Silicon Carbide (SiC) Foam

Molten Salt Containment in CSP-GEN-3 Systems

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Touchstone Research Laboratory, Ltd.

Contract DE-SC0018678

Project Period: July 02, 2019 – August 18, 2021

Dwayne Morgan (PI)

Phone: (304) 547-5800 Ext. 231

Email: drm@trl.com

Touchstone Research Laboratory, Ltd.

NATIONAL ENERGY TECHNOLOGY LABORATORY

Brian E. Joseph: President/CEO
Brian Gordon: Laboratory Director
Dwayne Morgan: PI/Sr. Research Scientist
J.W. Freeland: Contract Specialist

Phase II Team

Department of Energy (Sponsor)

- NETL (Grant Administration & Program Oversight)
- Ms. Barbara Carney, Project Manager
- Mr. Walter Strzepka, Contract Management Specialist

Touchstone Research Laboratory, Ltd.

- Mr. Brian Joseph, President and CEO
- Mr. Brian Gordon, R&D Director
- Mr. Dwayne Morgan, Sr. Research Scientist, (PI).
- Mr. J. W. Freeland, Contracting Specialist

TechOpp Consulting Inc. (TABA)

- Bob Fielder – President
- Mary Ann Bonadeo – Project Manager (POC)

Purpose

Touchstones main focus is on the development of silicon carbide products using domestic coal as the carbon source.

Carbon

- Bituminous coal (lv, mv, hv)
- Ash impurity <1%, Sulfur <1%
- Semi-coke, Met-Coke

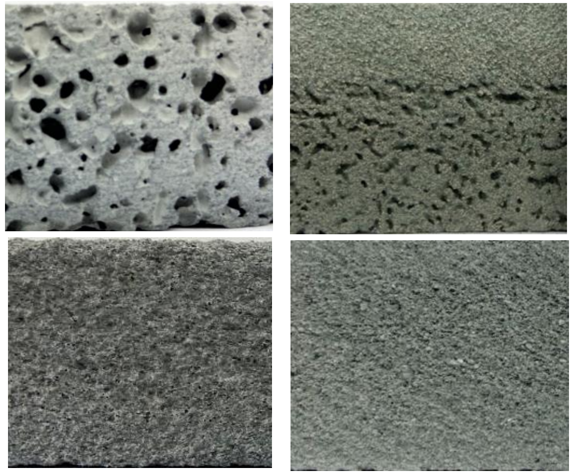
Silicon

- CFOAM conversion via polymer infusion pyrolysis (PIP), (preceramic polymers)
- Coal and resin blends
- Metallurgical grade silicon (Si)

CFOAM®– Carbon Foam from Coal

CFOAM carbon foam winglet machining

Porous Silicon Carbide



Strategic Alignment with Fossil Energy Objectives

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Develop technologies to maximize the value from fossil energy resources, including their production and use.

- Coal to products:
  - Touchstone utilizes coal as carbon feedstock to produce high-value materials and products.
    - Active Phase II SiC Foam development.
    - Track record of success in developing and commercializing carbon foam and graphite foam (CFOAM®) products from coal → CFOAM LLC.
- SiC manufactured from coal for use as a PCM substrate or heat exchanger in sCO_2 heat exchanger technology.
- Will coal enable low-cost and high-volume production of silicon carbide products that can meet TES and/or sCO_2 heat exchanger requirements?

Technology Benchmarking

sCO_2 Brayton Cycle – Recuperators (Heat Exchangers)

- Metals - High temperature nickel-based alloy current SOA.
- Ceramic – SiC current SOA
  - High thermal conductivity and serviceable up to 1600C in air.
  - Oxidation, corrosion, and erosion resistant.
  - High mechanical strength and creep resistant
  - High hardness is favorable attribute but makes machining difficult.
  - Process routes include RBSC, CVD, CVI, PIP; raw materials can be costly.
  - Product size and throughput potentially limited.
- SiC Foam from coal (Touchstone)
  - Current SOA process yield porous SiC (ρ<1.0 g/cm^2)
  - Coal and metallurgical grade silicon (preferred) are low-cost raw materials
  - Machinable, alternative near net shape manufacturing approach in development
  - Low density cellular structure designed for phase change material (PCM) for TES

Potential Applications for sCO_2 for Power Conversion

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Table from technology review meeting[1] was modified from previous workshop[2]

Application	Cycle type	Motivation	Size [MWe]	Temperature (°C)	Pressure [MPa]
Nuclear	Indirect sCO_2	Efficiency, Size, Water Reduction	10 - 300	350 - 700	20 - 35
Fossil Fuel (PC, CFB, …)	Indirect sCO_2	Efficiency, Water Reduction	300 - 600	550 - 900	15 - 35
Concentrating Solar Power	Indirect sCO_2	Efficiency, Size, Water Reduction	10 - 100	500 - 1000	35
Shipboard Propulsion	Indirect sCO_2	Efficiency, Size	<10 - 10	200 - 300	15 - 25
Shipboard House Power	Indirect sCO_2	Efficiency, Size	<1 - 10	230 - 650	15 - 35
Waste Heat Recovery	Indirect sCO_2	Efficiency, Size, Simple Cycles	1 - 10	< 230 - 650	15 - 35
Geothermal	Indirect sCO_2	Efficiency	1 - 50	100 - 300	15
Fossil Fuel (Syngas, nat gas)	Direct sCO_2	Efficiency, Water Reduction, CO_2 Capture	300 - 600	1100 - 1500	35

1. Quadrennial Technology Review 2015, Supercritical Carbon Dioxide Brayton Cycle Chapter 4: Technology Assessments
2. sCO_2 Power Cycle Roadmapping Workshop, SwRI, San Antonio, TX, February 2013

Status of the Commercialization Effort

Identified 33 Organizations and 50 Points of Contact

Industry	Contacts	Organizations	Examples
Energy (CSP)	16	11	BrightSource Ind., SunPower Corp., GE, Aztec Solar
Aerospace	9	4	GE Research, Lockheed Martin, Reaction Engines, Dynetics Technical Solutions, Inc.
Marine	7	3	Huntington Ingalls Industries, Commonwealth Center for Advanced Manufacturing, Block Research Group (ETH Zurich)
Construction	4	4	Saint-Gobain, Honeywell, Dupont, Block Research Group (ETH Zurich)
Federal	14	11	NREL, DARPA, SNL, ONR, MDA, Army ARDEC, NSWCCD
Total	50	33	

Current Status of the Project

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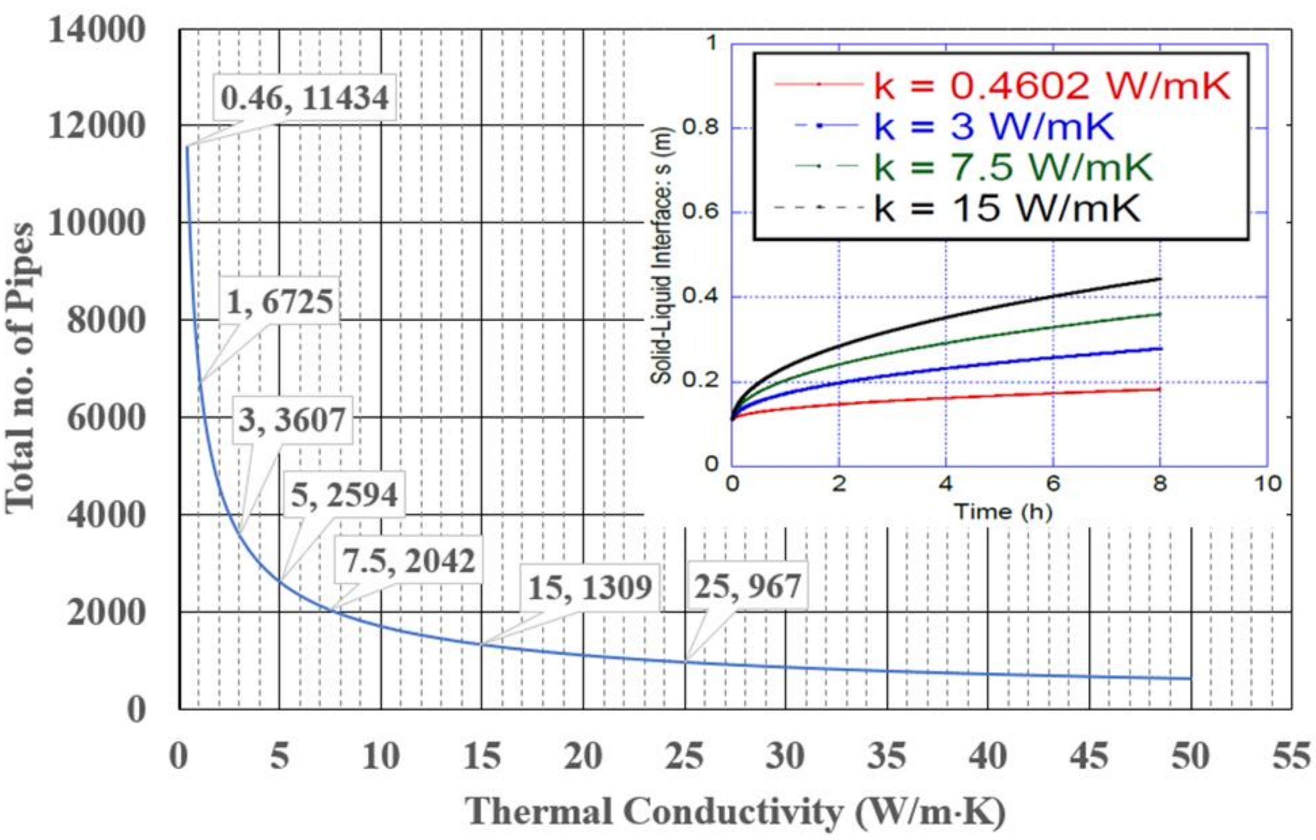
- SiC Foam process based upon silicon resin process has been narrowed down to a single mix formulation.
- Current SOA geometry is 8-12" dia. x 1" thick form factor.
- Preliminary design for a plate/fin cross-flow SiC heat exchanger core is complete.
- Seeking a dialog with Sandia Laboratory to refine sCO_2 Brayton cycle recuperator requirements.
- Materials development for higher density SiC continues.
  - Process optimization to enhance yields
  - Production of α-SiC

Summary of accomplishments

- To date, performed 142 trial runs consisting of various mix designs, processing conditions and geometry:
  - 3-hv, 2-mv, 1-lv coal type, of which two had low ash and low sulfur.
  - Evaluated coal pretreatment, semi-coke and calcined.
  - Evaluated 3 silicon (Si) source types, resin, metal, oxide (silica).
  - Explored the use of binders (pitch and resins) and foaming agent.
- Made first successful sintering run above 1600C.
- Project results accumulated during this reporting period are available in following slides.
  - TEC and sCO_2 heat exchanger concepts
  - Process methodology
  - Material Properties
  - Microstructures

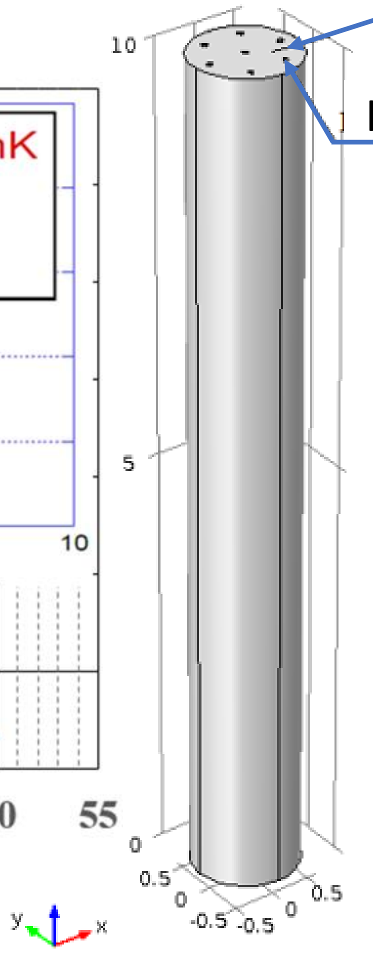
Proposed TES Concept

Silicon Carbide Foam PCM Substrate

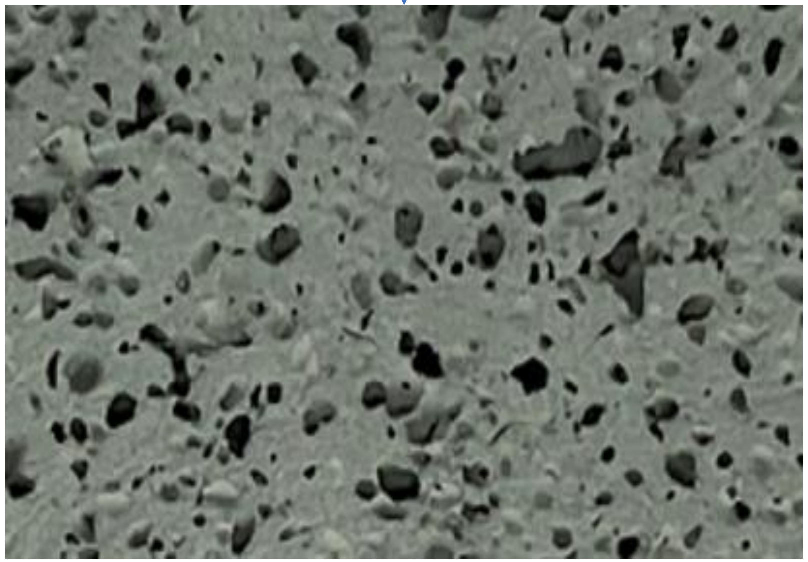


SiC Foam – Salt PCM

HTF pipe



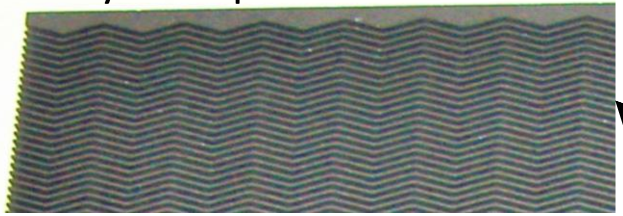
Unit in meter



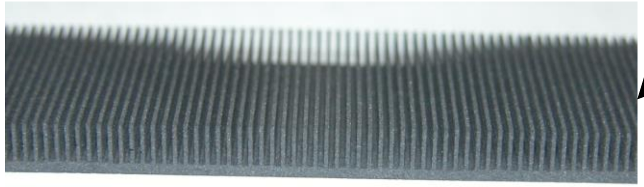
Design of Supercritical CO_2 Heat Exchanger

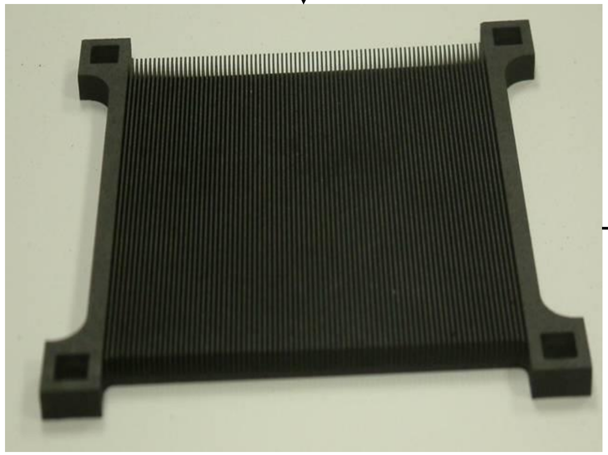
Dual purpose TES when filling/sealing flue gas channels with PCM

Wavy Fin Optimal Heat Transfer

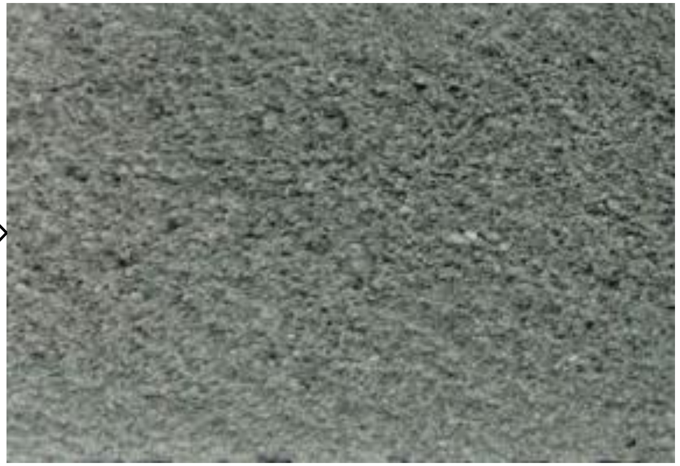


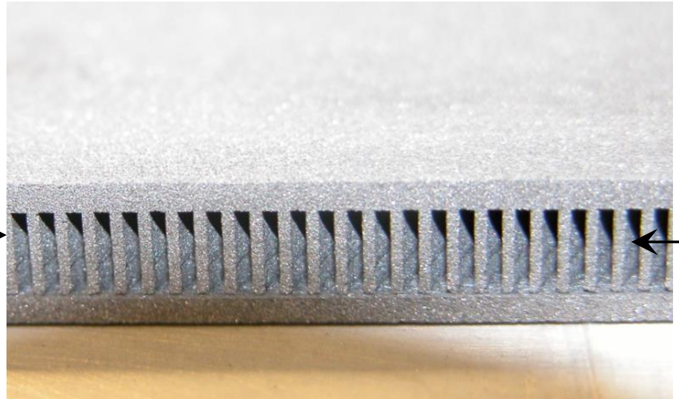
High Density Straight Fin





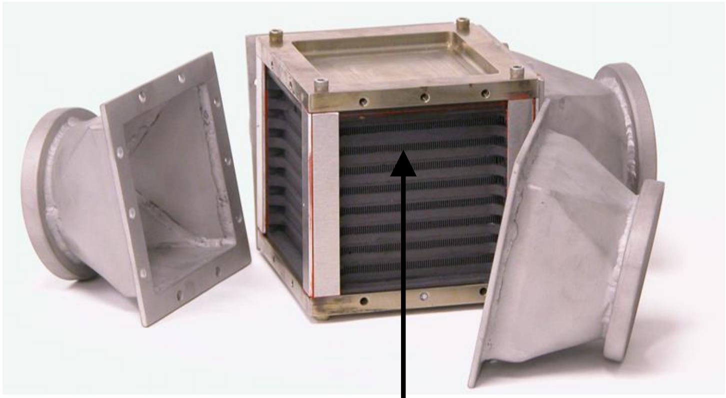
HD-SiC from Coal

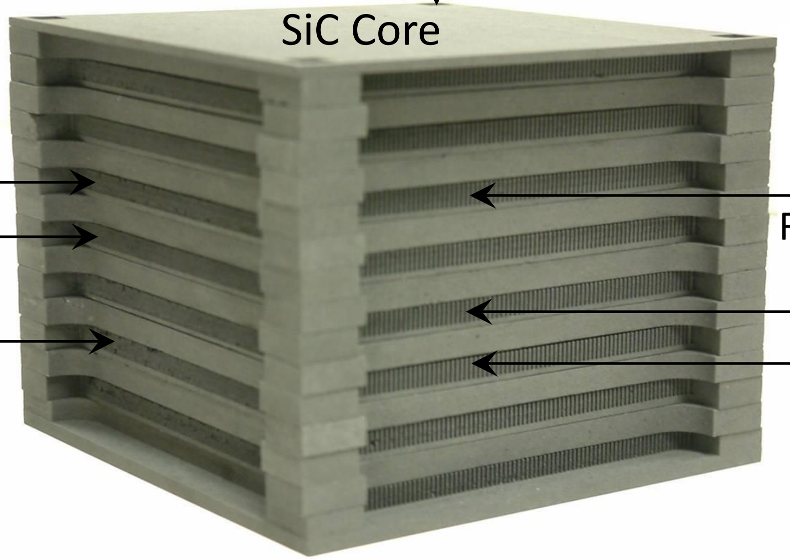




Parallel Plate with Fins

Metal or CFCC Manifold Case





Near Net Shape Processing

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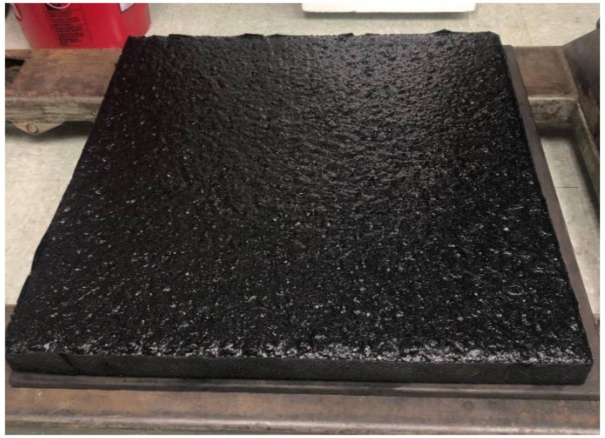
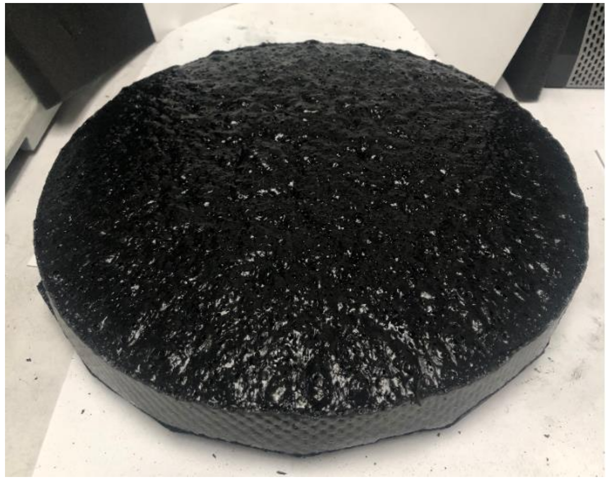
Preliminary Process
Uneven Surface





Near Net Shape

Pre-sintering

Properties

Preceramic polymer vs Si metal source

Property	Preceramic Polymer	Silicon Metal
Density (g/cm^3)	0.58	0.87
Porosity (%)	82	73
Compressive Strength (psi)	200	500
Weight Loss (%) G$\rightarrow$S	49[1]	15
Processing Temp. Limit (C)	1550[2]	1800[3]
α-SiC (6H)	N	TBD
β-SiC (3C)	Y	Y

[1] High SiO(g) production

[2] Decomposes at process temperature T>1600C

[3]1800C successful, future work scheduled for 2000C and 2200C

12" Diameter Mold (Ref. 2-43)

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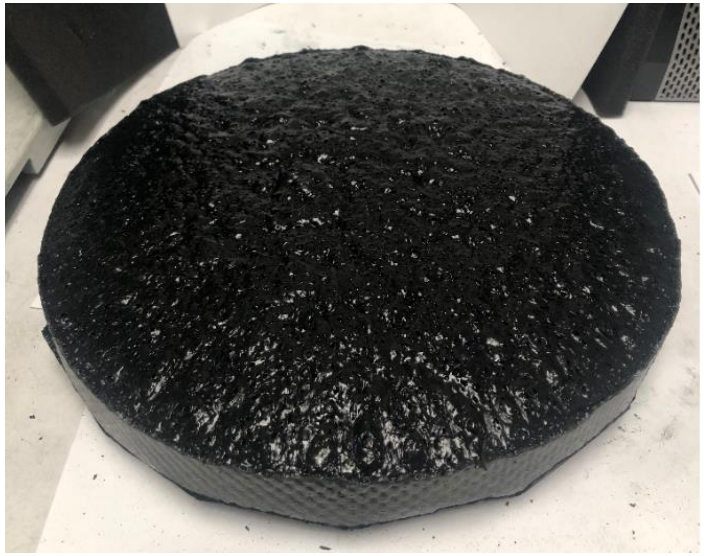
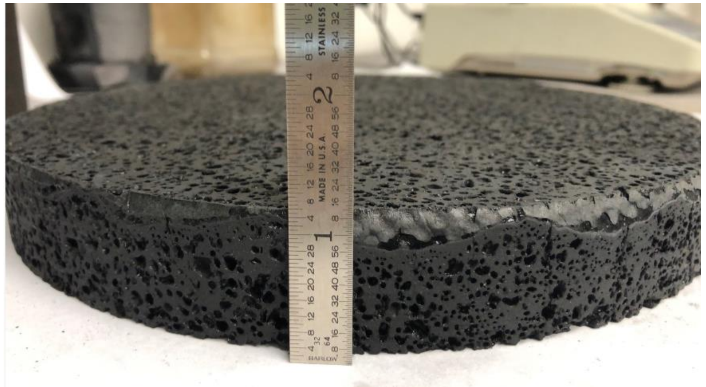
As-Foamed

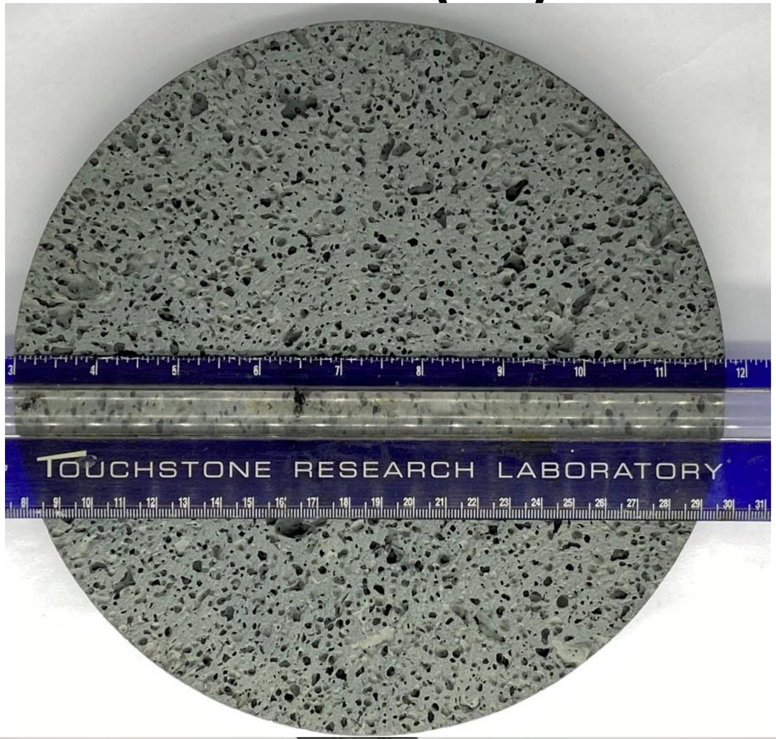


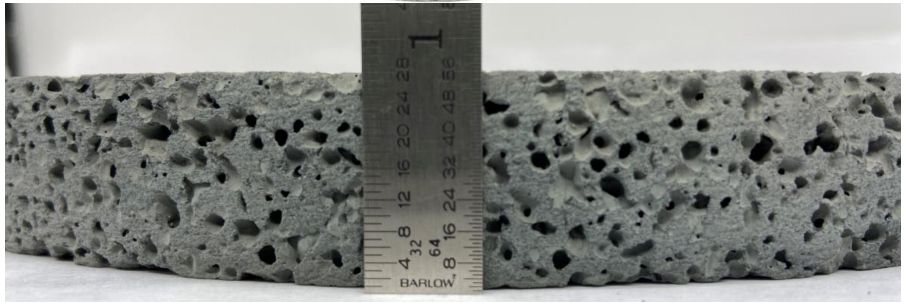
Trimmed



Sintered (SiC)

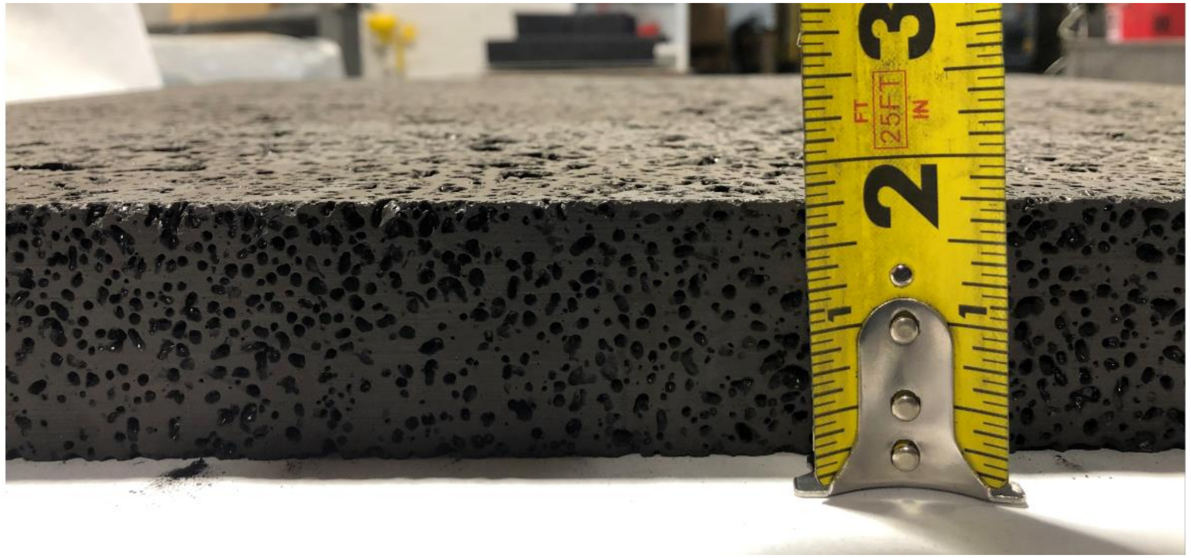
Sintered (SiC)





24x24 Inch Molded Panel

Outer skin removed



Microstructure Variations (cont.)

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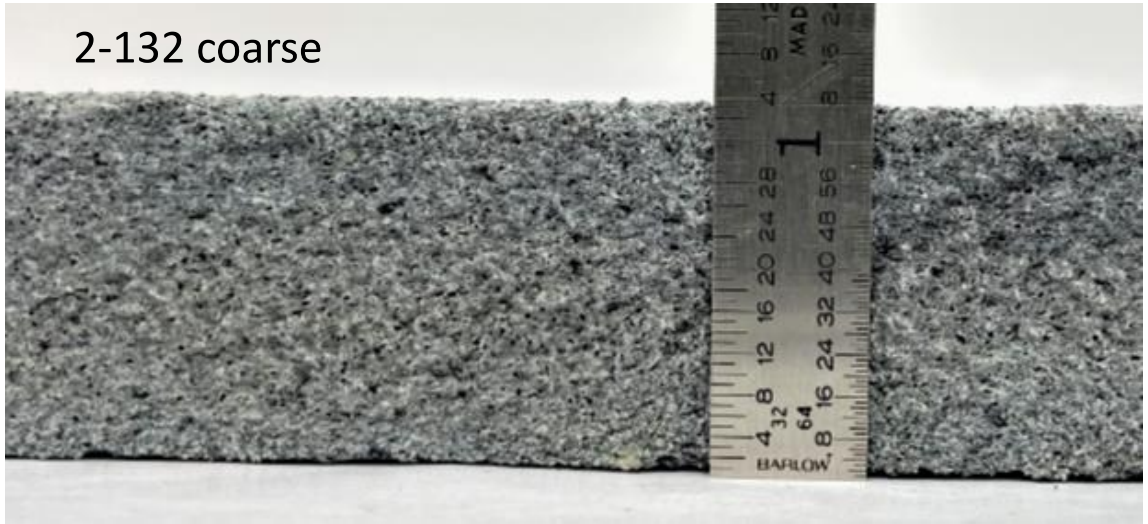

Microstructure 2-118

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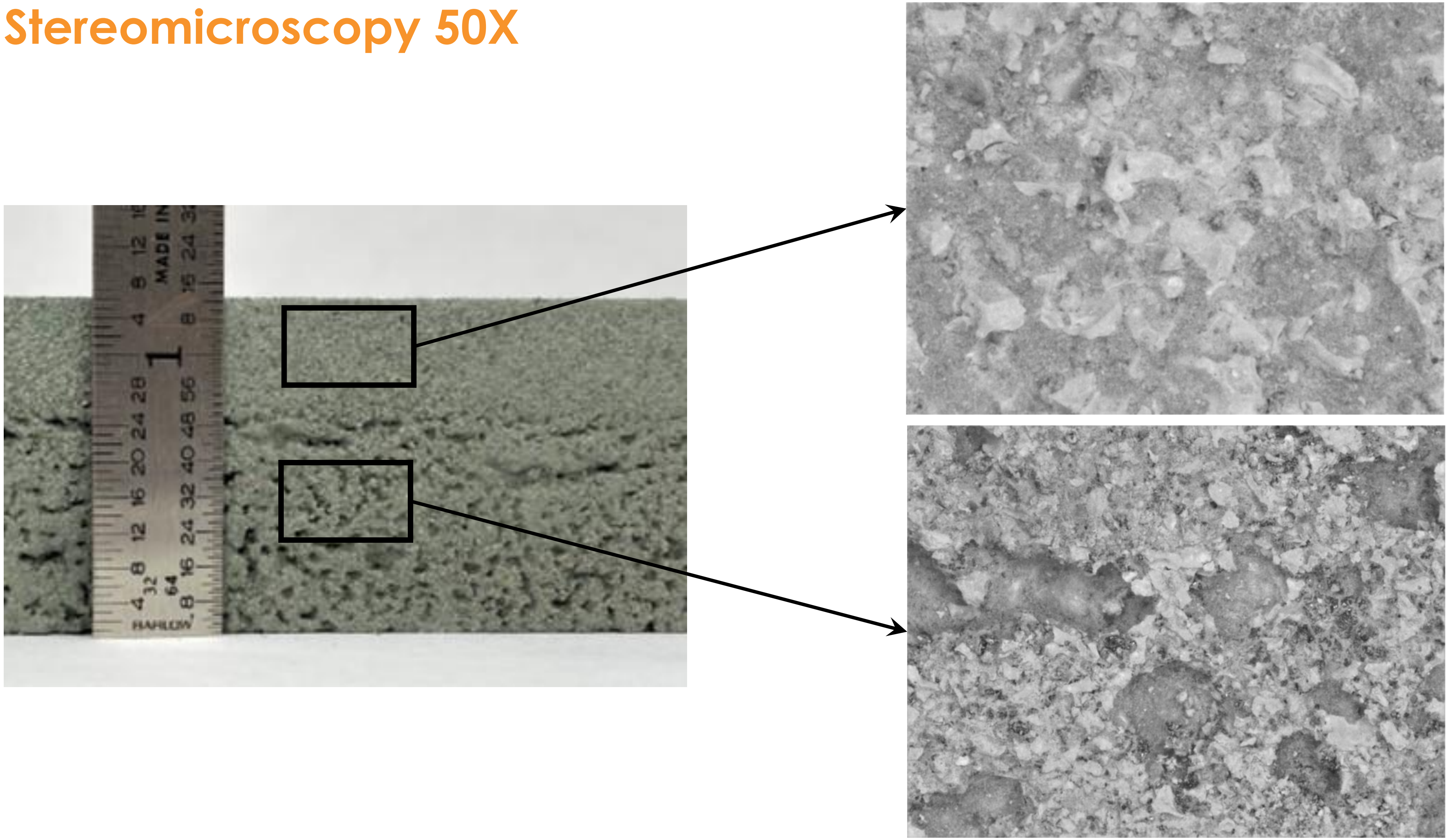
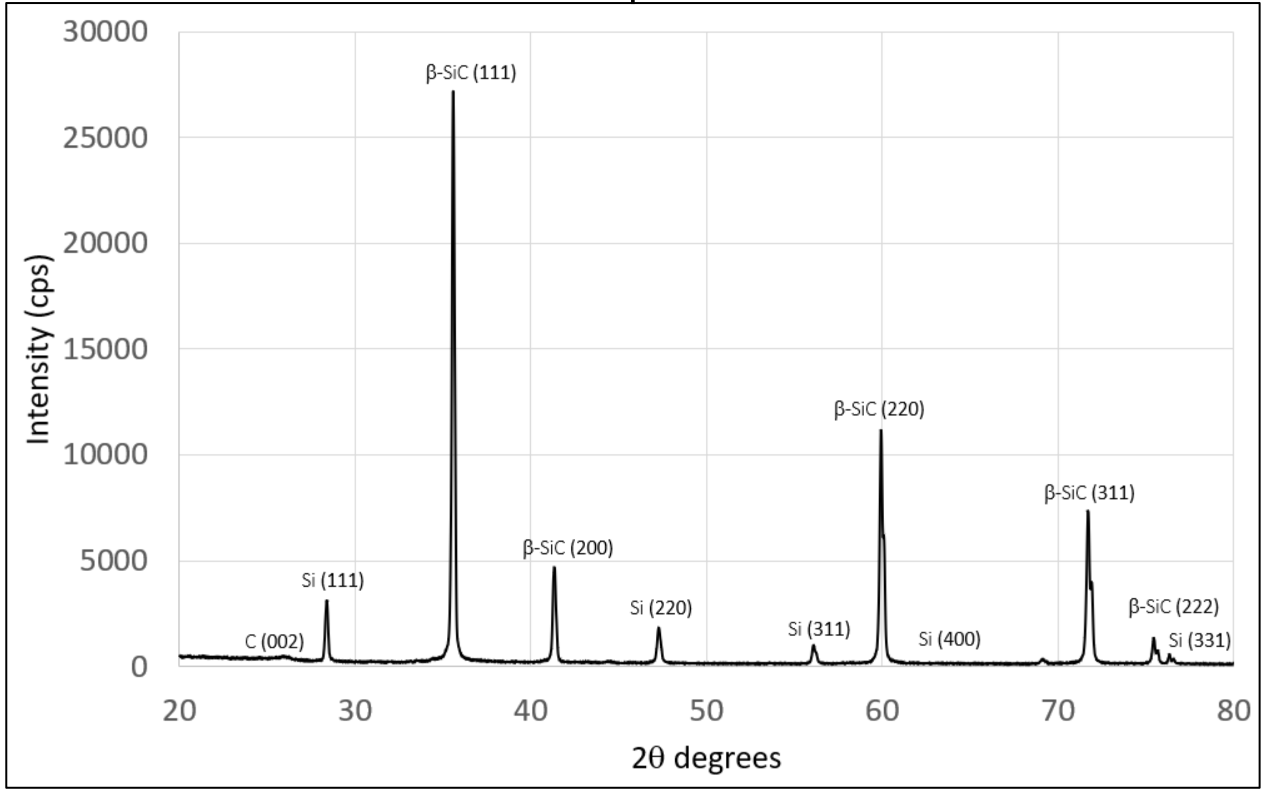
Stereomicroscopy 50X

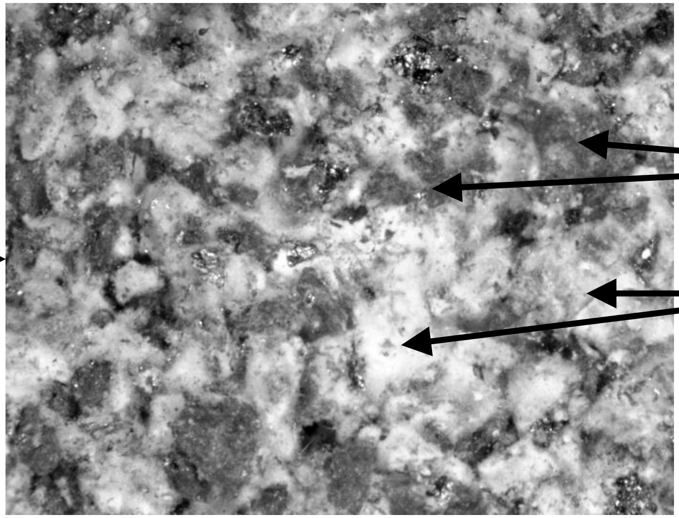


Microstructure 2-132

Stereomicroscopy at 32X



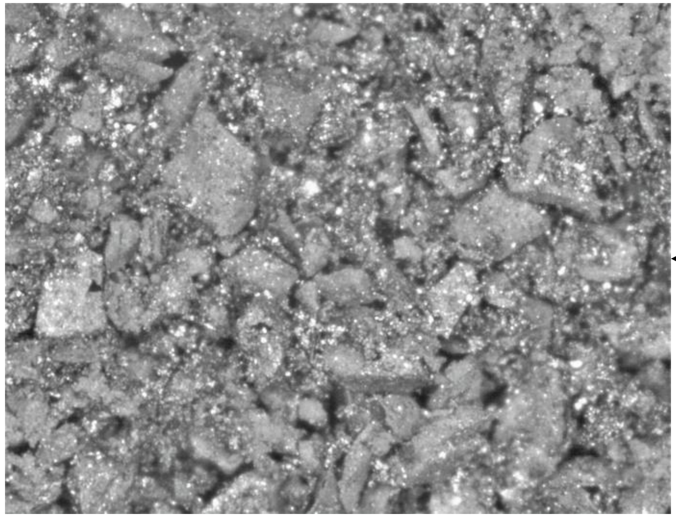
Sintered 1550C 12h soak



SiC and C

Unreacted Si

Sintered 1800C 2h soak



Technical Challenges

- CSP appears to have limited market potential as the solar market is being dominated via photovoltaics (PV).
- Resin based SiC systems:
    - Offer lightweight but low heat treatment restriction causes thermal conductivity to fall short of 25 W/m·K target.
    - Resins produce and abundant level of SiO gas when converting to SiC, excess forms cristobalite on the furnace walls.
    - Highest cost silicon source but not deemed prohibitive.
- Silica (SiO2) was not deemed suitable for a Si feedstock.
- Si-metal process should be pressure molded and heat treated to 1800C minimum to enhance thermal and structural properties for thermal energy storage and heat exchanger requirements for sCO_2.

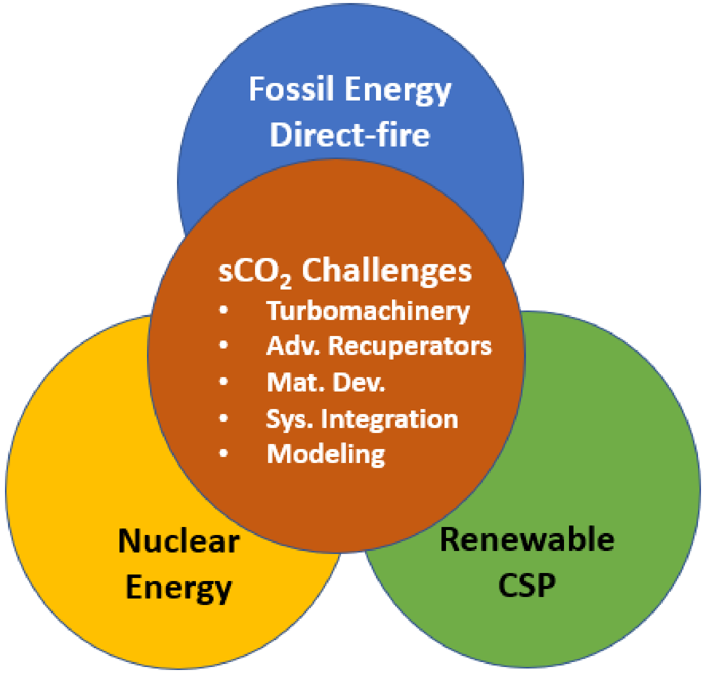
Pathway Forward

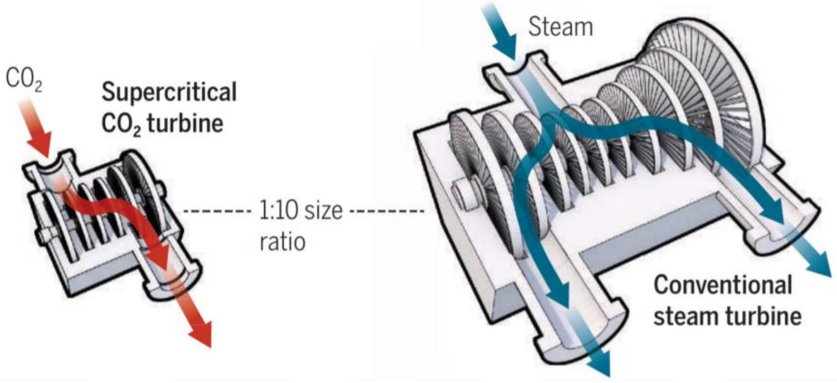
- Resin based SiC systems:
  - Determine how much PCM can be loaded into the structure and make final assessment for this application.
  - Align low-density high-porosity SiC foam for composite core sandwich structure technology markets.
  - Document manufacturing best practice documents.
- Coal/Si-metal systems:
  - Determine feasibility for pressure molding current mix design.
  - Complete high temperature sintering and finalize process based upon current recipe.
  - Update physical and thermal properties.
  - Develop solid works model geometry for single layer plate/fin heat transfer and pressure drop analysis.
  - Develop preliminary model for heat transfer and pressure drop analysis using ANSYS Analytical for different fin geometry and density (no. fins/inch).
- Update commercialization plan

Preparing Project for Next Steps

Market gap this project will address

- High performance, high volume, and low cost SiC products for general industry use.
- High temperature heat exchangers that can operate in harsh environment up to 1400-1500 °C.
- Compact modular heat exchanger design for sCO_2 Brayton recuperators.
  - Standard HX fin design practices can be utilized for maximizing heat transfer duties with small ΔT with minimal pressure drop.
  - High hardness of SiC should translate to high erosion resistance.
  - Design is better suited for high-temp heat exchange for sCO2



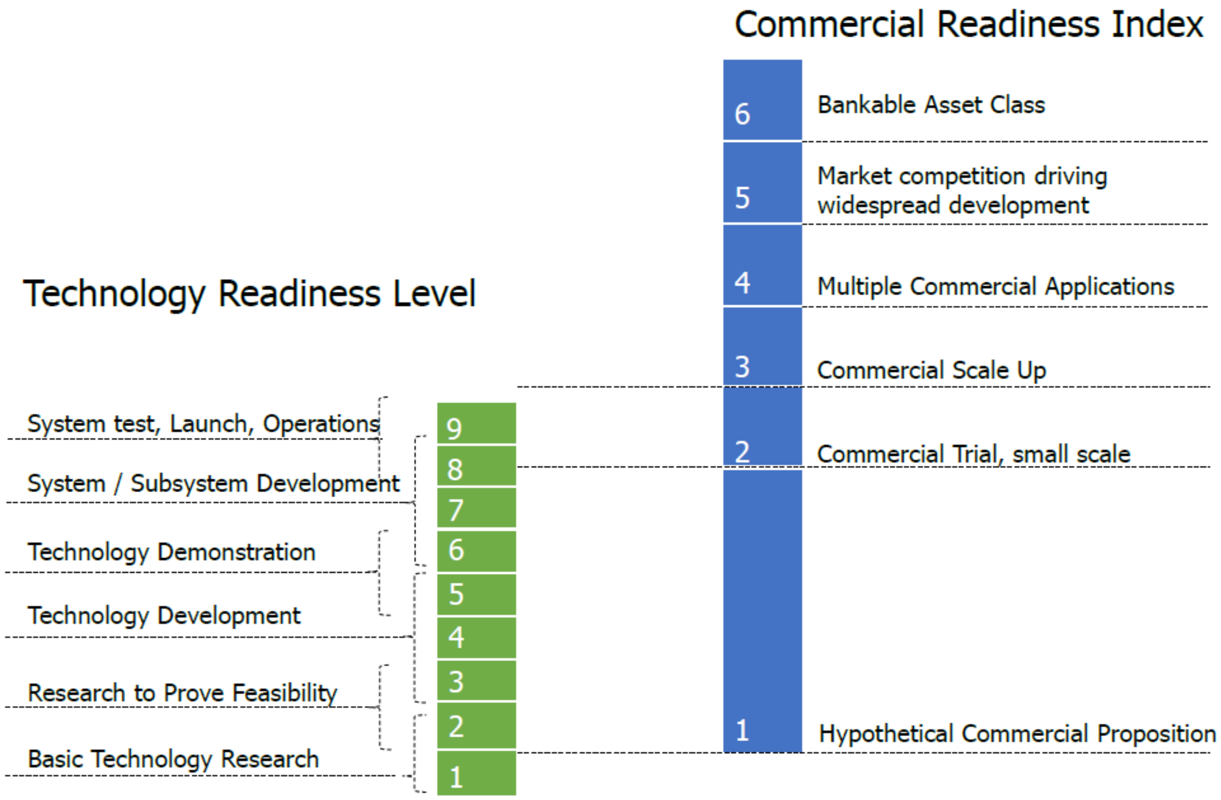


Ref: Next Generation Receivers R&D Virtual Workshop, Series Concentrating Solar Power Program

Preparing Project for Next Steps

Technology to market path

- Product market potential by end of project:
  - Small scale/commercial trials
- Remaining technology challenges:
  - High pressures in sCO_2 Brayton recuperators.
  - Demonstrate near net shape process for HD-SiC
- New research needs identified:
  - Model, Simulation, Design
    - Fin configuration, heat exchanger core sizing
    - Heat transfer vs. pressure drop analysis
  - Increase SiC strength/density for sCO_2
  - Near net shape pressure molding
- Industry collaborators:
  - Seeking collaboration with SNL (Tech Demo)
  - Solar Towers - BrightSource Industries
  - Aerospace Composites: GE Global Research, DARPA



https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf

Concluding Remarks

How results apply directly to Fossil Energy goals

- Greatest integration/transition challenge is getting molten salt into Foam Pores.
  - Pore size, distribution, and tortuosity.
  - Currently achieve 82% total porosity, 90% ideal.
  - PCM loading not precise
- Touchstone has discovered alternative silicon carbide materials processing from coal feedstock that have higher value proposition as high density SiC produced from coal offers a technical solution for sCO_2 heat exchangers and thermal energy storage.
  - Higher density→ higher strength→ higher thermal conductivity→ higher heat transfer
  - Channels in plate/fin technology offer optimal PCM loading.
  - Overcomes technical limitation present with PCM infusion into microstructure.
- Storing excess thermal energy produced from coal fired power plants is a more viable option as CSP is a risky proposition due to PVs availability and affordability in the solar industry.

End of Presentation