Porosity 2.9% (Cantrell & Westsik 2011; PNNL)  
Admixtures: Fly ash, sand, zeolite, wollastonite (CaSiO<sub>3</sub>), 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)

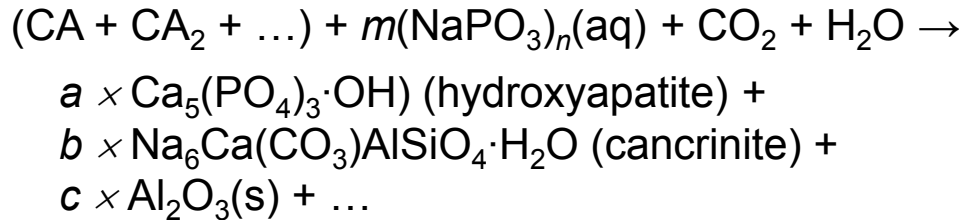
Ceramicrete: R&D 100 awards in 1996 and 2004 (*R&D Magazine*)

GRANCRETE YouTube URL: <https://www.youtube.com/watch?v=p7foDkuQi7U>

Ceramicrete YouTube URL: <https://www.youtube.com/watch?v=KxidwoJaC1c>

# 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)



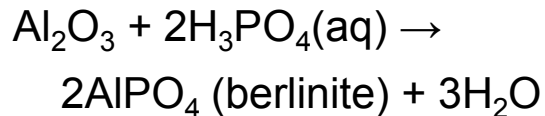
Tested CO<sub>2</sub> resistant in geothermal wells

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

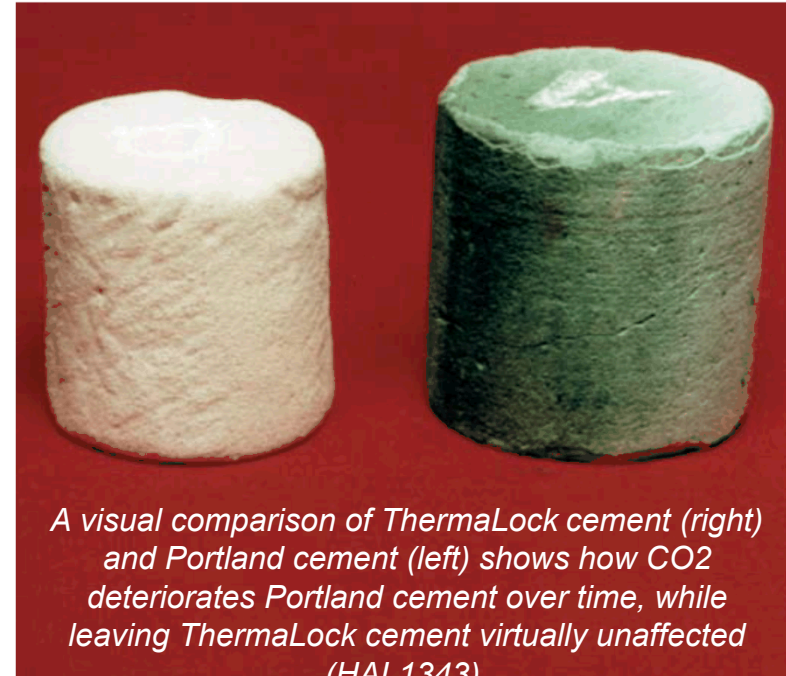
May have high porosity (e.g., >20%); boric acid may not function as retarder at higher temp.

Probable admixtures: fly ash, sulfonate plasticizer, betaine stabilizer

Alternative formulation (Wagh 2016, Table 16.3):

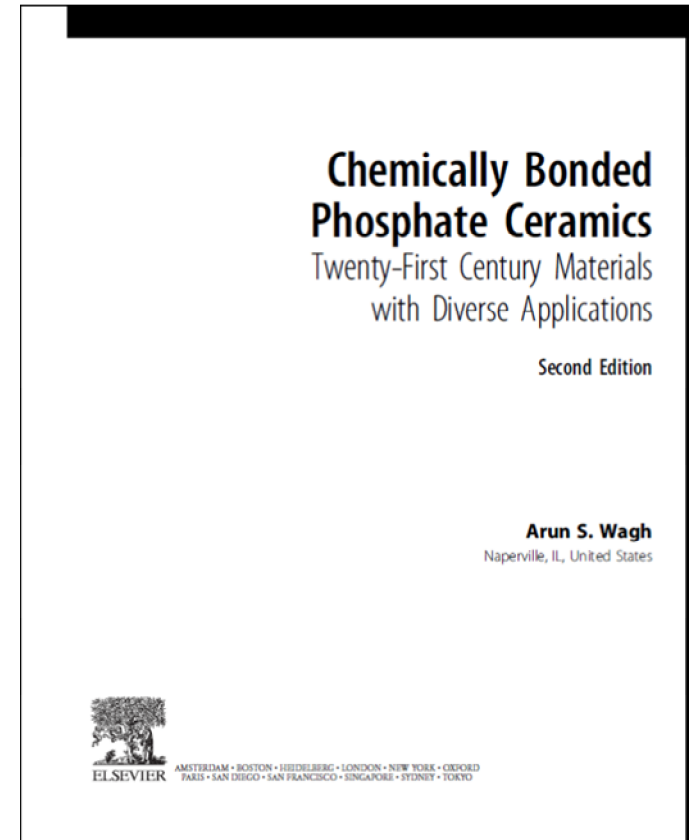


Forms AlH<sub>3</sub>(PO<sub>4</sub>) gel at low temperature (but converts to crystalline berlinite at 150°C)



# Selected Cement Types for Filler Investigation

- Generic OPC (fly ash, sand) for comparison
- Mg-phosphate (fly ash, fine silica sand, retarder)
- Ca-aluminate (fly ash, fine silica sand, retarder)
- Ca-aluminate-phosphate
  - ThermaLock as received from Halliburton
  - Ca-monoaluminate + Na-metaphosphate
  - Berlinite ( $\text{AlPO}_4$ )
- Defer testing of Ca-sulphoaluminate and Ca-phosphate (dental) cements
- Independent expert review of cement testing plan (March-April 2018): Arun Wagh, PhD



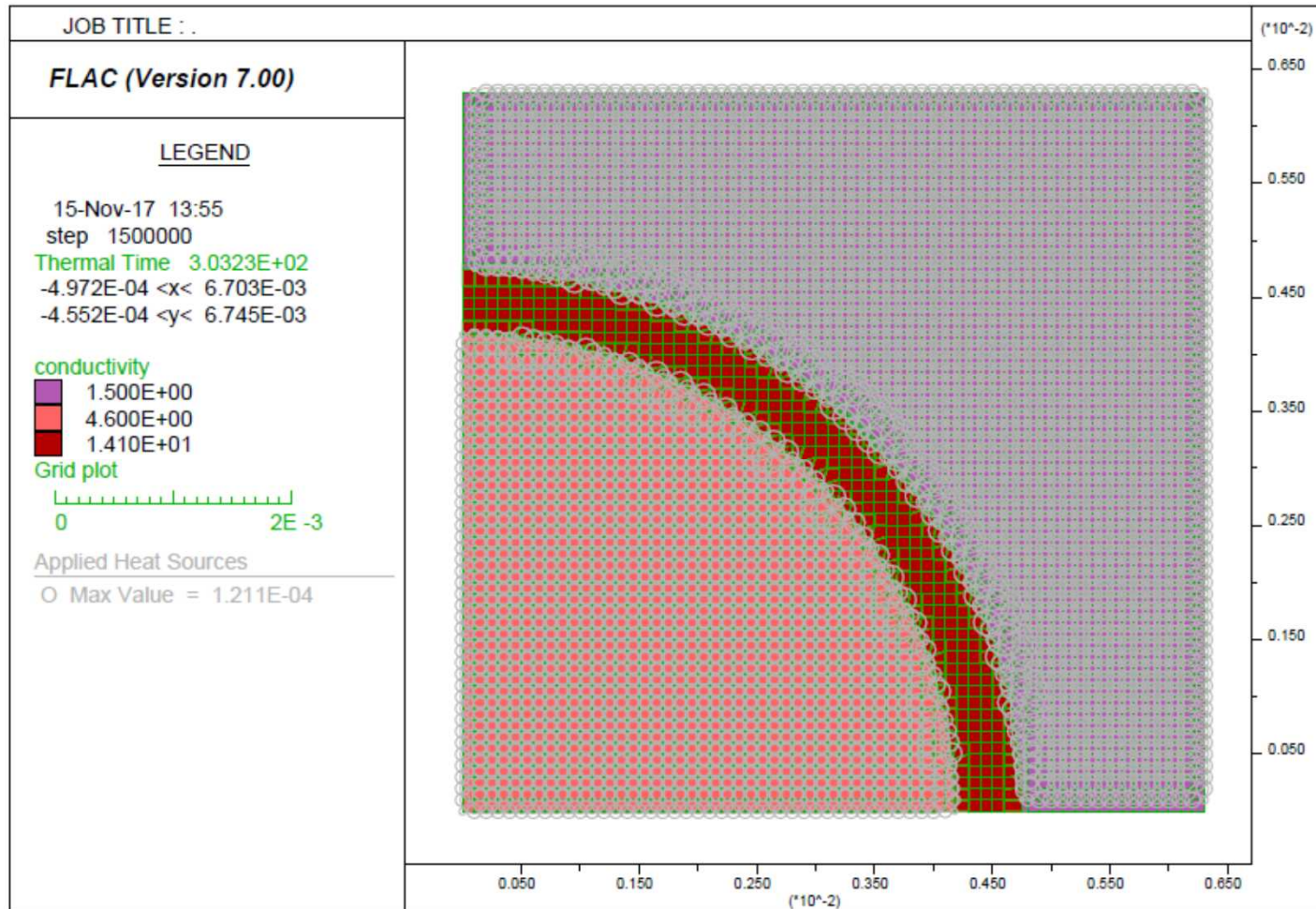
# Technical Questions

## Filler Behavior and Durability in the Canister Environment

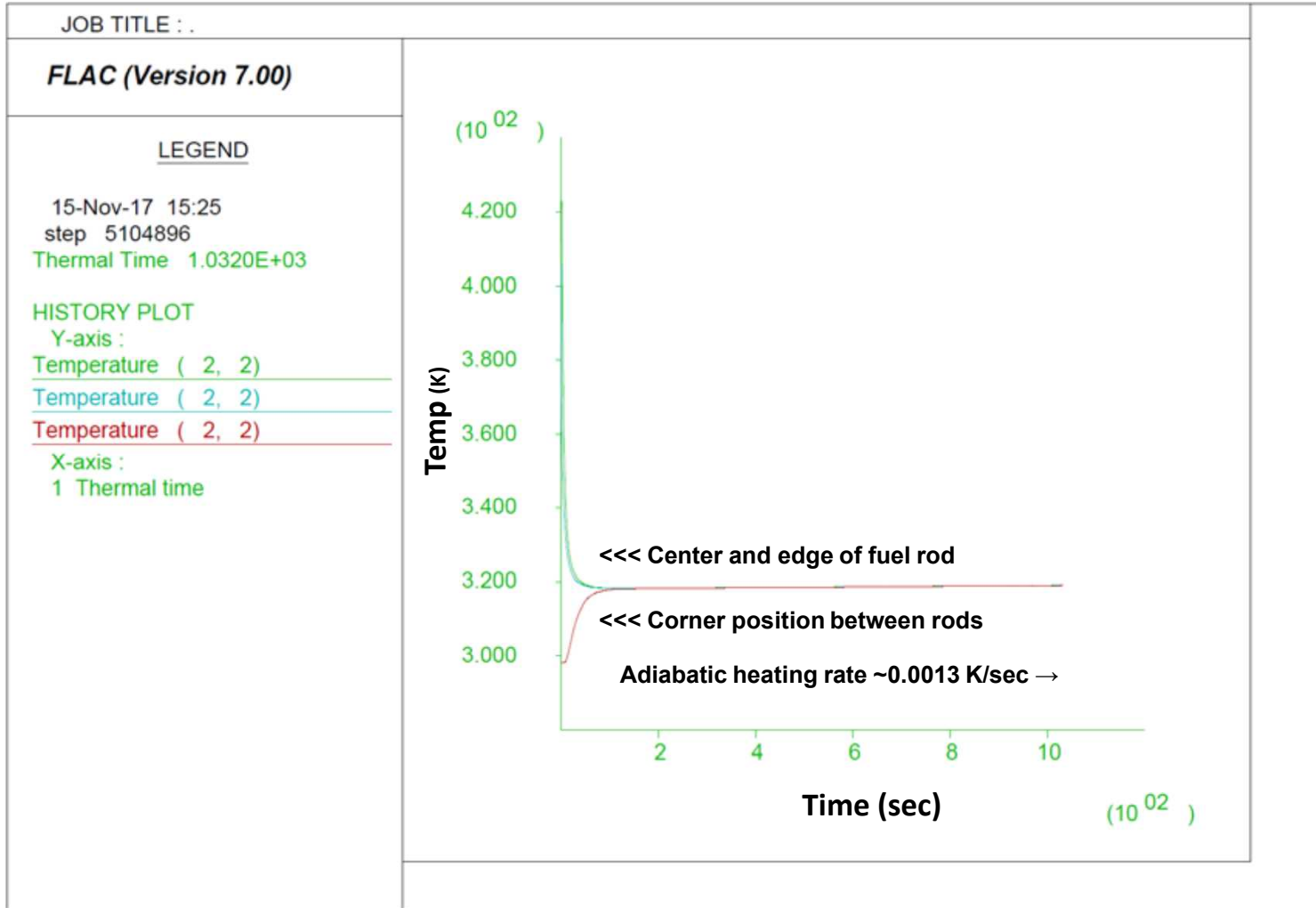
- **Temperature**
  - Early time during filling (initial filler temp., heat generation, heat of fusion/reaction)
  - After set (temp. limits or other requirements, filler aging)
- **Thermal Expansion**
  - Filler expansivity vs. canister, basket, and fuel, during initial set and long-term cooling
- **Radiolytic Gas Generation**
  - Gamma:  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$ - $^{90}\text{Y}$  ( $t_{1/2} \sim 30$  yr)
  - Neutron: Spontaneous fission of  $^{242}\text{Cm}$  ( $t_{1/2} < 1$  yr),  $^{244}\text{Cm}$  ( $t_{1/2} = 18$  yr)
  - $^{238}\text{Pu}$  ( $\alpha, n$ ) (target  $t_{1/2} = 88$  yr)
  - Other reactions as applicable, with decay ingrowth
  - Interaction with filler materials
- **Filler Cracking or Bond Failure**
  - Before/after package breach (moisture penetration)
- **Filler Dissolution and Alteration**
  - Before/after package breach (incl. wedging, galvanic corrosion)

# Scoping Adiabatic Model, Early-Time Fuel and Filler Temperature

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



# Early-Time Fuel and Filler Temperature from Scoping Adiabatic Model



# 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:

- Flow cone testing measures effective viscosity over time, e.g., at 30, 60 and 120 minutes.
- Separation (bleed) test (ASTM C-940)
- Adiabatic curing temperature history
- Slurry pH
- Curing expansivity



Flow cone testing apparatus: ASTM C-939

# Cement Slurry Testing Strategy (2/2)

## 2. Additional Screening:

- Modify/improve candidate cements, and add fillers like  $B_4C$

**Down-select 4-5 cement mixes**

## 3. Heat Treat Selected Samples:

- Follow simulated DPC temperature-time trajectory

**Down-select 2-3 cement mixes**

## 4. Characterization (approx. order of importance):

- Powder X-ray diffraction analysis (XRD; mineral identification)
- Thermal-gravimetric analysis (TGA; moisture and hydrous minerals)
- 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)

# Workplan Summary

## SFWD-SFWST-2018-000481 Rev. 0

Phase 1 <sup>A</sup>	Phase 2	Phase 3	Phase 4
6.1 Testing and Analysis for Cement Materials			
6.2 Testing and Analysis for Molten Metal/Alloy and Glass Materials			
<ul style="list-style-type: none"> <li>• Injectability</li> <li>• Durability (leaching)</li> </ul>	<ul style="list-style-type: none"> <li>• Injectability</li> <li>• Durability (leaching irradiated samples)</li> <li>• Retrievability</li> </ul>	<ul style="list-style-type: none"> <li>• Radiolysis Simulation</li> <li>• Postclosure Performance</li> </ul>	
	6.3 Testing and Analysis for Dry Particulate Materials		
7.1.1 Supporting Analysis for Cement Fillers <ul style="list-style-type: none"> <li>• Thermochemical Analysis Composition and Cure</li> <li>• Postclosure Leaching Analysis</li> <li>• Natural Analogues</li> <li>• DPC Shell Pressure Rating</li> <li>• Fate of Hydrogen Gas in Sealed Canisters</li> </ul>		7.1.2 Supporting Analysis for Metal/Metal Alloy and Glass Fillers <ul style="list-style-type: none"> <li>• Literature Review and Technology Survey</li> </ul>	
7.2.1 Phase 1 Numerical Simulation <ul style="list-style-type: none"> <li>• Criticality</li> <li>• Thermal</li> <li>• Flow</li> <li>• Filler Dose Analysis</li> </ul>	7.2.2 Phase 2 Numerical Simulation <ul style="list-style-type: none"> <li>• Thermal-Flow</li> <li>• Radiolysis</li> <li>• Pre-Test Predictions</li> </ul>	7.2.3 Phase 3 Numerical Simulation <ul style="list-style-type: none"> <li>• Thermal-Flow-Mechanical</li> <li>• Pre-Test Predictions</li> <li>• Postclosure PA</li> </ul>	7.2.4 Phase 4 Numerical Simulation <ul style="list-style-type: none"> <li>• Pre-Test Predictions</li> <li>• Final Project Documentation</li> </ul>
7.3.1 Phase 1 Physical Model Studies <ul style="list-style-type: none"> <li>• Molten Metal/Alloy Phase 1 Activities</li> </ul>	7.3.2 Phase 2 Physical Model Studies <ul style="list-style-type: none"> <li>• Cement Unit-Cell</li> <li>• Molten Metal/Alloy Unit-Cell</li> <li>• Dry Particulate Flow</li> </ul>	7.3.3 Phase 3 Physical Model Studies <ul style="list-style-type: none"> <li>• Cement Separate Effects Tests</li> <li>• Molten Metal/Alloy Separate Effects Tests</li> </ul>	7.3.4 Phase 4 Scaled Demonstration <ul style="list-style-type: none"> <li>• Final Project Documentation</li> </ul>
Notes: <sup>A</sup> Many Phase 1 activities can be supported in FY18 with currently available resources.			

# 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 <sub>4</sub> ·H <sub>2</sub> O, MgHPO <sub>4</sub> ·2H <sub>2</sub> O	Haysite	
MgHPO <sub>4</sub> ·3H <sub>2</sub> O	Newberyite	Secondary; lava tube caves
Mg(NH <sub>4</sub> HPO <sub>4</sub> ) <sub>2</sub> ·4H <sub>2</sub> O	Schertelite	Converts to struvite
MgNH <sub>4</sub> PO <sub>4</sub> ·6H <sub>2</sub> O	Struvite	Found in guano, bioliths, wastewater scales; endpoint phase = struvite
MgNH <sub>4</sub> PO <sub>4</sub> ·4H <sub>2</sub> O	Stercolite	
MgNH <sub>4</sub> PO <sub>4</sub> ·H <sub>2</sub> O	Dittmarite	
MgK(PO <sub>4</sub> ) <sub>2</sub> ·6H <sub>2</sub> O	Mg potassium phosphate	
Mg <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> ·4H <sub>2</sub> O	Mg phosphate	
Mg(H <sub>2</sub> PO <sub>4</sub> ) <sub>2</sub> ·2H <sub>2</sub> O	Mg dihydrogen phosphate	
Mg(H <sub>2</sub> PO <sub>4</sub> ) <sub>2</sub> ·4H <sub>2</sub> O		
Some other Mg-phosphate minerals		
Mg <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub>	Farringtonite	Meteorites
Mg <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> ·8H <sub>2</sub> O	Bobierite	Found in guano, elephant tusks
(Mg,Fe) <sub>2</sub> PO <sub>4</sub> F	Wagnerite	Pegmatite
Mg <sub>2</sub> (PO <sub>4</sub> )(OH)	Hydroxylwagnerite	Hydrated form
Mg <sub>2</sub> (PO <sub>4</sub> )(OH,F)	Althausite	With serpentine, magnesite
Mg <sub>3</sub> B <sub>2</sub> (PO <sub>4</sub> ) <sub>2</sub> (OH) <sub>6</sub> ·6H <sub>2</sub> O	Lünebergite	
Mg <sub>14</sub> (PO <sub>4</sub> ) <sub>6</sub> (PO <sub>3</sub> ,OH,CO <sub>3</sub> ) <sub>2</sub> (OH) <sub>6</sub>	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.		

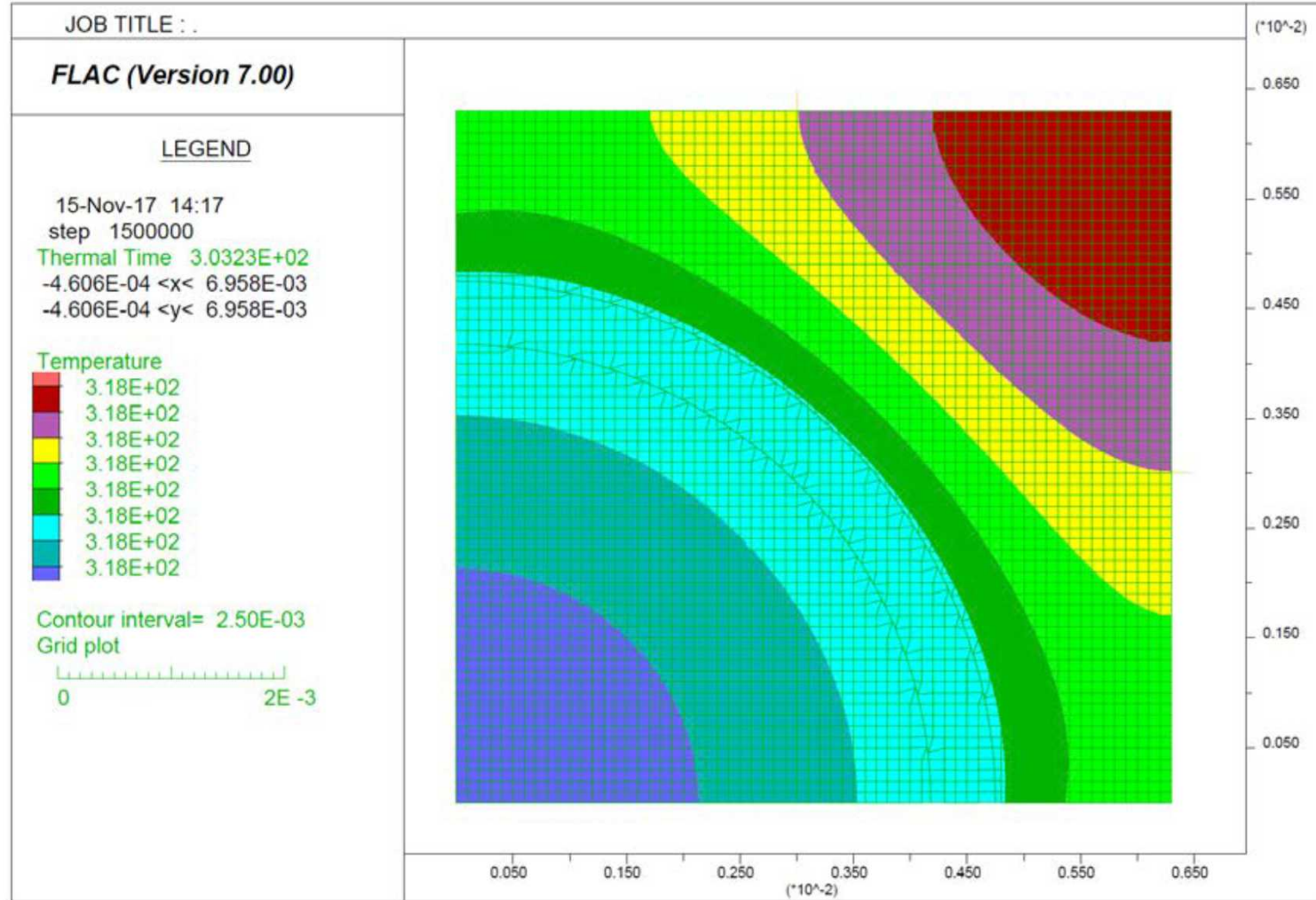
# Background: Ca-phosphate Phases

Ca-phosphate phases found in nature and in phosphate cements		
$\text{Ca}_5(\text{PO}_4)_3\cdot\text{OH}$	Hydroxyapatite	Bone, dental enamel
$\text{Ca}_5(\text{PO}_4)_3\text{F}$	Fluorapatite	Most common natural phosphate; igneous, metamorphic and sedimentary occurrences; a major component of phosphorite rock
$\text{Ca}_5(\text{PO}_4)_3\text{Cl}$	Chlorapatite	Igneous and metamorphic; forms in fluorine-deficient solutions
$\text{Ca}_5(\text{PO}_4\cdot\text{CO}_3)_3\cdot(\text{OH},\text{F})$	Dahllite	Carbonated apatite
$\text{CaHPO}_4\cdot 2\text{H}_2\text{O}$	Brushite	Cave minerals, bioliths, coal ash
$\text{CaAl}_3(\text{PO}_4)(\text{PO}_3\text{OH})(\text{OH})_6$	Crandallite	Phosphatic aluminous sedimentary rock, some carbonatites, pegmatites and metamorphics, anoxic marine sediments, clay-rich tropical soils
$\text{Ca}_4\text{O}(\text{PO}_4)_2$	Hilgenstockite	Artificial tetracalcium phosphate; alters to hydroxyapatite
$\text{Ca}_3(\text{PO}_4)_2$	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		
$\text{AlPO}_4$	Berlinite	High temperature
$\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$	Variscite	Hydrated form
$\text{KAl}_2(\text{PO}_4)_2(\text{OH},\text{F}) \cdot 4\text{H}_2\text{O}$	Minyulite	Secondary product from phosphate minerals
$\text{Al}_4\text{PO}_4(\text{OH})_3$	Trolleite	Metamorphic, exceptionally hard
$\text{Al}_3(\text{PO}_4)_2(\text{OH})_3$	Wavellite	Pegmatite mineral alteration
$\text{Al}_2\text{O}_3$	Alumina	Occurs naturally as corundum, in bauxite, etc.
$\text{Al}(\text{OH})_3$	Gibbsite	Common secondary mineral
$\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$	Bayerite	Polymorph of gibbsite (with doyleite and nordstrandite)
$\gamma\text{-AlOOH}$	Boehmite	Dimorphic with diaspore; component of bauxite
$\text{Ca}_2\text{Al}_2\text{SiO}_7$	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.		

# Adiabatic Model, Fuel and Filler Temperature Equilibrium at 300 sec



# 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