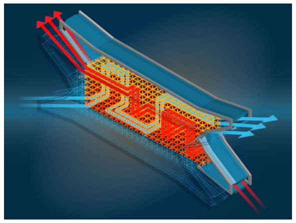


SHOTEAM: Superalloy Heat Exchangers Optimized for Temperature Extremes and Advanced Manufacturability

PI: *Timothy Fisher, UCLA*

Project Vision

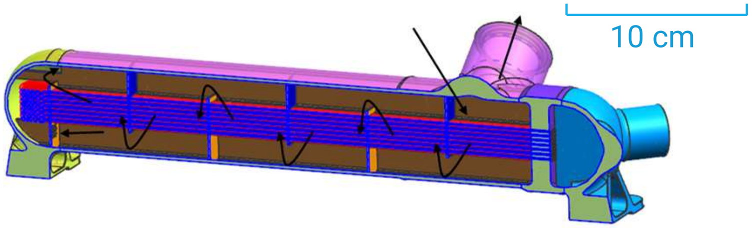
We solve a series of coupled optimization problems involving superalloy heat exchanger materials, manufacturing, cost, heat transfer, and reliability for new high-efficiency advanced recuperated power cycles targeting aviation applications

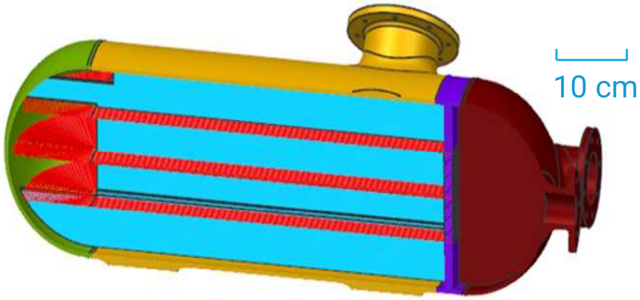
Brief Project Overview

Fed. funding:	$2.52M
Length	36 mo.

Team member	Location	Role in project
UCLA	Los Angeles, CA	Thermo-mechanical optimization, additive manufacturing
Honeywell Aerospace	Torrance, CA	Heat exchanger design and fabrication, T2M
University of Miami	Miami, FL	Creep and fatigue modeling (early stage)

Context/history of the project





50 kW prototype

Status: design complete, fabrication in progress

Highlights: microtubes, power density > 18 kW/kg

2.25 MW full-scale design

Status: design in progress

Highlights: microtubes, cost < $5000 K/kW

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Progress Against Tasks – Timetable

WBS	Task/Milestone Title	Start	End	2019	2020				2021				2022			
				1	2	3	4	5	6	7	8	9	10	11	12	13
M1.1	Go/No-Go: Refine the Tasks	1	1	🟩												
M2.1	Thermohydraulic Modeling Framework	1	1	🟩												
M2.2	Conceptual Design Review (50 kW HX)	2	2		🟩											
M2.3	Preliminary Design Review (50 kW HX)	4	5				🟩	🟩								
M2.4	Go/No-Go: Critical Design Review (50 kW HX)	6	8						🟩	🟩	🟩					
M2.5	Conceptual Design Review (Full-scale HX)	12	13												🟦	🟦
M3.1	Preliminary Augmentation Design	1	1	🟩												
M3.2	Fabrication of Augmented Tubes	2	2		🟩											
M3.3	Sub-scale HX Thermal Performance Evaluation	4	8				🟩	🟩	🟩	🟩	🟩					
M4.1	Thermomechanical Modeling Framework	2	2		🟩											
M4.2	Demonstration of Oxidation and Thermomechanical Resilience	4	12		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	🟦	🟦	
M4.3	Report on Haynes 282 Creep Behavior	8	13								🟩	🟩	▨	🟦	🟦	🟦
M5.1	Conceptual Fabrication Process Flow	4	4				🟩									
M5.2	Full Fabrication Process Flow	5	5					🟩								
M5.3	Gather Requirements for Test Interface from Test Vendor	6	8						🟩	🟩	🟩					
M5.4	Intermediate Manufacturing Review	7	7							🟩						
M5.5	Finalized Experimental Test Plan	8	11								🟩	🟩	▨	🟦		
M5.6	Go/No-Go: Complete 50 kW HX Fabrication	9	11										▨	🟦		
M5.7	Complete HX Shipped to the Test Site	11	12											🟦	🟦	
M5.8	Thermohydraulic Performance Test	12	13												🟦	🟦
M6.1	Preliminary Applications/ IP Landscape	3	3			🟩										
M6.2	T2M Paths	4	4				🟩									
M6.3	Target Candidate Aerospace HX Applications	4	7					🟩	🟩	🟩						
M6.4	Update T2M Plan	8	9								🟩	🟩				
M6.5	Final T2M plan	10	11										▨	🟦		
M6.6	Pursue funding	11	13												🟦	🟦
M7.1	Creep test machine upgraded	8	11										▨	🟦		
M7.2	Advanced TLP approach developed	8	12												🟦	
M7.3	Experimental validation of creep model	9	13													🟦

🟩	Completed
▨	In progress
🟦	Planned

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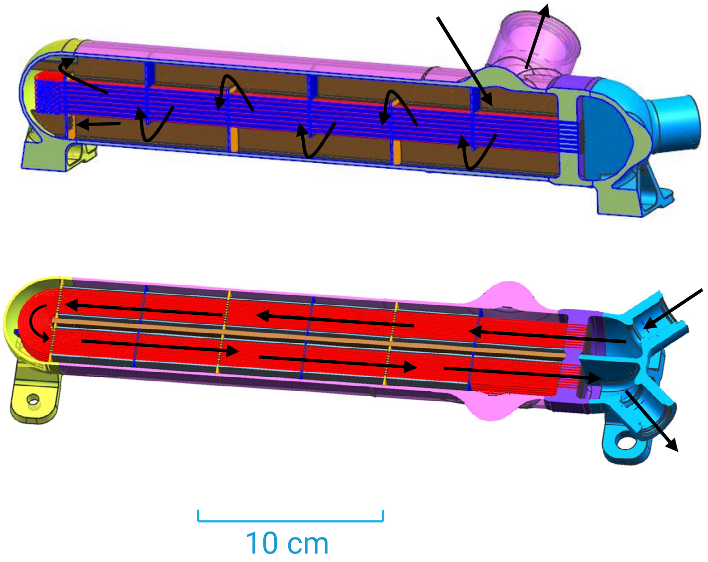
Design and Optimization Progress

Proposal design

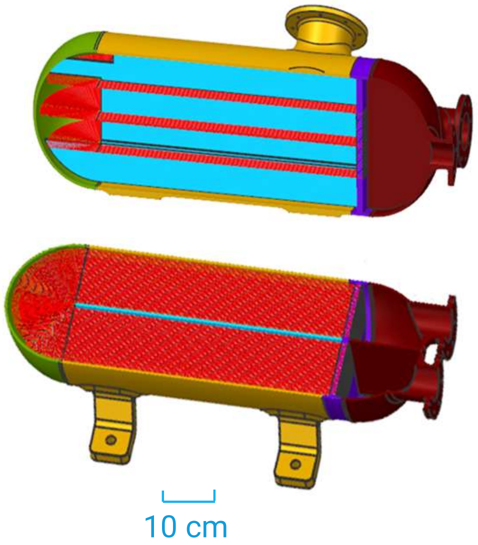
3mm tubes with cruciform cross-section

Current HX Design

50 kW HX prototype



2.25 MW full-scale HX



Main Metrics

	50kW design	2.25 MW design	Target
Power density (mass) [kW/kg]	18.1	>20	5.2
Power density (volume) [kW/m³]	54147	>25,000	20,000
Cost/UA [$·K/kW]	16,189	<5,000	4,900

- CDR for 50kW prototype completed and fabrication in progress
- Design for 2.25 MW full-scale HX in progress
  - Main performance and cost metrics achieved

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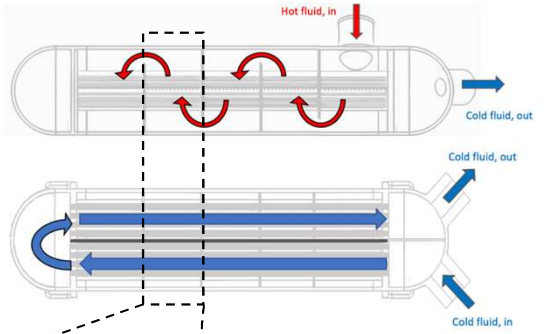
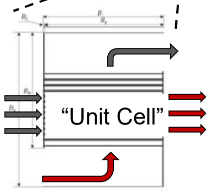
Model Development for Microtube Heat Exchanger

HX performance model





- **Fluid-phase energy (Shell-side):**

$$\rho_{f1}C_{pf1}\phi_{f1}\overline{u}\frac{\partial\overline{T_{f1}}}{\partial x}=h_{f1}S_{wf1}\left(\overline{T_{so}}-\overline{T_{f1}}\right)$$

- **Fluid-phase energy (Tube-side):**

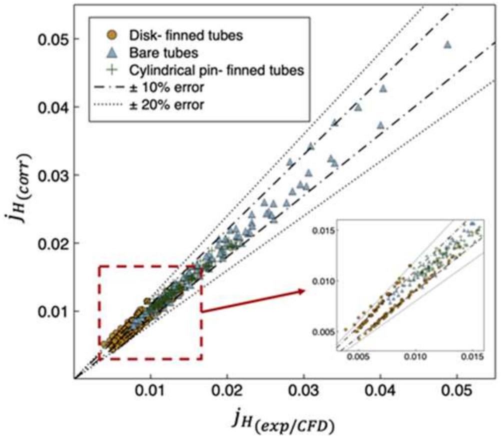
$$\rho_{f2}C_{pf2}\phi_{f2}\overline{u}\frac{\partial\overline{T_{f2}}}{\partial z}=h_{f2}S_{wf2}\left(\overline{T_{si}}-\overline{T_{f2}}\right)$$

- **Solid-phase energy:**

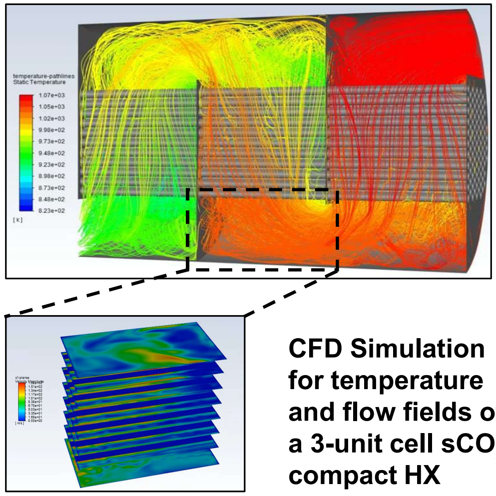
$$\phi_s\kappa_s\frac{\partial^2\overline{T_S}}{\partial x^2}=h_{f1}S_{w_{f1}}\left(\overline{T_{So}}-\overline{T_{f_1}}\right)+h_{f2}S_{w_{f2}}\left(\overline{T_{Si}}-\overline{T_{f_2}}\right)$$

Thermohydraulic Correlations

$$j_H\ or\ f=a_1\left(\frac{D_h}{D_E}\right)^{a_2}\left(\frac{P_t}{D_t}\right)^{a_3}\left(\frac{P_l}{2D_t}\right)^{a_4}\left(\frac{D_f}{D_t}\right)^{a_5}\left(\frac{P_f-\delta_f}{P_f}\right)^{a_6}Re_{D_h}^{a_7}$$



CFD model for flow non-ideality

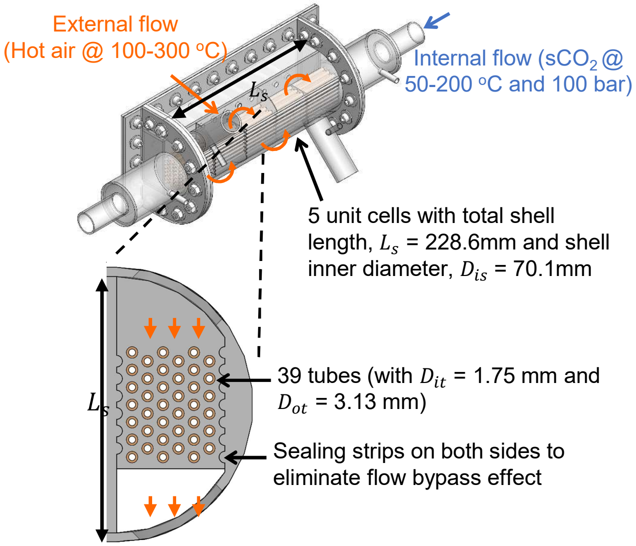


CFD Simulation for temperature and flow fields of a 3-unit cell sCO$_2$ compact HX

- HX performance model developed based on Volume Average Theory (VAT)
  - Improved correlations developed to estimate the Colburn factor and friction factor
  - CFD used to quantify flow maldistribution effects

Sub-scale Heat Exchanger Experiments

Sub-scale HX design

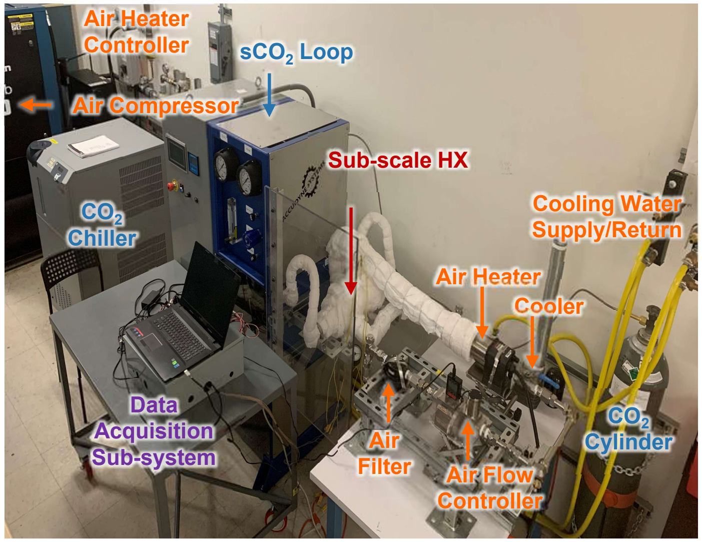


5 unit cells with total shell length, L_s = 228.6mm and shell inner diameter, D_{is} = 70.1mm

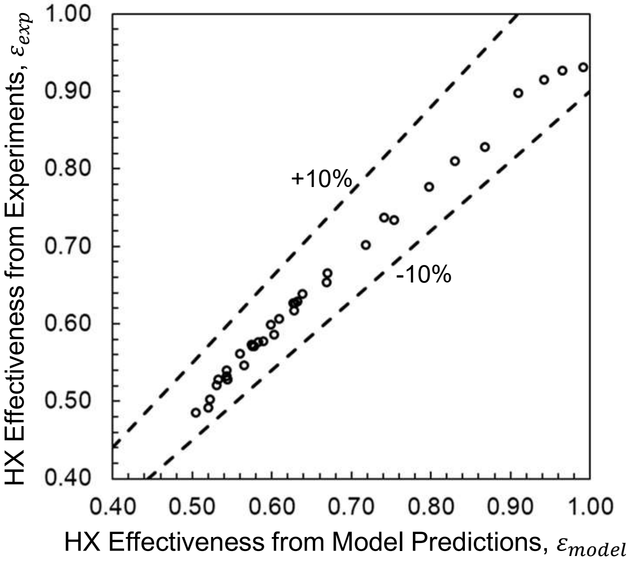
39 tubes (with D_{it} = 1.75 mm and D_{ot} = 3.13 mm)

Sealing strips on both sides to eliminate flow bypass effect

sCO_2-air test rig

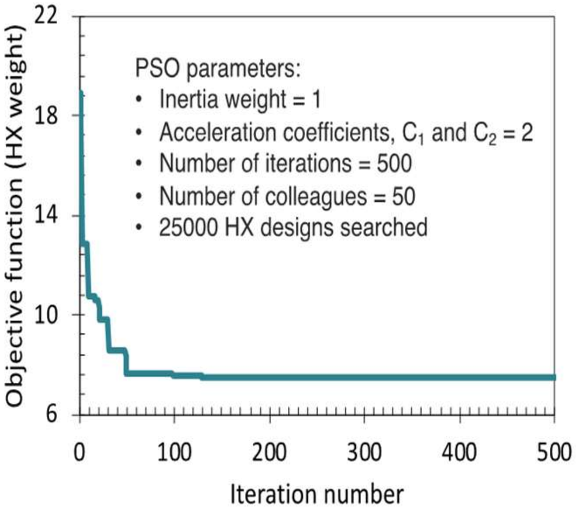


Model Validation



- Sub-scale microtube heat exchanger and test rig fabricated and exercised
  - Internal flow with sCO2, and external flow with air
  - Model predictions and test results agree very well (generally within ±5%)

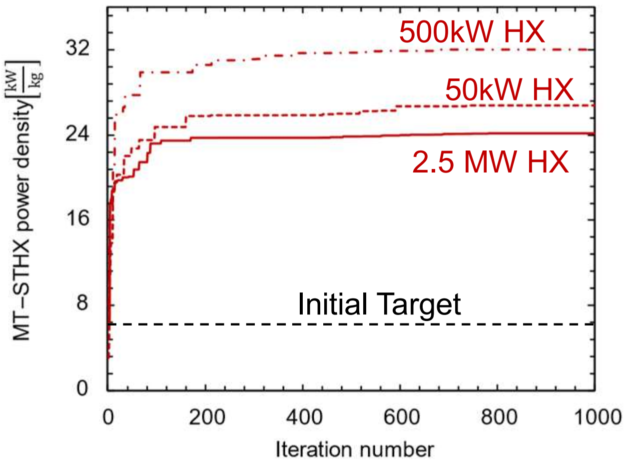
Heat Exchanger Optimization



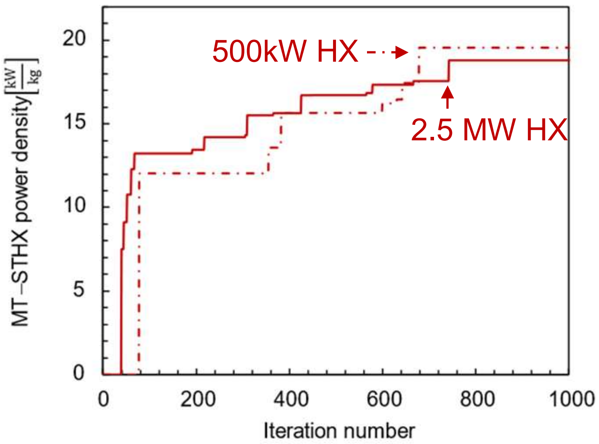
PSO optimization routine

PSO parameters:

- Inertia weight = 1
- Acceleration coefficients, C_1 and C_2 = 2
- Number of iterations = 500
- Number of colleagues = 50
- 25000 HX designs searched



Maximization of power density



Cost-constrained maximization of power density

- Optimization routine developed based on Particle Swarm Optimization (PSO)
  - >50,000 designs searched
  - Cost-constrained power density optimization demonstrated

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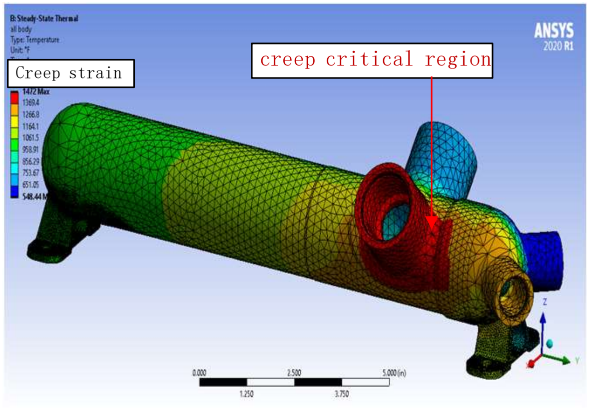
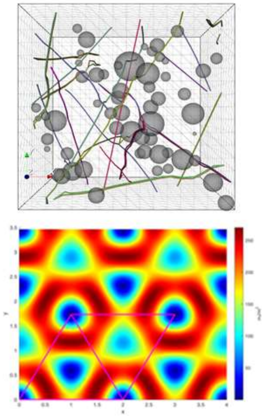
Thermomechanical Performance and Oxidation Resistance

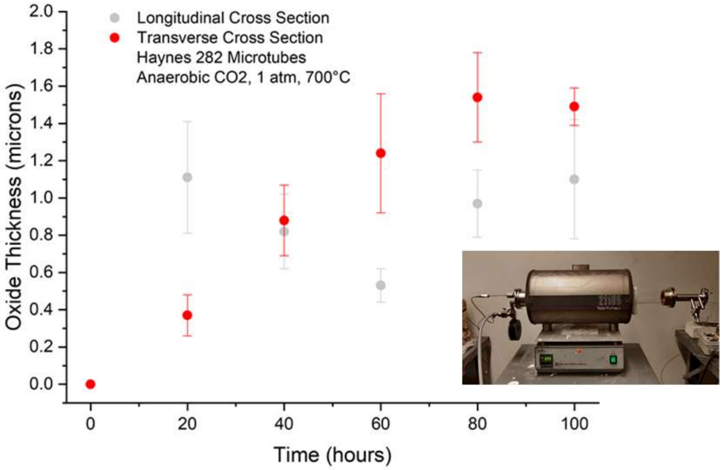
Linear creep model in ANSYS



Dislocation-diffusion continuum creep model



Oxidation rate for microtubes

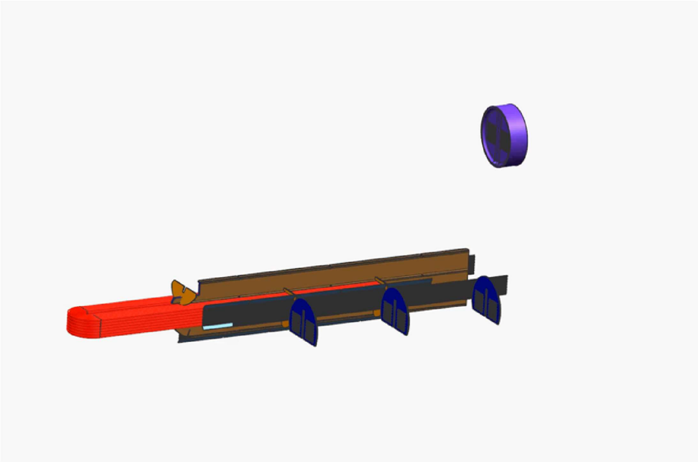


- Linear creep model developed in ANSYS
  - Flexible header with U-tubes applied
  - Creep life (MTBF) is equal or greater than 40,000 hours
- Non-linear creep model under development

- Haynes 282 oxidation in high-temperature CO2 is not mechanically detrimental
  - Thermal tests for microtubes completed

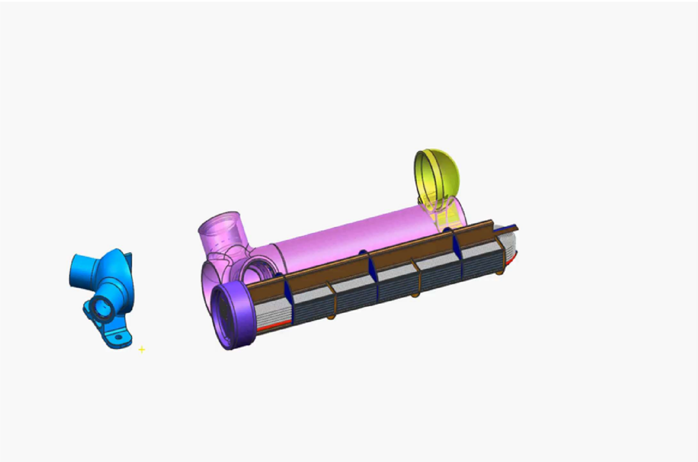
Manufacturing Process Sequence (50 kW Prototype)

Core Assembly



Sequence_CORE_assembly_MP4.mp4

Outer Assembly



Sequence_HX_assembly_MP4.mp4

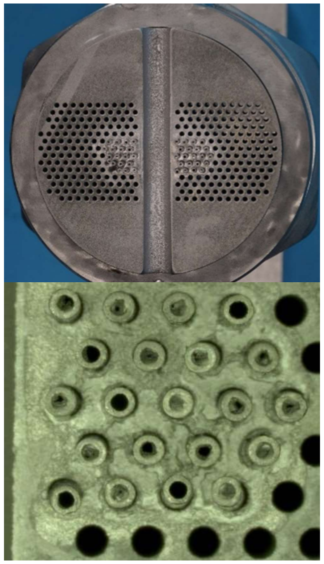
Core Assembly
- Stack Core
- Braze Core
- Heat Treat
- Pressure Test

Outer Assembly
- Weld Shell
- Weld Manifolds

Final Assembly
- Pressure Test
- Name Plate
- Final Inspection

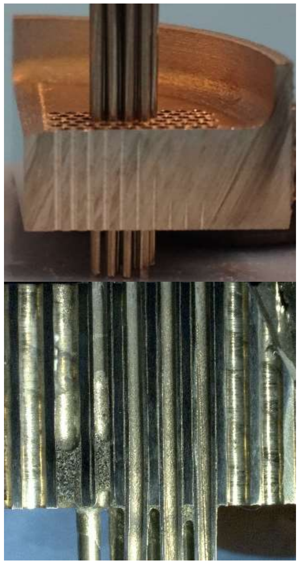
Brazing Development for Header Joining

Trial I

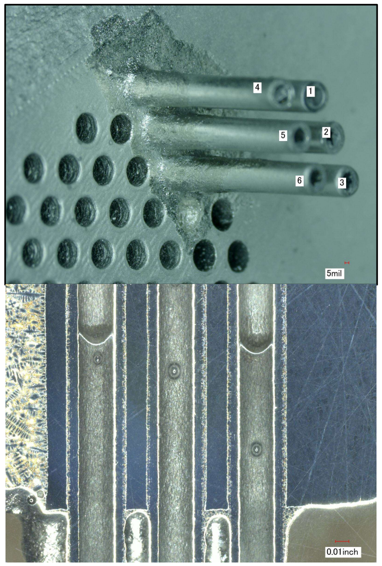


Trial II

Trial III

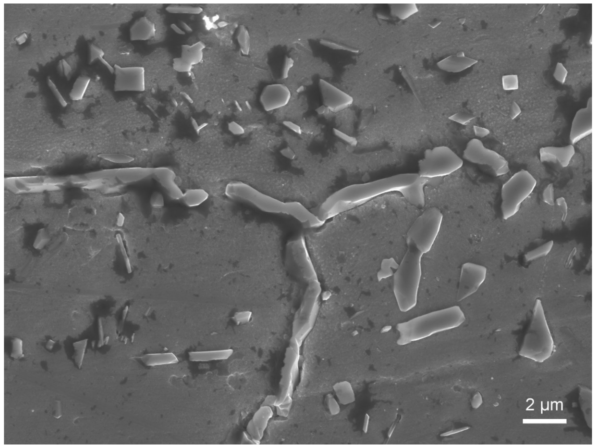


Trial IV

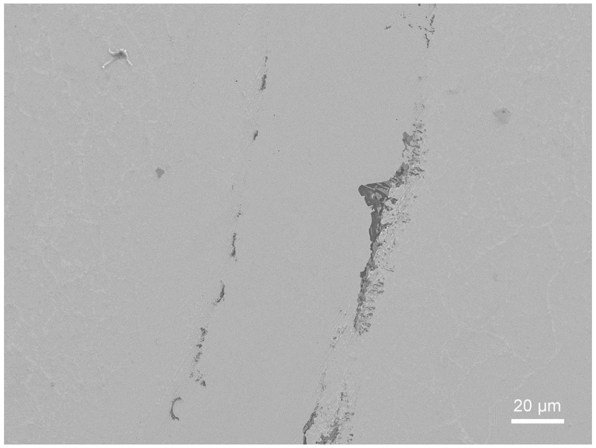


- Brazing development successfully completed
- Alternatives studied (e.g., TLP) – brazing remains the safest good choice

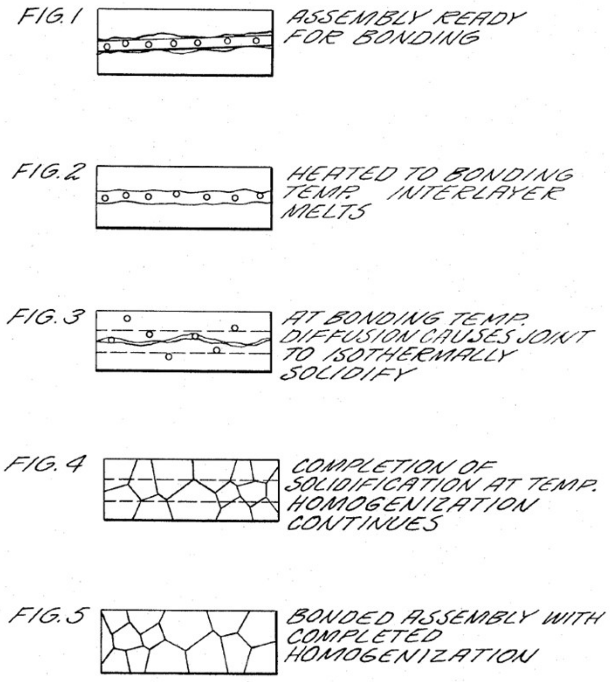
Alternative Joining Methods – Transient Liquid-Phase Bonding



Intergranular carbide coarsening in the microtube after joining



Cross section of the TLP joint



Paulonis, D. F., et al. **1972**

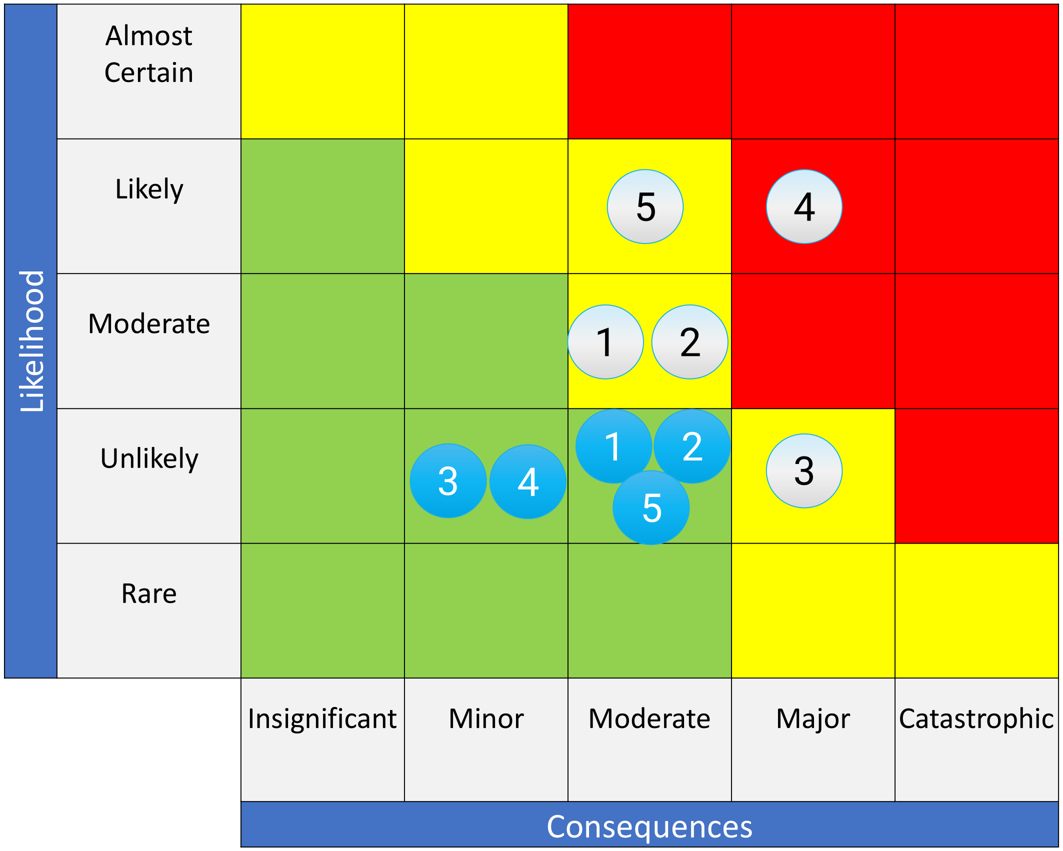
- Alternative Transient Liquid Phase (TLP) joining method under development
- Brazing tape (interlayer) liquidus is 1060°C
  - More work needed as a primary assembly method

Parts Fabricated by Additive Manufacturing

- Main components fabricated by 3D metal printing
- U-tubes obtained from wrought material

Risk Update

Risk
1. Material incompatibility between metal and fluid components at/near operating conditions
2. Material reliability compromised at/near operating conditions
3. Modest/no enhancement from topologically optimized inserts within manufacturing constraints
4. New header joining methods under development
5. Excessive projected cost of manufacturing for commercial-scale HX



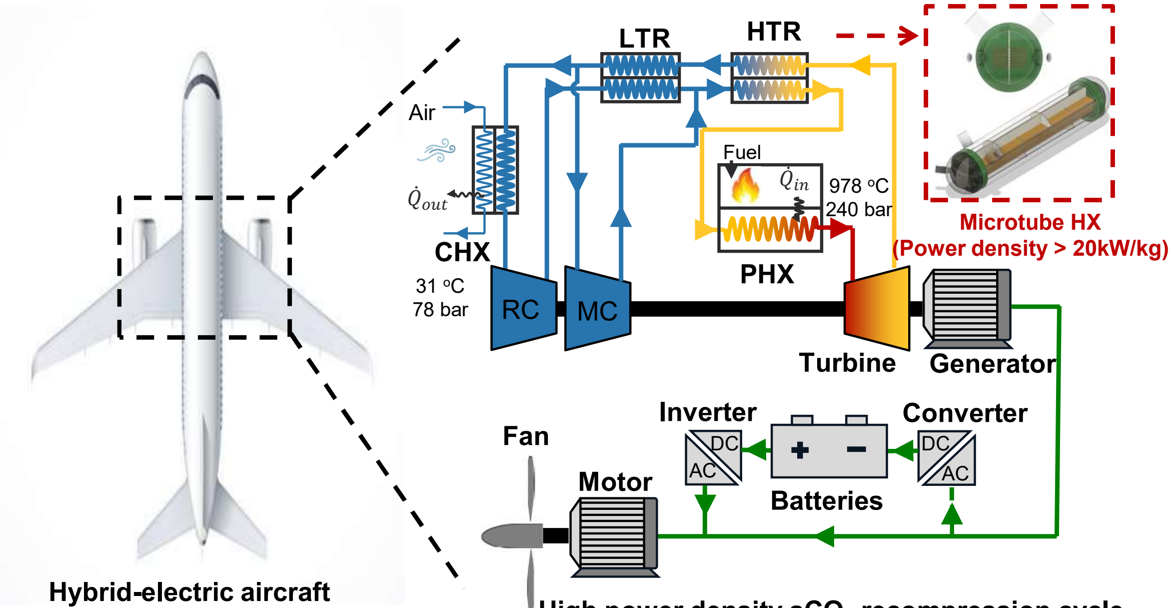
Likelihood	Insignificant	Minor	Moderate	Major	Catastrophic
Almost Certain	🟨	🟨	🟥	🟥	🟥
Likely	🟩	🟨	🟨 ○5	🟥 ○4	🟥
Moderate	🟩	🟩	🟨 ○1 ○2	🟥	🟥
Unlikely	🟩	🟩 ●3 ●4	🟩 ●1 ●2 ●5	🟨 ○3	🟥
Rare	🟩	🟩	🟩	🟨	🟨

Consequences

● Now

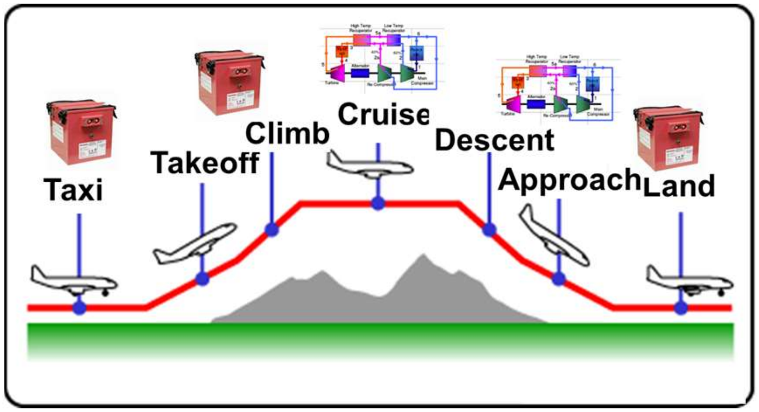
○ Start of project

sCO$_2$ Brayton Cycle for Hybrid Electric Propulsion



Hybrid-electric aircraft

High power density sCO$_2$ recompression cycle



Flight Stage	Taxi	Takeoff	Climb	Cruise	Descent	Land
Power Source	Batteries	Batteries	Batteries	sCO$_2$	sCO$_2$	Batteries
Battery Mode	Power	Power	Power	Charging	Charging	Power
sCO$_2$ Mode	Idle	Idle	Idle	Power	Power	Idle

- sCO$_2$ Brayton cycle for future hybrid electric aircraft
  - High thermal efficiency (47% vs. 29% for conventional aircraft engine)
  - **Microtube HX architecture is potentially applicable for all HXs in the system**

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Updated Cost Function

Total cost = Capital cost + Fuel cost[4] + Weight increment penalty cost + CO_2 penalty cost

Component	Source	Approximate Cost Scaling [$]
High T recuperator	SHOTEAM	$5{,}700 + 2.9 \times UA\ [W/K]$
Low T recuperator	SHOTEAM	$0.8 \times (5{,}700 + 2.9 \times UA)\ [W/K]$
Primary HX	ARPA-E Target	$5.0 \times UA\ [W/K]$
Cooling HX	Weiland et al.[1]	$33 \times (UA\ [W/K])^{0.75}$
Turbine	Weiland et al.[1]	$1.5 \times 9{,}800 \times (\dot{W}\ [kW])^{0.56}$
Compressor	Weiland et al.[1]	$78{,}000 \times (\dot{W}\ [kW])^{0.40}$
Combustor + air compressor	SHOTEAM	0.5× price of conventional engines with the same net power output ≈ $500 \times \dot{W}_{net}\ [kW]$

$$\boldsymbol{C_{op} = MTBF \times P_f \times \dot{m}_f}$$

- $MTBF = 40{,}000 \times 3600\ s$
- $P_f = \frac{\$0.53}{kg\ fuel}$
- $\dot{m}_f = \frac{\dot{Q}_{in}}{e_f} \frac{kg\ fuel}{s}$
- $e_f = 43.2 \times 10^6 \frac{J}{kg\ fuel}$

$$\boldsymbol{C_{wi} = c_w \times \left(\sum_i w_{sCO_2} - \sum_i w_{conv.}\right)}$$

- $c_w = \frac{\$1500}{kg}$
- w_i is the weight each main component in the sCO_2 cycle
- $w_{conv.}$ is the weight for a conventional engine and the fuel for a 5-hr operation (i.e., 1438 kg)

$$\boldsymbol{C_{CO_2} = w_{CO_2} \times P_{carbon}}$$

- $w_{CO_2} = MTBF \times \dot{m}_f \times \frac{C}{F}$
- $CO_2 \frac{C}{F} = 3.16 \frac{kg\ CO_2}{kg\ fuel}$
- $P_{carbon} = \frac{\$0.10}{kg\ CO_2}$

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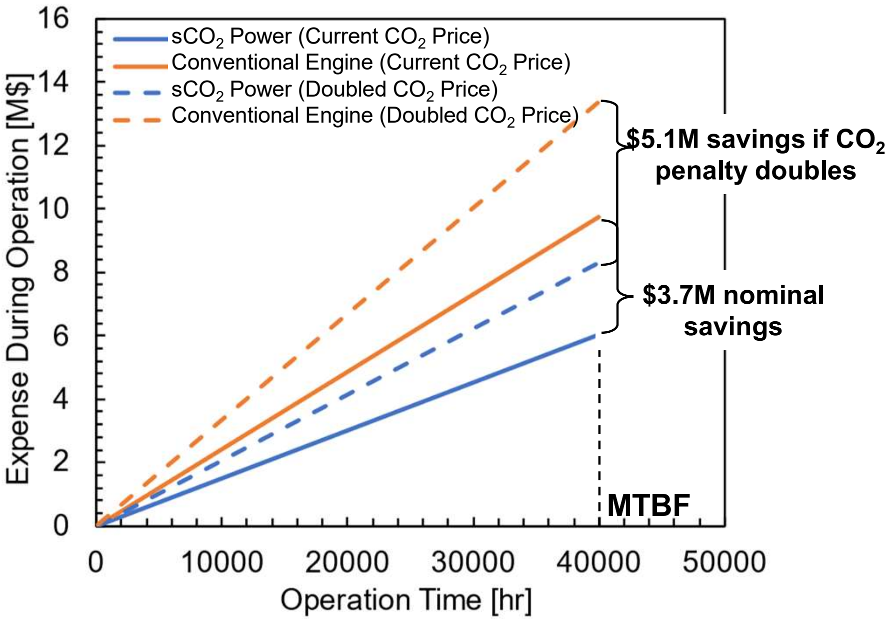
1. Weiland, N. T., Lance, B. W., & Pidaparti, S. R. (2019, June). In *ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition.* American Society of Mechanical Engineers Digital Collection.

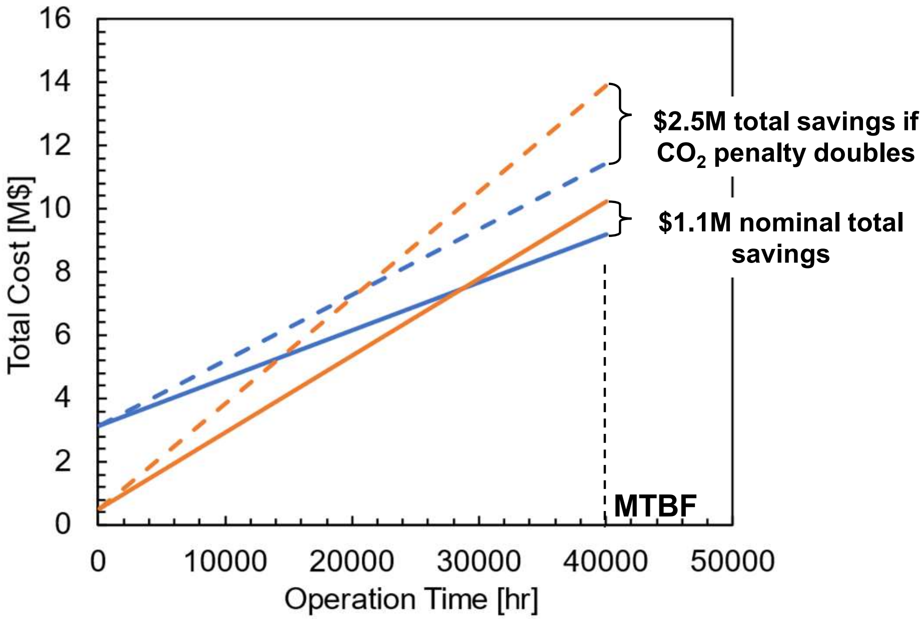
Cost Comparison between sCO_2 Cycle and Conventional Engine

- Expense during operation = Fuel cost + CO_2 emission price
- Total cost = Expense during operation + Capital cost + Weight penalty cost



$5.1M savings if CO_2 penalty doubles

$3.7M nominal savings



$2.5M total savings if CO_2 penalty doubles

$1.1M nominal total savings

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Thank you!

- This program has enabled unique synergies between academia and industry
  - Thermal performance modeling
    - Industry ‘spreadsheet’ model served as baseline
    - Emerging ‘data assimilation’ employed by academic team
    - Optimization: academics brought theory, industry brought cost realism
  - Thermomechanical reliability
    - Industry linear creep model served as baseline
    - Nascent theory developed for combined creep fatigue of thin-walled tubes
    - Possibility for insertion into industry practice
- Foregoing progress largely driven by ARPA-E’s T2M emphasis

Q & A

U.S. DEPARTMENT OF ENERGY

https://arpa-e.energy.gov