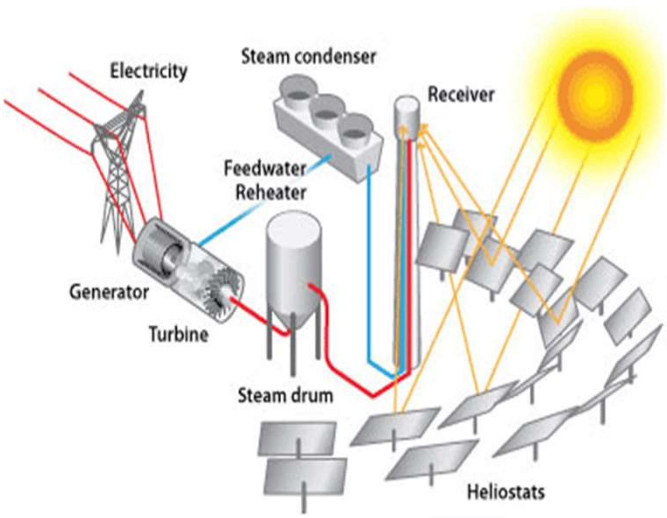

Concrete-based Molten Salt Thermal Energy Storage (TES) Tank Design

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Project Teams: NREL, MIT, Morgan Advanced Materials, JT Thorpe & Son, Worley

What's New I? A Concrete-based TES Tank Structure

- Concrete has been widely used for large-scale liquified natural gas (LNG) storage [1,2] that is in similar scale to molten salt TES.

A concrete liquified natural gas (LNG) tank near completion in Darwin, Australia

A concrete liquified natural gas (LNG) tank near completion in Barcelona, Spain

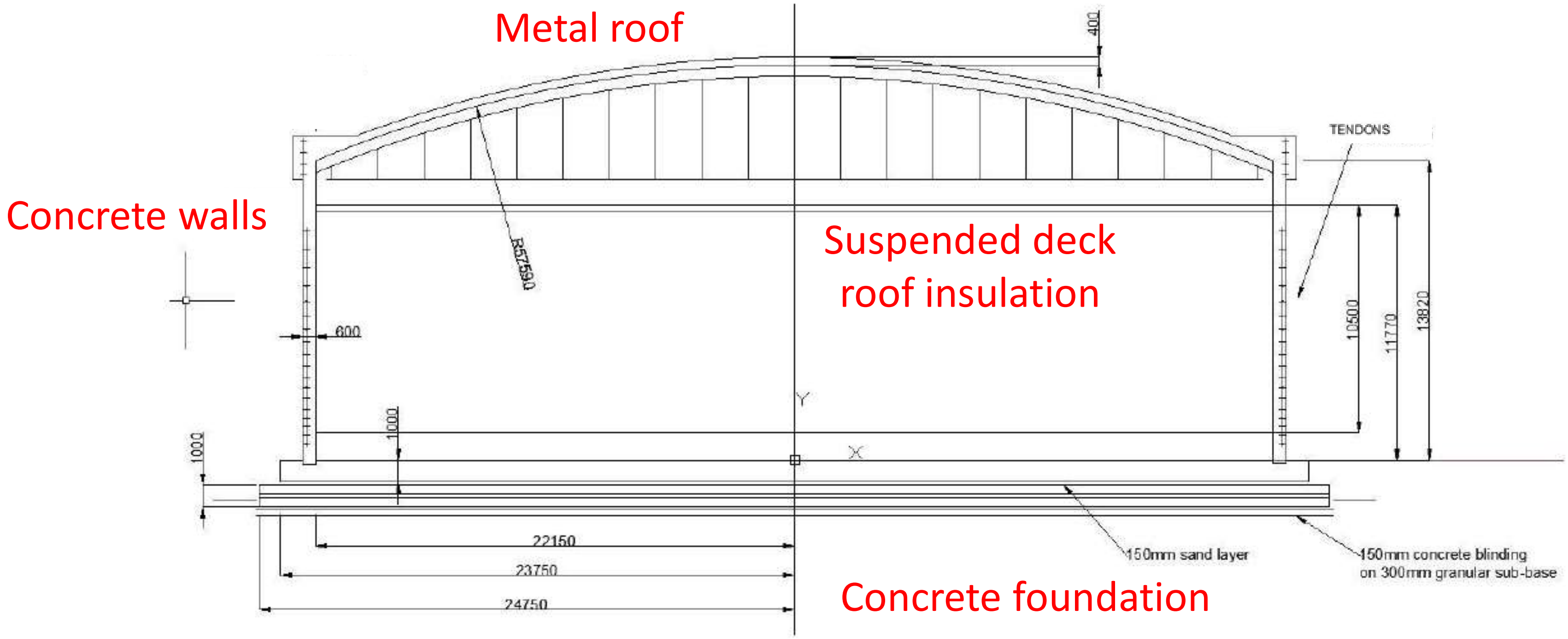
[1] Y. M. Yang, J. H. Kim, H. S. Seo, K. Lee, and I. S. Yoon, "Development of the world's largest above-ground full containment LNG storage tank," in *International Gas Union World Gas Conference Papers*, 2006, vol. 5, pp. 2508–2521.
[2] H. Lun, F. Filippone, D. C. Roger, and M. Poser, "Design and Construction Aspects of Post-Tensioned Lng Storage Tanks in Europe and Australasia," 2014.

What's New I? A Concrete-based TES Tank Structure

- Concrete has been widely used for large-scale liquified natural gas (LNG) storage [1,2] that is in similar scale to molten salt TES.
- Potential benefits
  - Avoid potential thermomechanical failure associated with a metal-based tank structure
    - One of the suspected failure modes for current Gen2 metal-based TES tanks
  - A concrete tank structure may mitigate certain differential thermal expansion at the metal tank/concrete foundation interface for a metal-based tank design
    - One of the known issues for current Gen2 metal-based TES tanks

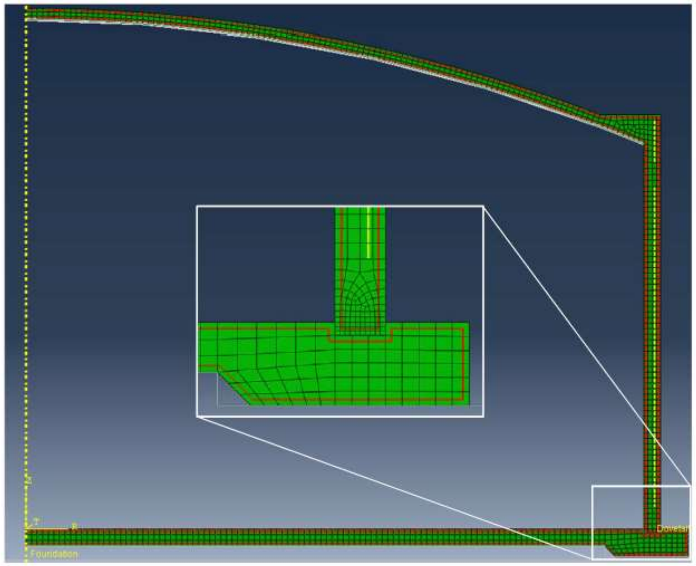
[1] Y. M. Yang, J. H. Kim, H. S. Seo, K. Lee, and I. S. Yoon, "Development of the world's largest above-ground full containment LNG storage tank," in *International Gas Union World Gas Conference Papers*, 2006, vol. 5, pp. 2508–2521.
[2] H. Lun, F. Filippone, D. C. Roger, and M. Poser, "Design and Construction Aspects of Post-Tensioned Lng Storage Tanks in Europe and Australasia," 2014.

Conceptual Concrete TES Design – Advisian/Worley



- Key challenge is to manage the thermal and mechanical stresses of the concrete walls, foundation, joints and the metal roof

Initial Mechanical and Thermal Finite Element Analysis – Advisian/Worley



Stress profile of concrete structures

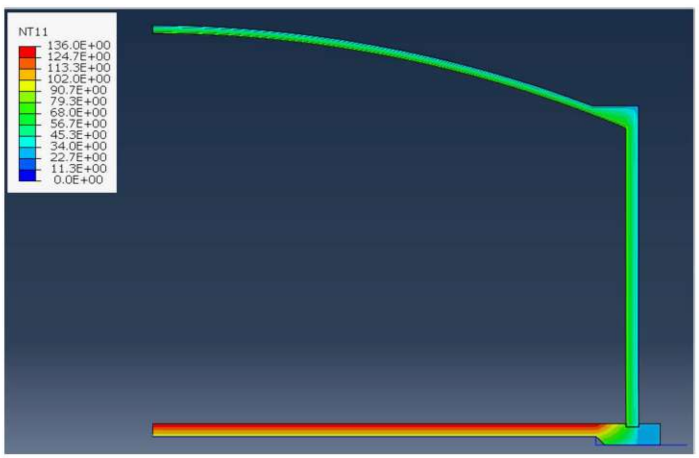
Green = Concrete

Red = Rebar

Yellow Tendons

Grey = Roof Structure

- Inset closeup showing dovetail connection – wall supported by base using contact enforcement



Temperature profile of concrete structures

1. Initial temperature is assumed to be 20°C
2. Operating temperature profile generated based on linear through-wall temperatures for wall/roof and base, with approximated transitions at corners

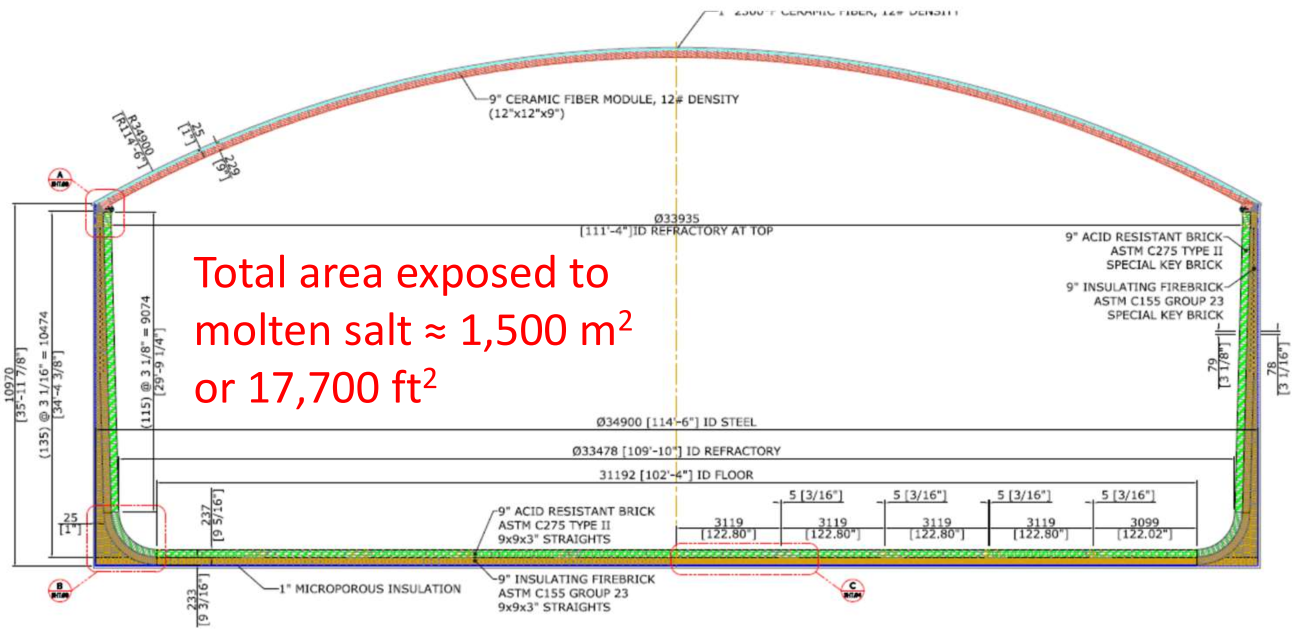
What's New II?
A New Concept for Internal Thermal Insulation

- Using internal thermal insulation to manage the temperature and temperature gradient of the concrete is key.
  - The objective is NOT to develop a high-temperature concrete material.
    - High-temperature concrete can be costly
    - Chemical resistance to molten salt is unknown if in direct contact
    - Thermal insulation of high-temperature concrete can be poor meaning tank size/cost can be prohibitive
  - Instead, the objective is to use current Portland-cement material for structure support only.
    - Various construction Codes require to keep concrete temperature as low as possible.

Main question is how to design internal thermal insulation to reduce temperature of concrete structure (also applicable to metal-based tank structure)

Current State-of-the-art Internal Insulation Design

Gen3 CSP Topic 1 Liquid Pathway TES Design by NREL [1]



Total area exposed to molten salt ≈ 1,500 m^2 or 17,700 ft^2

Green = Dense hot-face (low porosity to prevent salt permeation)

Yellow = Back-up insulation (high porosity to provide thermal insulation)

Red = Insulation fiber board/blanket (highly porous and lightweight to provide thermal insulation)

Key risks:

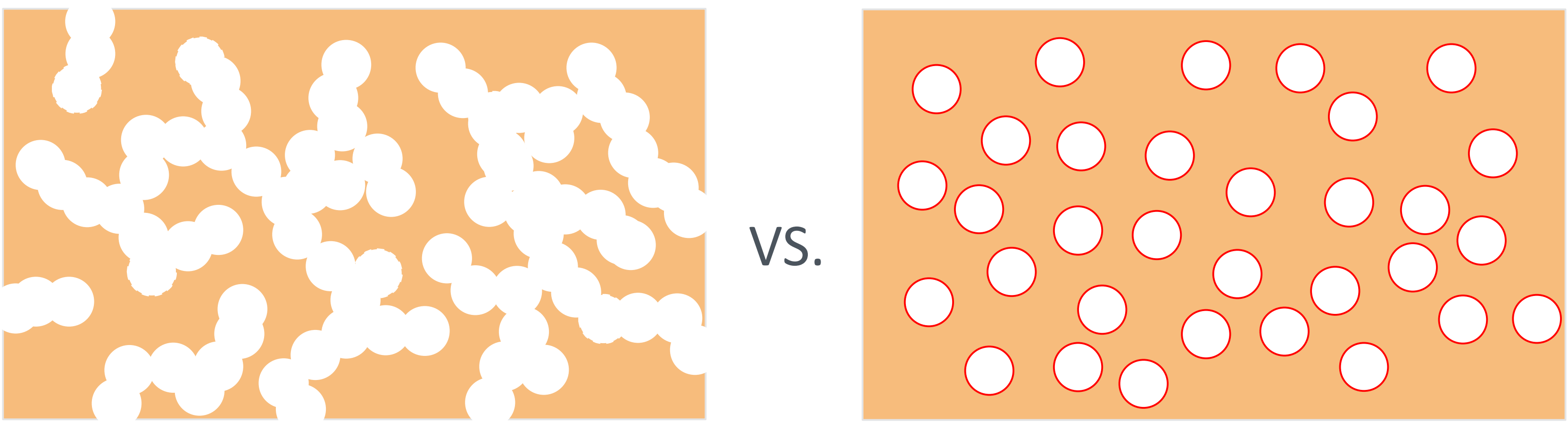
1. Failure of hot-face (1) at mortar joints, (2) at expansion joints, (3) due to cracking, etc. can cause salt leakage into back-up insulation leading to reduced thermal insulation
2. Clogging of open porosities in the porous roof insulation due to salt condensation can lead to reduced thermal insulation. Weight gain of roof insulation is another potential issue.

The open and interconnected porosity in these internal insulation materials is a major risk

[1] C. Turchi, S. Gage, J. Martinek et al. 2021. CSP Gen3: Liquid-Phase Pathway to SunShot. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-79323. https://www.nrel.gov/docs/fy21osti/79323.pdf.

What's New II?
A New Concept for Internal Thermal Insulation

- The primary technical objective is to replace open porosity with independent and closed porosity (NREL collaboration with Morgan Advanced Materials and Olivetti Group at MIT DMSE).
- However, this concept is a compromise by its nature
  - Independent and close porosities can not overlap
  - The max. amount of closed porosity and thermal insulation are both limited
  - A matrix is still needed to provide structural integrity and protection from molten salt. The matrix is usually much more thermally conductive.

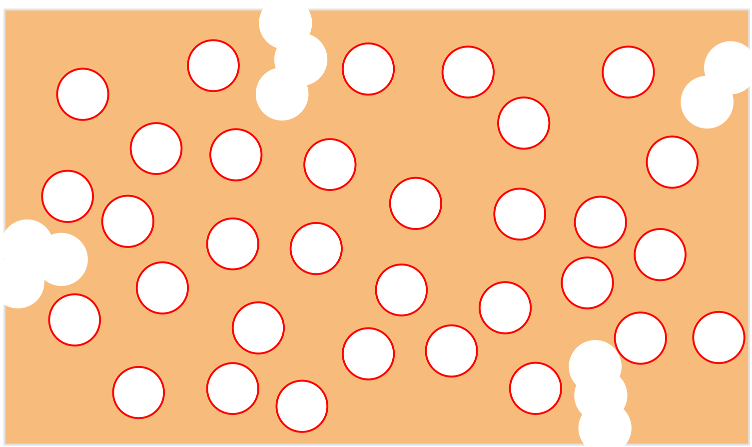


Open porosity Matrix

Closed porosity Matrix

What's New II?
A New Concept for Internal Thermal Insulation

- Main challenge is to find the method of introducing closed porosity while balancing the thermal insulation, mechanical strength and chemical resistance to molten salt
- Our material system of choice:



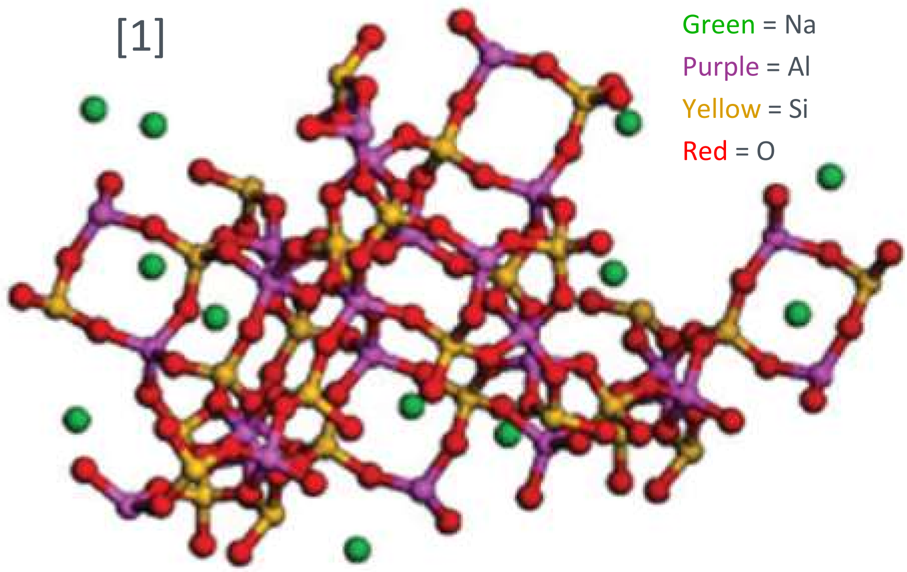
1. Open porosity around 10-20 vol.%
   - Due to dehydration and curing of Na-aluminosilicate geopolymer
2. Closed porosity around 20-30 vol.%
   - 20-30 vol.% is close to the upper limit before significant reduction of mechanical strength

Matrix: amorphous Na-aluminosilicate geopolymer

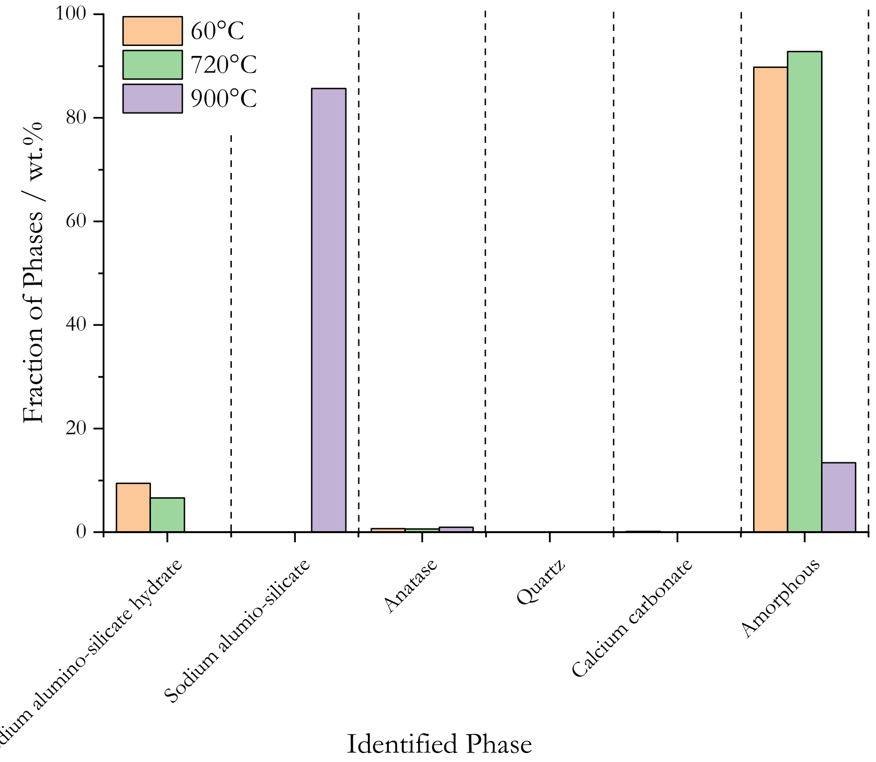
Closed porosity: aluminosilicate cenospheres

Geopolymer Relevance to Molten Salt TES Application

Na-aluminosilicate geopolymer structure



Heat treatment effect



Relevance to molten salt applications:

1. Water escape pathway during drying/curing and degree of geo-polymerization vs. open porosities
2. Maximum amount of hollow cenosphere addition vs. effective thermal conductivity
3. Stability of the interface between geopolymer matrix and additives
4. Na from the activator solution vs. chemical stability (cation diffusion, ion exchange, etc.)
5. Overall mechanical properties of geopolymers

[1] Concrete Institute of Australia, "Recommended Practice: Geopolymer Concrete," *Concrete Solutions 2011*. Concrete Institute of Australia, North Sydney, Australia, 2011

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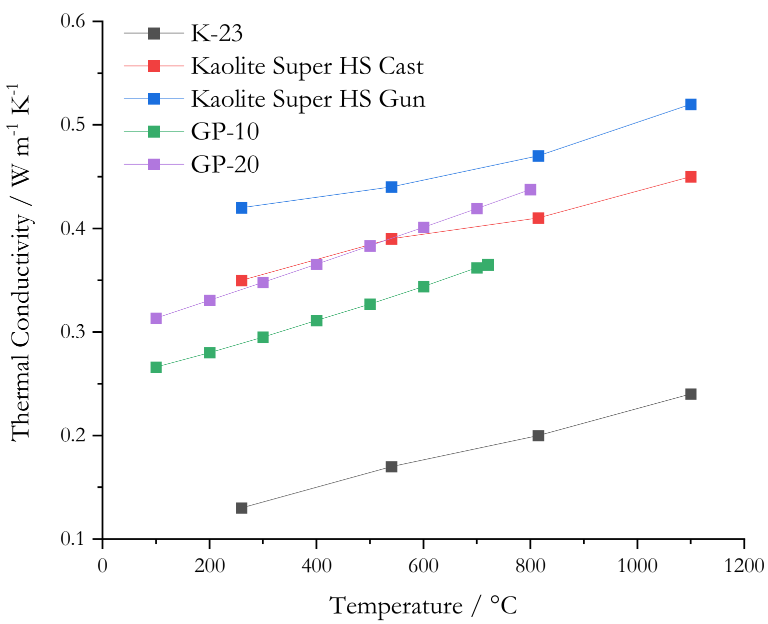
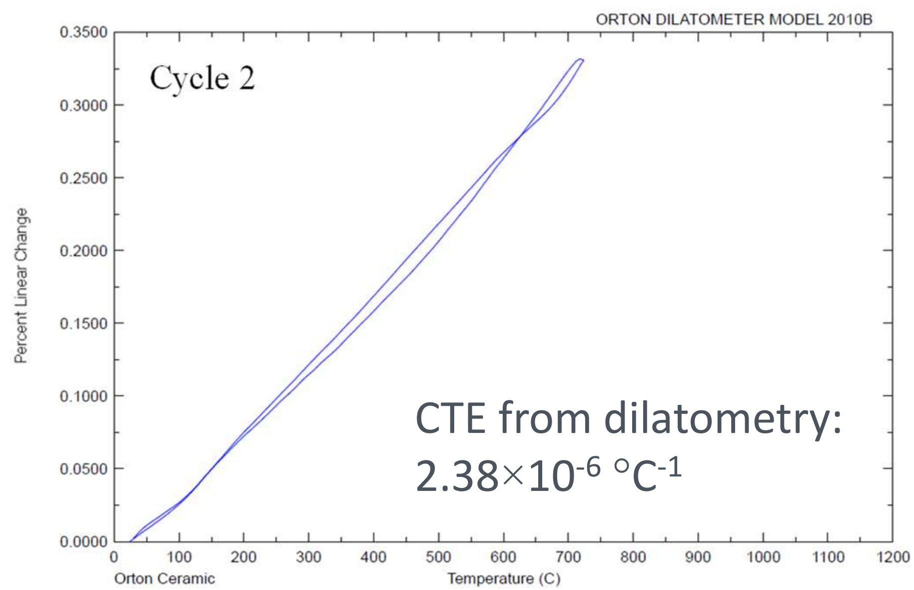
Geopolymer Properties – Key Properties

Curing Steps	Density (g/cm3)		Open Porosity (vol.%)		Permanent Linear Change (%)	
	GP-10	GP-20	GP-10	GP-20	GP-10	GP-20
1. Room Temperature for 24 hours	1.05	1.09	Not measured		Not measured	
2. 60°C for 7 days (after step 1)	0.86	1.01	22.0	11.1	-0.27	-0.27
3. 400°C for 5 hours (after step 1 and 2)	0.82	0.93	20.8	10.9	-0.90	-0.72
4. 720°C for 5 hours (after step 1 and 2)	0.83	0.90	20.7	10.7	-1.36	-0.40
5. 900°C for 5 hours (after step 1 and 2)	0.87	0.88	9.0	8.1	-3.37	-0.70





Comparison to Commercial Insulation

	Insulation Materials with Open Porosity	Conductivity (W/m K)		% Increase	
		Dry	Wet		
	GP w/ 25%	0.25	0.381	52.4%	Best balance
	GP w/15%	0.30	0.378	26.0%	
Group I	K-23 w/ 73%	0.10	0.803	703%	Too much increase
	Kaolite 2200 w/ 56.8%	0.2	0.583	191.5%	
Group II	Kao-tuff CV w/ 21.5%	1.3	1.473	13.3%	Bad insulation
	SR-90 w/ 18%	3.0	3.156	5.2%	

Biggest design question: Can we design to operate GP in the wetted state (no more salt permeation*)?

*The main assumption is that cenospheres remain intact when the insulation is immersed in molten salt. NREL is currently investigating this assumption.

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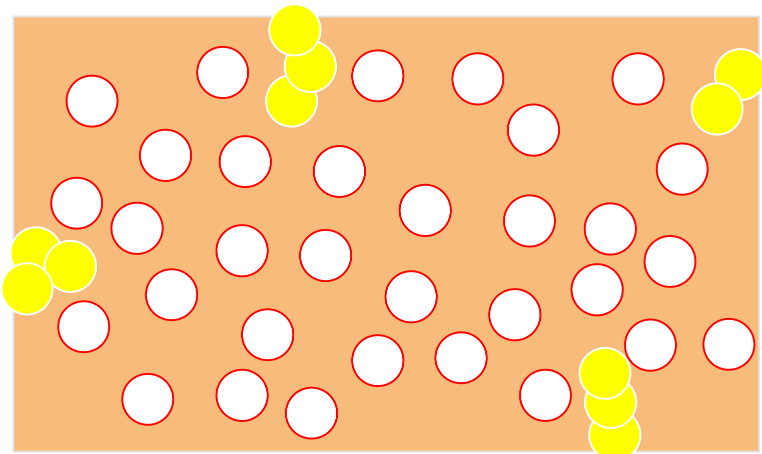
Wet Operation of GP Insulation?

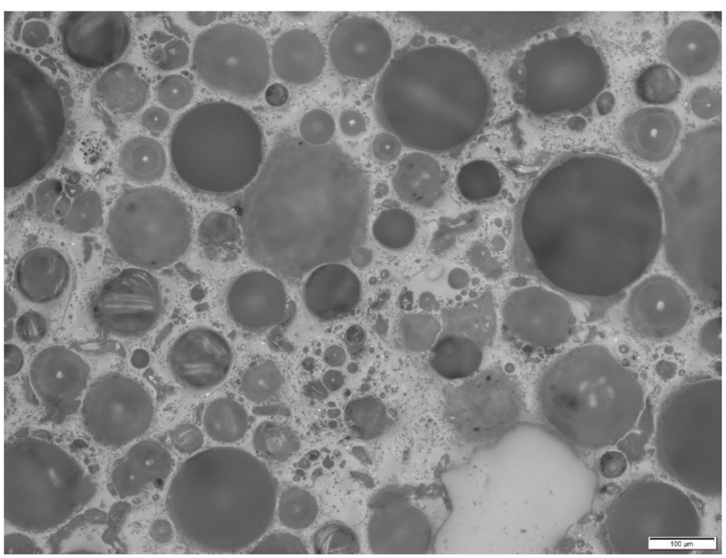


Matrix: amorphous Na-aluminosilicate geopolymer

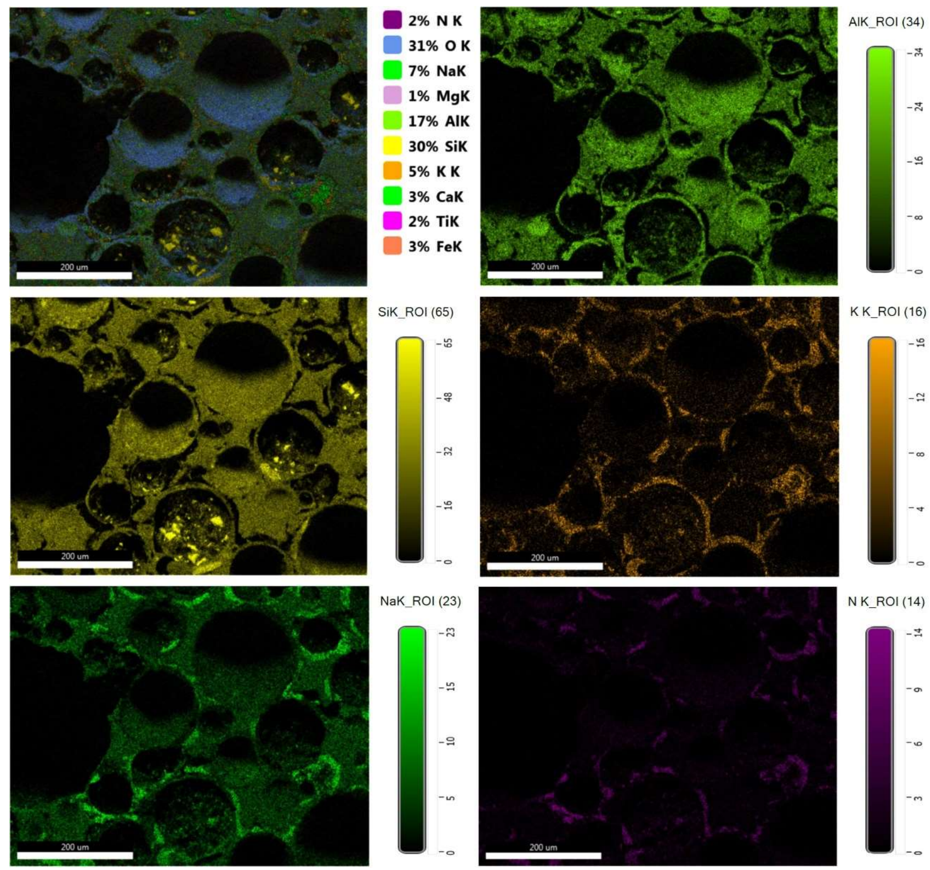
Closed porosity: aluminosilicate cenospheres

Open porosity wetted by molten salt

GP before salt immersion



EDS after 24-hr salt immersion



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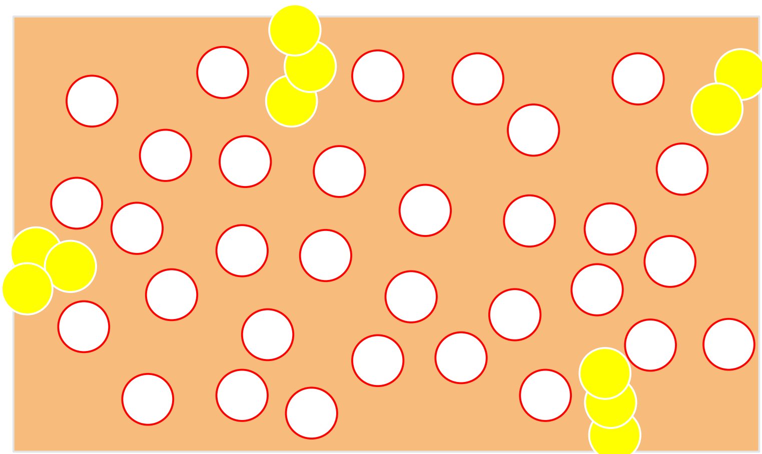

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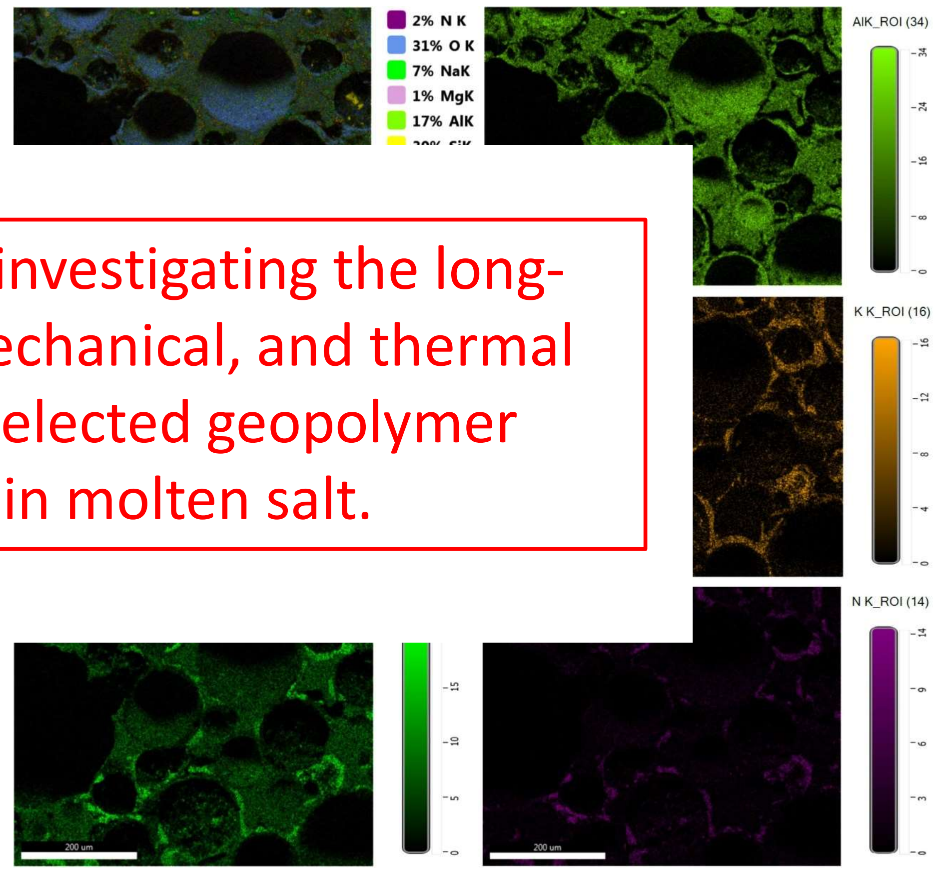
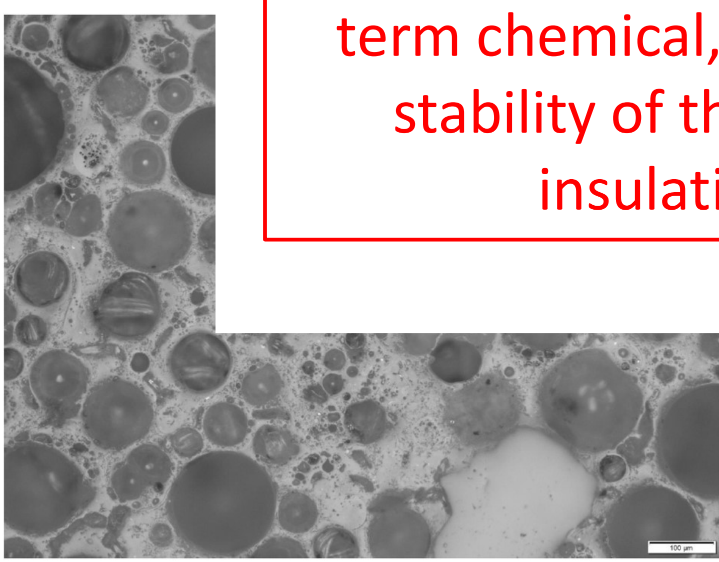


GP b



NREL is currently investigating the long-term chemical, mechanical, and thermal stability of the selected geopolymer insulation in molten salt.

Thank you

Contact Information

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NREL Thermal Energy Science & Technologies Group

https://www.nrel.gov/csp/

Backup Slides

Preliminary Costing and Insulation Effectiveness

Material	Thermal cond.	Gravimetric Cost	Density	Volumetric cost	M
	W/m K	$/kg	kg/m^3	$\$/m^3$	$(W/m\ K)^{-1} \cdot (kg/m^3)^{-1} \cdot (\$/kg)^{-1}$
Dry GP-10 and GP-20	0.35	5.61	900	5049.0	0.000566
Wetted GP-10 and GP-20	0.45	5.61	900	5049.0	0.000440
Dry Ref. Porous Insulation	0.08	1.8	513	923.4	0.013537
Wetted Ref. Porous Insulation	1	1.8	513	923.4	0.001083
Dry Ref. Dense Insulation	1.3	0.65	2270	1475.5	0.000521
Wetted Ref. Dense Insulation	1.3	0.65	2270	1475.5	0.000521

$$M = \frac{1}{\kappa \rho C}$$

where κ is thermal conductivity, ρ is the bulk density and C is gravimetric cost of the insulation material.

Clarifications for M:

- It does not include higher tank structure cost due to increase of tank diameter
- It does not include increased salt inventory cost due to salt permeation into insulation
- It does not assume any protective layer such as a hot face layer – this is not a comparison to Gen3 Liquid Pathway design
- It does not include any other costs due to potential maintenance, repair, etc.

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Implications:

- If geopolymer's cost can be reduced by ~2x, it can be (1) one of the most cost-effective molten salt insulation with little salt permeation concerns, and (2) comparable to wetted porous insulation but more advantageous in terms of tank structure cost
- Conservative estimation is that salt inventory increase due to wet operation is 0.6–0.9% of total TES cost.
- NREL is currently analyze the technical feasibility of wet operation (a fail-"safer" design) – mainly for long-term chemical compatibility of embedded cenospheres.