SunShot
U.S. Department of Energy

CSP Program Summit 2016

Robust, Cost-Effective Heat Exchangers for 800°C Operation with Supercritical CO_2

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The Team

Principal Investigators:

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School of Mechanical Engineering
Georgia Institute of Technology, Atlanta, GA

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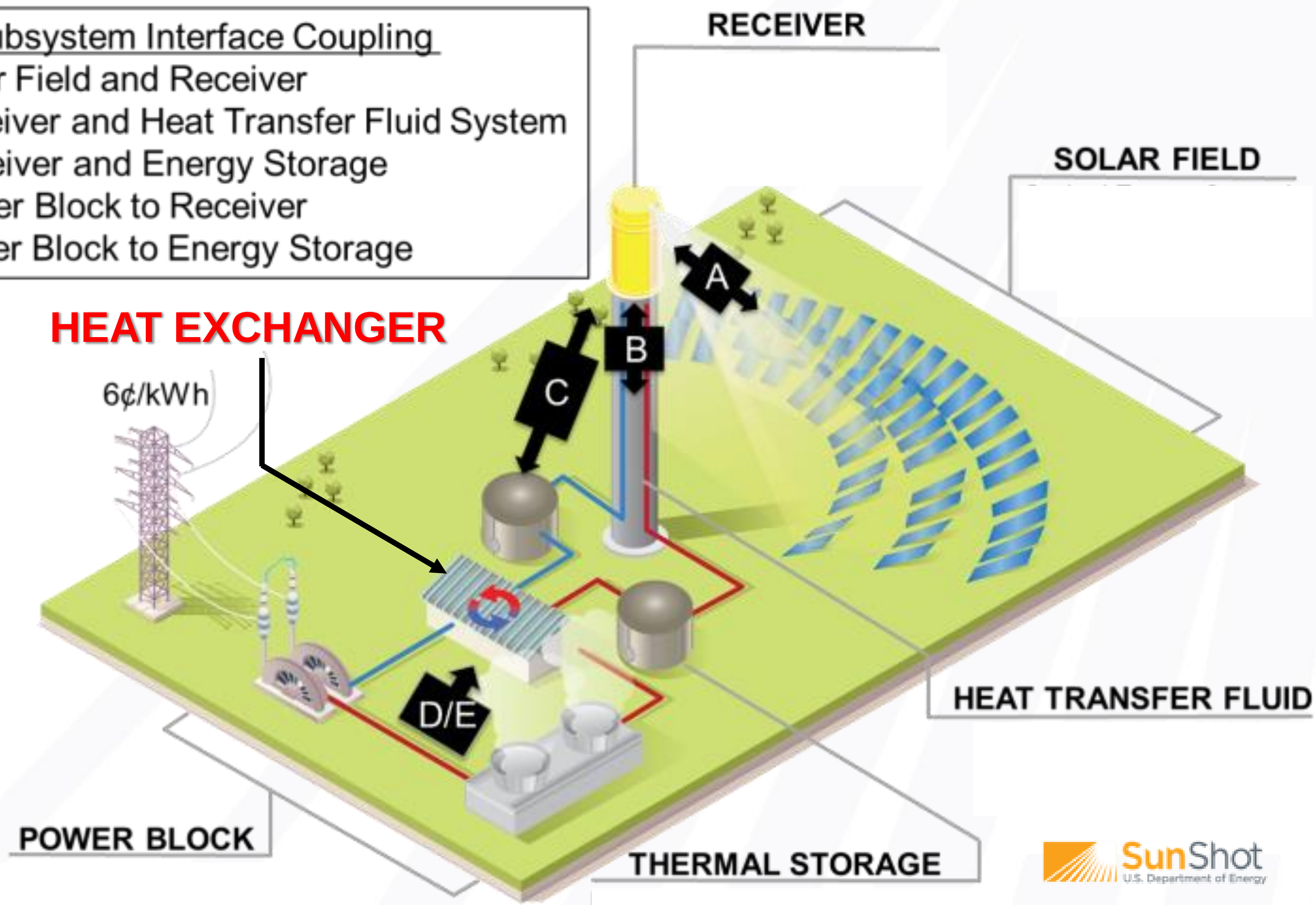
University of Wisconsin, Madison, WI

Areas of Expertise:

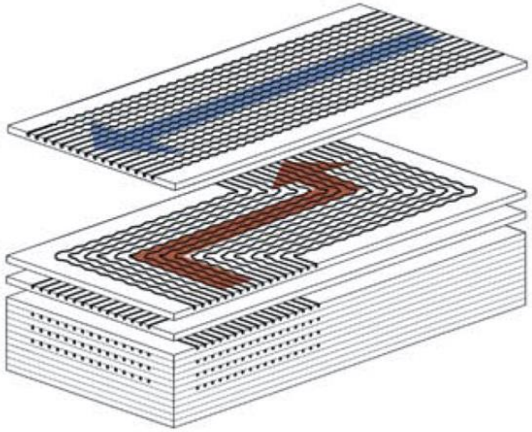
- Ceramics processing
- Net-shape/net-size manufacturing
- Simulation and testing of thermal behavior
- High-temperature, high-pressure fluid dynamics
- High-temperature, high-pressure corrosion
- Design of high-temperature supercritical systems

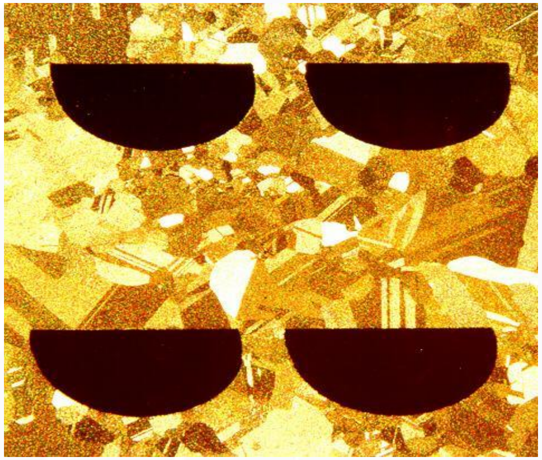
Technology Focus

CSP Subsystem Interface Coupling
A: Solar Field and Receiver
B: Receiver and Heat Transfer Fluid System
C: Receiver and Energy Storage
D: Power Block to Receiver
E: Power Block to Energy Storage



State of the Art: Metallic Alloy Printed Circuit HEXs



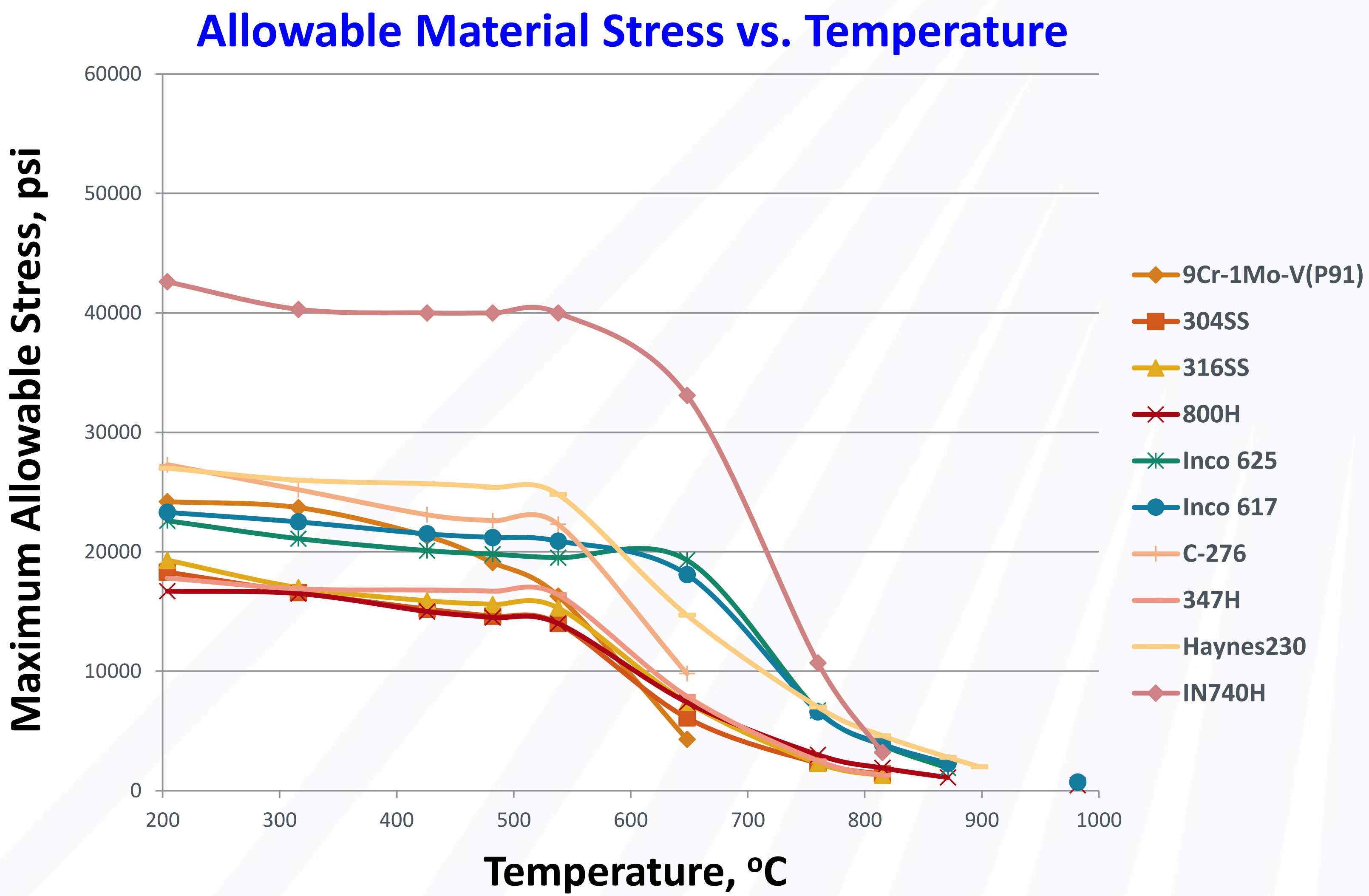


Current Technology:

- **Printed Circuit HEXs: patterned etching of metallic alloy plates, then diffusion bonding**
- **Upper use temperature of conventional alloys < 600°C**

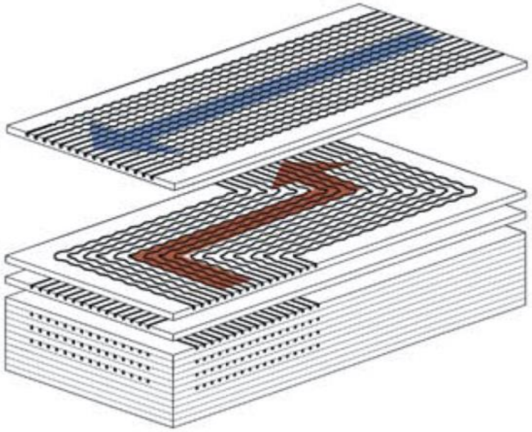
D. Southall, S.J. Dewson, *Proc. ICAPP '10*, San Diego, CA, 2010; R. Le Pierres, et al., *Proc. SCO_2 Power Cycle Symposium 2011*, Boulder, CO, 2011; D. Southall, et al., *Proc. ICAPP '08*, Anaheim, CA, 2008.

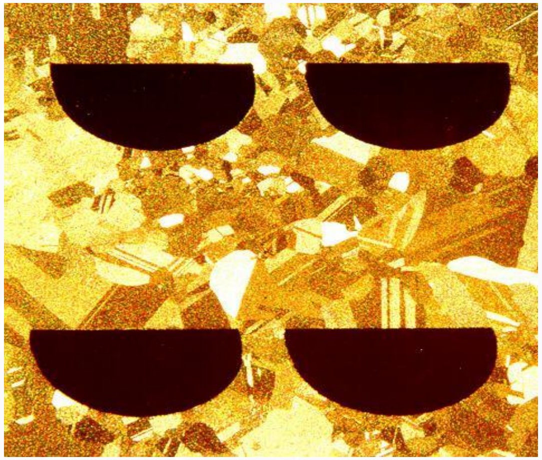
State of the Art: Metallic Alloy Printed Circuit HEXs



2010 ASME Boiler Pressure Vessel Code, Sec. II, from Tables 1A and 1B, July 1, 2010, New York, NY (compiled by Mark Anderson)

State of the Art: Metallic Alloy Printed Circuit HEXs





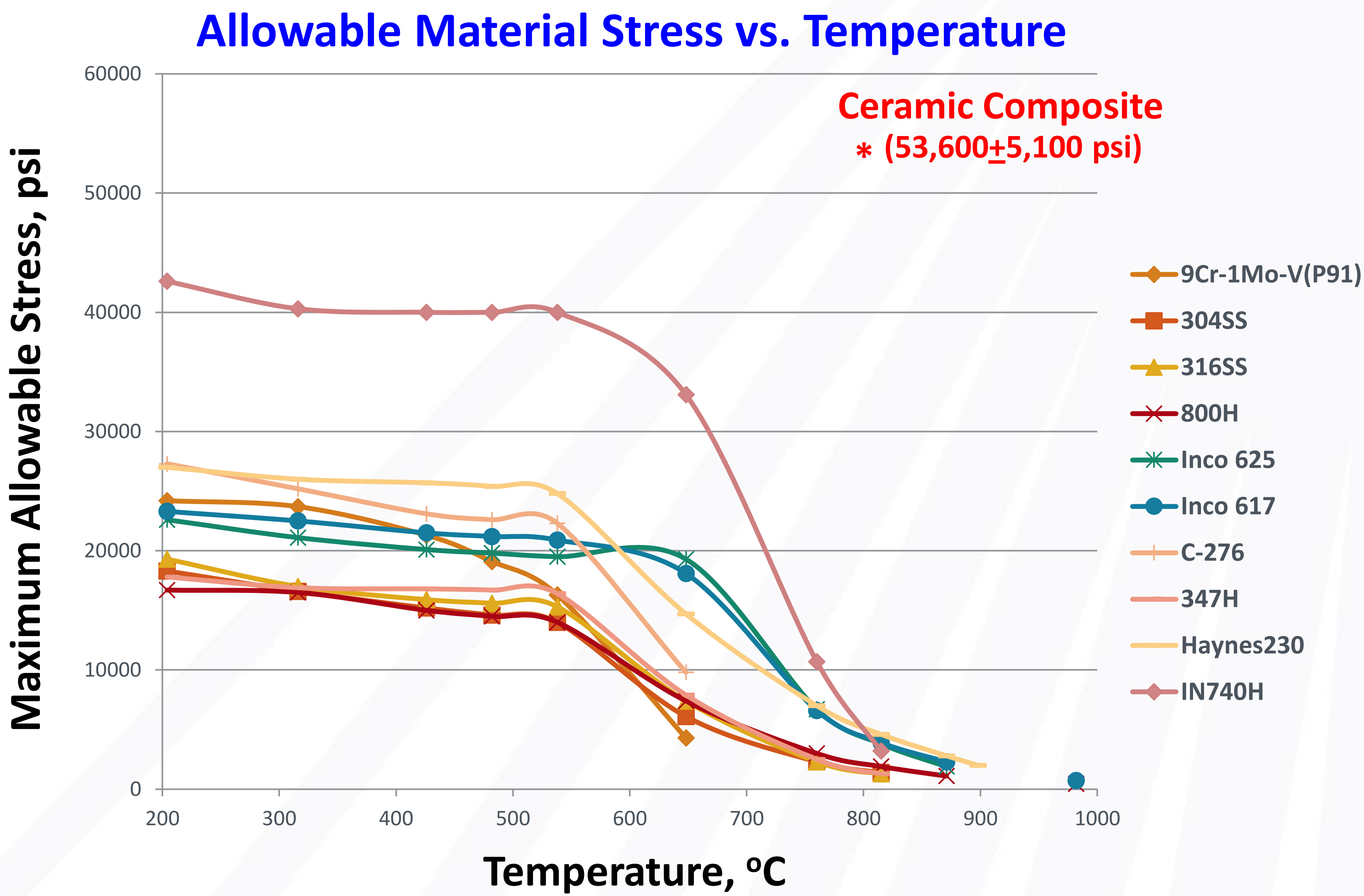
Current Technology:
- Printed Circuit HEXs: patterned etching of metallic alloy plates, then diffusion bonding
- Upper use temperature of conventional alloys < 600°C

New Technology:
- Toughened ceramic-based HEXs: preform pressed into HEX shape, then converted into toughened composite
- Higher temperature, higher stiffness, thermally-conductive material for use at ≥ 800°C

Attractive Characteristics of Our Toughened Ceramic Composite Material

- **High melting point** **(T_m > 1,600°C; higher than conventional stainless steels or Ni-based structural alloys)**
- **Retention of stiffness and strength at 800°C** **(E $\geq$ 28x10^6 psi/ 193 GPa; $\sigma_F \geq 50 \times 10^3$ psi/350 MPa at RT and at 800°C)**

State of the Art: Metallic Alloy Printed Circuit HEXs



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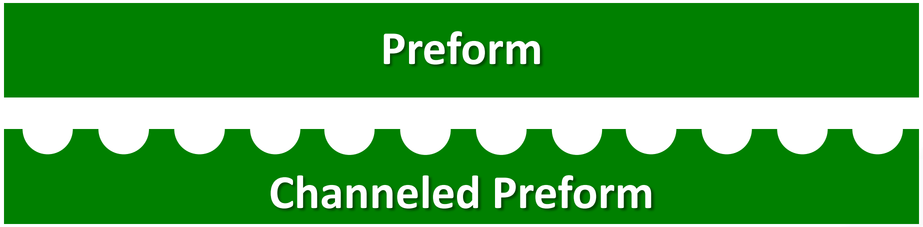
Attractive Characteristics of Our Toughened Ceramic Composite Material

- **High melting point** (T_m > 1,600°C; higher than conventional stainless steels or Ni-based structural alloys)
- **Retention of stiffness and strength at 800°C** ($E \geq 28 \times 10^6$ psi/193 GPa; $\sigma_F \geq 50 \times 10^3$ psi/350 MPa at RT and at 800°C)
- **Enhanced toughness w.r.t. conventional monolithic ceramics** ($K_{1C} = 8 \pm 2$ MPa·m$^{1/2}$ vs. $\leq$ 0.8 MPa·m$^{1/2}$ for Pyrex glass, $\leq$ 1.4 MPa·m$^{1/2}$ for concrete, and $\leq$ 4.6 MPa·m$^{1/2}$ for Hexoloy SiC)
- **High thermal conductivity** (κ = 65.8 W/m·K at 800°C vs. 22.1 W/m·K for IN740H alloy, and 24.4 W/m·K for H230 alloy)
- **Chemical stability** (Thermodynamic calculations indicate resistance to chloride fluids at 800°C; Chemical tailoring underway for resistance to SC-CO_2 fluids at 750-800°C and 20 MPa)
- **Low-cost pressing + net-shape/size reaction process** ($\Delta L/L_o$ < 1%)

Net-Shape, Net-Size Ceramic Composites

- **Green body ("preform") plates with desired channel patterns are first generated by low-cost forming (e.g., pressing with stamped channel patterns).**

Low-Cost Fabrication of Plate-Shaped Preforms



Fabricate pairs of plate-shaped preforms, with one of the plates containing patterned milli-channels, via uniaxial pressing

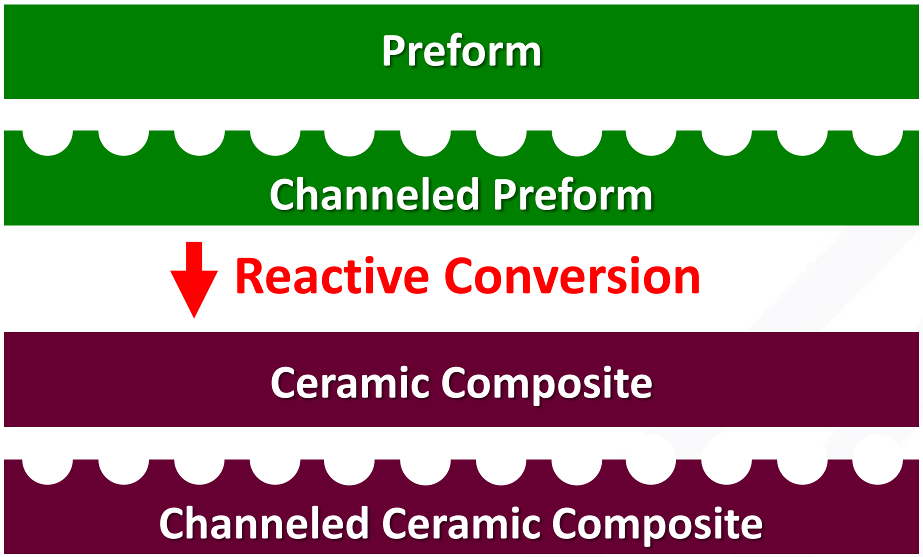
Top-down view of an airfoil millichannel pattern

Top-down view of a zig-zag millichannel pattern

Net-Shape, Net-Size Ceramic Composites

- **Green body ("preform") plates with desired channel patterns are first generated by low-cost forming (e.g., pressing with stamped channel patterns).**
- **The preform is then converted into the final desired high-temperature ceramic composite material via a *shape-preserving* reaction process.**
- **The dimensional changes before and after such reaction are well below 1%. => This is also a *size-preserving* process.**

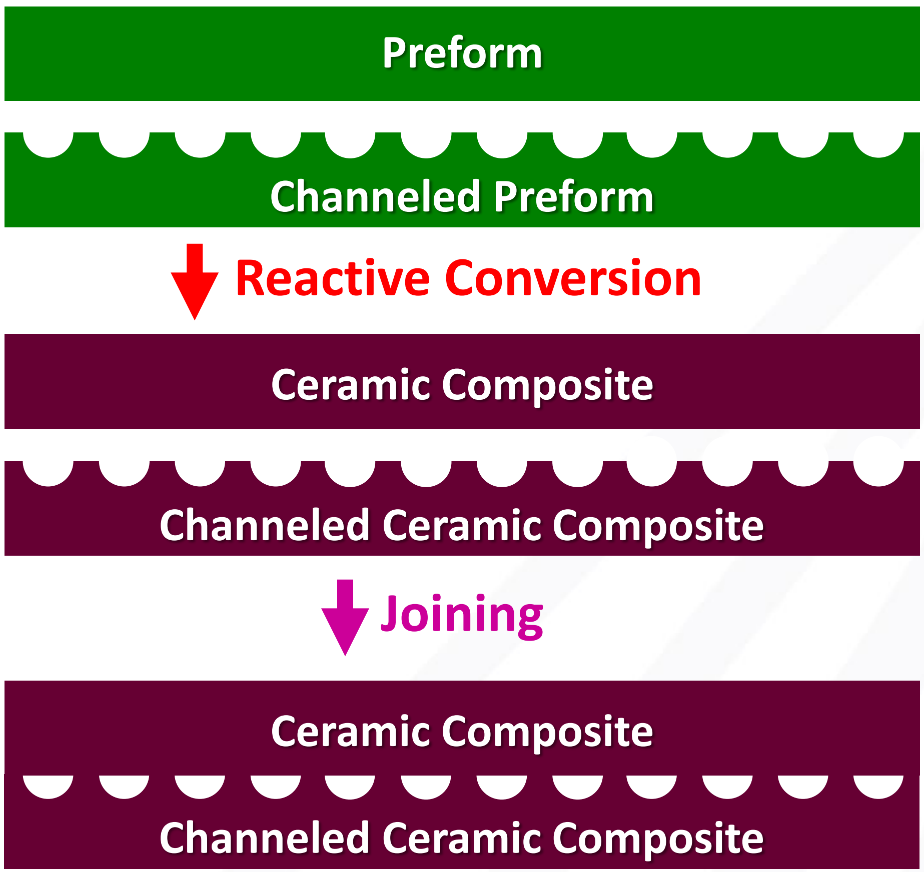
Shape- and Size-Preserving Reaction Process



Fabricate pairs of plate-shaped preforms, with one of the plates containing patterned milli-channels, via uniaxial pressing

Generate net-shape, net-size toughened ceramic composite plates via reaction process

Joining of Heat Exchanger Components



Fabricate pairs of plate-shaped preforms, with one of the plates containing patterned milli-channels, via uniaxial pressing

Generate net-shape, net-size toughened ceramic composite plates via reaction process

Join pairs of ceramic composite plates* and join plates to headers and tubing

***Note: the reaction and joining processes for the ceramic composite plates may be conducted in the same step.**

Net-Shape, Net-Size Ceramic Composites

- Green body ("preform") plates with desired channel patterns are first generated by low-cost forming (e.g., pressing with stamped channel patterns).
- The preform is then converted into the final desired high-temperature ceramic composite material via a *shape-preserving* reaction process.
- The dimensional changes before and after such reaction are well below 1%. => This is also a *size-preserving* process.

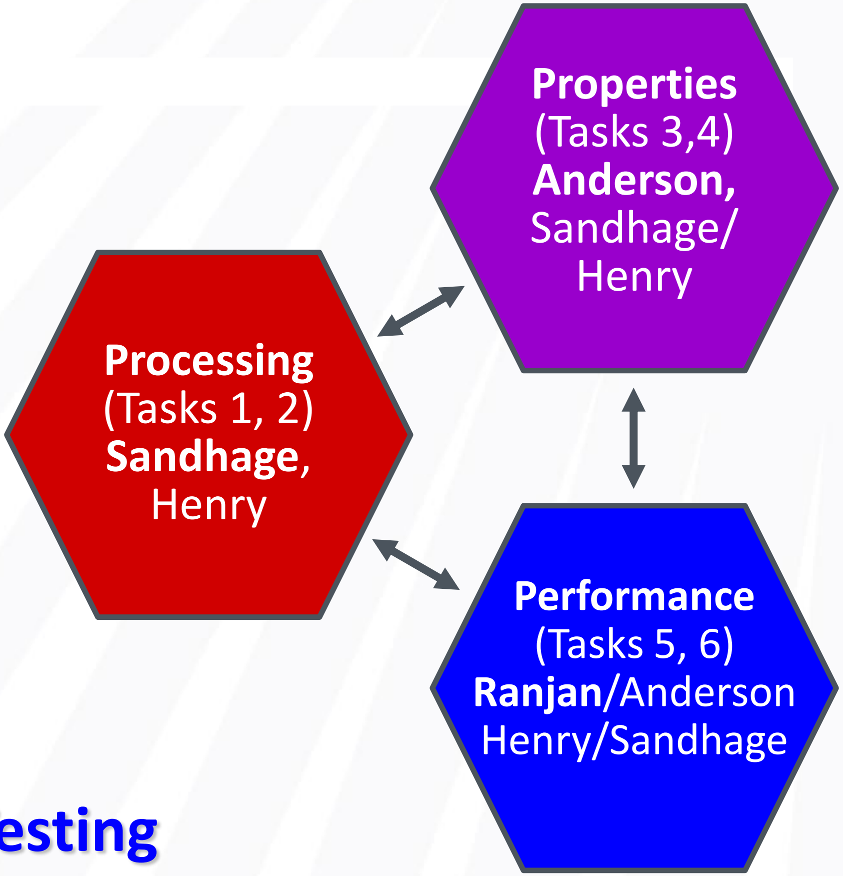
=> Such a low-cost pressing/stamping and net-shape/size reaction process avoids:

i) the chemical etching step of metallic alloy PCHEXs and

ii) the shrinkage and distortions associated with conventional ceramic sintering of shaped green bodies.

Workplan

- **Processing Thrust:**
  - Task 1: Manufacturing of Ceramic Composite HEXs
  - Task 2: Component Joining
- **Properties Thrust:**
  - Task 3: Corrosion Testing in Molten Salts, SC CO_2
  - Task 4: Thermal and Mechanical Properties
- **Performance Thrust:**
  - Task 5: HEX Modeling and Testing
  - Task 6: Techno-Economic Analyses



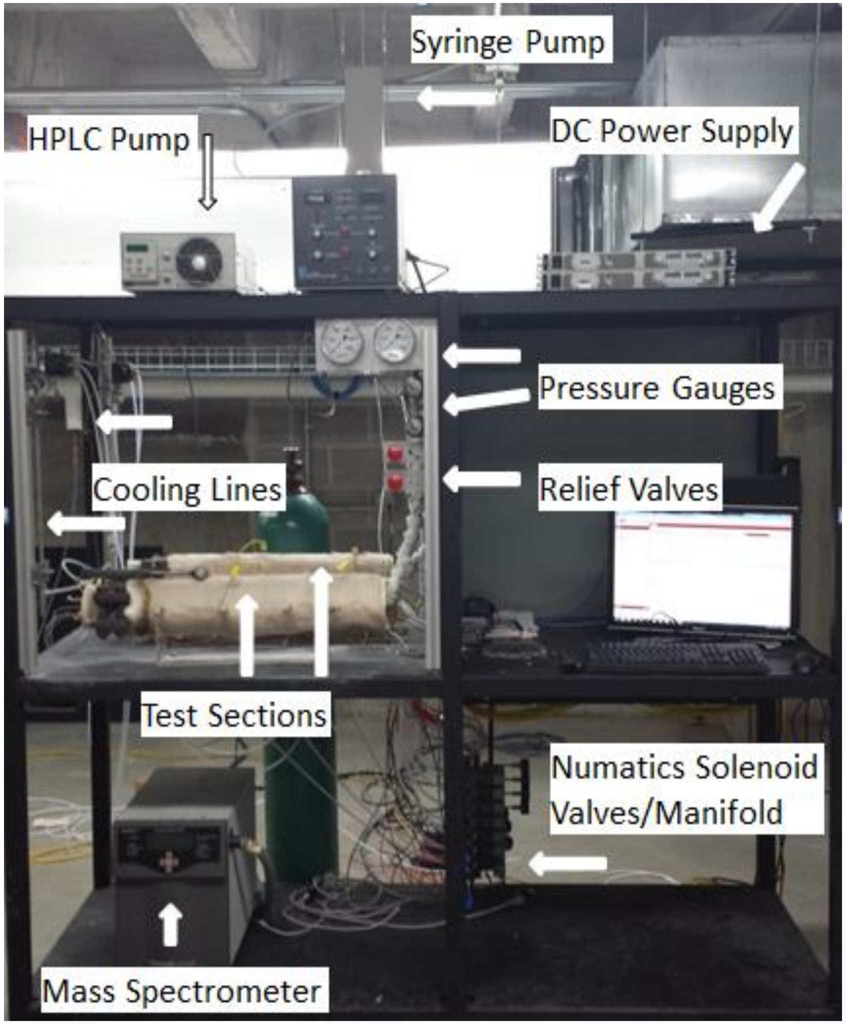
Properties Thrust

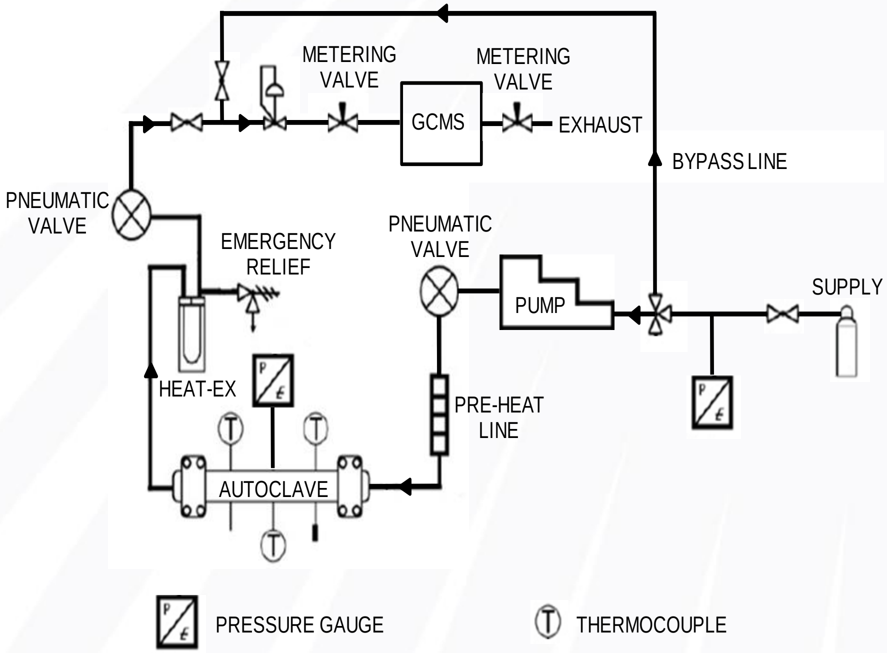
- **Goal:**
  - To evaluate the chemical, thermal, and mechanical behavior of the ceramic composite materials
- **Approaches:**
  - Corrosion testing in SC-CO_2 at 750-800°C and 20 MPa
  - Corrosion testing in molten chlorides (NaCl(l) and $MgCl_2$-NaCl(l)) at $\geq$ 800°C and ambient pressure
  - Laser flash tests to obtain thermal conductivity (as per ASTM standards E-1461/ASTM-E1269)
  - Four point bend tests (as per ASTM standards C1161-13 and C1211-13)

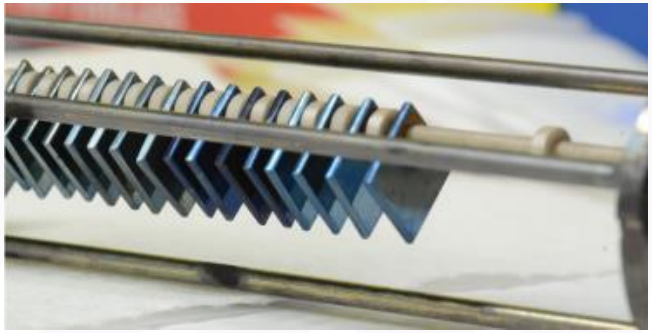
Anderson, Sandhage, and Henry groups

High-T, High-P, SC-CO_2 Corrosion Testing

SC-CO_2 Autoclave Testing







Anderson group

Performance Thrust

- **Goals:**
  - To develop a simulation framework to guide the design of ceramic composite-based HEXs with optimal geometries

- **Approaches:**
  - A coupled Navier-Stokes and energy equation solver is being used to study thermohydraulic behavior inside the channels.

Ranjan, Henry, Sandhage groups

Georgia Institute of Technology

PURDUE UNIVERSITY

Performance Thrust

- **Goals:**
  - To develop a simulation framework to guide the design of ceramic composite-based HEXs with optimal geometries
  - To develop and utilize a HEX testing facility to evaluate the performance of ceramic composite-based HEXs
- **Approaches:**
  - A coupled Navier-Stokes and energy equation solver is being used to study thermohydraulic behavior inside the channels.
  - An existing test facility will be upgraded and instrumented for HEX testing (heat transfer, pressure drops) with flowing SC-CO_2.

Ranjan, Henry, Sandhage groups

Georgia Institute of Technology

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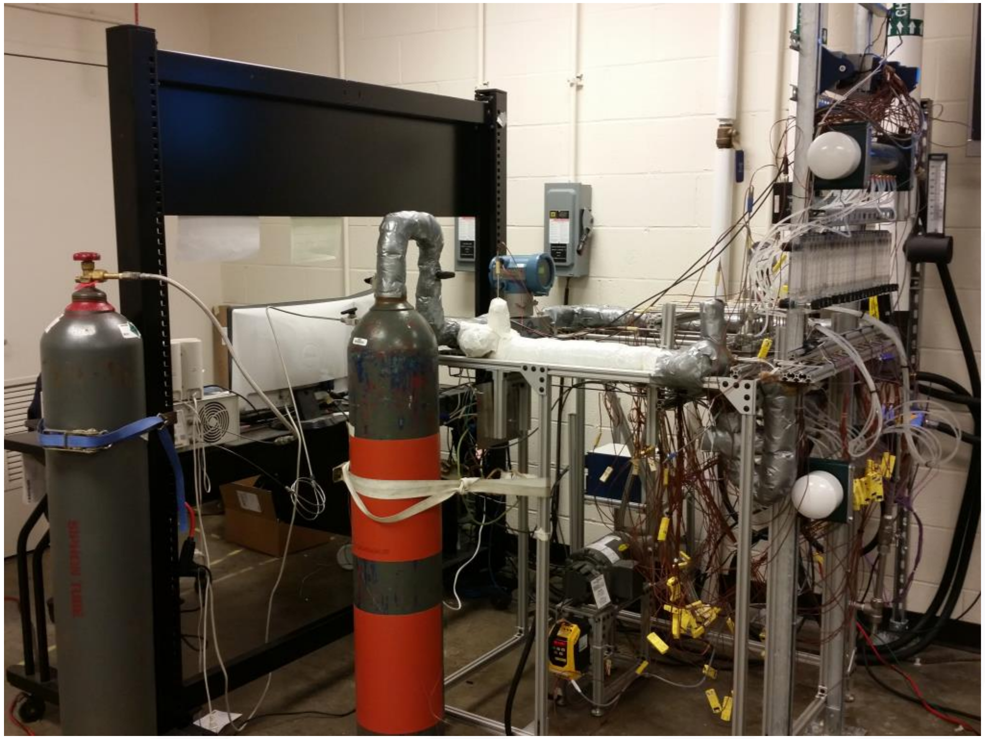
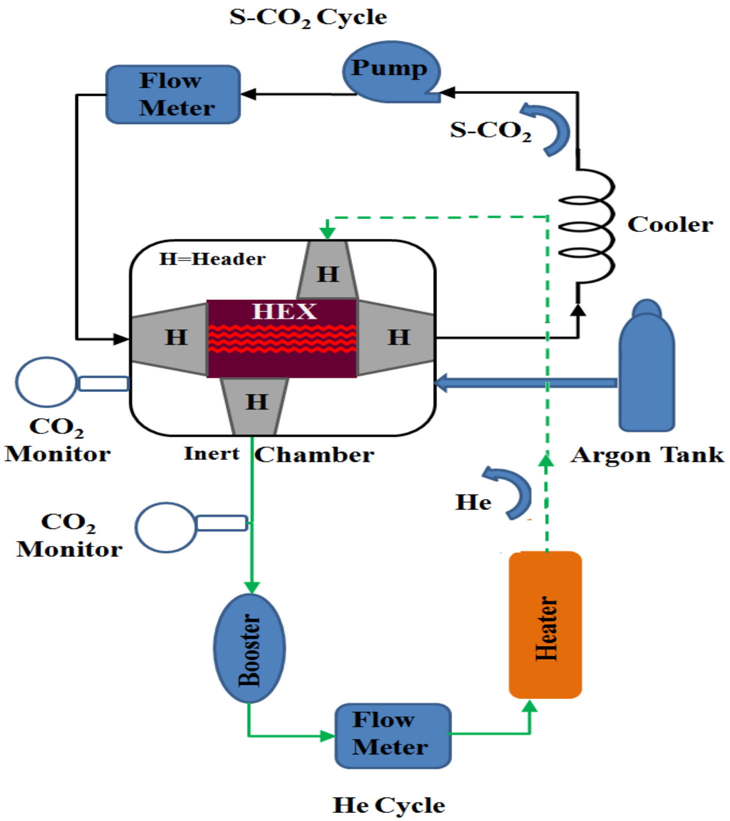
Heat Exchanger Performance Testing

- **A circulating SC-CO_2 loop capable of withstanding pressures of 20 MPa at temperatures up to 800ºC**





Ranjan and Anderson groups

Performance Thrust

- **Goals:**
  - To develop a simulation framework to guide the design of ceramic composite-based HEXs with optimal geometries
  - To develop and utilize a HEX testing facility to evaluate the performance of ceramic composite-based HEXs
  - To develop techno-economic models for the manufacturing of ceramic composite-based HEXs
- **Approaches:**
  - A coupled Navier-Stokes and energy equation solver is being used to study thermohydraulic behavior inside the channels.
  - An existing test facility will be upgraded and instrumented for HEX testing (heat transfer, pressure drops) with flowing SC-CO_2.
  - A T2M Advisor is being engaged to help develop detailed techno-economic models to help guide manufacturing scaleup.

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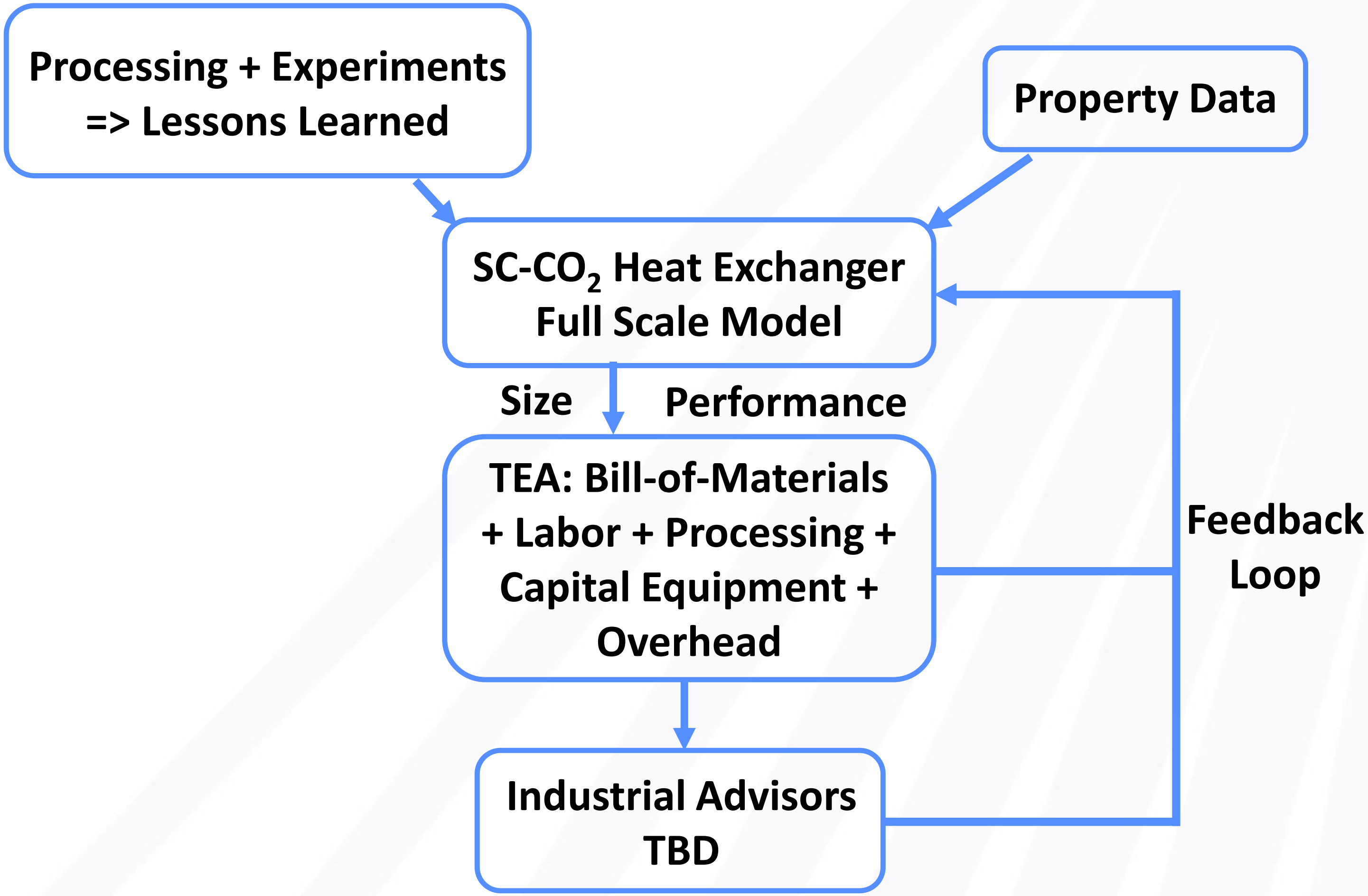
Detailed Techno-Economic Analyses



Henry and Sandhage groups

Summary

- High-melting, thermally-conductive, stiff, toughened ceramic composite materials are being developed for use in high-temperature HEXs for CSP.
- A pressing/net-shape, net-size reaction/joining process is being evaluated for the scaled-up manufacturing of such ceramic composite-based HEXs.
- The thermal, mechanical, and chemical behavior of the ceramic composites are being evaluated for use as HEXs exposed to molten chlorides at $\geq$ 800ºC and to SC-CO_2 at 750-800ºC, 20 MPa.
- A simulation framework is being developed to guide the design of the HEXs for optimal heat transfer behavior.
- A detailed techno-economic model is being developed to determine the scaled-up manufacturing cost of the ceramic composite-based HEXs.

Questions?

Suggestions?