Technical Performance of Refractory Liners for Molten Chloride Salt Thermal Energy Storage Systems

Samuel Gage, Ph.D.

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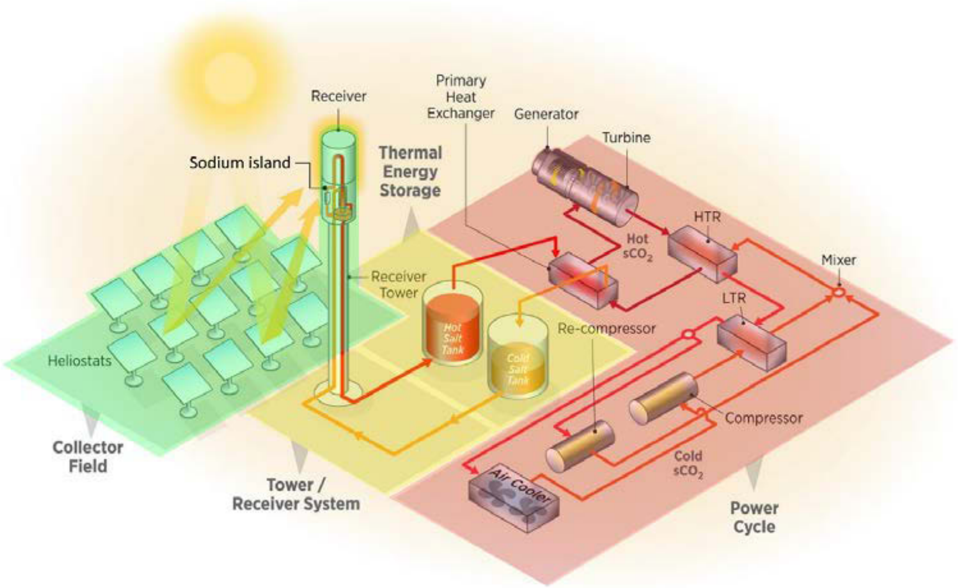
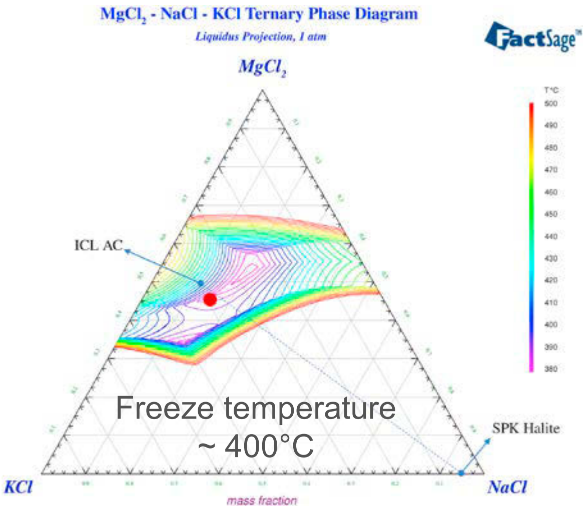
Generation 3 Concentrating Solar Power (Gen3 CSP)
Liquid Pathway





Freeze temperature
~ 400°C

Zhao and Vidal, *Sol. Energy Mater. Sol. Cells*, **2020**

TES System:
Hot salt tank (720 °C)
Cold salt tank (500 °C)

<u>Nominal salt composition</u>
$NaCl:KCl:MgCl_2$
20:40:40 mol.%

- ***The ternary-chloride salt is stable to temperatures well above the proposed operating point of 720°C, which enables the use of more efficient supercritical CO_2 (sCO_2) closed-loop Brayton cycles, with predicted net-cycle efficiencies of ≥ 50%.***

Molten Chloride Salt Thermal Energy Storage Tanks

Overview

- Temperature and corrosivity of chloride salt requires use of internal tank liners
  - Salt is not compatible common steels
  - Internal lining is only economic choice

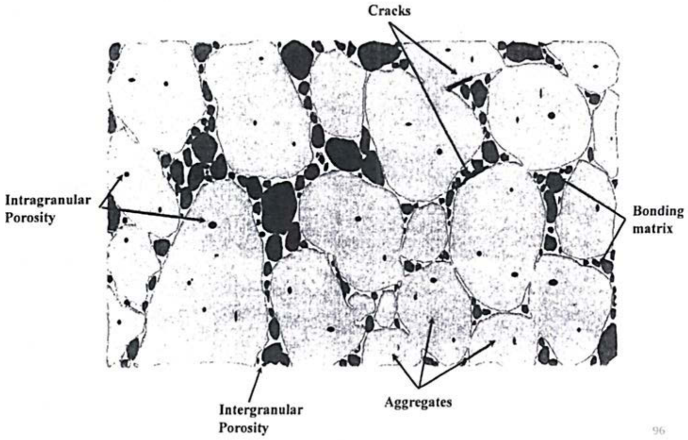
- Refractory-ceramic liners selected
  - Thermal, chemical, mechanical stability
  - Proven efficacy in similar industries
  - Cost

Tank Project Research

- Materials compatibility and down selection
  - Material immersion in molten salt

- Commercial scale tank design and analysis
  - Drafting tank and refractory engineering drawings
  - Finite element analysis of thermal and mechanical profile of tank in operation
  - Cost analysis and estimating $\$/kWh_{th}$

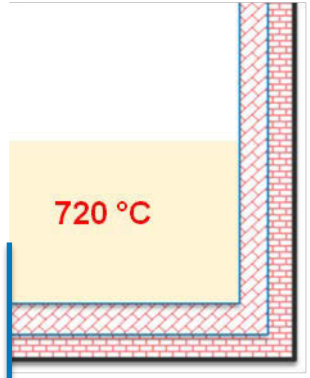
Refractory-Ceramics



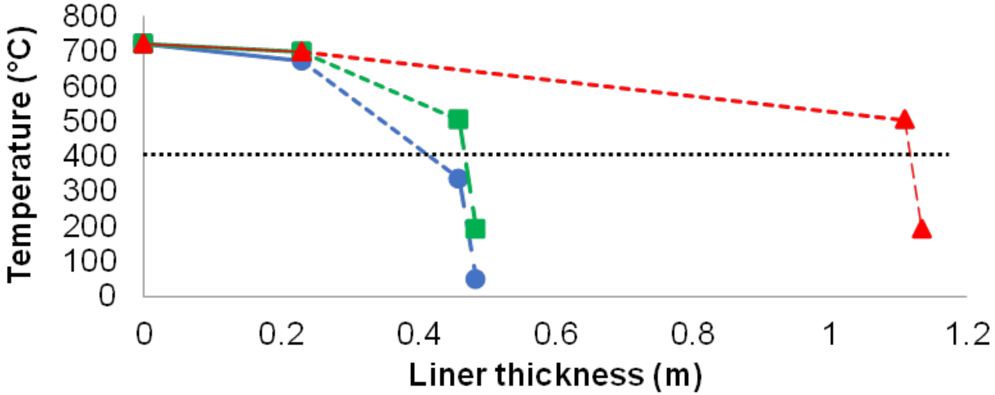
Class of ceramics, considered complex composites consisting of multiple ceramic phases, bonding matrixes, and/or defects

Tank Liner Model and Method Development

- Developed a 1-D heat transfer modelling tool in conjunction with industry partners
- NREL modelled the effective thermal conductivity of refractories wetted by molten salt
  - Validated data by comparing to known dry vs. wetted insulation thermal conductivity values
- Modelled various liner configurations and liner failure modes for target heat flux of ≤ 276 W/m^2
  - Analysis led to choosing “cold walls” (<100 °C) as the final design over initially proposed “hot walls” (500 °C) design



Salt (720°C)
1. Hot Face
2. Insulating Firebrick
3. Microporous Insulation
Carbon Steel Shell



Possible designs
Red: “hot walls” (wet)
Blue: “cold walls” (dry)
Green: “cold walls” (wet)

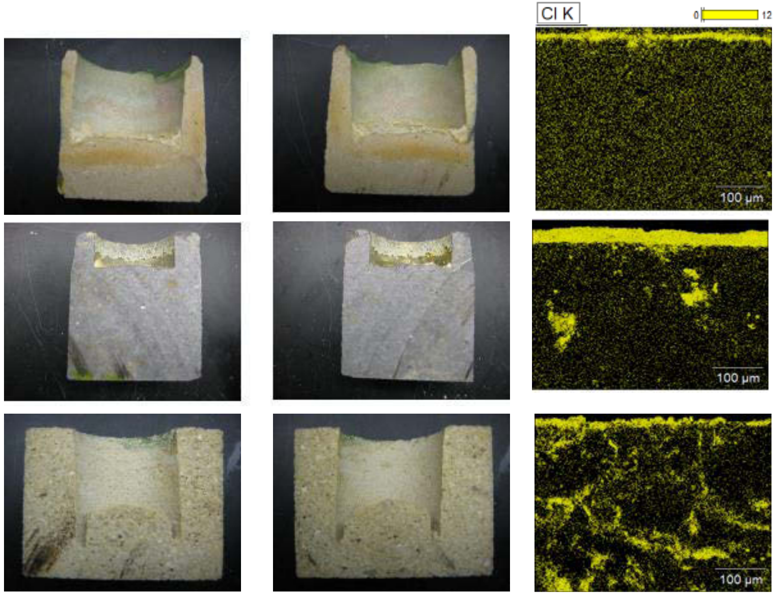
“Cold Walls”, Dry: carbon steel shell with <0.5 m liner (276 W/m^2)

“Cold Walls”, Wetted: risk of tank failure (436 W/m^2)

“Hot Walls”, Wetted: stainless steel shell with >1 m liner (260 W/m^2)

- ***Only “cold walls” design that is kept dry meets heat flux and cost targets***

Hot Face Materials Testing and Down Selection



Hot Face A → Salt penetration arrested at surface

Hot Face B → Connected porosity transports surface salt to material bulk

Hot Face C → Extensive salt penetration

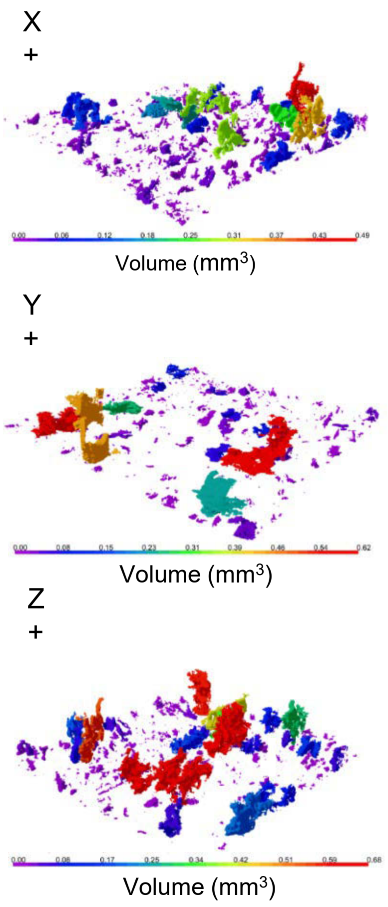
- Three hot face candidates were tested for compatibility with molten chloride salt
  - Selection based on similarity with a reference refractory currently used in magnesium chloride electrolysis cells
- Cups testing was performed in accordance with industry standard (*Alcoa Modified Aluminum Cup Penetration*)
  - 50-hour isothermal exposure to molten chloride salt at 720 °C

Hot Face Porosity via X-ray CT

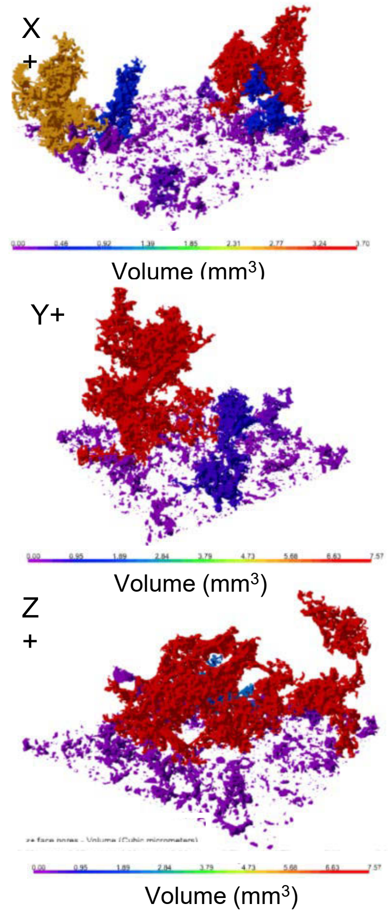
- X-ray computed tomography (X-ray CT) used to probe the porosity of the hot face brick material

- Hot Face A exhibits less surface-connected porosity connected porosity than Hot Face B

- Hot Face A selected for further analysis
  - Long-duration chemical compatibility
  - Mechanical durability

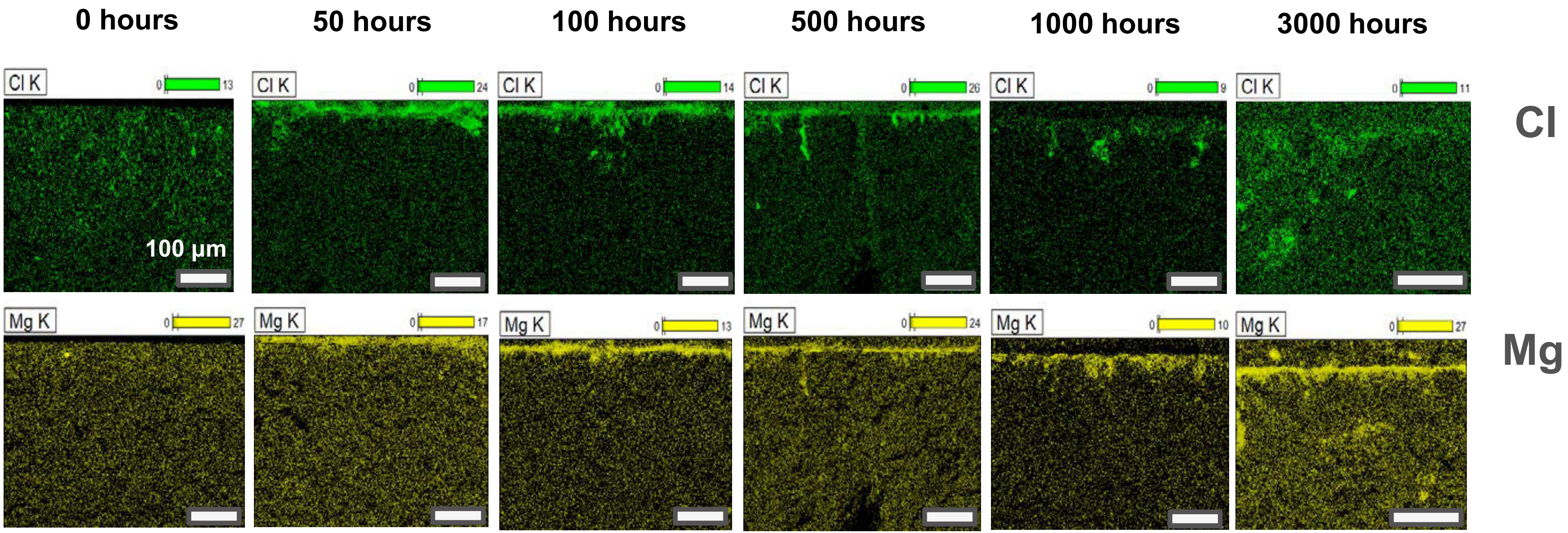


Hot Face A



Hot Face B

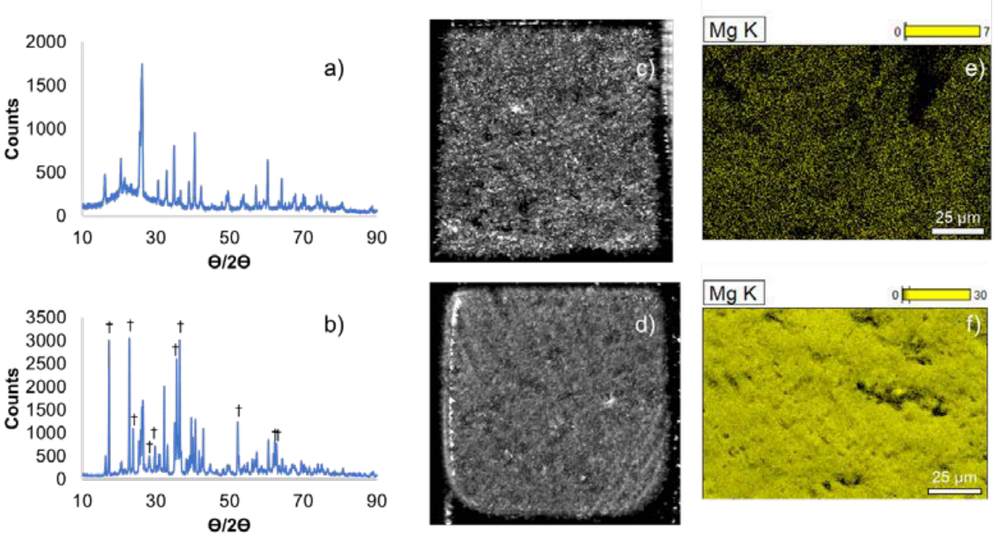
Long Duration Exposure Tests on Hot Face A



Salt permeation into Hot Face A as a function of time. Energy dispersive X-ray spectroscopy (EDS) maps of cross-sectioned brick sample immersed in molten chloride salt up to 3000 hours. Each is a different sample. Salt permeation is measured as the depth of Cl into the bulk of the material.

Surface Secondary Phase Formation

Forsterite (Mg_2SiO_4)



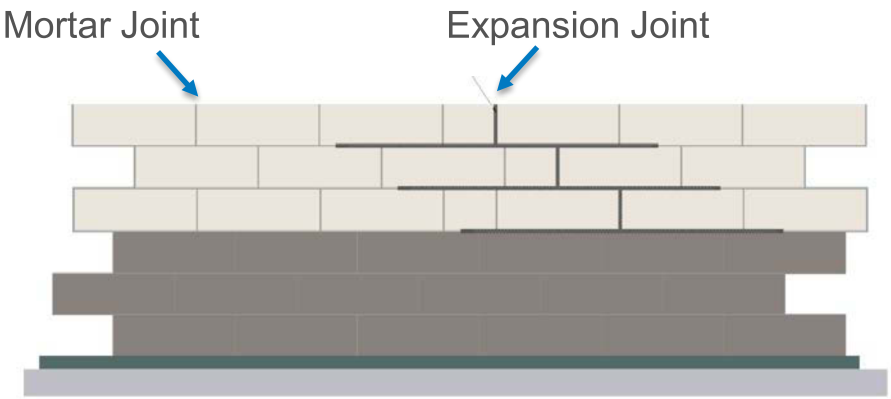
Hot Face A- Native		Hot Face A- 3000 h	
Sample Number	**CCS (MPa)**	**Sample number**	**CCS (MPa)**
1	111.8	1	116.5
2	109.9	2	103.0
3	119.9	3	115.3
4	101.2	4	120.4
5	123.2		
Mean	*113.2*	***Mean***	*113.8*
StDev	*8.7*	***StDev***	*7.5*

- Native Hot Face A and Hot Face A immersed in salt for 3000 hours: X-ray diffractograms (a) and (b) respectively,
  - The † symbols in the X-ray diffractogram of the 3000-hour immersed hot face A coupon highlight peaks that belong to the secondary phase that is formed on the material surface due to reaction with molten salt (forsterite, Mg_2SiO_4).[1,2]
- Scanning acoustic microscopy of coupon surfaces (c) and (d) respectively, and EDS Mg maps (e) and (f).
- Table shows the cold crush strength (CCS) of native and immersed Hot Face A
  - Formation of secondary phase does not adversely affect mechanical strength

[1] Wang et al., *Int. J. Appl. Ceram. Technol.*, **2017**

[2] Sun et al., *J. Am. Ceram. Soc.*, **2009**

Major Project Risks



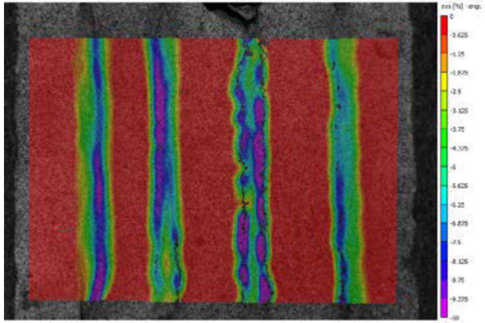
- Mortar Joints
  - High porosity regions of the hot face layer
  - Low viscosity molten salt can readily slip through joint and wet backup insulation

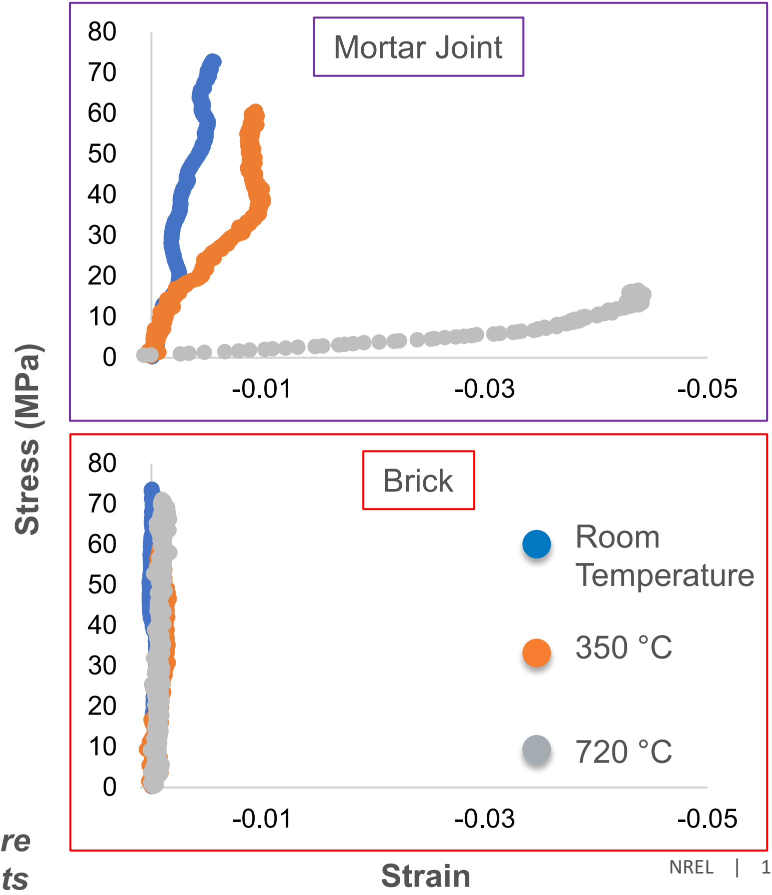
- Expansion Joints
  - Engineered gaps in the liner, designed to accommodate thermal expansion during startup
  - Should the expansion joint not fully close, molten salt will immediately permeate through gap
  - Should the expansion joint not be wide enough, high mechanical stress could crack liner

➢ ***NREL has developed novel mortar using Hot Face A material***
➢ ***Mechanical property data is needed on the mortar to mitigate risk***

Strain/Strain Analysis of Brick/Mortar Composites

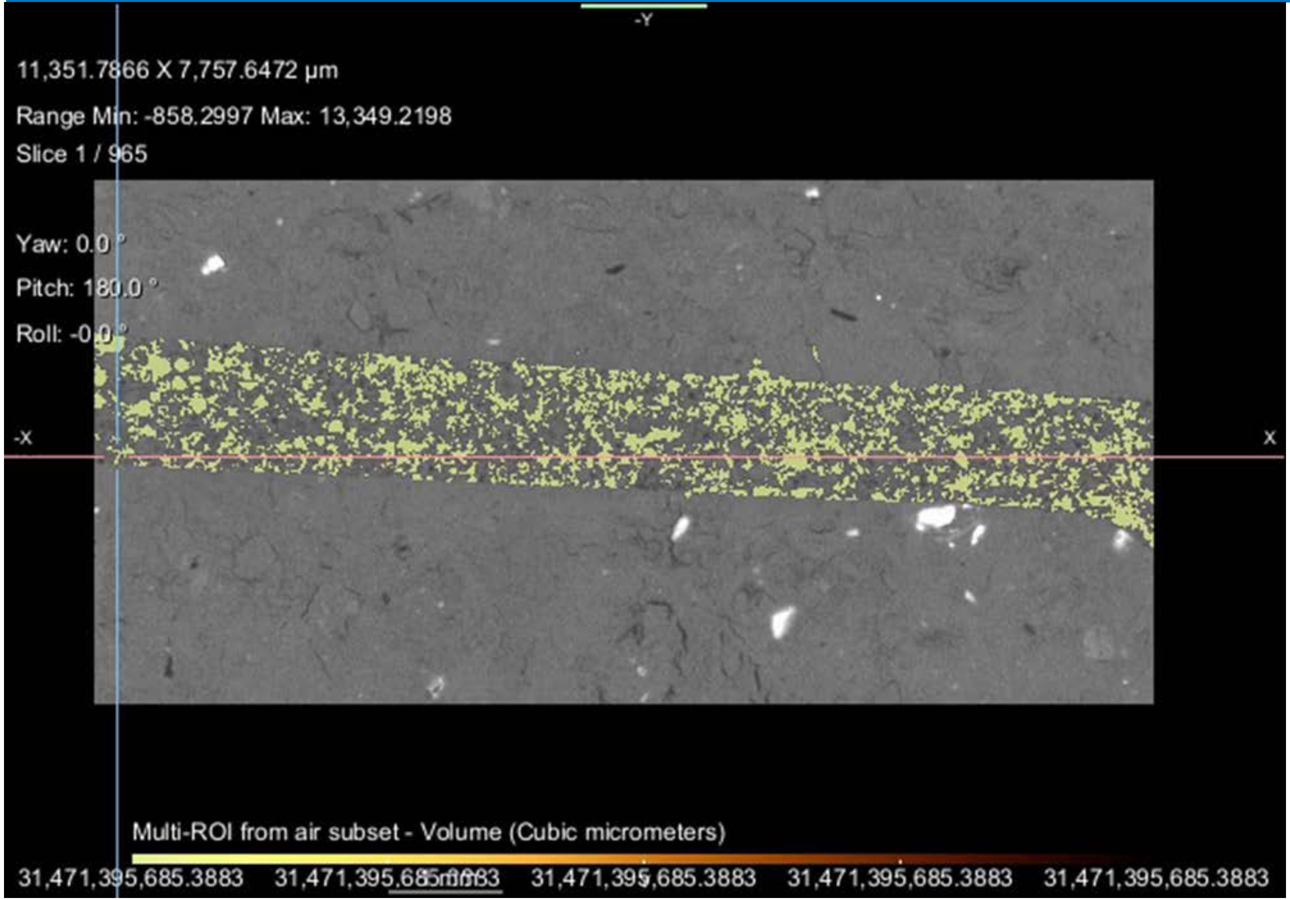
Elasticity of Mortar Joint





- ➢ *Modulus of elasticity decreases 97% at high temperature*
- ➢ *High mortar compressibility will reduce expansion joints*

in-situ X-ray CT Studies of Mortar Joint



- Use X-ray CT to measure the porosity of mortar
- in-situ compression X-ray CT
  - Identify crack formation
  - Coupled with heating (up to 350° C), high temperature behavior of pores under compression may be examined

Thank you

Samuel.Gage@nrel.gov

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