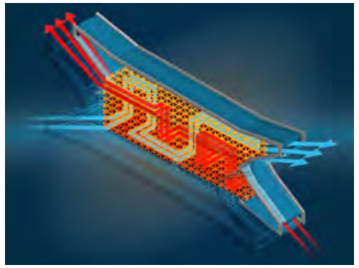
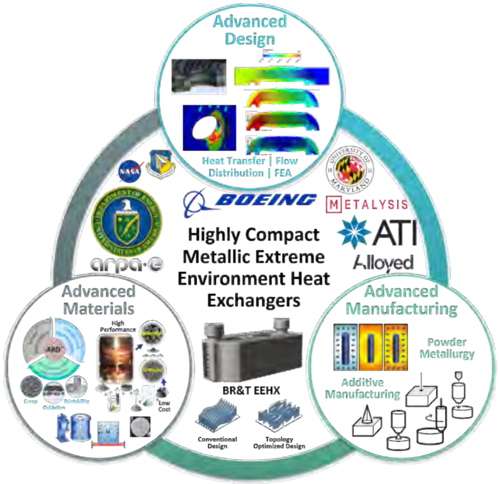
CHANGING WHAT'S POSSIBLE

Highly Compact Metallic Heat Exchangers for Extreme Environments (EEHX)

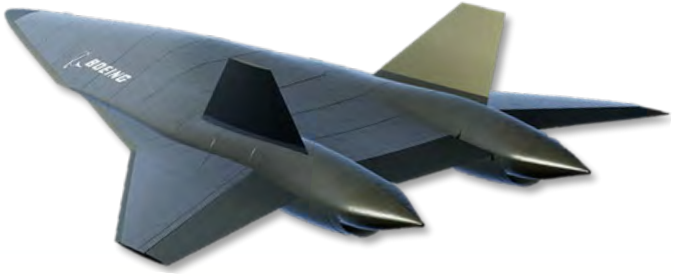


Dr. Ali Yousefiani
Boeing Research & Technology

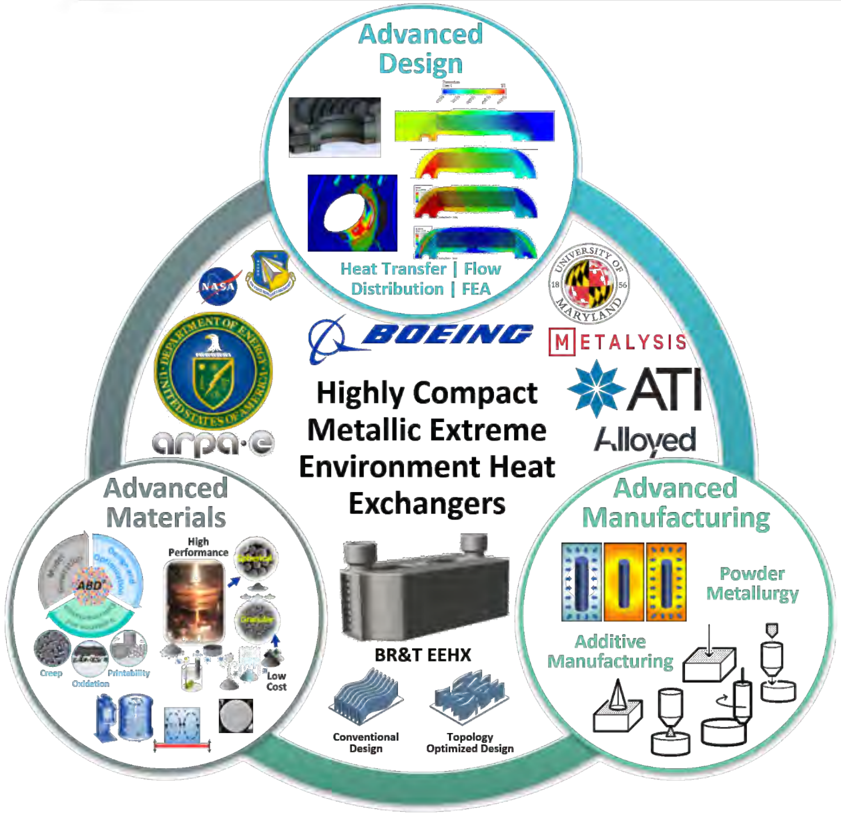


Project Vision

Develop topologically optimized heat exchangers, advanced materials, and manufacturing processes for use in long-life sCO_2 Brayton power cycles, which can be employed in Terrestrial Power Generation and in high efficiency Integrated Power & Thermal Management Systems (IPTMS) for high speed aircraft



Brief Project Overview



Boeing Research & Technology

PI: Dr. Ali Yousefiani

Co-PI: Dr. Arun Muley

- Lead EEHX design & development
- Lead materials and hybrid manufacturing process development
- Aerospace Tech-to-Market and Techno-economic Analysis
- Program management

Key Subs/Partners

- **NASA-GRC** (Dr. Tim Smith)
- **Alloyed** (Dr. David Crudden)
- **Voxel** (Mr. Daniel Herrington)

ATI Specialty Materials (Dr. John Foltz)
- Alloy powder production
- Materials characterization
- Additive Manufacturing

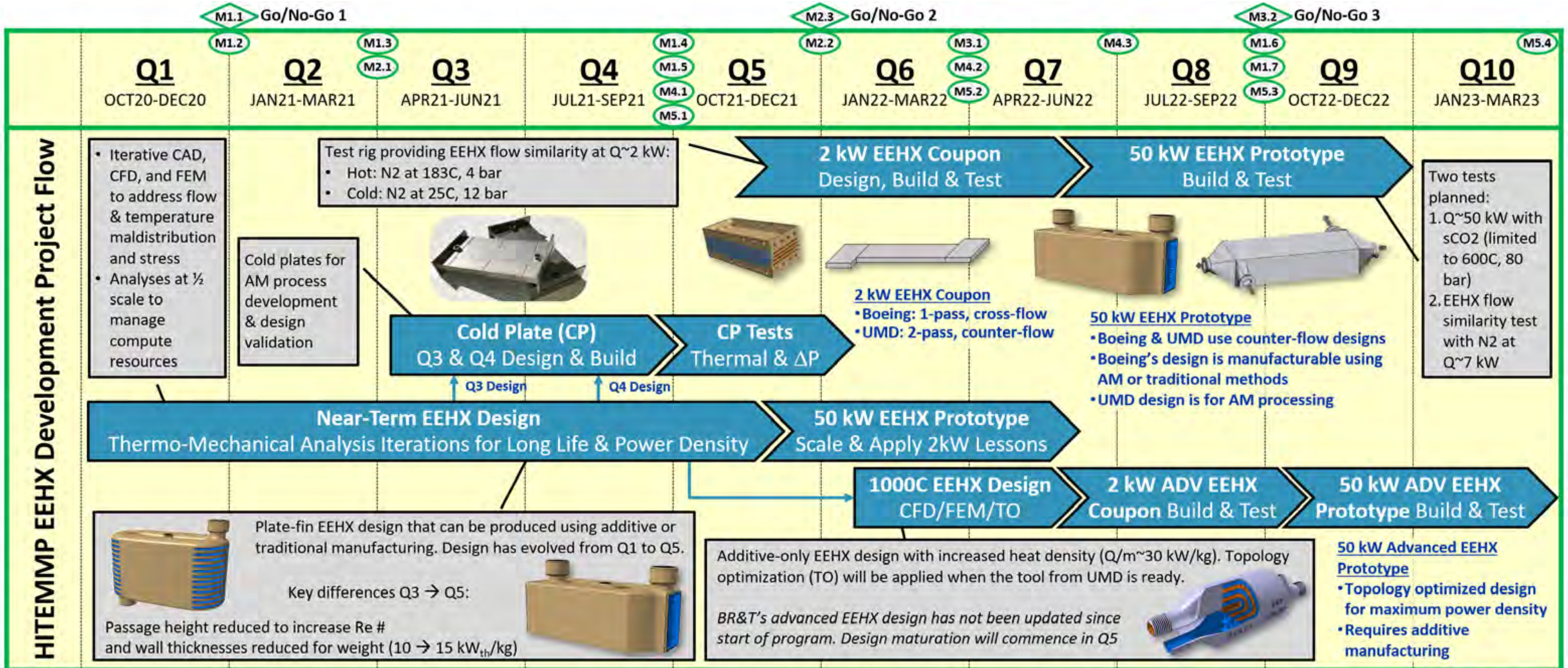
University of Maryland (Professor Hugh Bruck)
- Heat exchanger topology optimization
- EEHX testing
- Power generation Tech-to-Market

Air Force Research Laboratory (Dr. Eric Payton)
- Alloy selection
- Alloy production
- Materials characterization

Metalysis (Dr. Ian Mellor)
- Non-traditional alloy powder production
- Tech-to-Market for non-traditional powder production
- Materials characterization

- Metallic materials solutions capable of continuous operation at temperatures up to 1000°C (1832°F) and pressures above 80 bar (1160 psi) for tens of thousands of hours
- Design and fabricate topologically optimized heat exchangers for use in long-life sCO_2 Brayton power cycles, which can be employed in Terrestrial Power Generation and in high efficiency Integrated Power & Thermal Management Systems for high speed aircraft

Progress Against Tasks – Timetable



- Iterative CAD, CFD, and FEM to address flow & temperature maldistribution and stress
- Analyses at ½ scale to manage compute resources

Cold plates for AM process development & design validation

Test rig providing EEHX flow similarity at Q~2 kW:
- Hot: N2 at 183C, 4 bar
- Cold: N2 at 25C, 12 bar

2 kW EEHX Coupon
- **Boeing: 1-pass, cross-flow**
- **UMD: 2-pass, counter-flow**

50 kW EEHX Prototype
- **Boeing & UMD use counter-flow designs**
- **Boeing's design is manufacturable using AM or traditional methods**
- **UMD design is for AM processing**

Two tests planned:
1. Q~50 kW with sCO2 (limited to 600C, 80 bar)
2. EEHX flow similarity test with N2 at Q~7 kW

Plate-fin EEHX design that can be produced using additive or traditional manufacturing. Design has evolved from Q1 to Q5.

Key differences Q3 → Q5:

Passage height reduced to increase Re # and wall thicknesses reduced for weight (10 → 15 kW_{th}/kg)

Additive-only EEHX design with increased heat density (Q/m~30 kW/kg). Topology optimization (TO) will be applied when the tool from UMD is ready.

BR&T's advanced EEHX design has not been updated since start of program. Design maturation will commence in Q5

50 kW Advanced EEHX Prototype
- **Topology optimized design for maximum power density**
- **Requires additive manufacturing**

Milestone Titles

M1.1: Go/No Go 1: Finalize environmental durability requirements and refine tasks/milestones [Q1]
M1.2: Initial T2M Plan submitted for ARPA-E acceptance and initial impact sheet drafted [Q1]
M1.3: Preliminary applications identified for EEHX technology and presented to ARPA-E [Q2]
M1.4: Small Business Mentoring [Q4]
M1.5: Intermediate T2M Plan submitted for ARPA-E acceptance [Q4]
M1.6: Final T2M Plan submitted for ARPA-E acceptance [Q8]
M1.7: Technical assessment of commercial potential of additively-manufactured heat exchangers [Q8]
M2.1: Candidate materials for EEHX presented to ARPA-E [Q2]
M2.2: Candidate materials ready for fabrication of EEHX coupons [Q5]
M2.3: Go/No-Go: Candidate materials with demonstrated environmental durability presented to ARPA-E [Q5]
M3.1: Manufacturing processes for Near-Term EEHX presented to ARPA-E [Q6]
M3.2: Go/No-Go: Manufacturing processes for Aircraft IPTMS EEHX presented to ARPA-E [Q8]
M4.1: Design and thermo-mechanical analyses for a Near-Term EEHX presented to ARPA-E [Q4]
M4.2: MDTO EEHX design tool validation presented to ARPA-E [Q6]
M4.3: Design and analyses for an aircraft IPTMS EEHX presented to ARPA-E [Q7]
M5.1: Test facility and plan presented to ARPA-E [Q4]
M5.2: EEHX Test facility setup and checkout complete [Q6]
M5.3: Near-Term EEHX Demonstration test results presented to APRA-E [Q8]
M5.4: Advanced EEHX Demonstration test results presented to ARPA-E [Q10]

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Material Selection Goals/Requirements

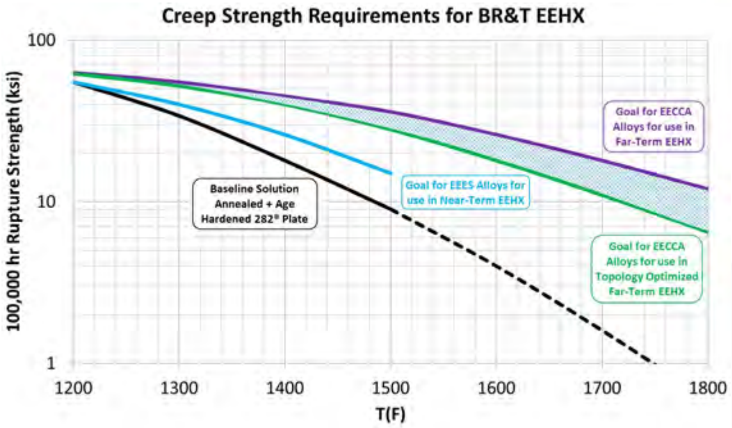
800°C Alloys

Property	Goal	Test Method
Room Temperature Tensile Properties	YS > 100 ksi, UTS > 150 ksi, %El > 10 %	ASTM E8
800°C Tensile Properties	YS > 80 ksi, UTS > 100 ksi, %El > 10 %	ASTM E21
100,000 hour Creep Rupture Strength at 800°C	Demonstrated to be greater than 15 ksi, based on extrapolation of data from 10/100/1,000/4,000 hour creep rupture tests	ASTM E139
Thermal Conductivity at 800°C	> 170 Btu·in/h·ft^{2}·°F	ASTM E1225
Linear Coefficient of Thermal Expansion (RT - 800°C)	< 8.5 (in/in.°F) x 10^{-6}	ASTM E228
SCO_2 Environmental Resistance	No Failure after 10,000 hr exposure	BR&T specialized simulated service testing at 800°C
Thermal Stability	RT tensile properties after 10,000 hr exposure > 80% unexposed values	BR&T specialized simulated service testing at 800°C

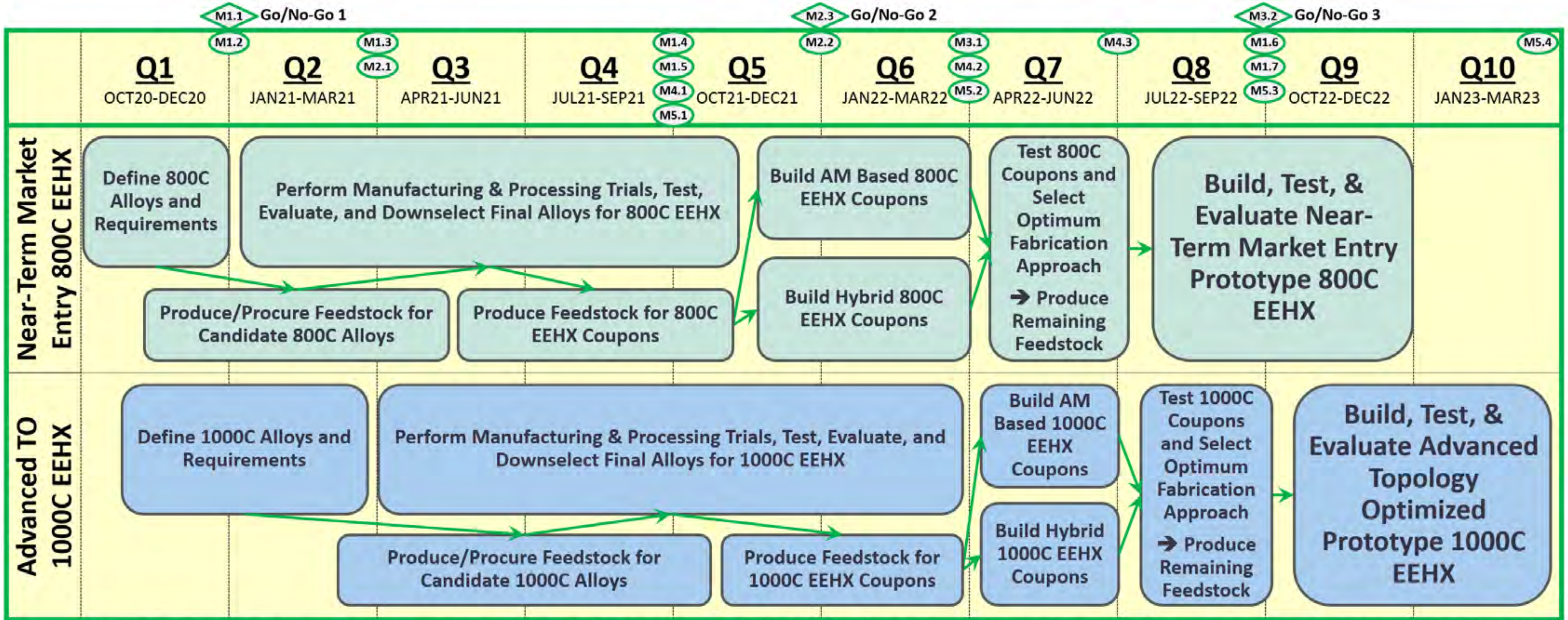
1000°C Alloys

Property	Goal	Test Method
Room Temperature Tensile Properties	YS > 100 ksi, UTS > 150 ksi, %El > 10 %	ASTM E8
1000°C Tensile Properties	YS > 35 ksi, UTS > 60 ksi, %El > 10 %	ASTM E21
100,000 hour Creep Rupture Strength at 1000°C	Demonstrated to be greater than 6.5 ksi, based on extrapolation of data from 10/100/1,000/4,000 hour creep rupture tests	ASTM E139
Thermal Conductivity at 1000°C	> 190 Btu·in/h·ft^{2}·°F	ASTM E1225
Linear Coefficient of Thermal Expansion (RT - 1000°C)	< 9.5 (in/in.°F) x 10^{-6}	ASTM E228
SCO_2 Environmental Resistance	No Failure after 10,000 hr exposure	BR&T specialized simulated service testing at 1000°C
Thermal Stability	RT tensile properties after 10,000 hr exposure > 80% unexposed values	BR&T specialized simulated service testing at 1000°C

Key Governing EEHX Failure Mechanisms:
Creep Deformation/Rupture, Oxidation, Environmentally Assisted Cracking, Microstructural Degradation, and Thermal Stability


Creep Strength Requirements for BR&T EEHX

Material Selection & Manufacturing Timetable



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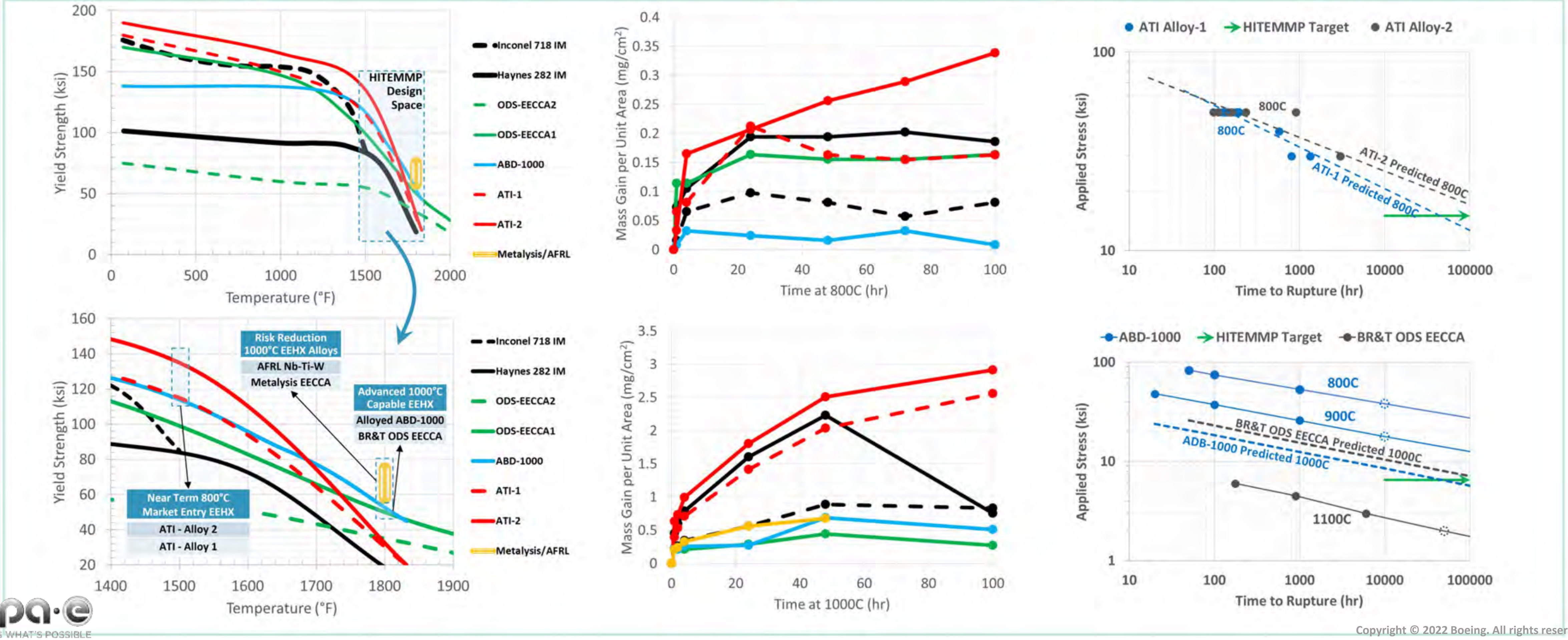
CHANGING WHAT'S POSSIBLE

Material Selections

- **Near Term Market Entry 800°C EEHX Alloys**
  - ATI Alloy 1
  - ATI Alloy 2
- **Advanced Topology Optimized 1000°C EEHX Alloys**
  - Alloyed ABD®-1000
  - BR&T ODS-EECCA
- **Risk Reduction 1000°C EEHX Alloys**
  - Metalysis EECCA
  - AFRL EECCA



arpa·e CHANGING WHAT'S POSSIBLE

Manufacturing Process Development Updates

Near Term Market Entry
800°C EEHX Alloys

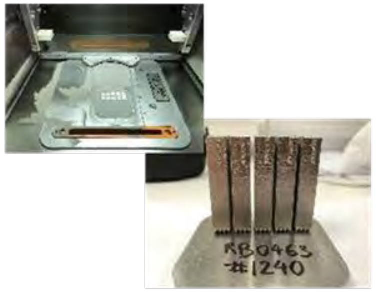
ATI Alloy 1

ATI Alloy 2

Advanced Topology Optimized
1000°C EEHX Alloys

Alloyed ABD®-1000

BR&T ODS-EECCA

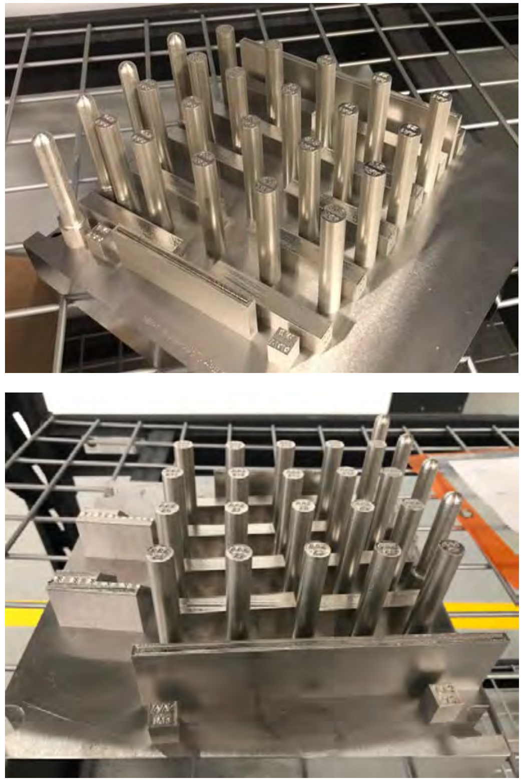


Risk Reduction
1000°C EEHX Alloys

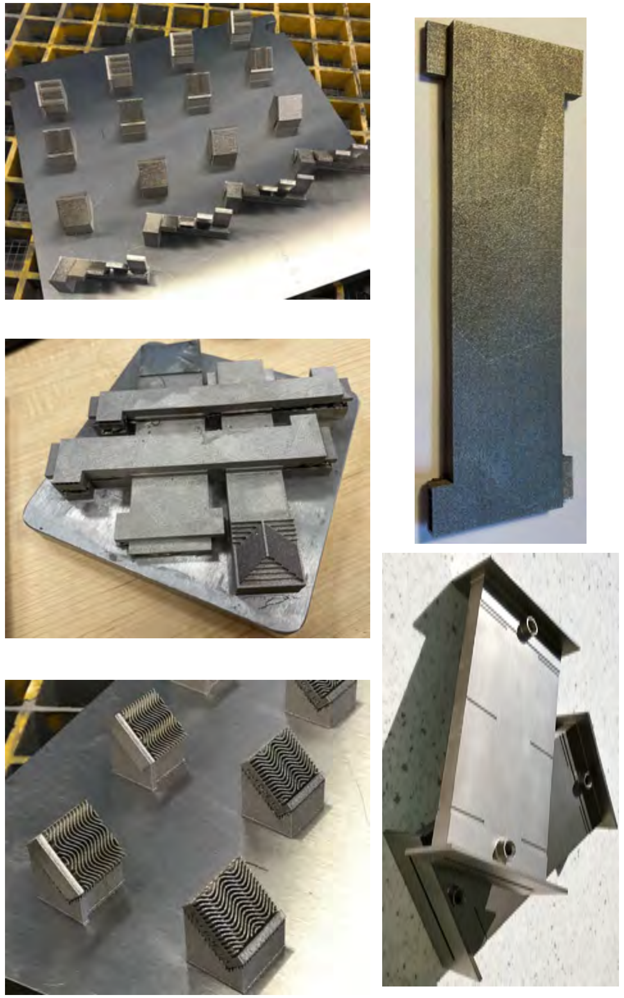
Metalysis EECCA

AFRL EECCA

Fabrication of Protype Heat Exchangers

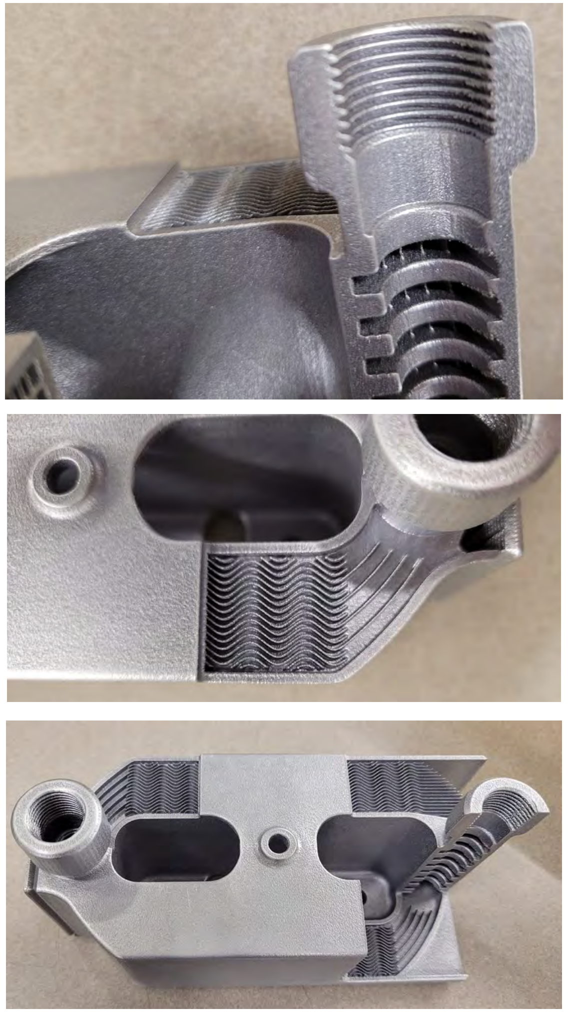


Property Coupons



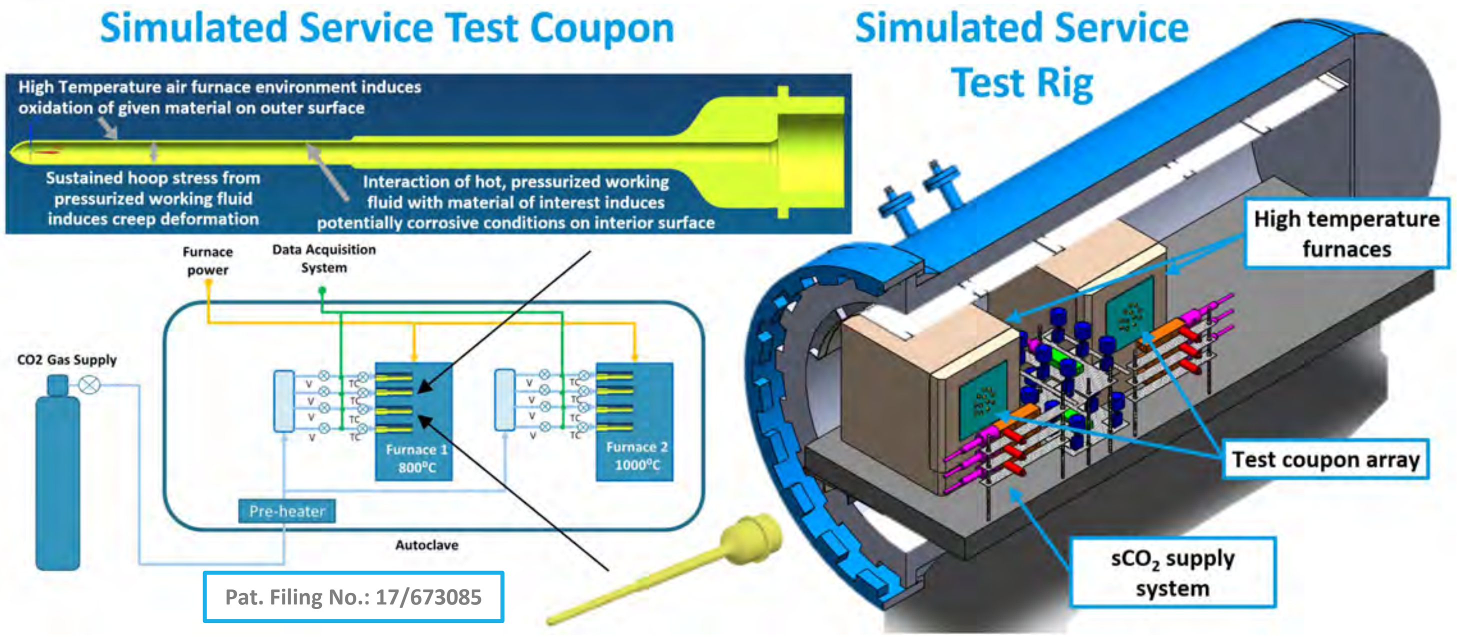
Feature/Test Coupons

2 kW EEHXs



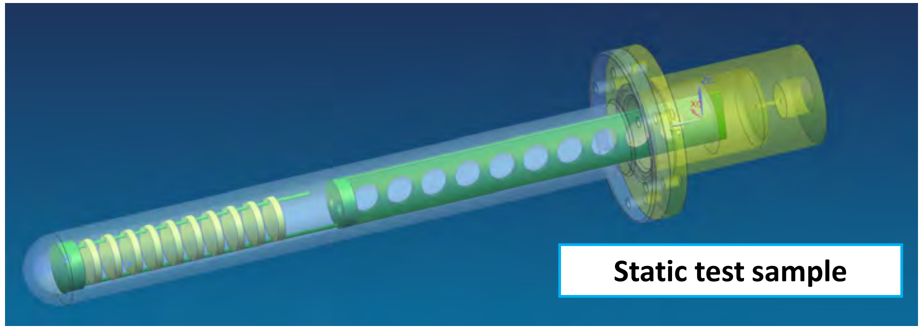
Scaled 50 kW Prototype

Boeing’s Simulated Service and Material Compatibility Test Rig



Pat. Filing No.: 17/673085

Testing starts April-May



- Test bed capable of high temperature (currently up to 1100°C), long-term exposure of multiple alloys and/or processing conditions under predetermined sustained stresses
- A dynamic system, simultaneously exposing test specimens to high temperature corrosion (oxidation), creep, and environmentally assisted cracking in a given working fluid (currently SCO_2)
- Test sample geometry allows replication of thermomechanical loading profile and environmental exposure aspect of Boeing EEHX designs
- Test rig will also be utilized for evaluation of static high temperature corrosion (oxidation) in SCO_2 of multiple alloys and/or processing conditions

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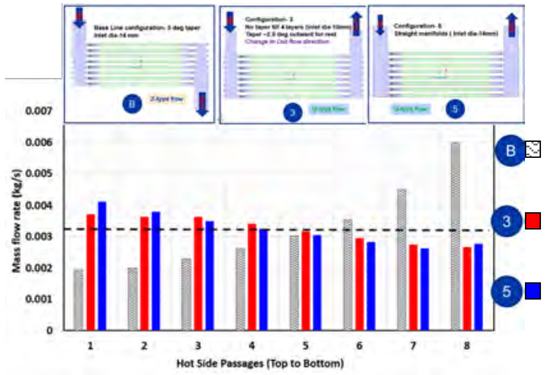
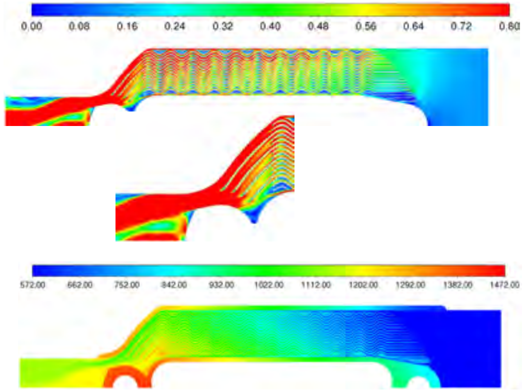
Boeing Near-Term EEHX Design and Analysis

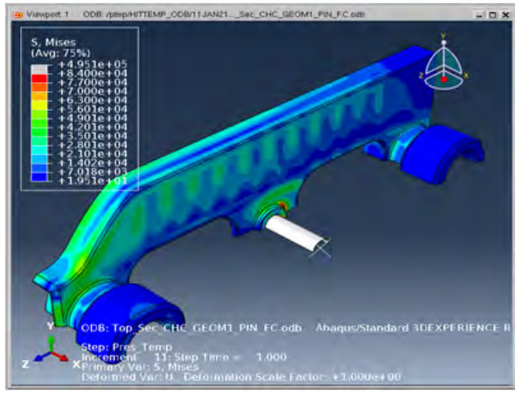
Initial Design



Porous Media CFD to assess Manifold Flow Maldistribution



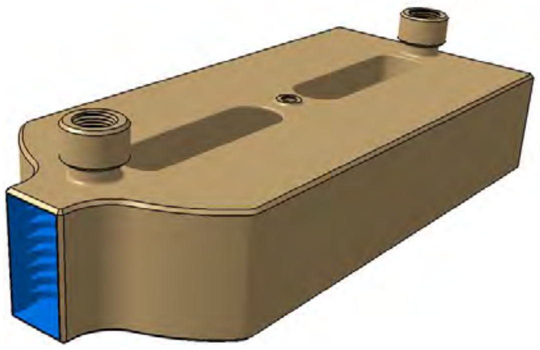
Conjugate Heat Transfer Analysis for Velocity & Temp Distributions



FEM Structural Analysis for Stress Distributions

- Boeing's EEHX design is manufacturable using traditional or additive processes
  - Achieves very low dP/P at expense of heat density
- Design and Analysis approach
  - Initial design that balances performance and manufacturability
  - Porous media CFD analysis to optimize manifold flow distribution
  - Conjugate heat transfer to establish internal flow and temperature distributions
  - FEM analysis to evaluate stress levels and inform design

HX Parameters	50kW Design
Capacity [kW]	51.0
Fluid	sCO2
Pressure drop ratio, both sides	<0.05%
T_hot in [C], P_hot in [bar]	800, 80
T_cold in [C], P_cold in [bar]	300, 250
Mass flow rate [kg/s]	0.104
Effectiveness	0.81
Number of passes	1
Gravimetric heat density [kW/kg]	15
Volumetric heat density [kW/L]	53



50 kW EEHX Design

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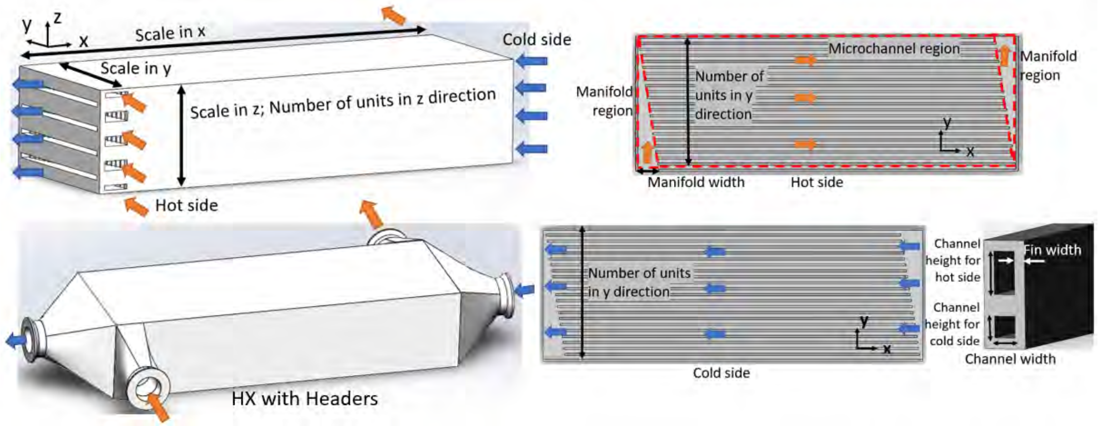
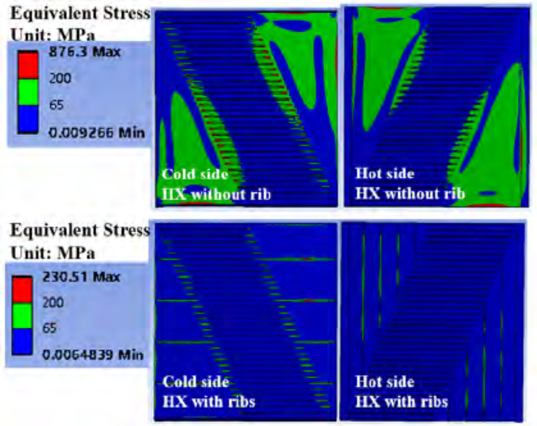
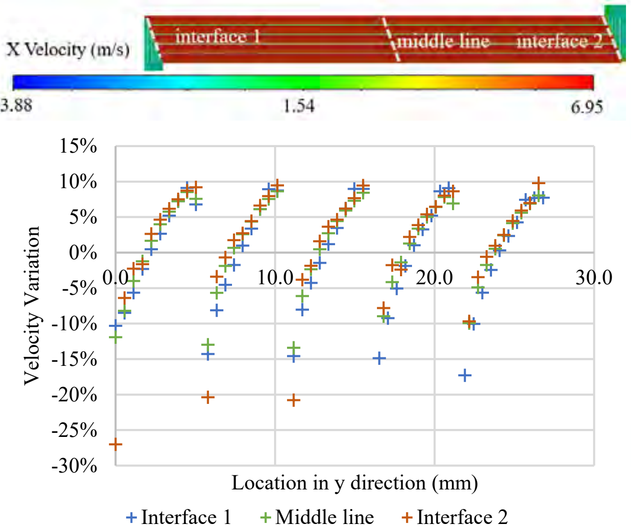
UMD Manifold Microchannel (MMC)_ EEHX Design & Analysis



Schematic Diagram of HX Design as well as The Internal Structure for Cold and Hot Sides



FEM Stress Analysis for a Simplified Model



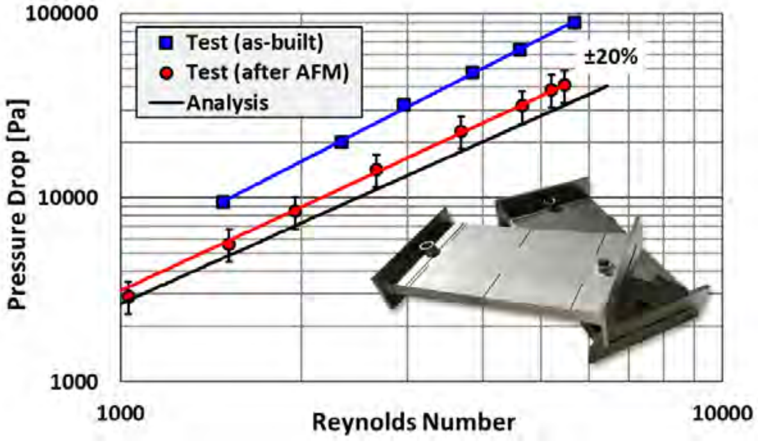
Porous Media CFD Analysis to Assess Flow Maldistribution

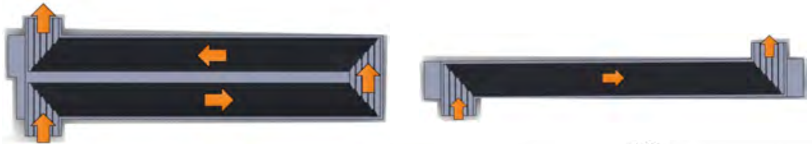
- UMD's EEHX is manufacturable using the DMLS technique
- Design and analysis approach
  - Correlation-based prediction model to develop HX design
  - FEM analysis to evaluate mechanical performance
  - Porous media CFD to evaluate flow distribution in the microchannel region

HX Parameters	50kW Design
Capacity [kW]	50.6
Fluid	sCO2
Pressure drop ratio, both sides	1.2%
T_hot in [C], P_hot in [bar]	800, 80
T_cold in [C], P_cold in [bar]	300, 250
Mass flow rate [kg/s]	0.1
Effectiveness	0.8
Number of passes	2
Gravimetric heat density [kW/kg]	49
Volumetric heat density [kW/L]	284

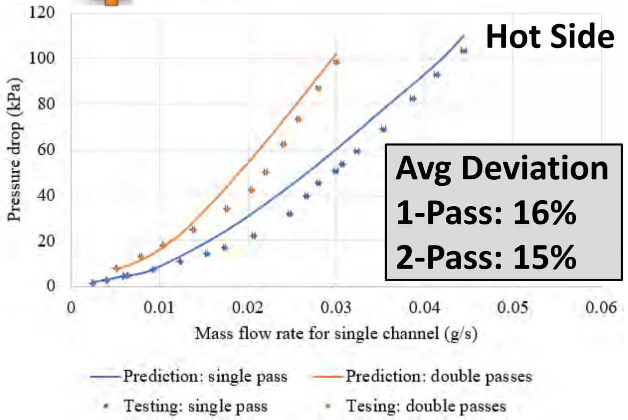
EEHX Coupon Testing

- EEHX coupons subjected to isothermal pressure drop testing using air
  - Average deviation between test and model results within 20%

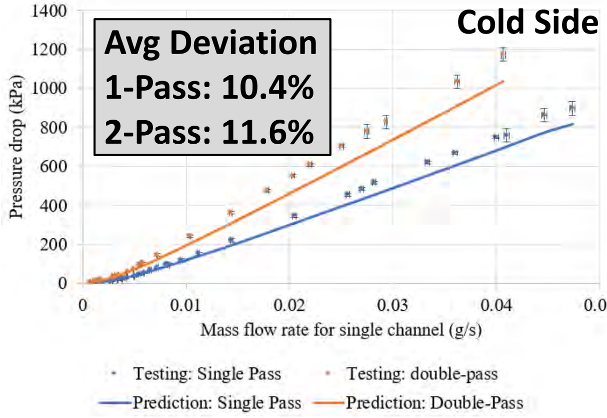




Dual and single pass MMC HXs



Avg Deviation
1-Pass: 16%
2-Pass: 15%

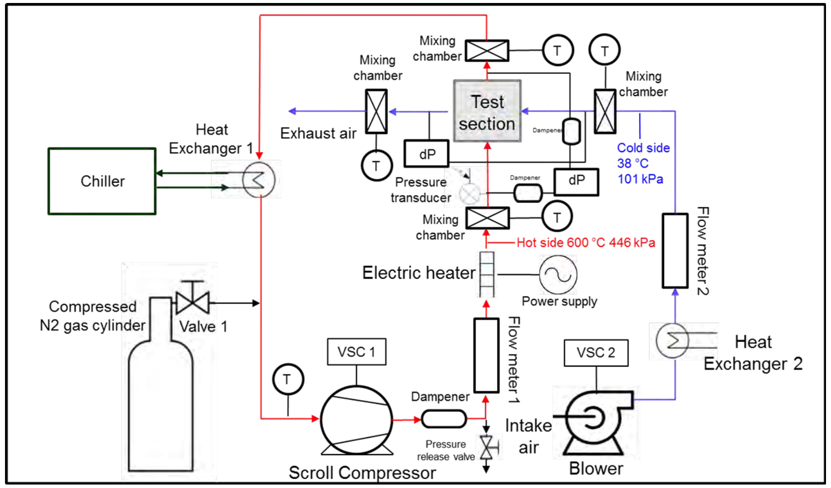


Avg Deviation
1-Pass: 10.4%
2-Pass: 11.6%

- Preparations for thermal testing at UMD are underway
  - 2 kW EEHX units to be tested using existing low temperature rig (air-N2)
  - 50 kW EEHX prototypes to be tested using new closed-loop CO2 rig

CHANGING WHAT'S POSSIBLE

UMD Heat Exchanger Test Rigs



Low Temperature Air-N2 Rig

- Testing of 2 kW EEHX coupons

High Temperature sCO2 Test Rig

- Closed-loop 50 kW test rig using sCO2
  - Operation limited to 80 bar and 600C
- Estimated completion in May 2022

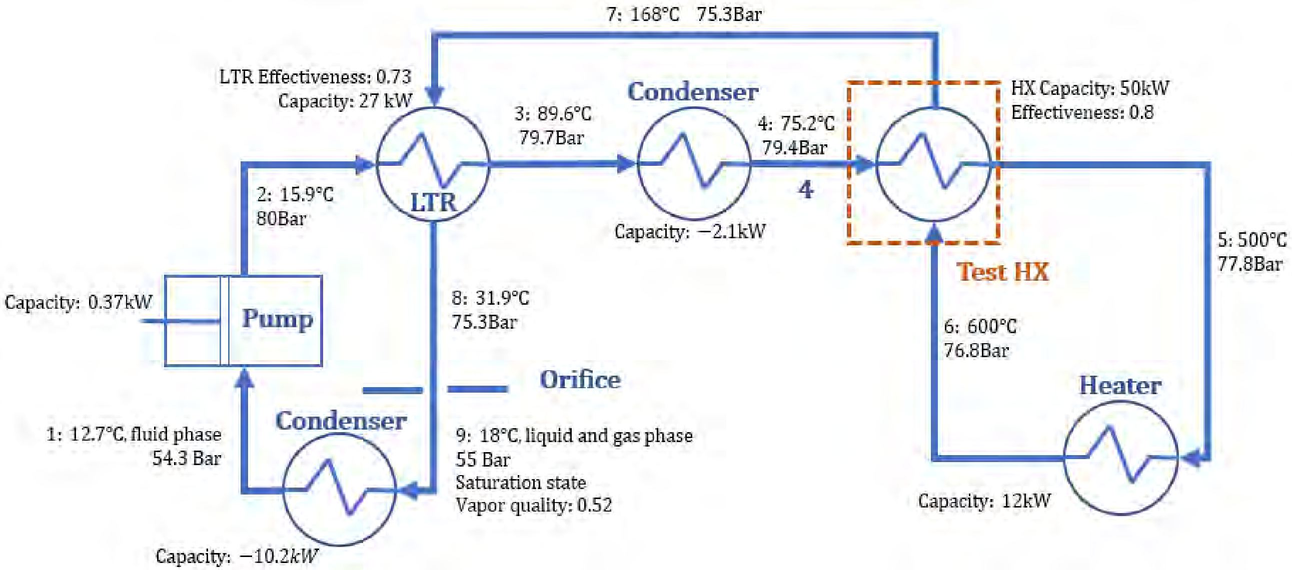
❖ **Hot-side Temp: 600°C**

❖ **Hot-side Pressure: 76 Bar**

❖ **Cold-side Temp: 75°C**

❖ **Cold-side Pressure: 80 Bar**

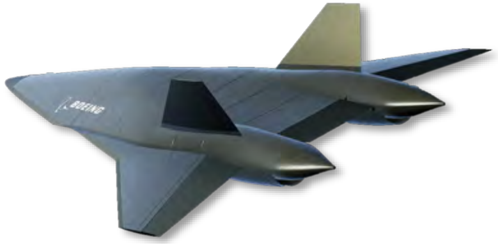
❖ **CO2 mass flow: 0.1 kg/s**

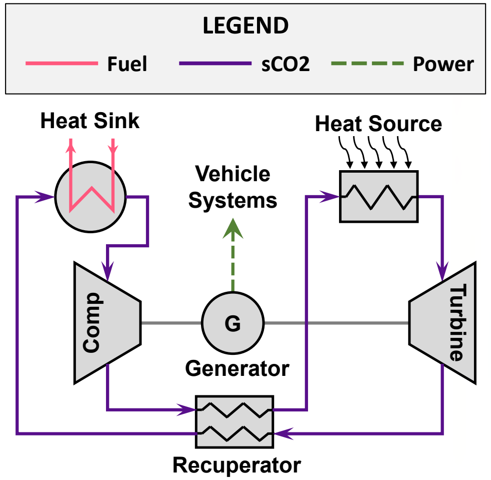


Technology-to-Market Updates: Aerospace

Integrated Power & Thermal Management System (IPTMS) for High-Mach Vehicles

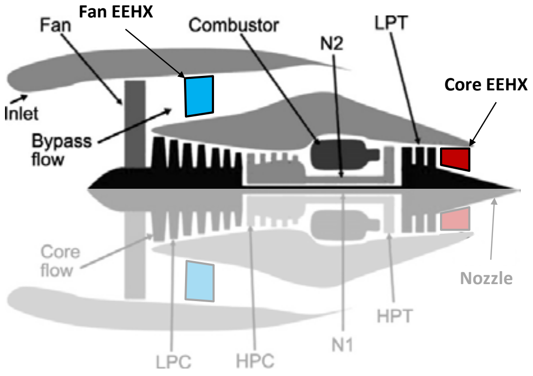
- Improve cruise SFC by 10-15%
- Follow-ons & Partnerships
  - NASA hypersonic civil aircraft study (executing)
  - DOD IPTMS ground demonstration (in negotiations)
- Patents & Publications
  - US20200407072A1 (IPTMS patent app)
  - AIAA-2021-3531 (2021 AIAA Propulsion & Energy Forum)

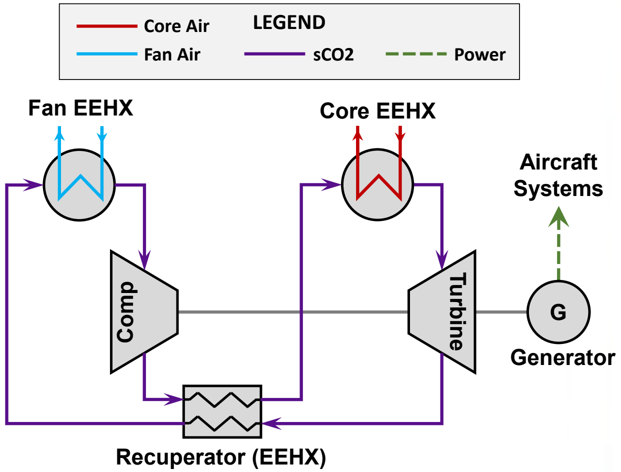




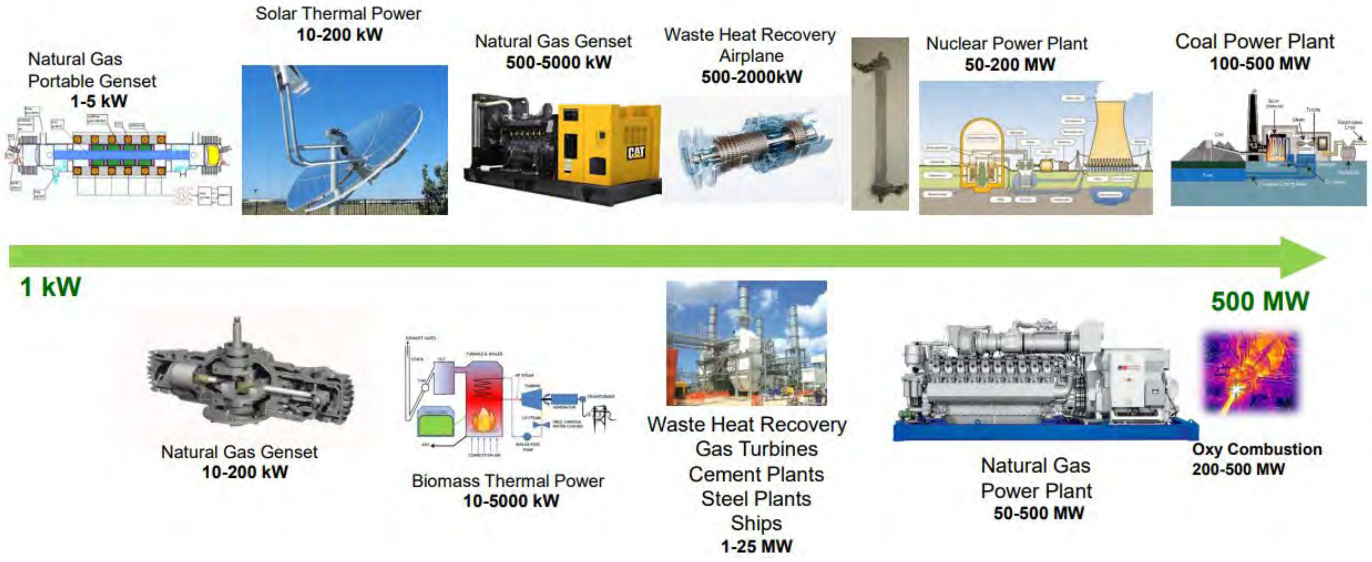
Waste Heat Recovery (WHR) from Aircraft Engines

- Improve SFC by up to 4.5%
- Follow-ons & Partnerships
  - NASA: Study ammonia as aviation fuel, WHR using sCO2 Brayton cycle (starting 3Q22)
    - Partners: UCF, GA Tech, Purdue, GE
- Patents & Publications
  - AIAA-2022-1407 (2022 AIAA SciTech Forum)
  - ASME-GT2022-84359 (2022 ASME Turbo Expo)

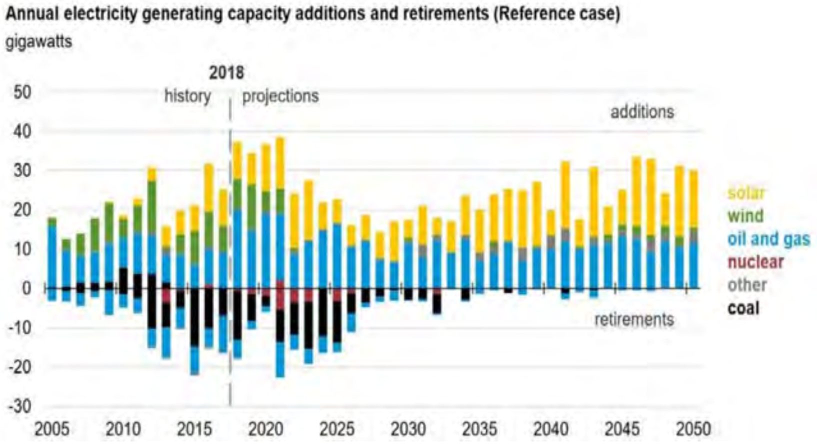




Technology-to-Market Updates: Terrestrial



- Challenges
  - CO2 CAPEX is high
  - LCOE similar to NGCC plants
- Advantages
  - Higher plant efficiency
  - Dry-cooling for arid climates



https://www.osti.gov/servlets/purl/1606297

- Projected Market through 2050
  - 2-3 GW of new sCO2 capacity
    - Assumes 20-30% of Natural Gas Combined Cycle (NGCC) plants replaced by sCO2
  - $0.8-$1.2B HITEMMP HX market
    - HX estimated at ~19% of total equipment costs

Risk Update

ID#	Risk
1	Thermal: HX Flow maldistribution on low pressure side fluid. Additional flow maldistribution possible in HX core or z direction inside the cold side fluid header
2	Mechanical: HX cannot withstand required pressure at desired temperature. Also, excessive temperature gradient in the EEHX core. Steep temperature variation can result in localized hot spots and breach of structural robustness
3	Materials: Lack of environmental durability in novel alloys
4	Manufacturing: Novel alloy printability, machinability, formability, joinability, and capability to meet tight channel tolerances during PECM and surface roughness and wall tolerance requirements during LBPBF AM
5	Adoption (EEHX): Market value for improved power cycle efficiency stemming from operation at >1000°C (vs. 800°C) may not overcome added cost and complexity associated with balance of plant (BOP) hardware designed for >1000°C service
6	Adoption (EEHX Materials): Novel alloys will have limited commercial uses and may be prohibitively expensive to produce in low volumes, which could compromise the market value of improved thermodynamic efficiency associated with operating at >1000°C

The materials risk (#3) has been downgraded to "unlikely", based largely on 1000-hour oxidation studies of the candidate EEHX alloys