Demonstration of Improved CHP Systems utilizing Improved Gas Turbine and sCO2 Cycles Using Additive Manufacturing (AM)

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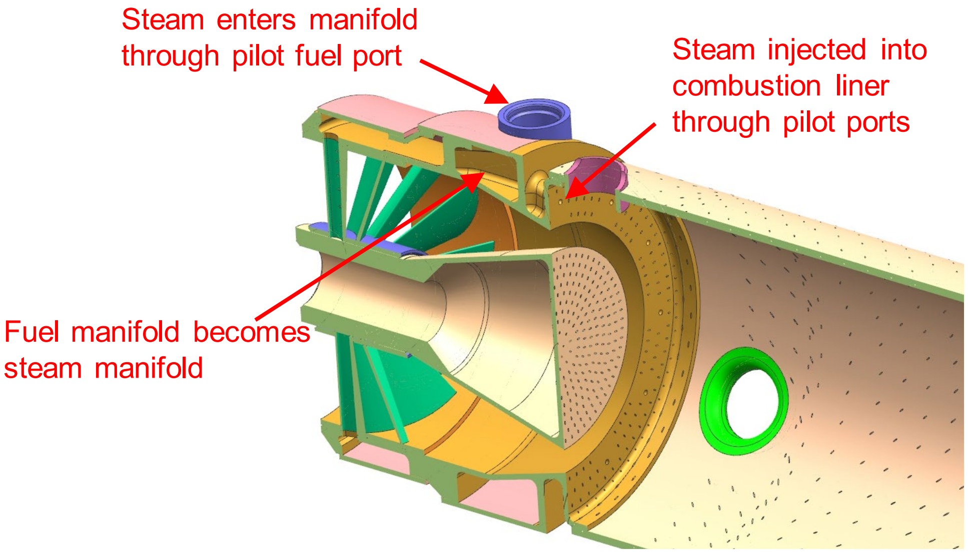
Project Objective(s)

- Strongly support AMO's initiative to conduct research and development activities to further the utilization of cost-effective, highly efficient combined heat and power (CHP).
- Target - Electricity generation component of a 1-20 MWe CHP system - Gas turbine based CHP system must be able to operate at a fuel to electricity generation efficiency of 25% and must demonstrate a total CHP efficiency of 85% at 50% rated electrical capacity.
- A supercritical CO_2 bottoming cycle will meet this requirement due to the size of its turbomachinery and demonstrated factory assembled design, however the cost of heat exchanger needs to be addressed.
- The project seeks to enable a new type of a flexible CHP system by adding a supercritical carbon dioxide (sCO_2) bottoming cycle and a steam injection system to an existing 5.3 megawatt (MW) gas turbine to increase its peak electrical efficiency to 50% and maintaining 30% electrical efficiency at 50% of load.

Technical Approach

Steam Injection Planned at Pilot Manifold (after starting) for Potential Emissions Improvement



Hardware/Software Changes Needed:

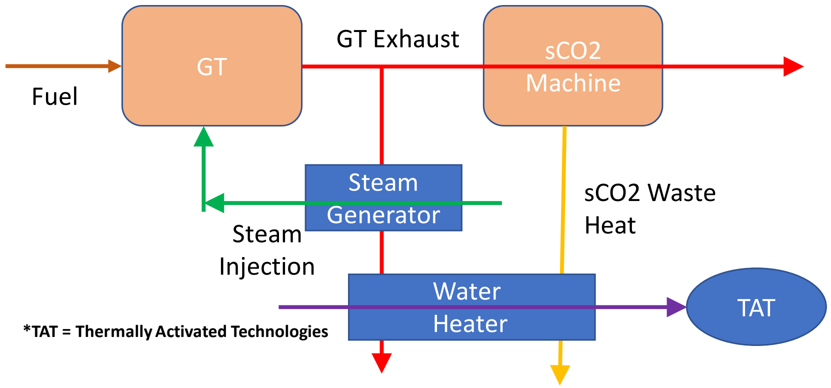
- Steam manifold
- Valves for fuel shutoff and steam manifold switch
- injected into combustion liner through pilot ports
- Control system for fuel and steam valves

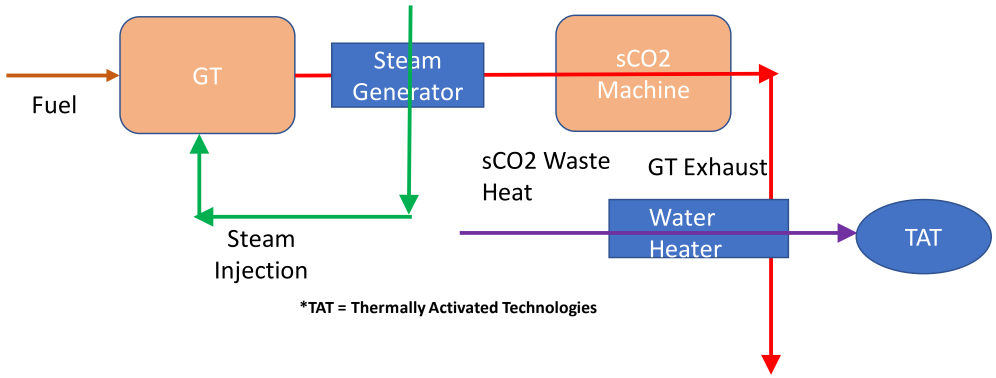
Supercritical CO2 Heat exchanger

- Microstructure and mechanical properties of the AM HX materials
- Exposure in ORNL SCO2 rigs at 400°C-600°C and 200-300 bars for duration up to 2,000h to compare Determination of AM HX lifetime and ORNL lifetime model in SCO2

Integrated/Synergistic approach for technology advancements

Technical Approach





- Different combined GT, sCO2 and TAT system configurations possible
- Goal is to maximize electrical output from waste heat with reasonable quality left for TAT
- GT waste heat must also generate the steam injected into GT
- Mass flow and temperature of waste heat required for GT efficiency improvement must balance with meaningful benefits from downstream devices

Siemens and Oak Ridge National laboratory (ORNL) have unique Infrastructure and Expertise for detailed thermodynamic simulation of cyber-physical systems for optimization of cost/performance for desired targets

Overall Performance of CHP System (latest)

GT Conditions	sCO2 Cycle Configuration	GT Power	GT Efficiency	sCO2 Power	net Fuel LHV	Net Electric Power	Net Electric Efficiency	Waste Energy to CHP	Waste Energy Temp	CHP Efficiency
		kW		kW	kW	kW		kW	K	
952 F	A	6193	0.343	2242	18069	8435	0.467	7756	397	0.896
1000 F	A	6720	0.346	2593	19403	9313	0.480	8227	396	0.904
952 F	B	6193	0.343	2189	18069	8382	0.464	7495	412	0.879
1000 F	B	6720	0.346	2436	19403	9156	0.472	7975	422	0.883

Overall Work and Heat Output and Heat Quality

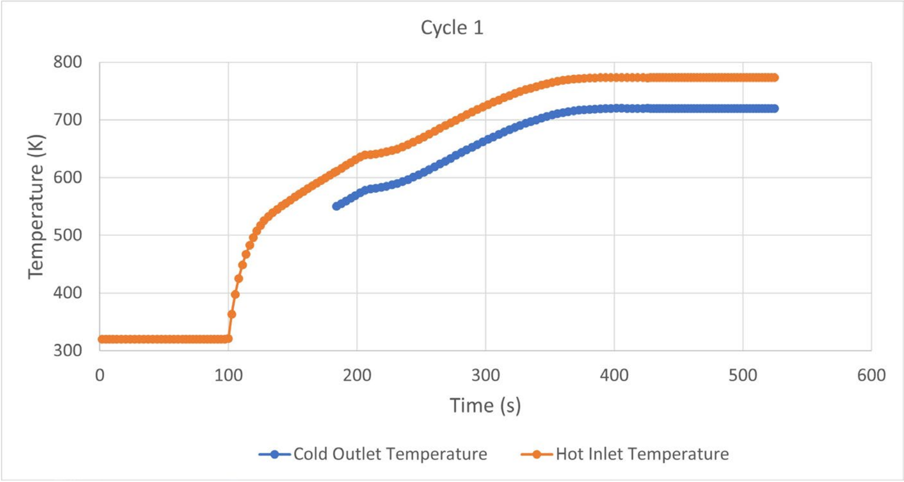
- Increasing GT Exhaust (firing as well) temperature will improve both sCO2 and CHP heat quality
- Increasing steam injection will improve GT efficiency monotonically but will likely be disadvantageous to overall system beyond a point – dependent on bottoming cycle as well
- System Optimization ongoing

Modeling and Estimating Dynamic Response of Power Plant

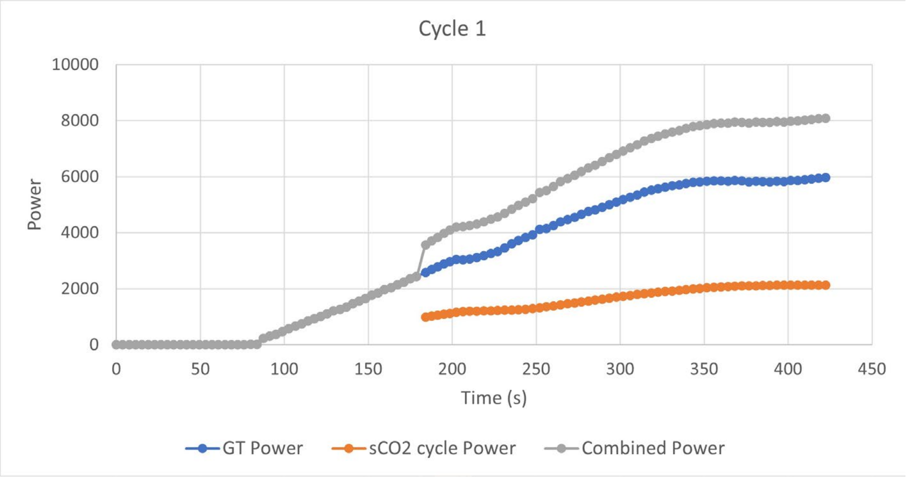
Ongoing work is focused on developing a dynamic model that can simulate the start-up and load changes for the combined Gas Turbine and sCO2 power plant

- Gas Turbine response data is obtained from actual AO5 test data for power generated, mass flow, exhaust temperature, fuel flow etc.
- A dynamic heat recovery heat exchanger (HRX) model to transfer energy to the sCO2 has been developed

GT Exhaust and sCO2
Heat Recovery Temperature



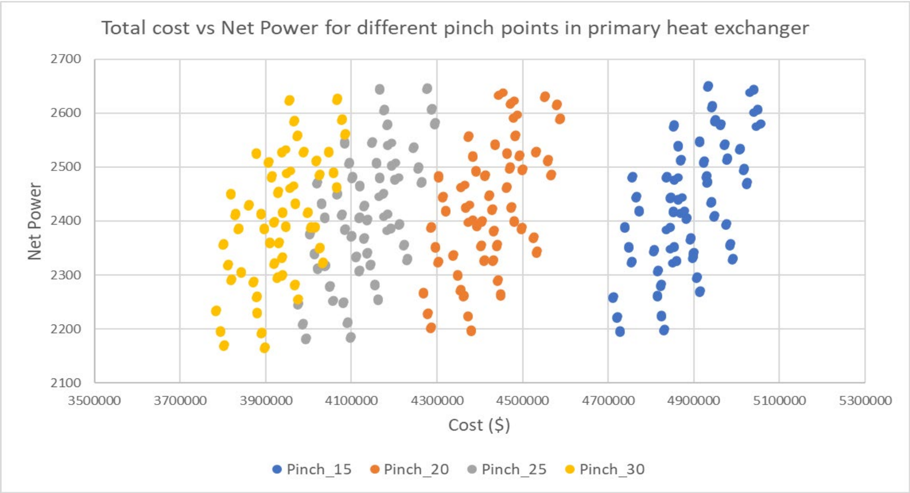
GT, sCO2 cycle and Net
Power Response from Cold Start



Ongoing Overall System Thermo-Economic Optimization

Ongoing work is focused on developing an optimization algorithm and method to find the trade-off between most efficient system and best economic value

- Premise : Most efficient system may not be the best system because the cost may rise significantly to buy marginal efficiency. Currently sCO2 cycle costs are being generated and analyzed based on the developed models and sensitivity to relevant cycle parameters investigated



Heat exchanger pinch temperature = [15, 20, 25, 30] K

High temperature recuperator pinch temperature = [10, 15] K

Low temperature recuperator pinch temperature = [15] K

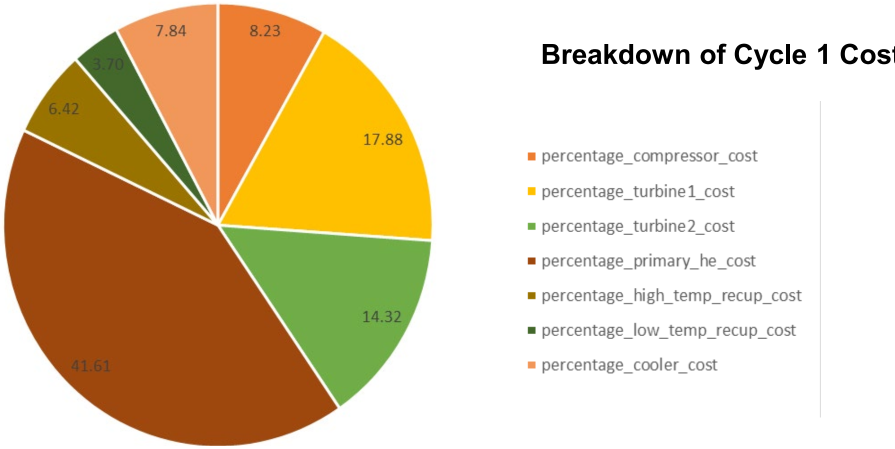
Heat exchanger hot side inlet temperature = [790, 800, 810] K

Efficiency compressor = [0.85, 0.87, 0.9]

Efficiency turbine = [0.85, 0.89, 0.92]

Pressure drop = [0.02, 0.04, 0.06] MPa

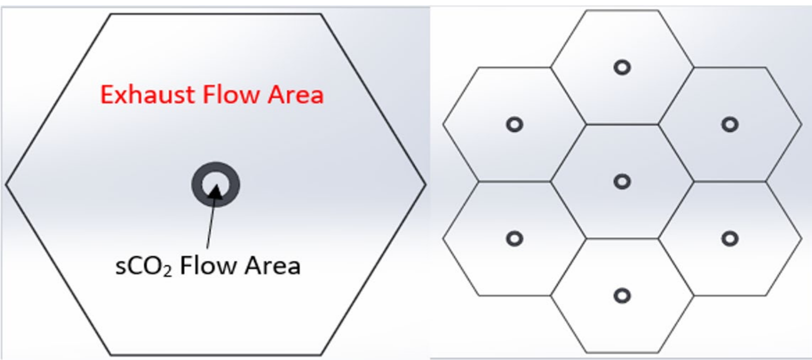
Return on Lower Pinch Point on Primary HX is not significant but much higher UA and Cost



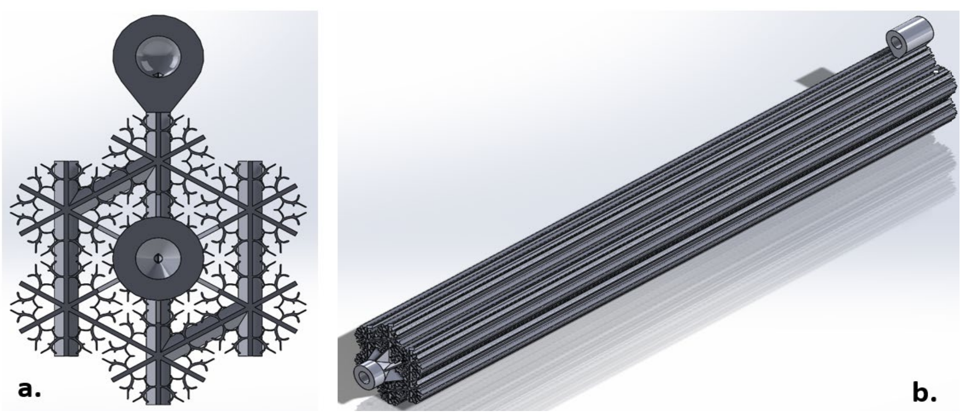
HX Design Development

- ORNL and Penn state have initiated a partnership to design new high performance Heat exchanger

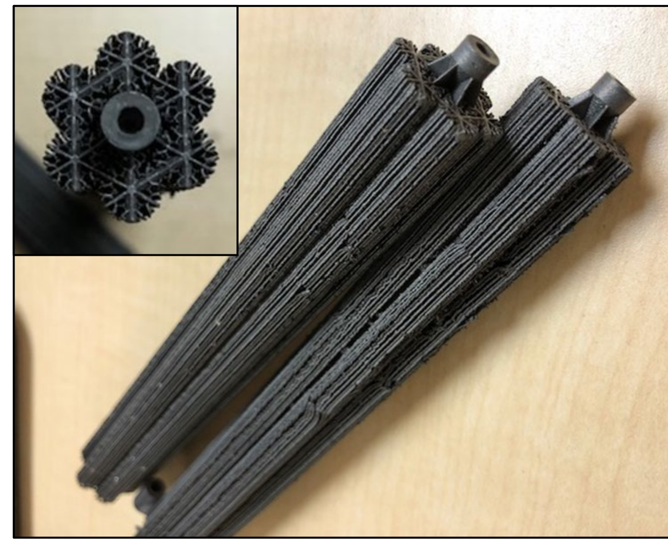
Single hexagonal unit cell



Heat exchanger test cell



PBF AM trials



Lessons learned:

- Recommend Increasing Cooling Fin Size Slightly
- Recommend Reducing Height to Improve Aspect Ratio.
- Recommend leaving a peak on the internal cooling passages

Materials Property Evaluation for sCO2 Environments

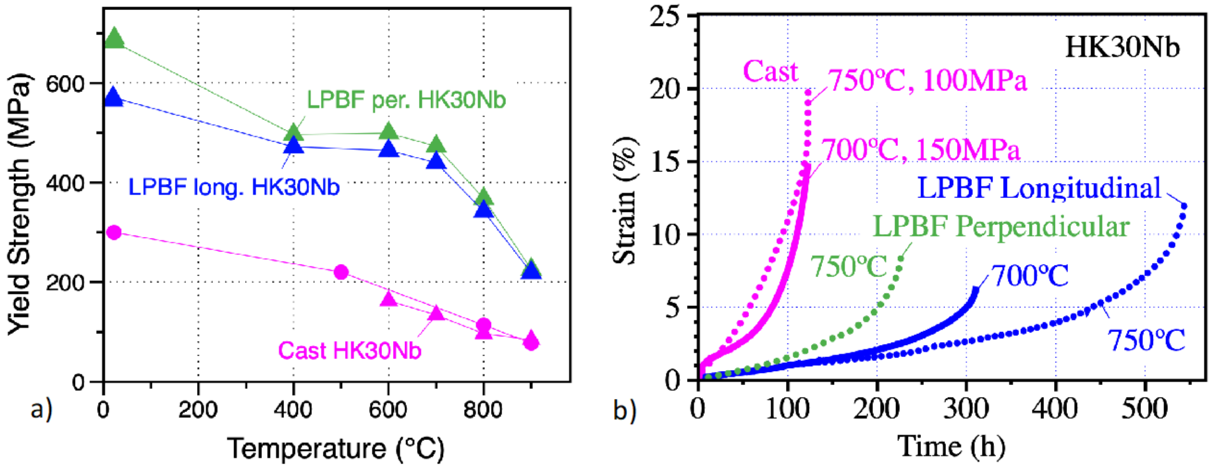


Figure : Comparison of the mechanical properties of the LPBF and cast HK30Nb steels, a) Yield strength and b) creep curves at 700° and 750°C.

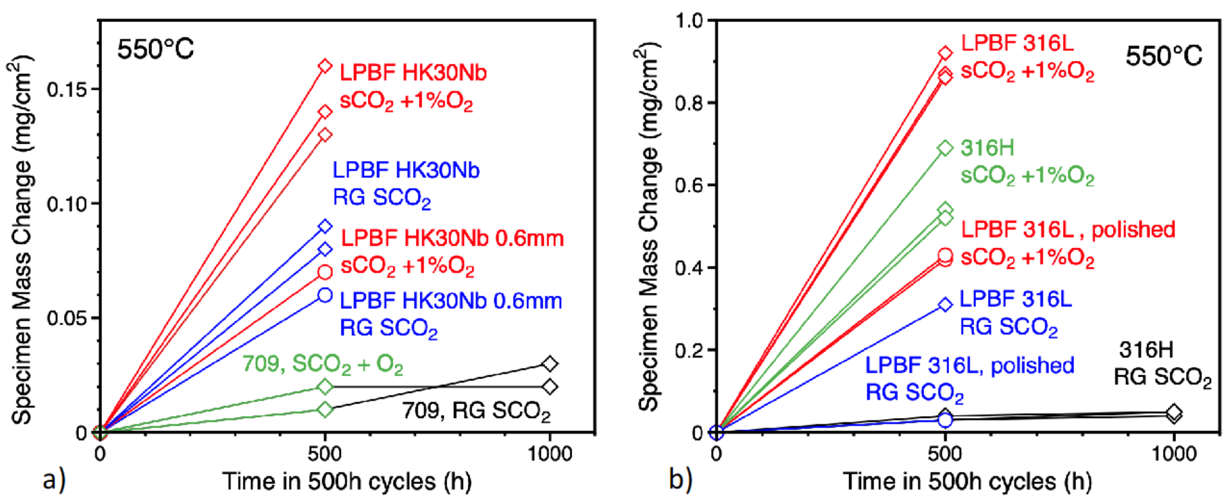
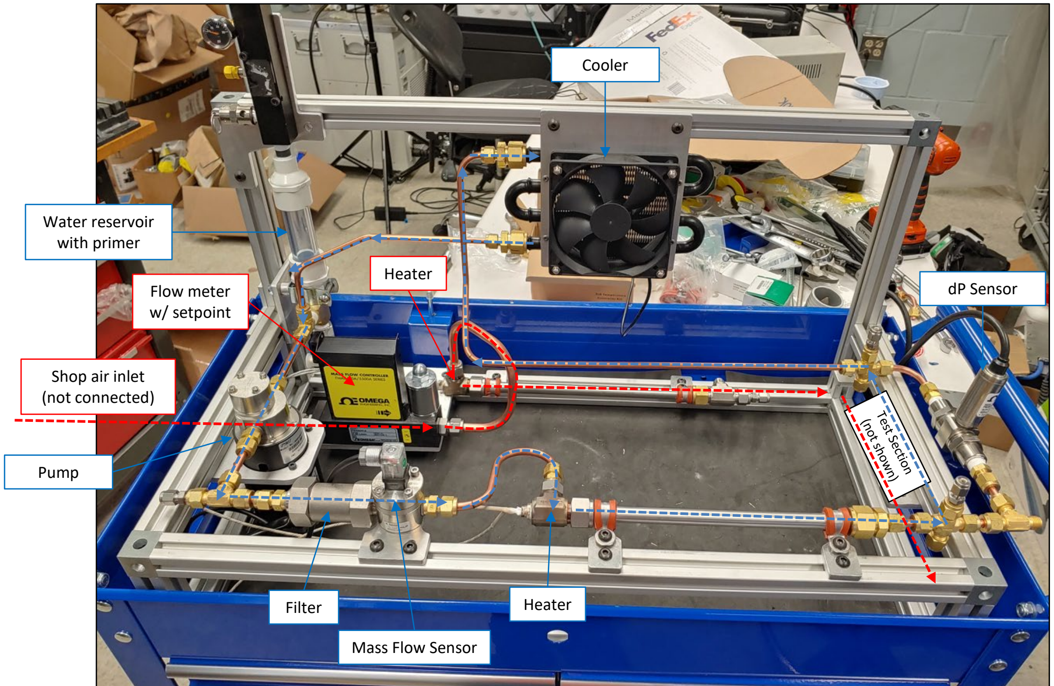
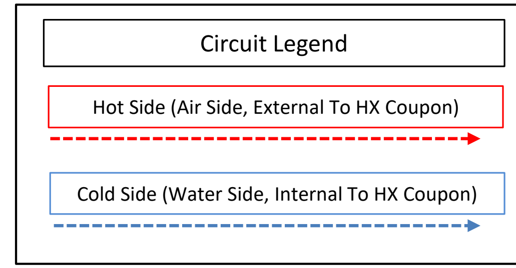


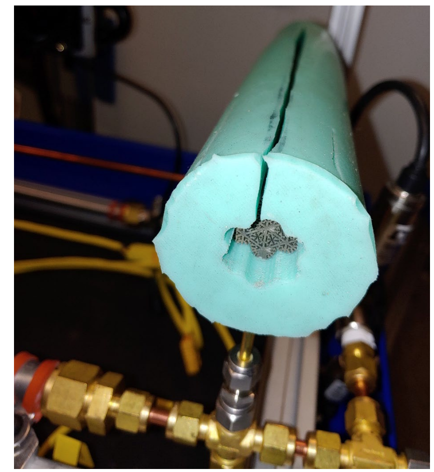
Figure Mass change data at 550°C in RG sCO_2 and sCO_2 + 1%O_2, a) LPBF HK30Nb and wrought 709 and b) LPBF 316L and wrought 316H

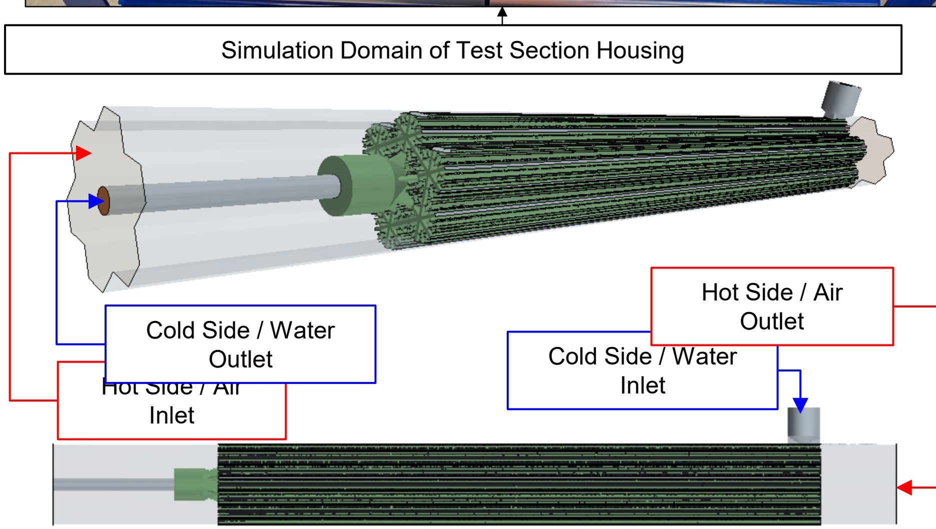
Superior yield strengths were observed for the LPBF both along and perpendicular to the build direction in comparison with the cast alloy. The creep lifetimes of the LPBF at 700-750°C were ~3 to 5 times higher than the lifetime for the cast alloy

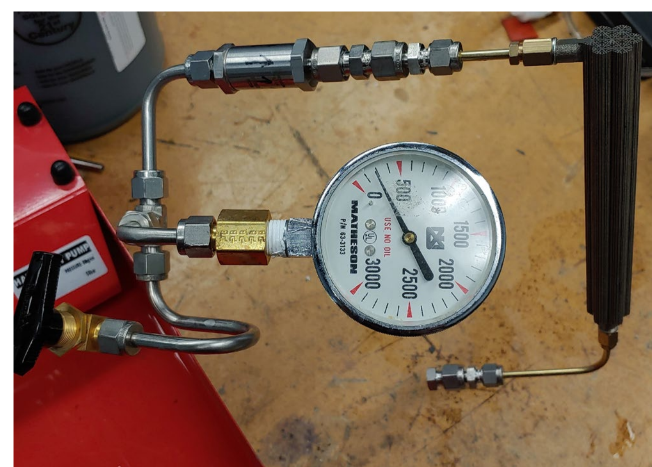
Heat Exchanger Test Setup at PSU











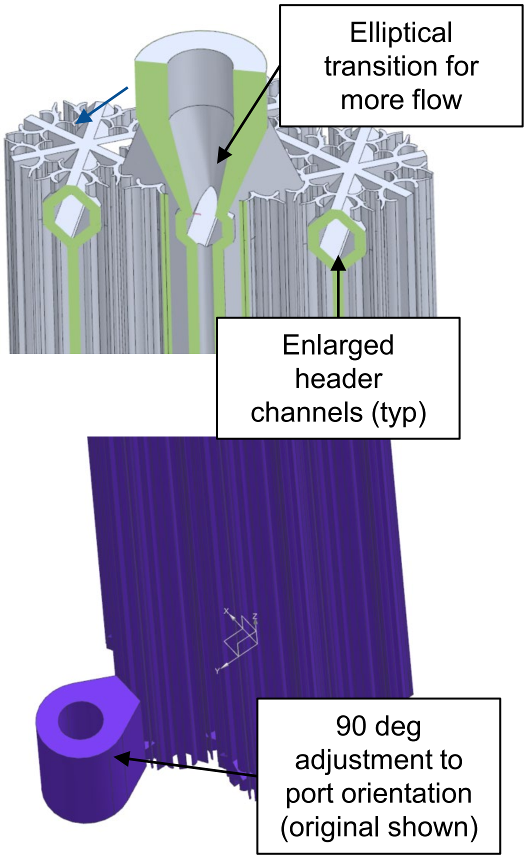
Coupon Design Modifications

CAD Definition

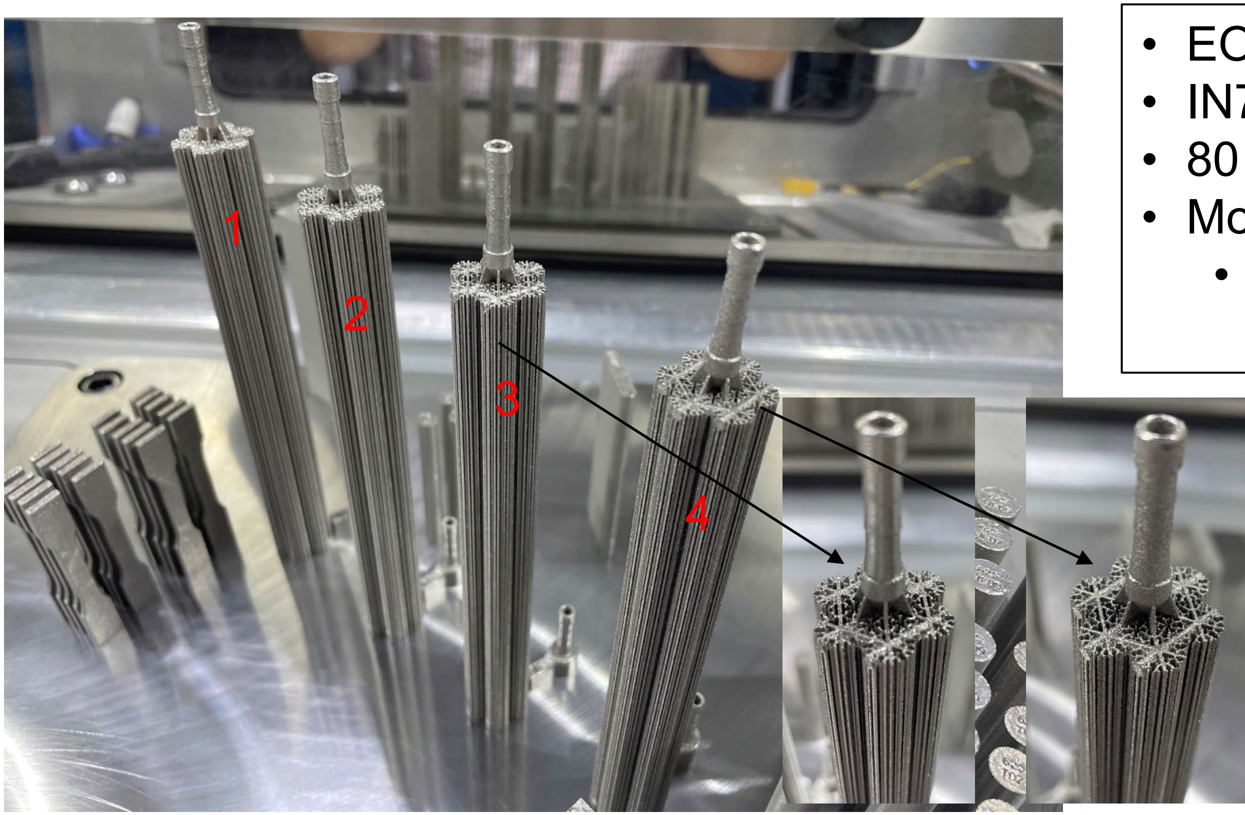
1. Start from 500 um Fin CAD model. All pressurized channel walls have minimum thickness of 0.50 mm.
2. Increase header (at both ends) internal (cold side) flow area such that internal mass flux is maximized along axial length.
3. Adjust top (away from base plate) header port for increased internal (cold side) flow area without blocking hot side flow.
4. Adjust header port near base plate to discharge 90 deg for easier drill access. Thicken connection to tube bundle for mechanical integrity. Include external feature for centerline identification and off centered de-powdering holes (not pilot hole).
5. Rounds added for all internal channel edges.

Print/Post-Print Processing

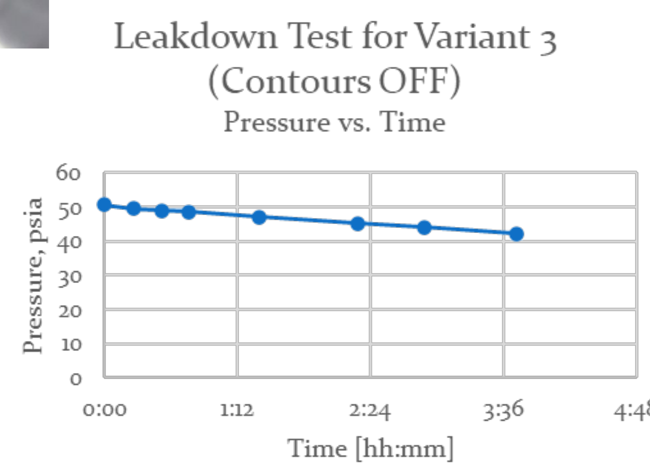
1. Add 6 mm stock for baseplate attachment (band saw cuts) with integral de-powdering channels



New HX Designs for Flow Testing



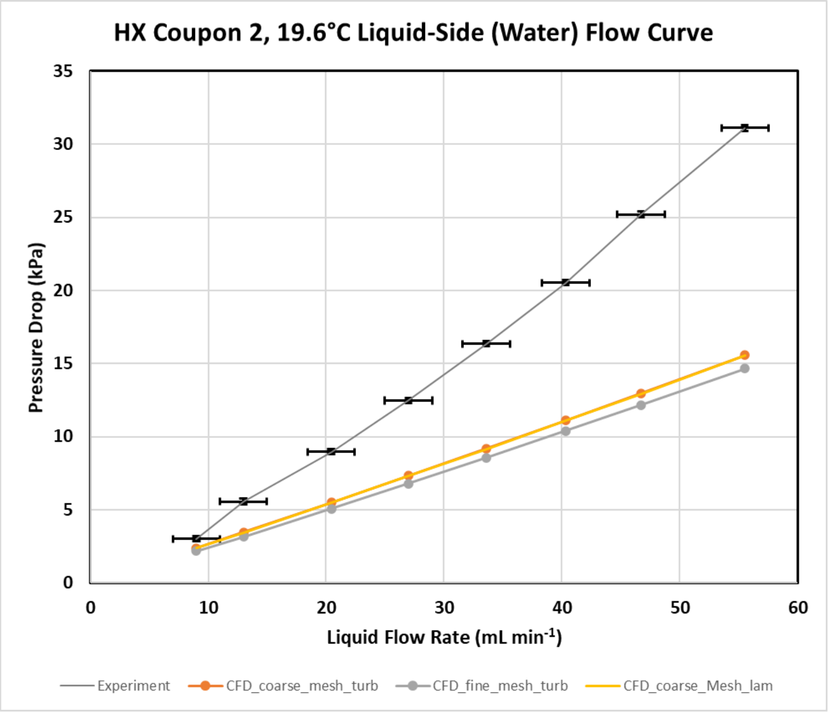
- EOS M400 printer
- IN718 material
- 80 um build layer
- Modified 500um CAD model
    - Barbs added for quick flow/leak test

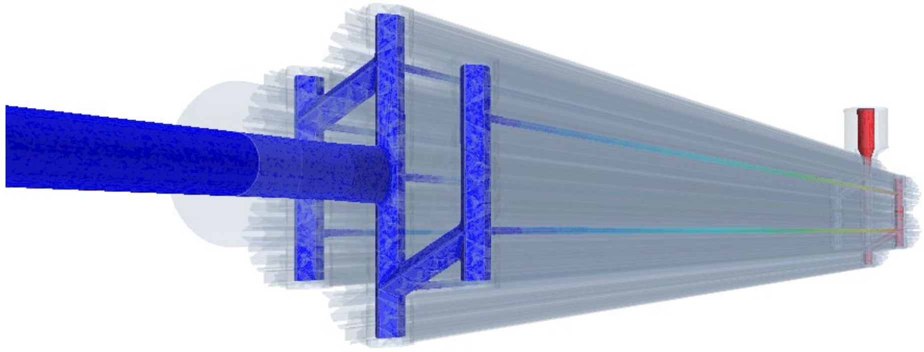


5 samples of the correct configuration printed and sent to PSU for performance testing

Cold Flow Sweep

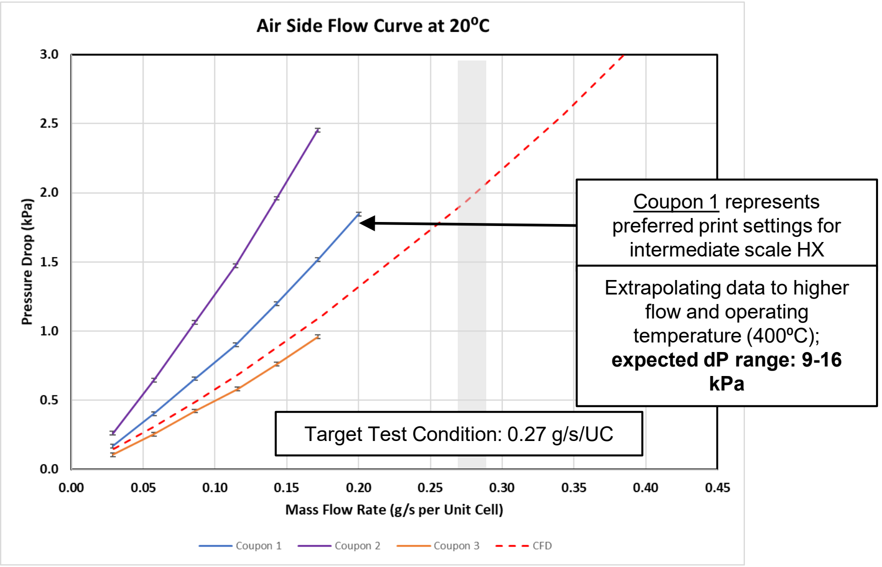
- AM HX coupon testing underway with water/cold side flow test
  - A representative fluid-side (internal channels) pressure drop curve is presented for room temperature distilled water flow through coupon #2
  - CFD simulations of cold flow sweep were completed and compared to experimental measurements. CFD showed relatively lower (20-50% less) pressure drop than test data. Differences are likely caused by geometry disparities (ideal CFD model vs. rough printed part) including surface roughness, as-build diameters or partial blockages.
- Next step: hot/air side flow test at room temperature for pressure loss measurement

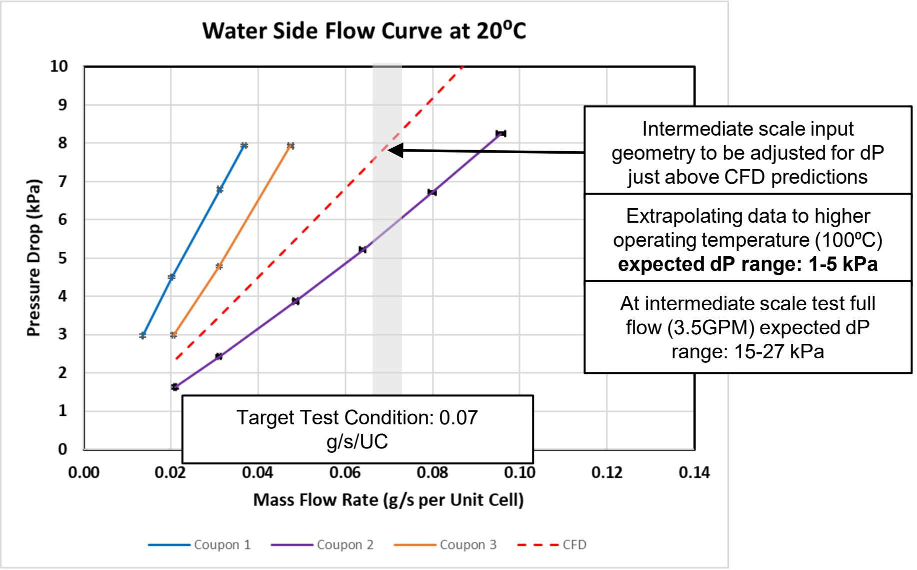




Heat Exchanger Testing

Test Coupon Representative Xsections

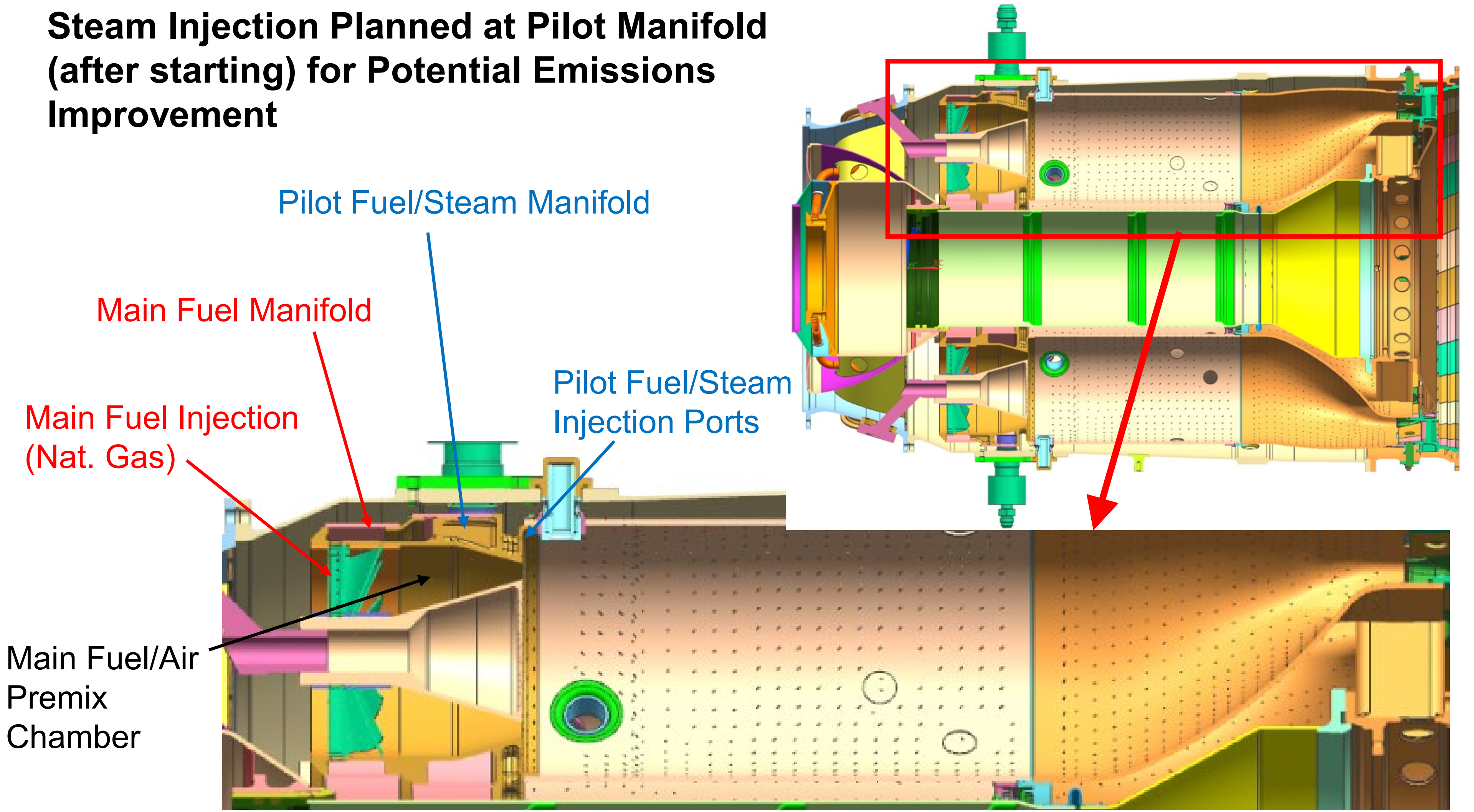




Based on this testing we have a preference for coupon 1 with slight modification for intermediate scale print and testing.

Steam Injection from Pilot Manifold

Steam Injection Planned at Pilot Manifold (after starting) for Potential Emissions Improvement

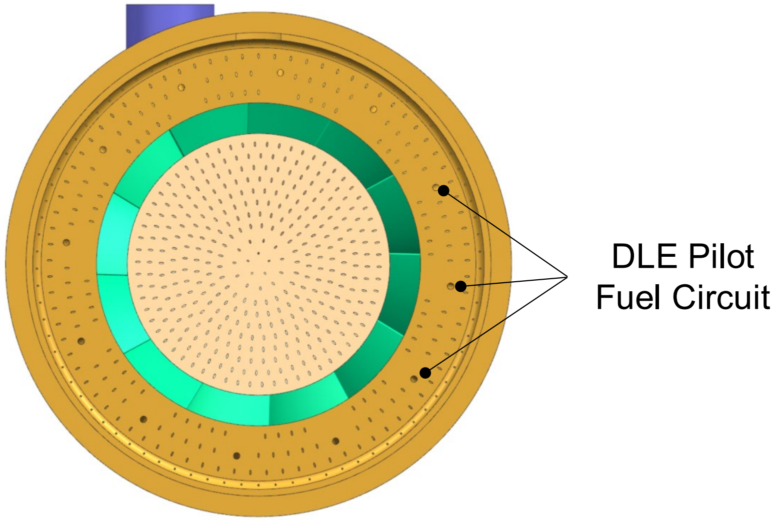


Original Proposal for Steam Manifold

Original Proposal – Inject steam through the DLE pilot fuel circuit

<u>Challenges:</u>

1. Maintain lean combustion without affecting flashback requires a dome redesign.
2. DLE fuel manifold is bulky and there is no room to accommodate a steam manifold and maintain emissions guarantee
3. Control system rework is required and a new fuel schedule has to be developed

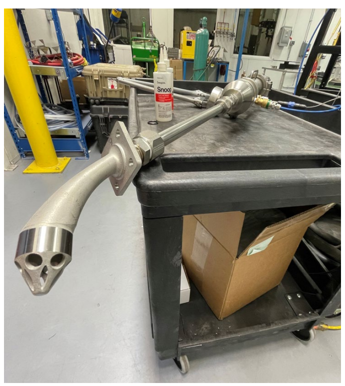


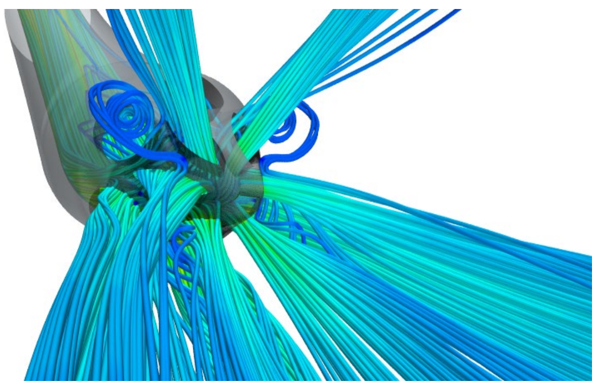
Updated Proposal – Move to Gas/Water style combustion system.

1. Design challenges are greatly reduced
2. Steam manifold design exists and no DLE fuel manifold is required
3. Diffusion flame combustion system is more robust
4. Emissions at full load would be nearly unaffected

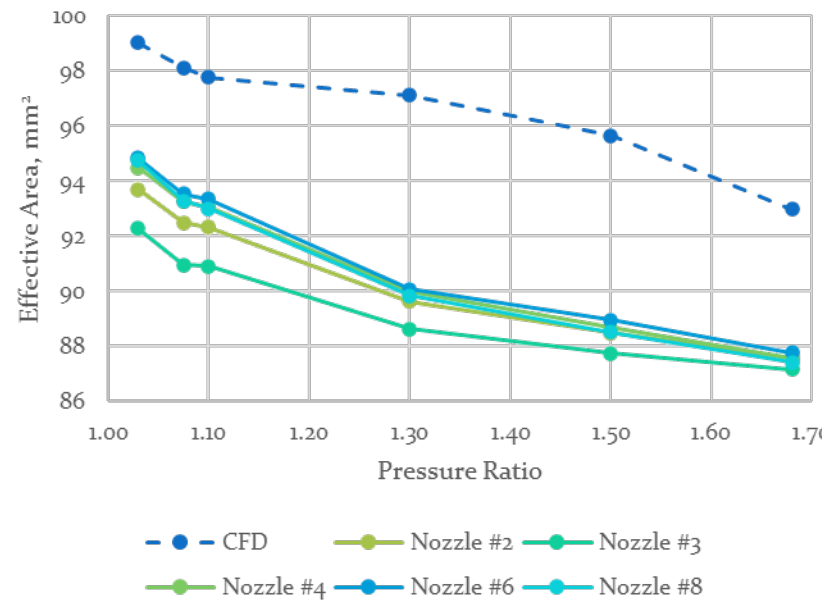
Design of AM Steam Nozzles

Steam injection nozzle





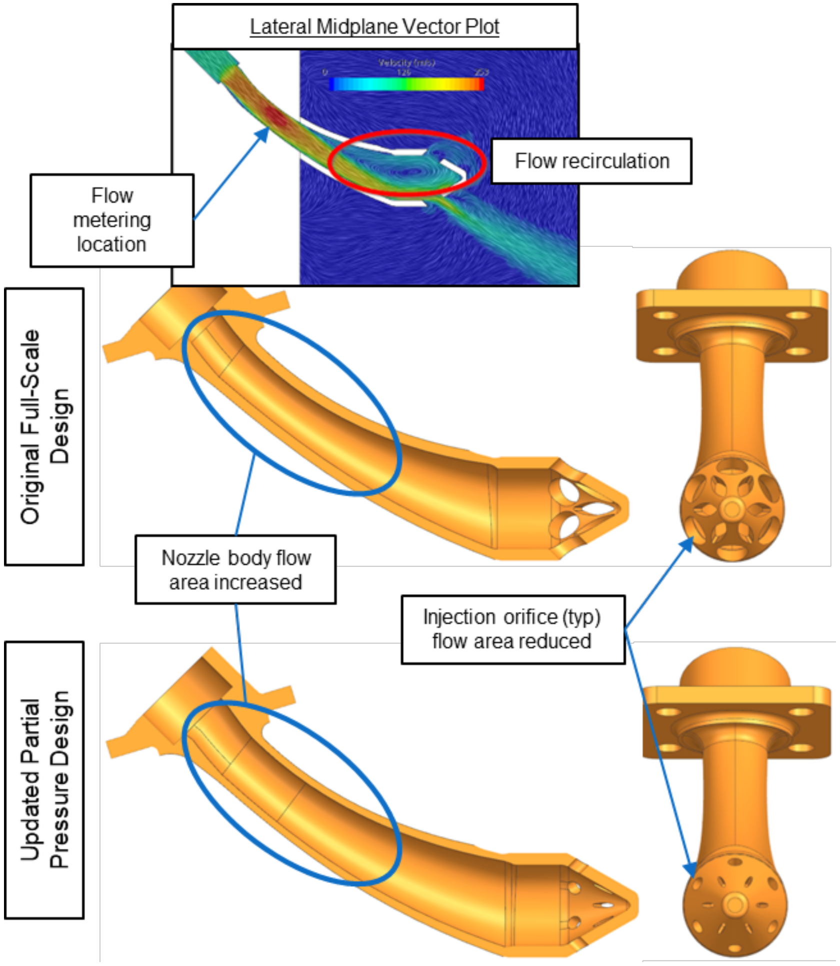
- **Cold flow sweep complete**
- Average effective area of ~90 mm^2
- Parts consistent with max part to part deviation of 3%
- Measurements compare relatively well with CFD simulation
  - CFD overpredicts measurement by with average deviations of 5-8%. Such differences may be due to roughness effects and/or differences in as printed geometry.



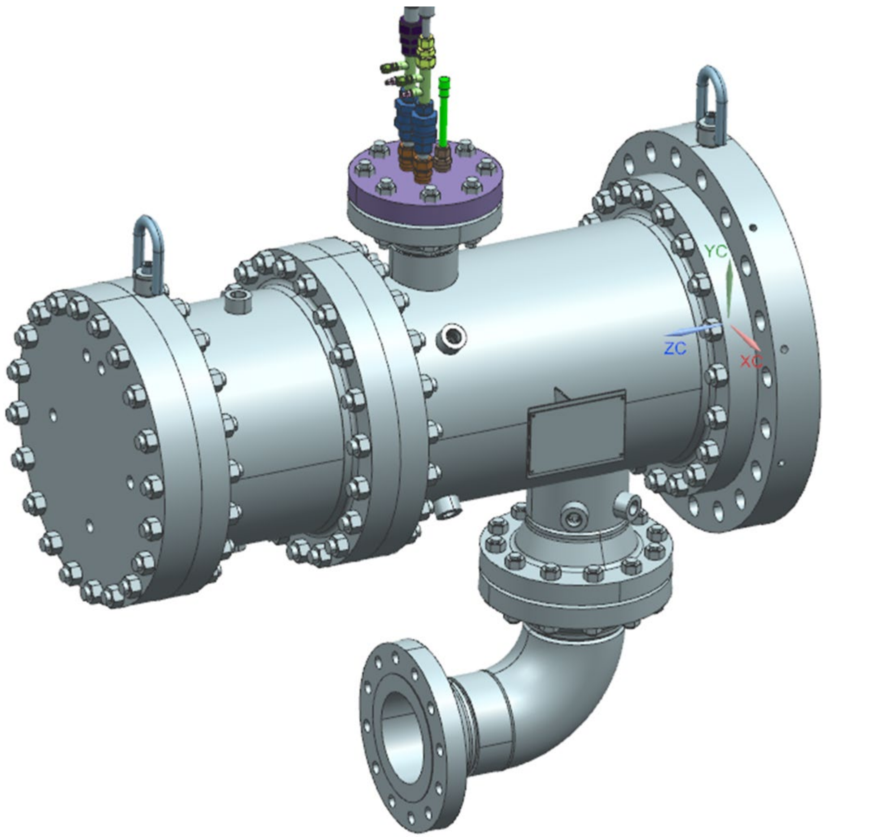
- Effect of steam injection (1 – 3 lb/sec) to be evaluated through nozzle
- Effect on efficiency, combustion dynamics and exhaust temperature

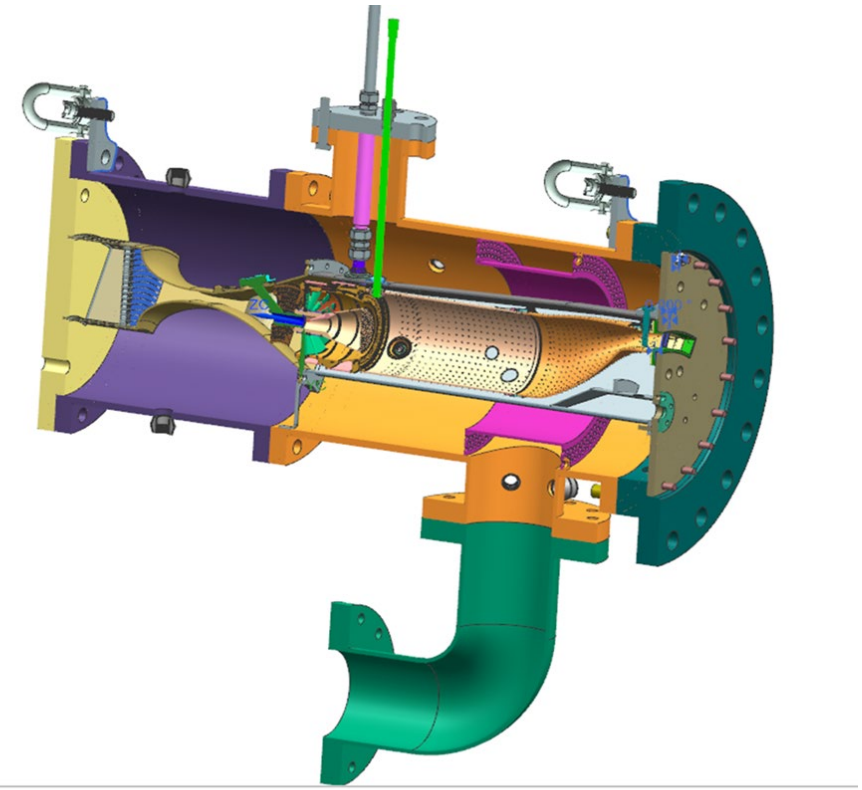
Steam-Fuel Injection Nozzle Testing

- **Nozzle originally manufactured for full scale application flow but must be adjusted for partial pressure testing**
- Injection orifice uniformly reduced by ~80% to maintain full scale injector velocities
- Nozzle body flow area increased such that flow is metered at injector orifice
  - Original design metered flow within nozzle body and recirculation is observed within nozzle body near tip, This causes reversed flow, ingestion through several injectors.
- New partial pressure nozzles to be printed in Charlotte



Existing SGT-A05 Combustion Liner Rig

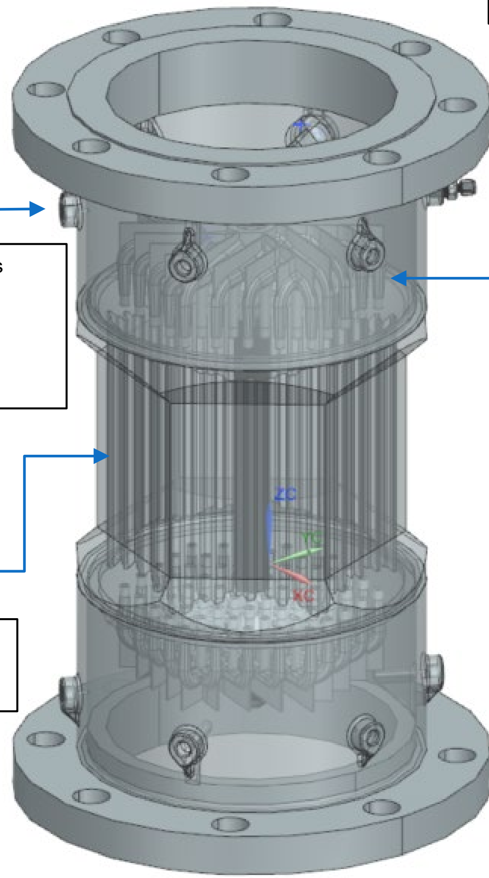




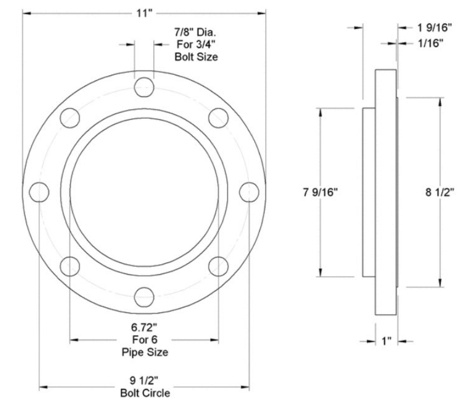
- Retrofit rig for LE3.4 liner configuration. (Gas/Water Config)
- Use printed DOE AM nozzles
- Make steam injection available
- The testing will be focused on capability of the nozzle for steam and stable combustion at the high steam level.
- Combustion model available for GT efficiency or exhaust temperature effect

Heat Exchanger Design

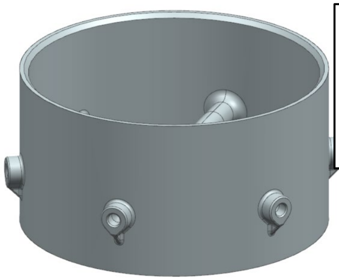
Gross axial length of 437 mm [17.2”] (flange to flange)



6” 304 SS Pipe Flange (typ of 2)

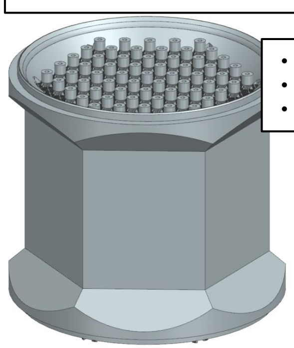


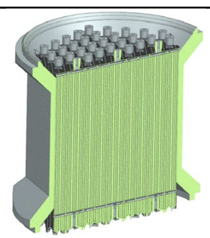
Instrumentation Section (typ of 2)



- Integral internal manifold egress
- (2) hypotubing ports for Ps measurement
- (3) TC ports with ~1” rake
- All ports have 1/8” NPT female thread

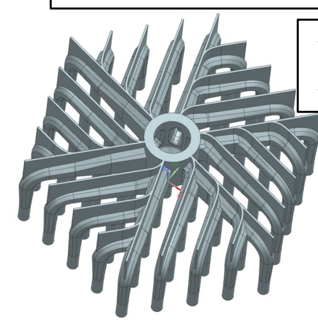
Core Tube Bundle





- 61 “bench scale” clusters
- 427 total unit cells
- 3.5 mm thick exterior wall

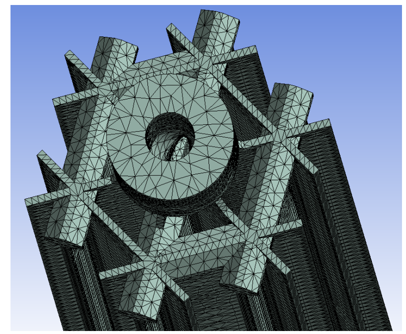
HX Manifold (typ of 2)

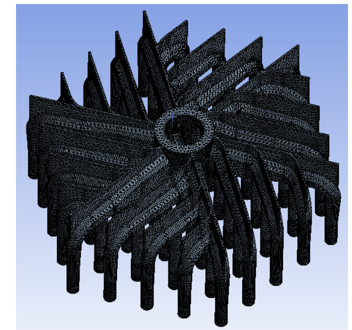


- Periodic DFAM construction
- 61 connecting fingers

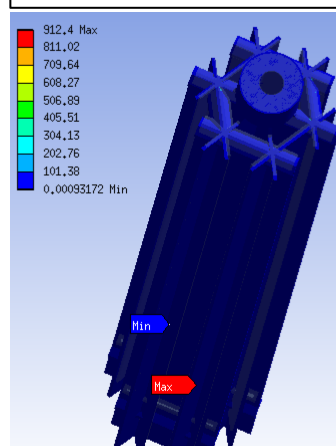
Heat Exchanger Design

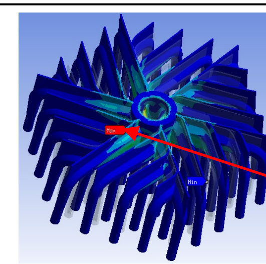
- **Structural FEA of 7-unit cell bundle/manifold to determine test viability**
- Several design iterations completed
- 405k tetrahedral elems with local refinement
  - Small fins removed for meshing ease
- <u>Full scale pressure (31 MPa)</u> and temperature (constant 500^0C)
- Fixed displacements at one connection
- Representative alloy 718 LPBF material properties
- Stress levels are generally low with very local peaks on interior surface transitions. Local yield is possible but is low risk for short term testing.





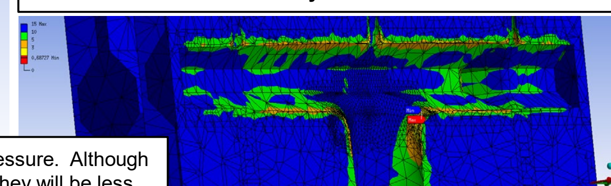
Von-Mises Stress





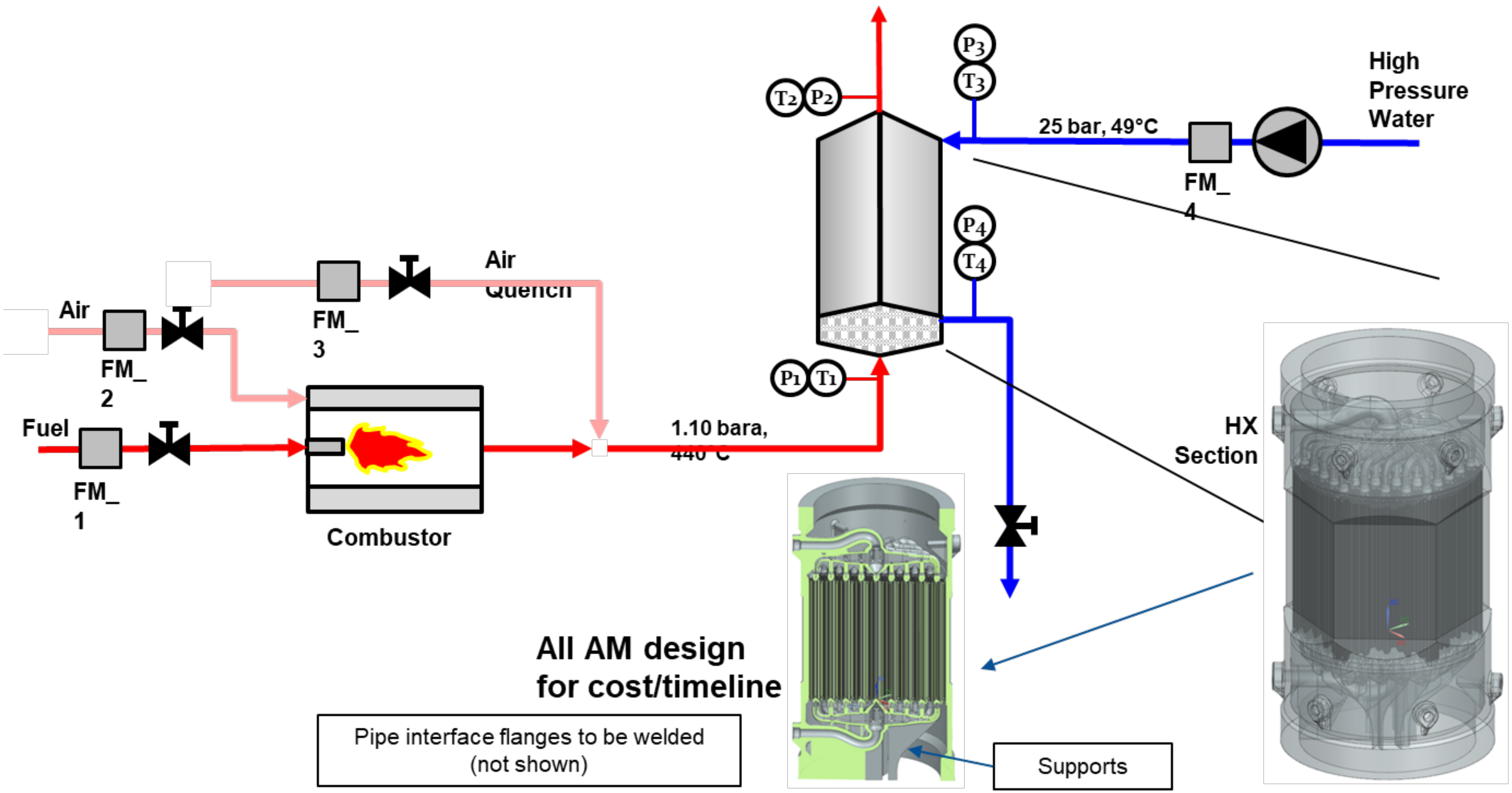
Higher stresses near manifold center with increased internal radii

Safety Factor



Stress levels scale with internal pressure. Although test conditions are not finalized, they will be less than full scale application/analysis pressure

Integrated Heat Exchanger – Gas Turbine Testing



Rig being setup in Charlotte Mid July for integrated testing – validate models

Results and Accomplishments

- Completed steady-state analysis of power system components and thermodynamic modeling to identify system designs meeting electrical efficiency goal at rated power and 50% rated power

- 3 sCO_2 system architectures for bottoming cycle and a range of steam injection in the GT cycle have been studied
  - Rated Efficiency varies between 0.47 and 0.49 based on current technology but will increase beyond 0.5 with further optimization
  - Electrical efficiency at 50% turndown (total system power) will exceed 35%
  - Overall CHP efficiency varies between 0.87 to 0.90

- Novel all AM design for Heat exchanger being printed for integrated gas turbine rig testing

- Combustion rig setup being assembled for integrated heat exchanger - GT exhaust gas/sCO_2 interfacing