Ceramic Castable Cement Tanks and Piping for Molten Salt

PI: Asegun Henry, Massachusetts Institute of Technology
Co-PI: Kenneth Sandhage, Purdue University
Co-PI: Kenneth McGowan & Bob Cullen, Westmoreland Advanced Materials

Control Number: 1697-1599

SunShot U.S. Department of Energy

GEN3CSP

Technology Addressed

Tanks and Piping for 750°C Molten Chloride Salts

Innovative Aspect

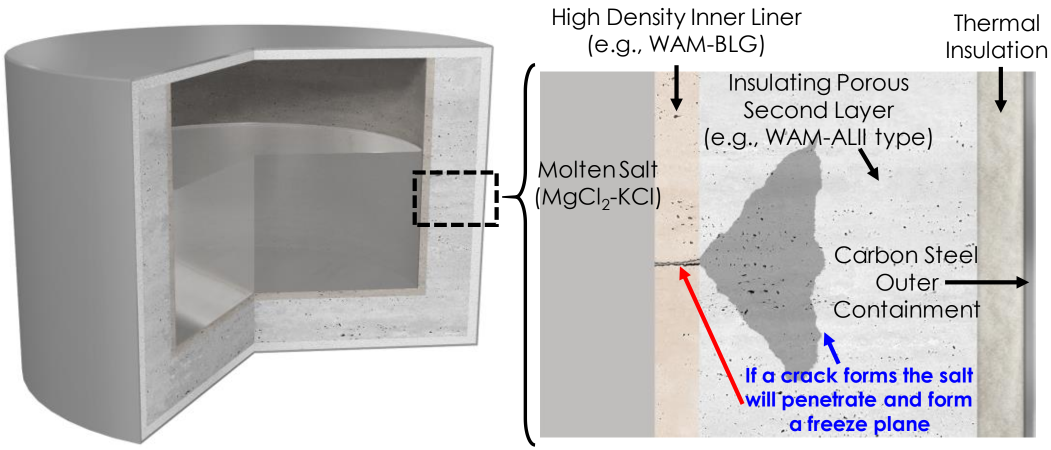
The usage of ceramic castable cements to make inexpensive tanks and piping. Castable cements simply require the addition of water to form an emulsion, which can then be poured into a mold of any desired shape and then cured.

Impact

- Cheaper materials that are compatible with molten salts allow for a less expensive infrastructure and enable achievement of the SunShot goals for the cost of storage

Background and Proposed Work

- Currently envisioned materials (H230 and 740H) for the infrastructure are ~ 4X more expensive than SS316. Castable cements are much less expensive.
- Demonstrate a lab scale tank and flanged pipe section, to prove that flowing salt doesn't corrode
- Optimize the castable chemistry and microstructure to minimize penetration
- Test a cast flanged pipe section for leakage under pressure
- Develop a cost model for the tank and pipes



	Key Milestones & Deliverables
Year 1	• Demonstrate the system is fully constructed and working with a molten salt and a flow rate between 0.1-5 gpm • Demonstrate that a castable chemistry can limit penetration by the salt to less than 1 cm over 30 years
Year 2	• Demonstrate that the castable cement tank and pipe section do not leak and do not exhibit excessive penetration when exposed to flowing salt • Demonstrate that the cost of the tank and piping meets the SunShot goals

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What is the problem at 750C?

Conventional welded metal is too expensive because of corrosion

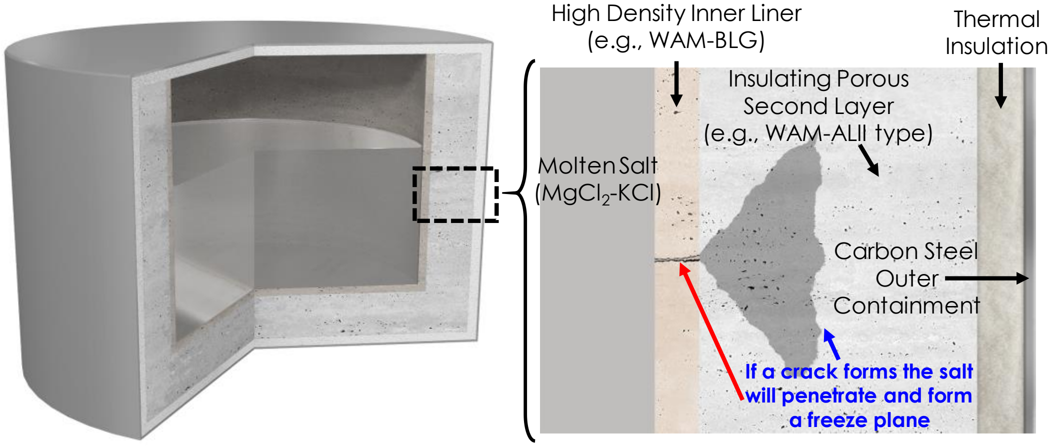
G. Glatzmaier, Report No. NREL/TP-5500-53066

Table 1. Component costs for direct, two-tank molten salt TES system (base case).

Component	Materials ($/kWh$_{th}$)	Installation ($/kWh$_{th}$)	Total Cost ($/kWh$_{th}$)
High-temperature tank—stainless steel	5.20	1.84	7.04
Low-temperatures tank—carbon steel	1.30	1.84	3.14
Tank supports, foundations, and site work	1.10	1.55	2.65
Storage medium	11.74	0.36	12.10
Electrical and instrumentation	0.47	0.43	0.90
Piping, valves, and fittings	0.20	0.18	0.39
Totals	20.01	6.22	**26.22**

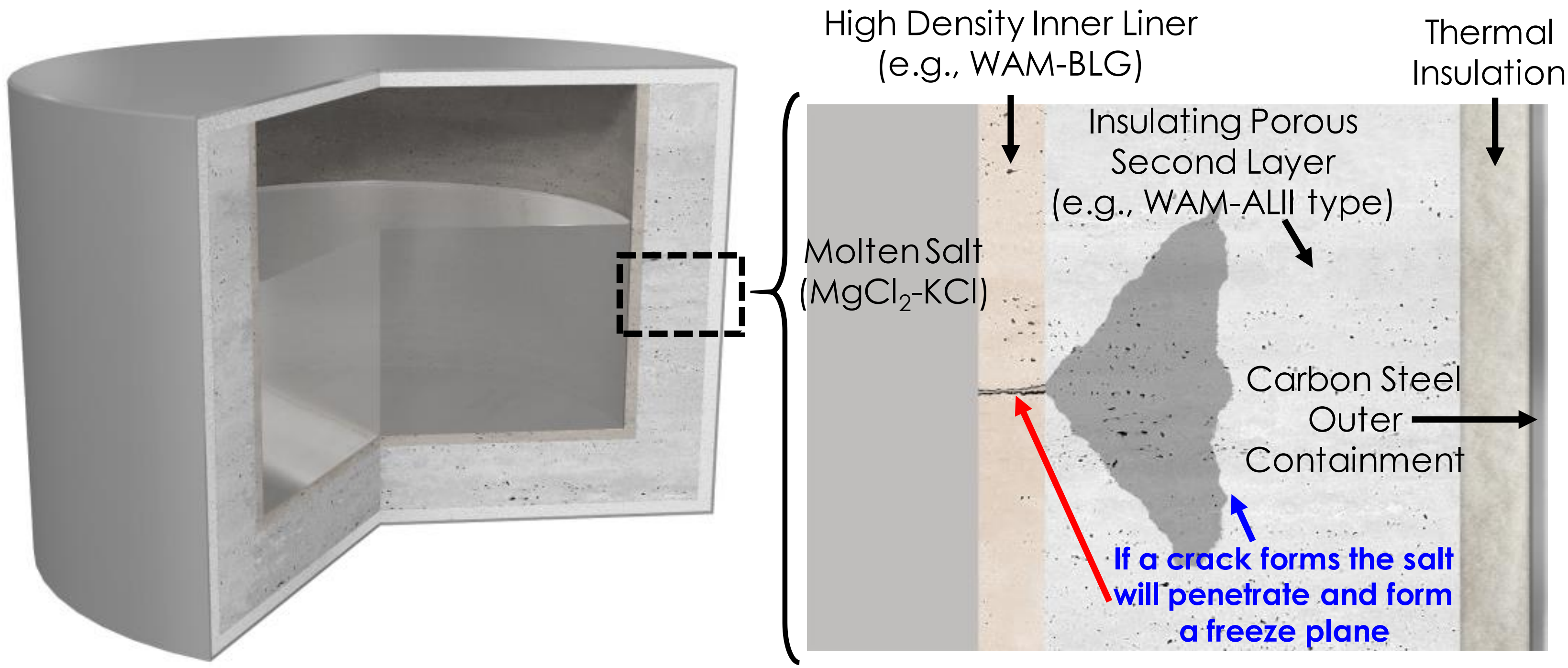
Multiply by 4X for Ni alloys → > $20/kWh-t for the tank alone

SOLUTION = Use ceramics
Castable cements from WAM
Add water, mold into shape, cure in place
Very inexpensive $5,950/m^3
New internal insulation architecture
Redundant leak protection mechanisms
Can also use for piping



INNOVATION

- A different design & class of materials
- Lower cost material that is easy to fabricate
  - Add water & mold
  - Ability to tune/engineer the composition/microstructure
- Redundant leak protection
- Also use as pipes, with cast flanges



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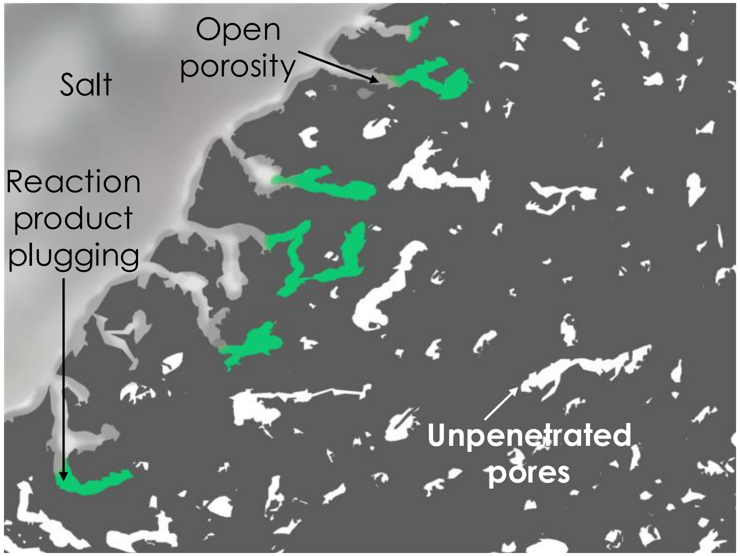
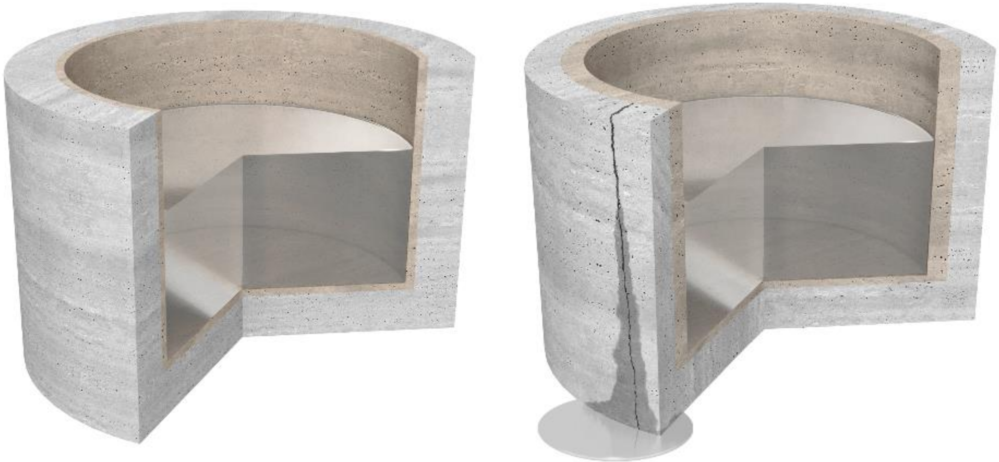
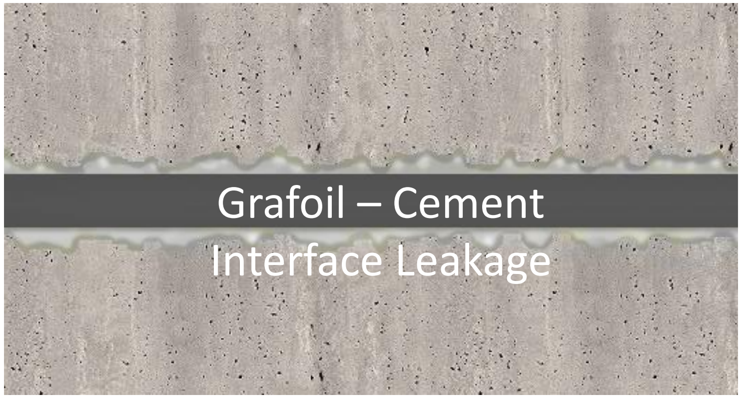
What are the potential issues?

- Reaction with salt
- Convective enhancement
- Salt penetration into pores
- Tank wall cracking
- CTE mismatches between layers
- Seal leakage at pipe flanges
- Cost







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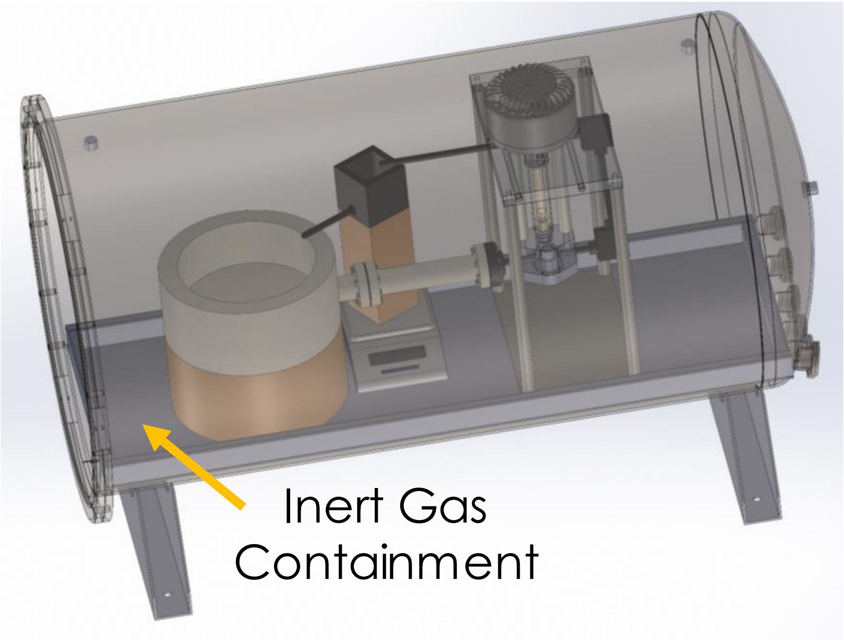
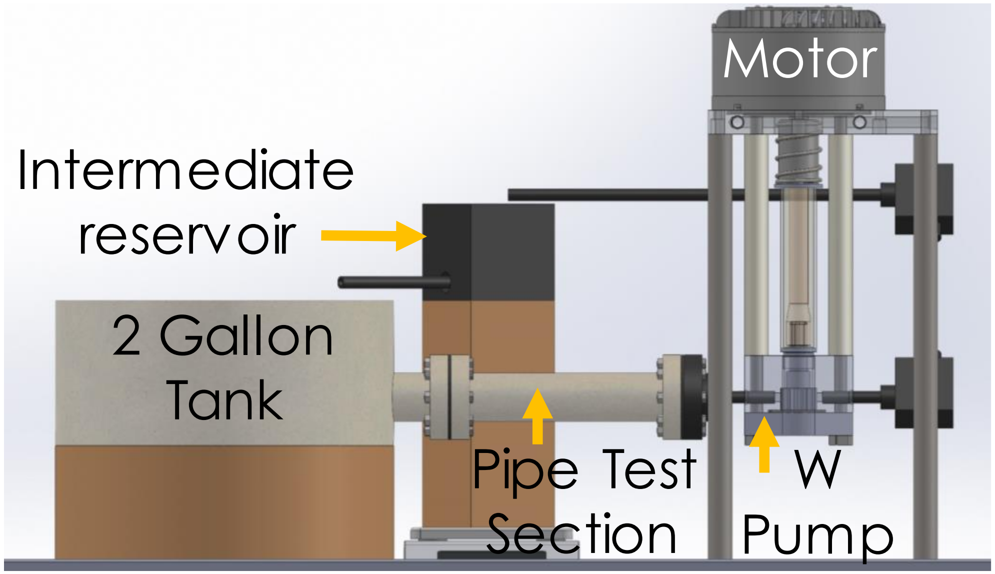
What are the project objectives?

(1) Demonstrate minimal/acceptable salt penetration
(2) Demonstrate corrosion resistance to flowing salt
(3) Demonstrate pipe sections with flanged interfaces and no leakage
(4) Demonstrate $\leq$ \$15/kWh-t via a comprehensive cost model

Prototype System Test Rig





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What are we proposing to do?

- Reaction with salt

--- *Testing modified compositions with small crucibles*

- Salt penetration into pores

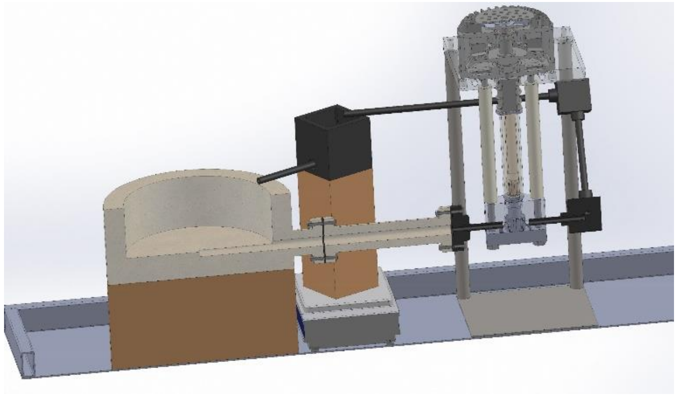
--- *Testing full tanks and pipe sections in prototype loop (salt level in tank - static)*

- Convective enhancement

--- *Testing full tanks and pipe sections in prototype loop (salt level in tank - flowing)*

- Tank wall cracking

--- *Thermal cycles during prototype loop tests*



- CTE mismatches between layers

--- *Measure CTE + 3D Modeling*

- Seal leakage at pipe flanges

--- *Testing pipe section interfaces under applied pressure*

- Cost

--- *3D modeling + Cost model (materials + labor etc.)*

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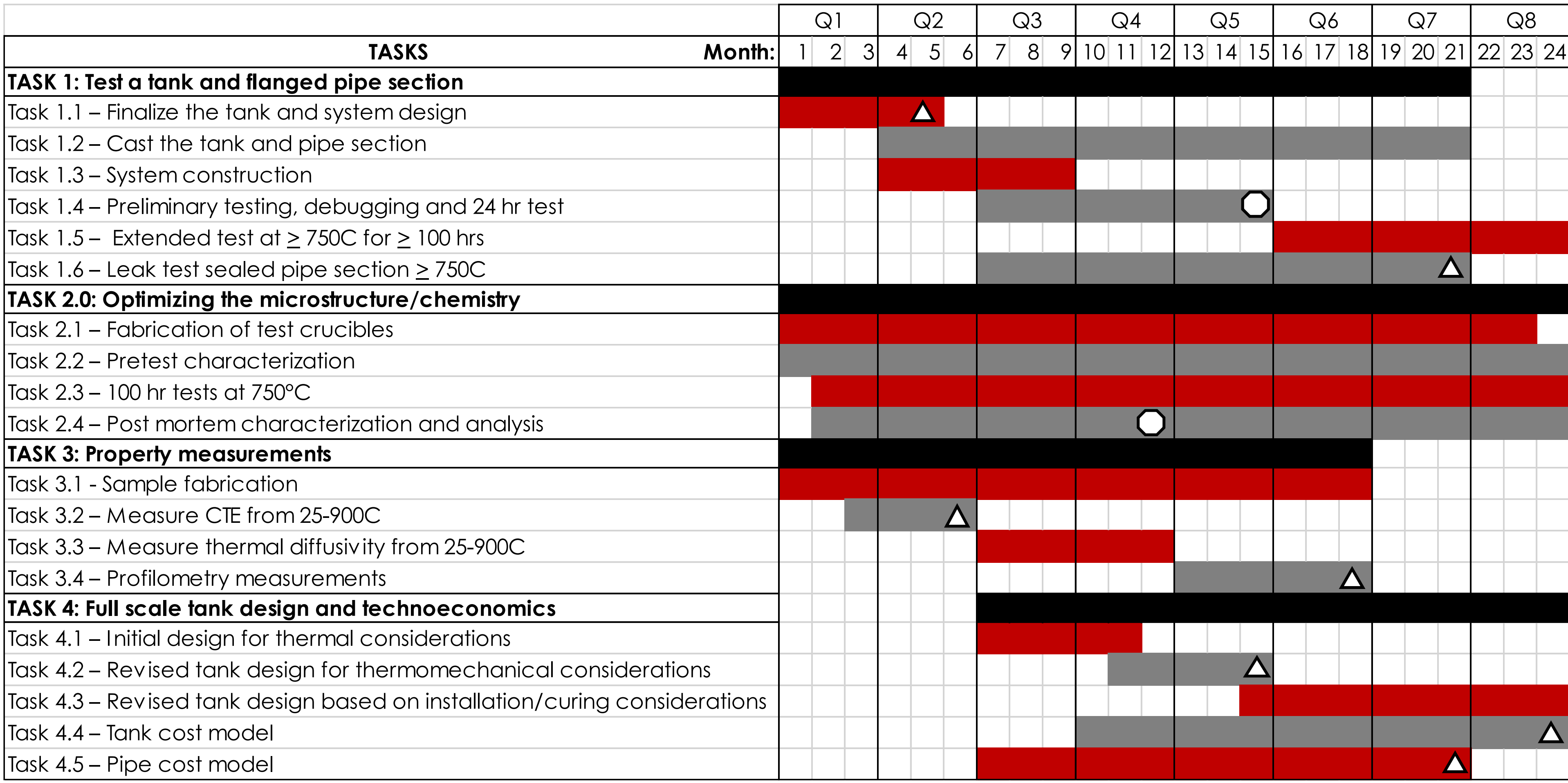
TIMELINE



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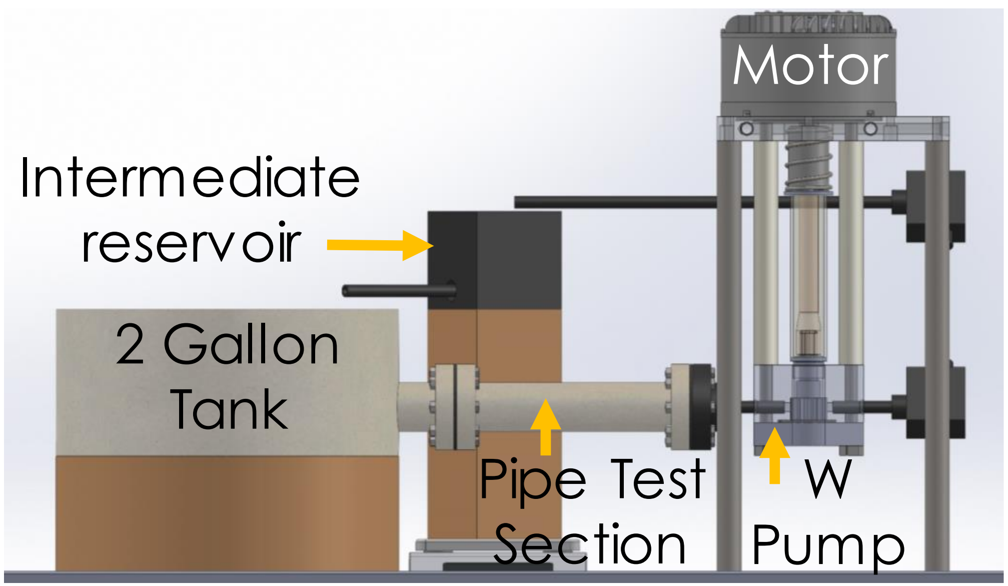
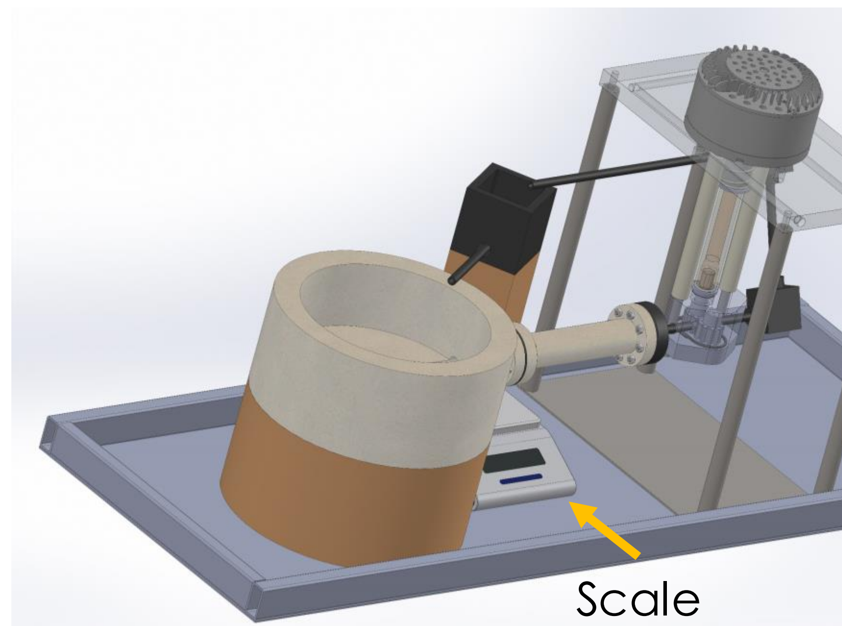
TASK 1: PROTOTYPE TEST LOOP-

	Q1			Q2			Q3			Q4			Q5			Q6			Q7			Q8		
TASKS **Month:**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
TASK 1: Test a tank and flanged pipe section																								
Task 1.1 – Finalize the tank and system design					△																			
Task 1.2 – Cast the tank and pipe section																								
Task 1.3 – System construction																								
Task 1.4 – Preliminary testing, debugging and 24 hr test															⬡									
Task 1.5 – Extended test at ≥ 750C for ≥ 100 hrs																								
Task 1.6 – Leak test sealed pipe section ≥ 750C																					△			





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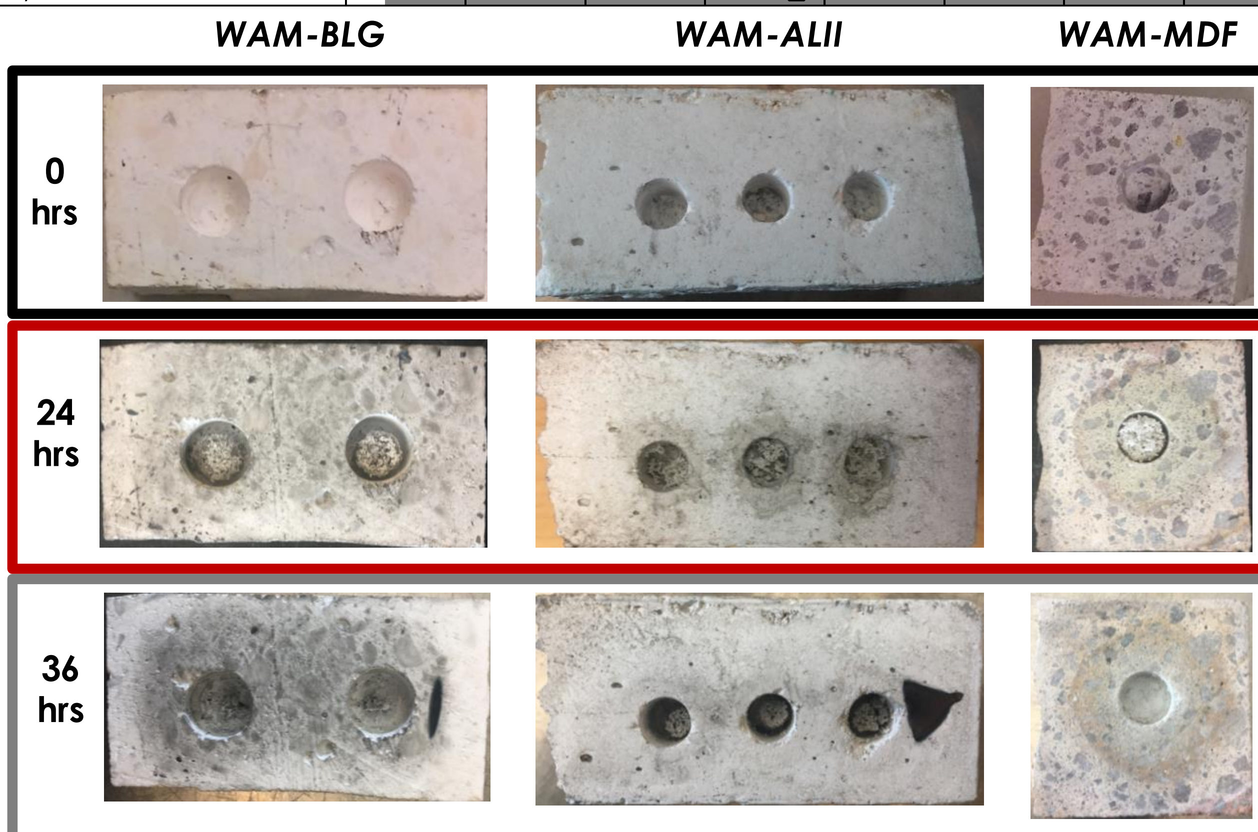
TASK 2: CEMENT CHEMISTRY/MICROSTRUCTURE OPTIMIZATION

	Q1			Q2			Q3			Q4			Q5			Q6			Q7			Q8		
TASKS Month:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
TASK 2.0: Optimizing the microstructure/chemistry																								
Task 2.1 – Fabrication of test crucibles																								
Task 2.2 – Pretest characterization																								
Task 2.3 – 100 hr tests at 750°C																								
Task 2.4 – Post mortem characterization and analysis																								

An example of failure with another salt



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TASK 3: PROPERTY MEASUREMENTS

	Q1			Q2			Q3			Q4			Q5			Q6			Q7			Q8		
TASKS **Month:**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
TASK 3: Property measurements																								
Task 3.1 - Sample fabrication																								
Task 3.2 – Measure CTE from 25-900C						△																		
Task 3.3 – Measure thermal diffusivity from 25-900C																								
Task 3.4 – Profilometry measurements																		△						

Netzsch TMA 402 F1 Hyperion

Steel Furnace
Up to 1100C

Netzsch LFA 467

Furnace
Up to 1250C

Handheld Profilometer
10 micron resolution

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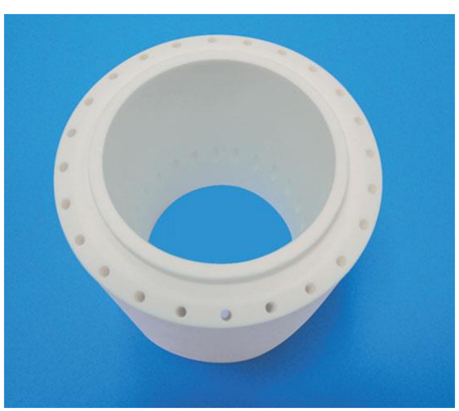
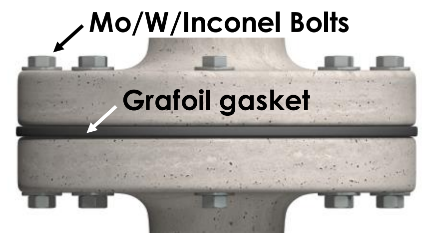
TASK 4: FULL SCALE DESIGN & COST MODELS

TASK 4: Full scale tank design and technoeconomics
Task 4.1 – Initial design for thermal considerations
Task 4.2 – Revised tank design for thermomechanical considerations
Task 4.3 – Revised tank design based on installation/curing considerations
Task 4.4 – Tank cost model
Task 4.5 – Pipe cost model

CTE match → Tanks grow together





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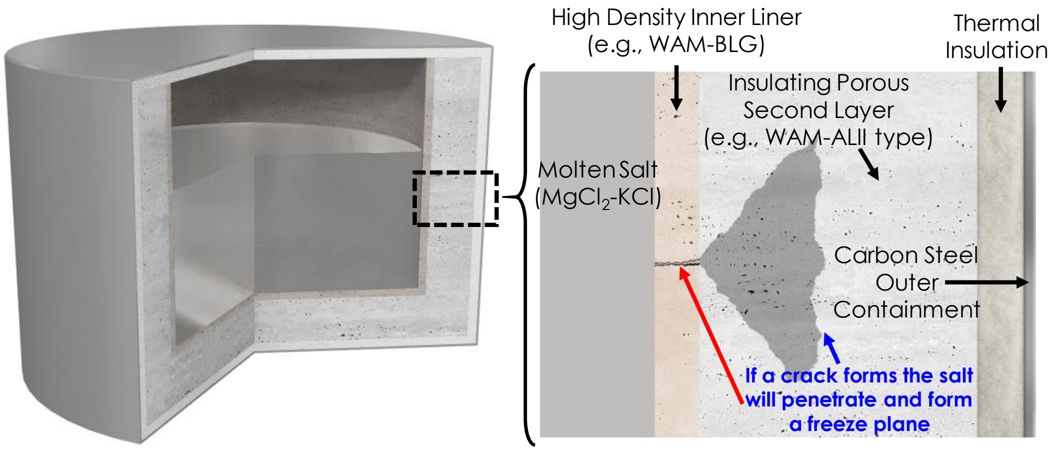

Resources ($)		
Total Project	DOE Funds	Cost Share
$2,214,831	$1,771,798	$443,033

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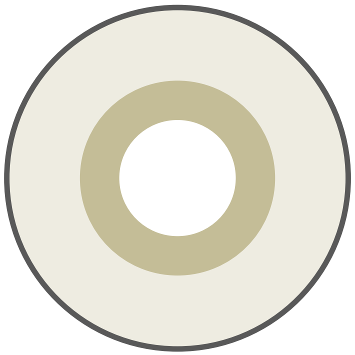
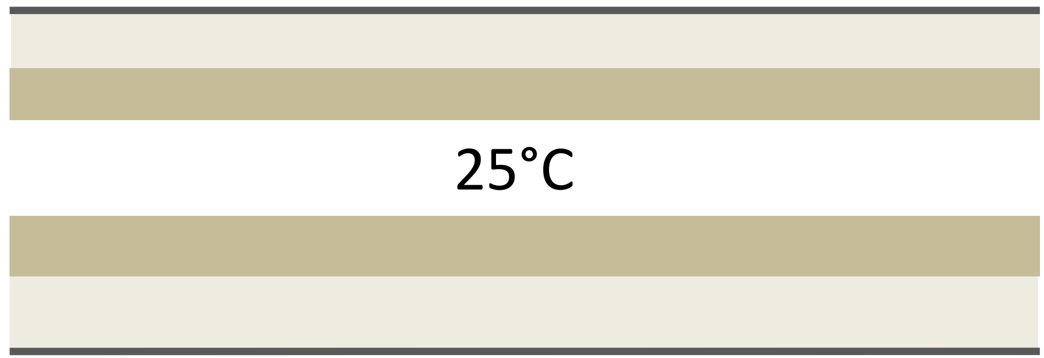
Why ceramic lined pipes won’t work

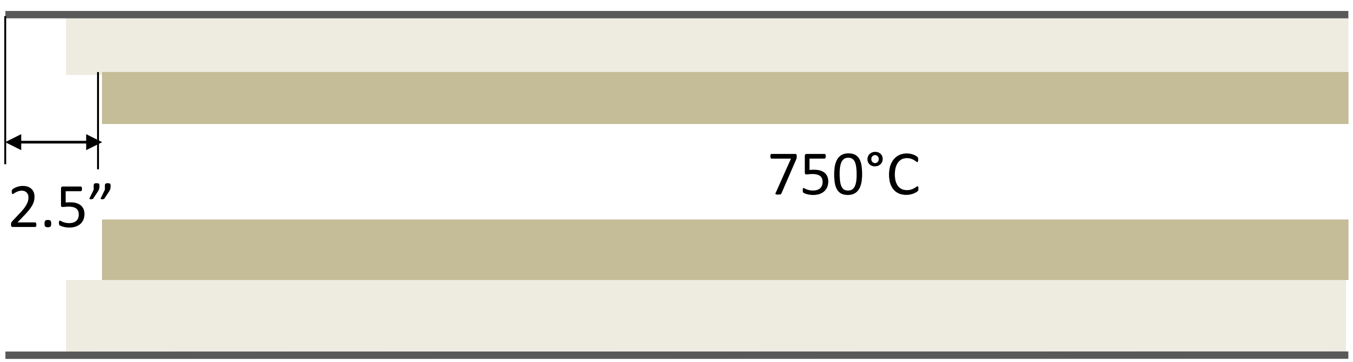




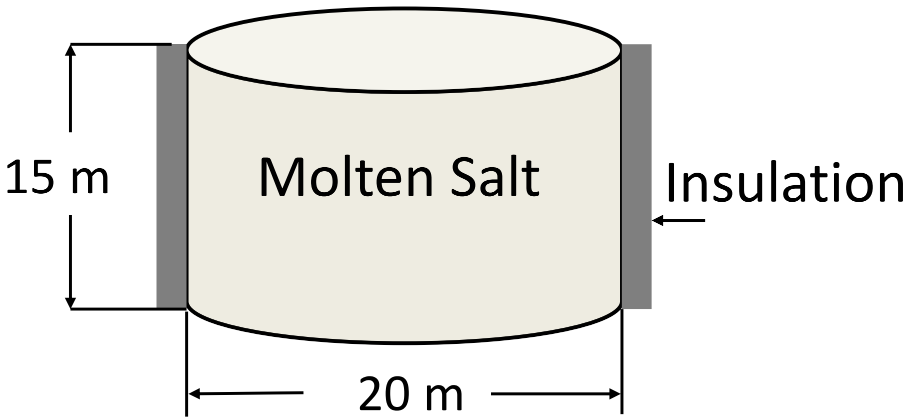
$$\alpha \cdot \Delta T \cdot L_0$$

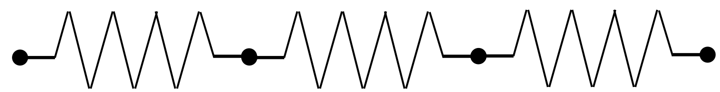
$$20e-6K^{-1} \times 725K \times 6m = 0.087m$$

$$5e-6K^{-1} \times 725K \times 6m = 0.022m$$



Why tank thermal cycles are not very significant





$$R_{tot} = \cancel{R_{conv}} + R_{cond} + R_{conv}$$

$$\frac{d}{dt}\left(m \cdot C_P \cdot T\right) = \frac{\left(T_{salt} - T_\infty\right)}{R_{tot}}$$

$$T = T_\infty + \left(T_0 - T_\infty\right)\exp(-t/\tau) \qquad \tau = m \cdot C_P \cdot R_{tot}$$

The time constant is large because the mass is large.

τ ~ 50 days

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Addressing Crack Formation and Propagation

Particle Packing
Choice of Material
    Perm. Lin. Change
Water Content
    Surfactant Choice
Dryout Schedule
Compression
Use of Large Aggregate or Fiber
    Work of Fracture

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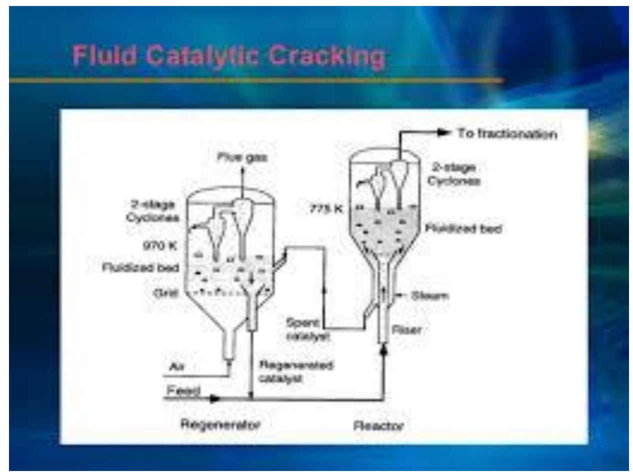
Abrasion Resistance

ASTM C-704



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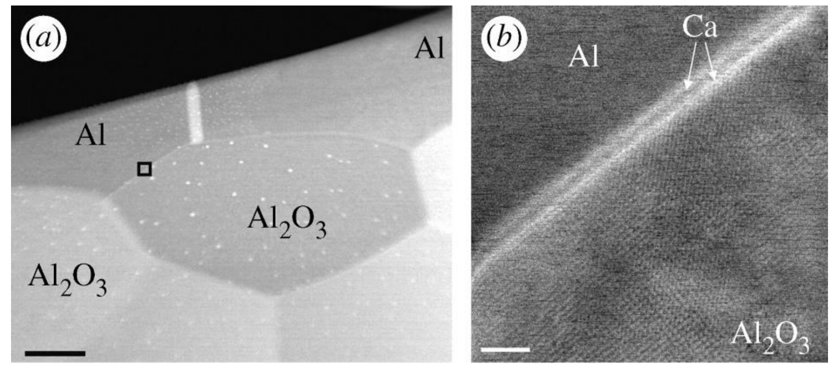
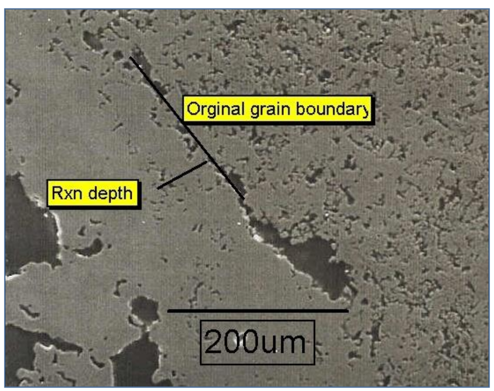
Alkali and Alkaline Earth Resistance

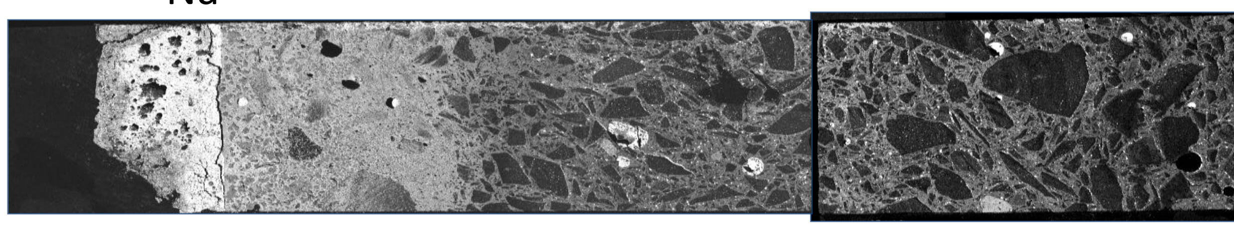
Metallics Grain Boundary Attack
Grain Size Change (temp)

Ceramics Grain Boundary Attack





Na



Method of Use of Calcium Hexa Aluminate Refractory Linings and/or Chemical Barriers in High Alkali or Alkaline Environments
Inventors: McGowan, Kenneth A., Cullen, Robert M., Keiser, James R., Hemrick, James G., Meisner, Roberta A. UNITED STATES FCA 9/19/2007 11/901,909 10/22/2013 8,563,083 ISSUED 0047205-000036
CANADA 0047205-000043 DCA 9/19/2007 2,663,798 1/19/2016 2,663,798 ISSUED
15END OF REPO

With ORNL

Ceramic Castable Cement Tanks and Piping for Molten Salt

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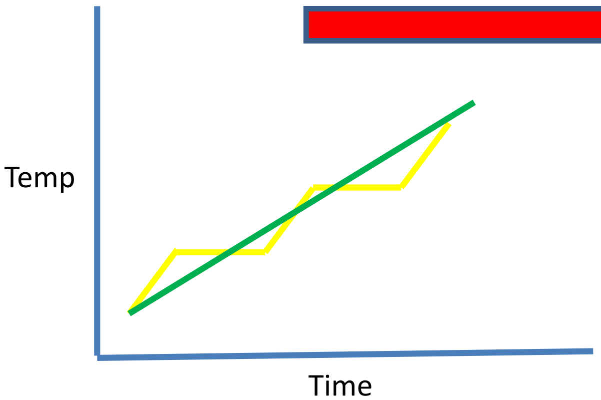
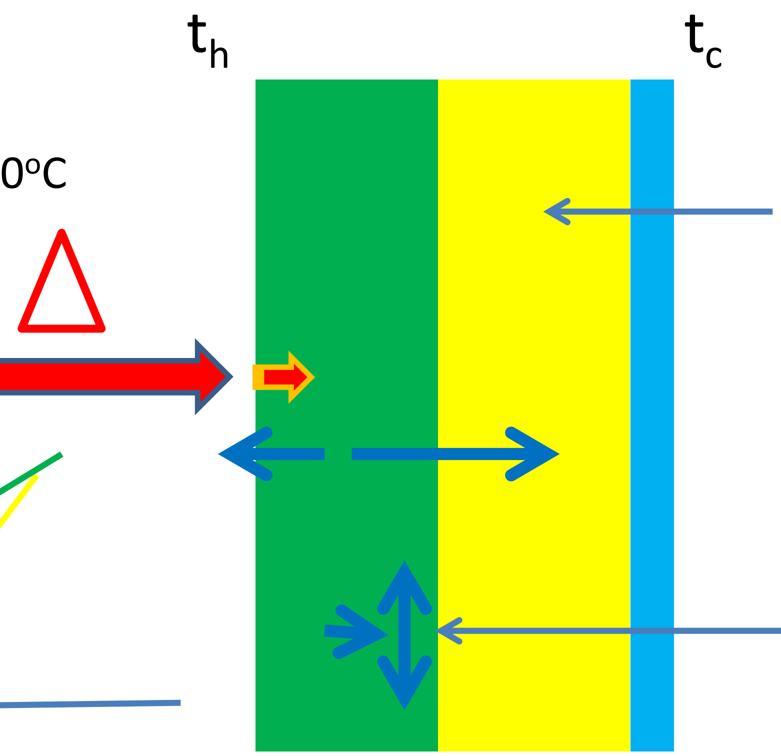
- Dry-Out
  - Water Must be Removed Prior to Molten Metal Contact

H_2O bp = 100°C

$3CaAl_2O_4$-$6H_2O$ decomposes 240-370°C





Highly insulating Micro porous board systems like Excelfrax products from Unifrax are water soluble.

These must be protected with a foil lining and interface temp needs to be below the melting point of the foil

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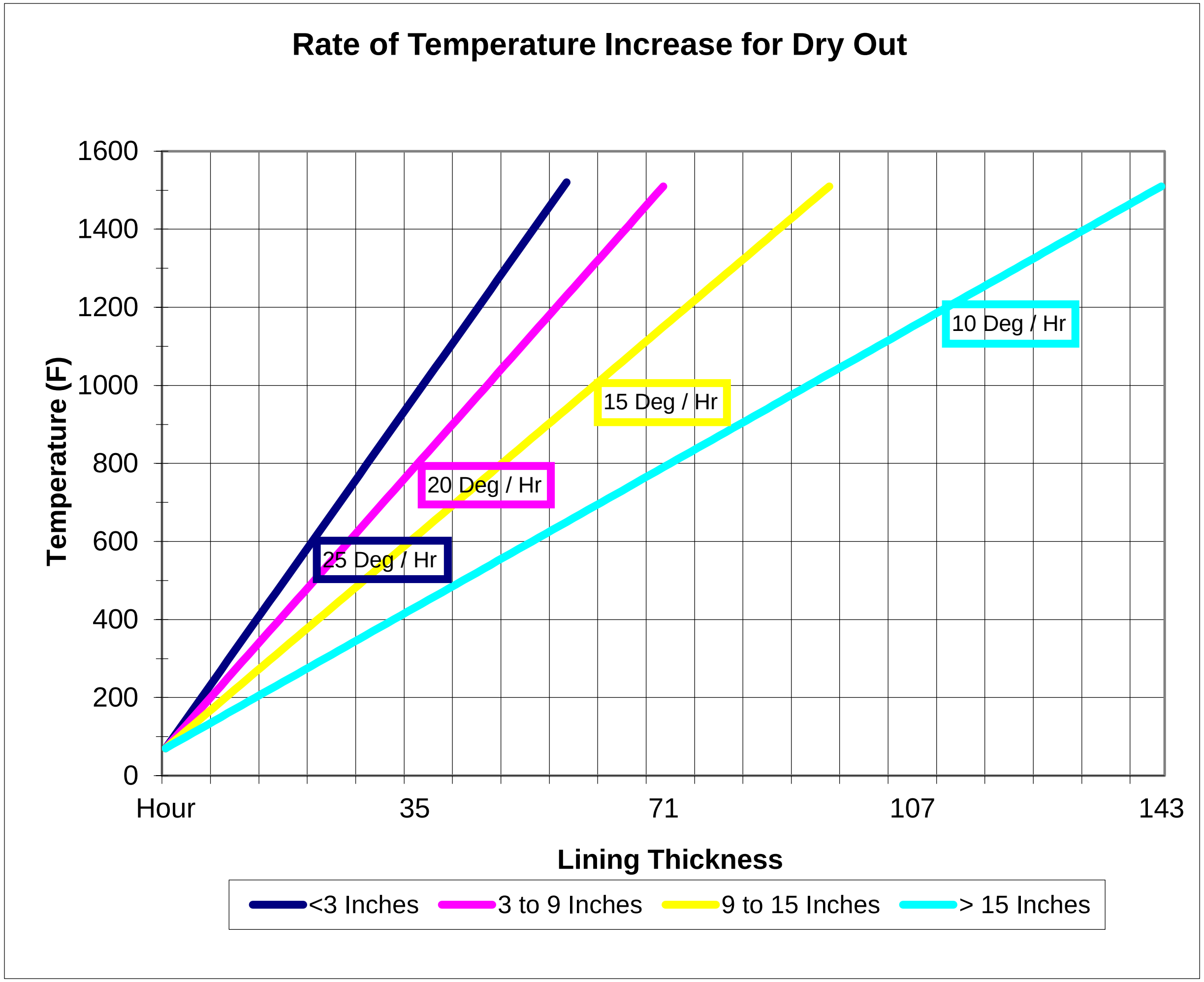

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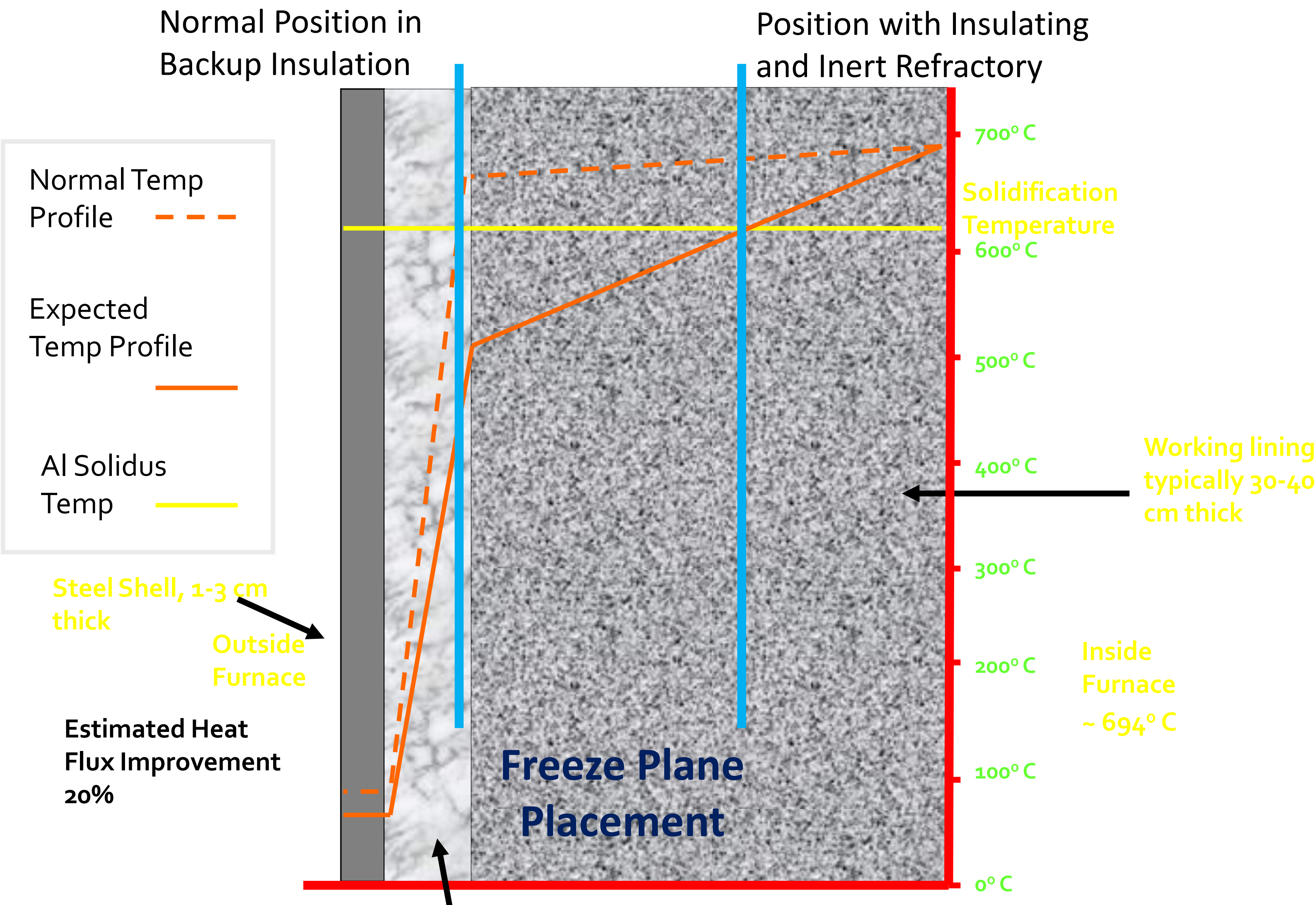

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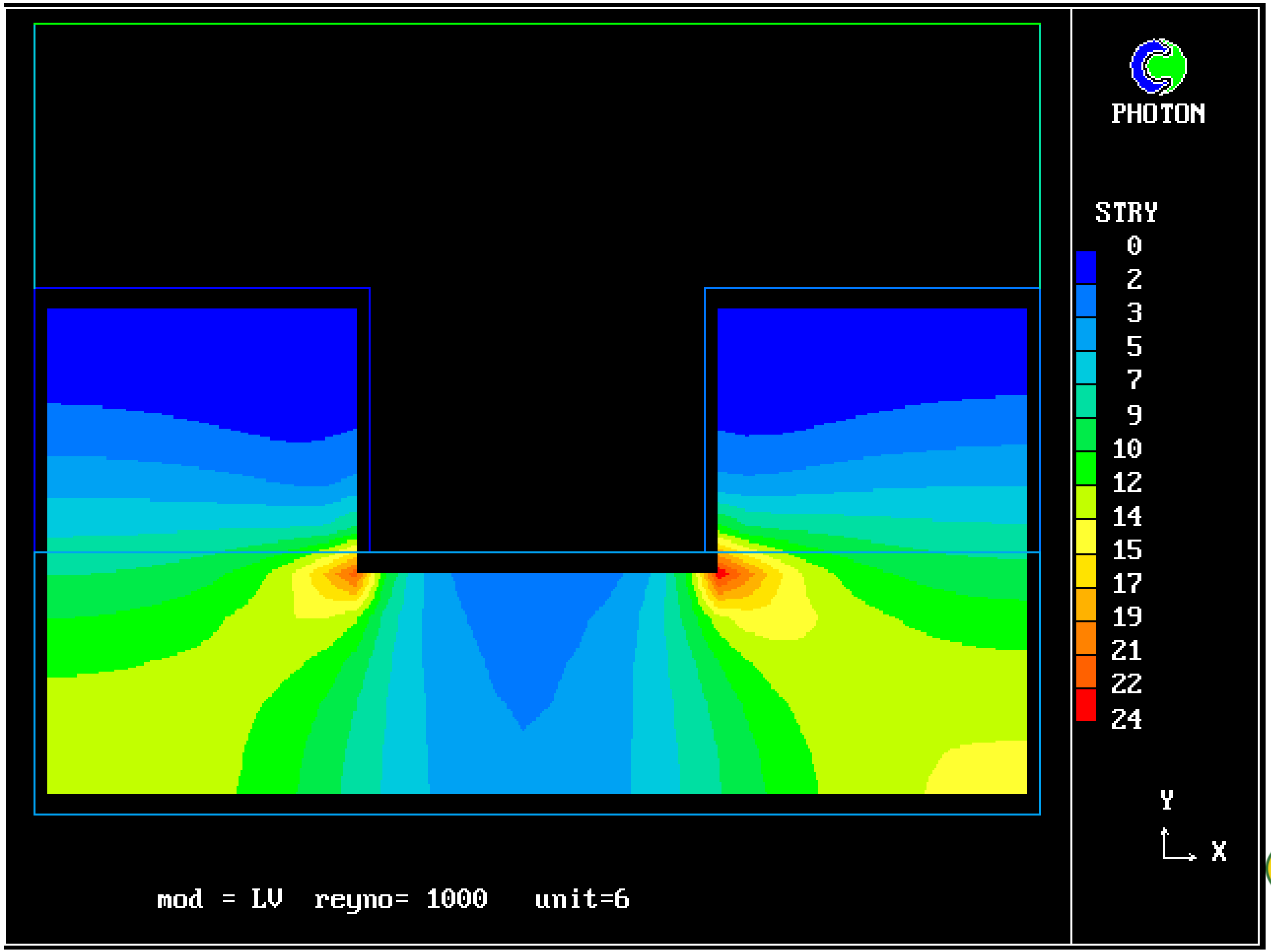
- Thermal Induced Stress in the Y-Direction



Westmoreland Advanced Materials

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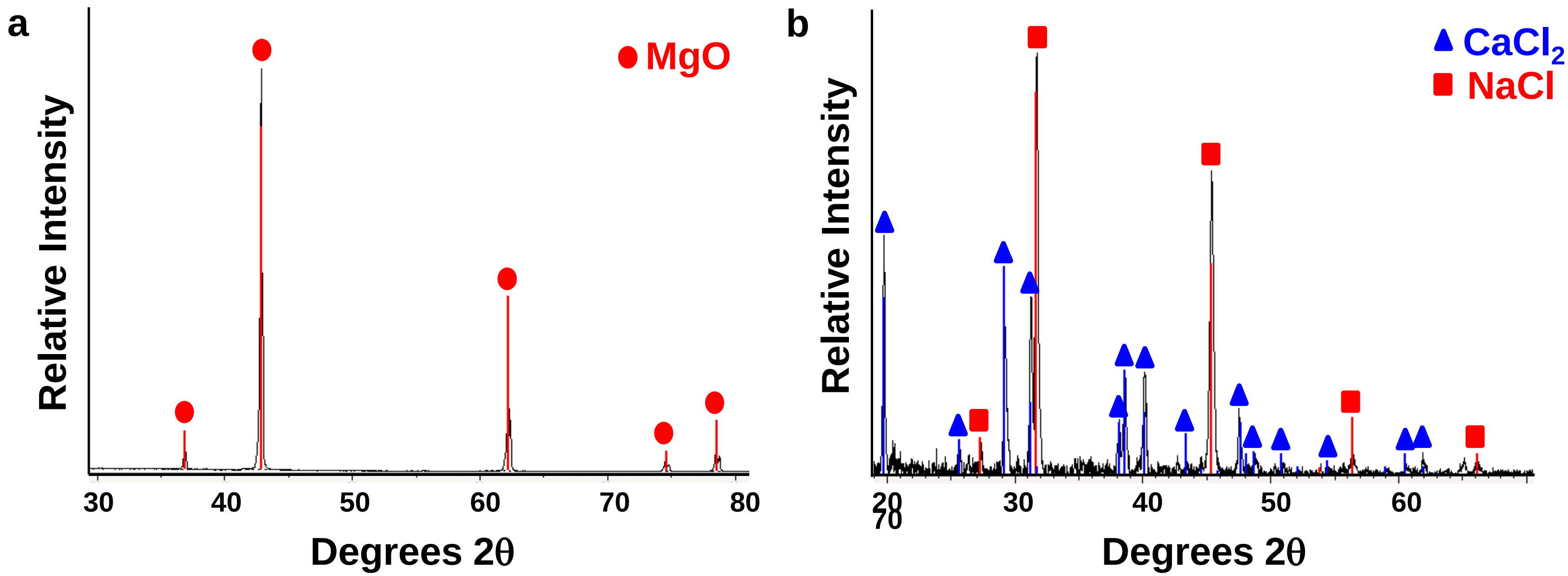

X-ray diffraction patterns obtained from solidified products generated upon exposure to ambient air at 750°C for 50 h of: **a)** a 32 mol% $MgCl_2$/68 mol% KCl molten salt, and **b)** 53 mol% $CaCl_2$/47 mol% NaCl molten salt.

CONFIDENTIAL

[1]**K. H. Sandhage, *U.S. Provisional Patent Application*, 2017.**