Oscillating Heat Pipe (OHP) Development for Electric Aircraft Thermal Management Systems

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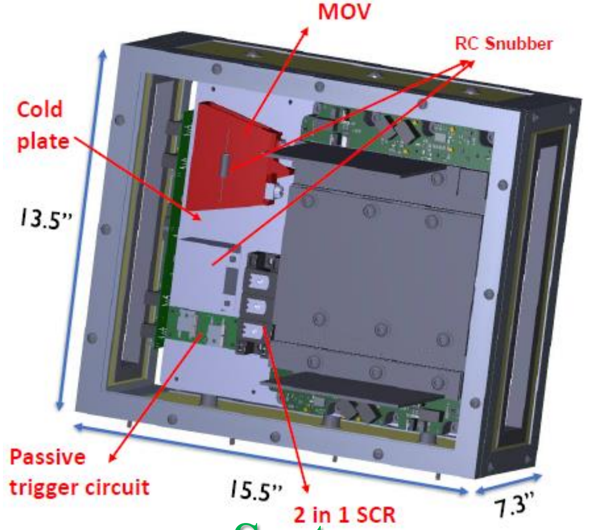
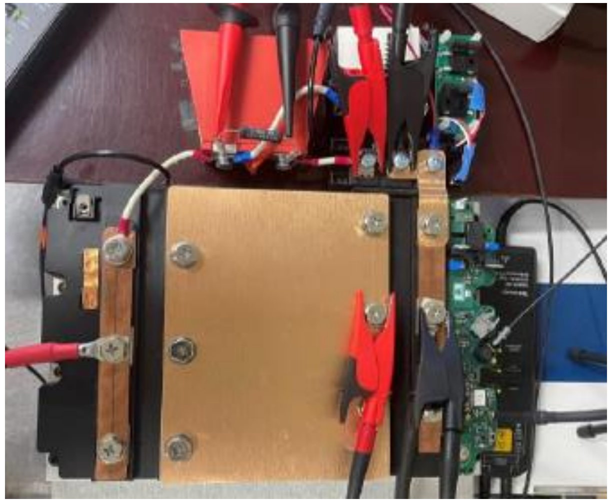
Application Overview

Solid State Circuit Breaker (SSCB)



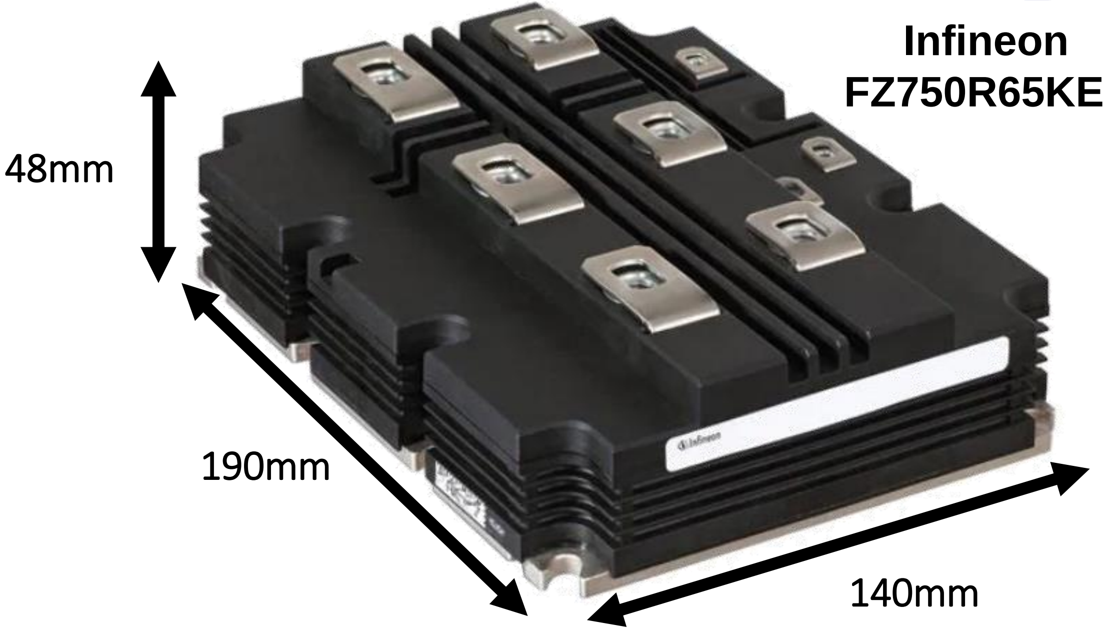
System



NNL Feasibility Testing of SSCB

Test Rig

Infineon FZ750R65KE3



Component

Fault Management Systems Cooling Overview:

- NASA Phase III SBIR funded through NASA Glenn Research Center's Advanced Air Transport Tech Project (AATT)
- Solid state circuit breaker design from Naval Postgraduate School (top left) requires efficient thermal rejection path as Infineon (top right) generates 5kW of waste heat (99.5% efficiency of 1MW electrical).
- NASA design uses thermoacoustics to transport waste heat through aircraft.
- Additively Manufactured Oscillating Heat Pipe (AM-OHP) serves as low thermal resistance interface between rectangular surface of breaker device to tubular surface of thermoacoustic tube in waste heat recovery system.

Application Overview

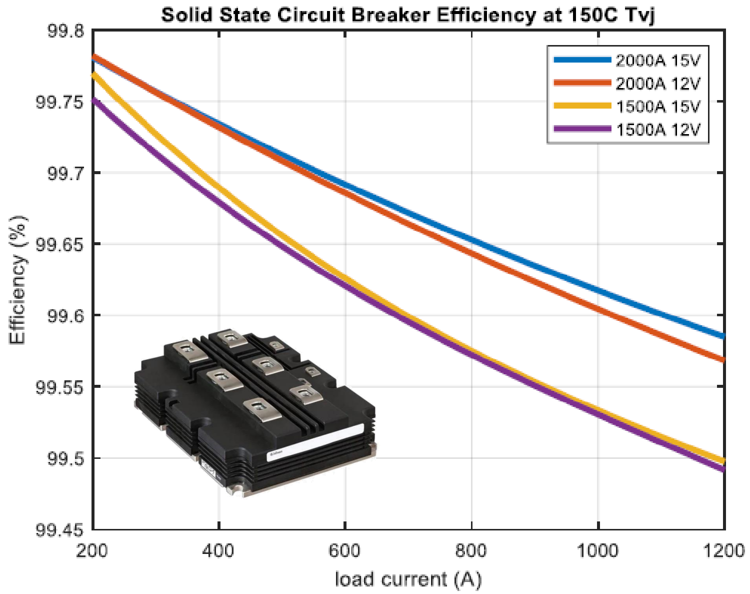
Key Performance Characteristics of AM-OHP

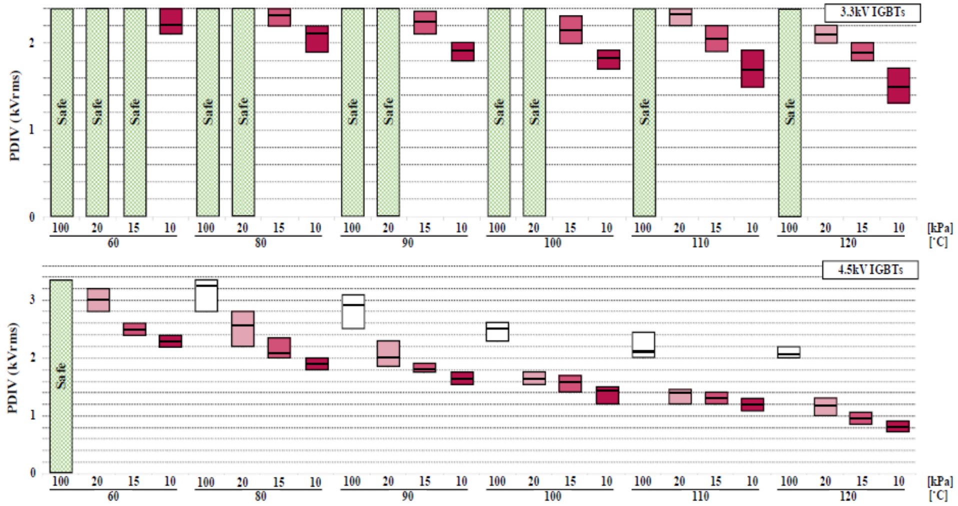
- Provide design flexibility to power electronics by demonstrating variable distribution (x, y location) of heat sources with minimal performance impact
- Additive manufacturing to dramatically reduce time through design cycle for rapid concept de-risking
- AM to enable impossible form factors for conventional fabrication methods for OHPs
- Demonstrate high power (>5kW) and high power density (>4kW/kg) heat transfer away from power electronics
- Demonstrate gravity independence of performance
- Demonstrate ThermAvant predictions line up with performance

Application Overview

AM-OHP reduces thermal load by reducing device temperature:

- The efficiency of Infineon FZ750R65KE3 depends on temperature with ~99.5% at 150C (right).
- This 99.5% efficiency drives thermal load of AM-OHP (1MW * 0.5% = 5kW).
- AM-OHP reduces temperature to 120C or below. Thus AM-OHP will reduce thermal load below 5kW.



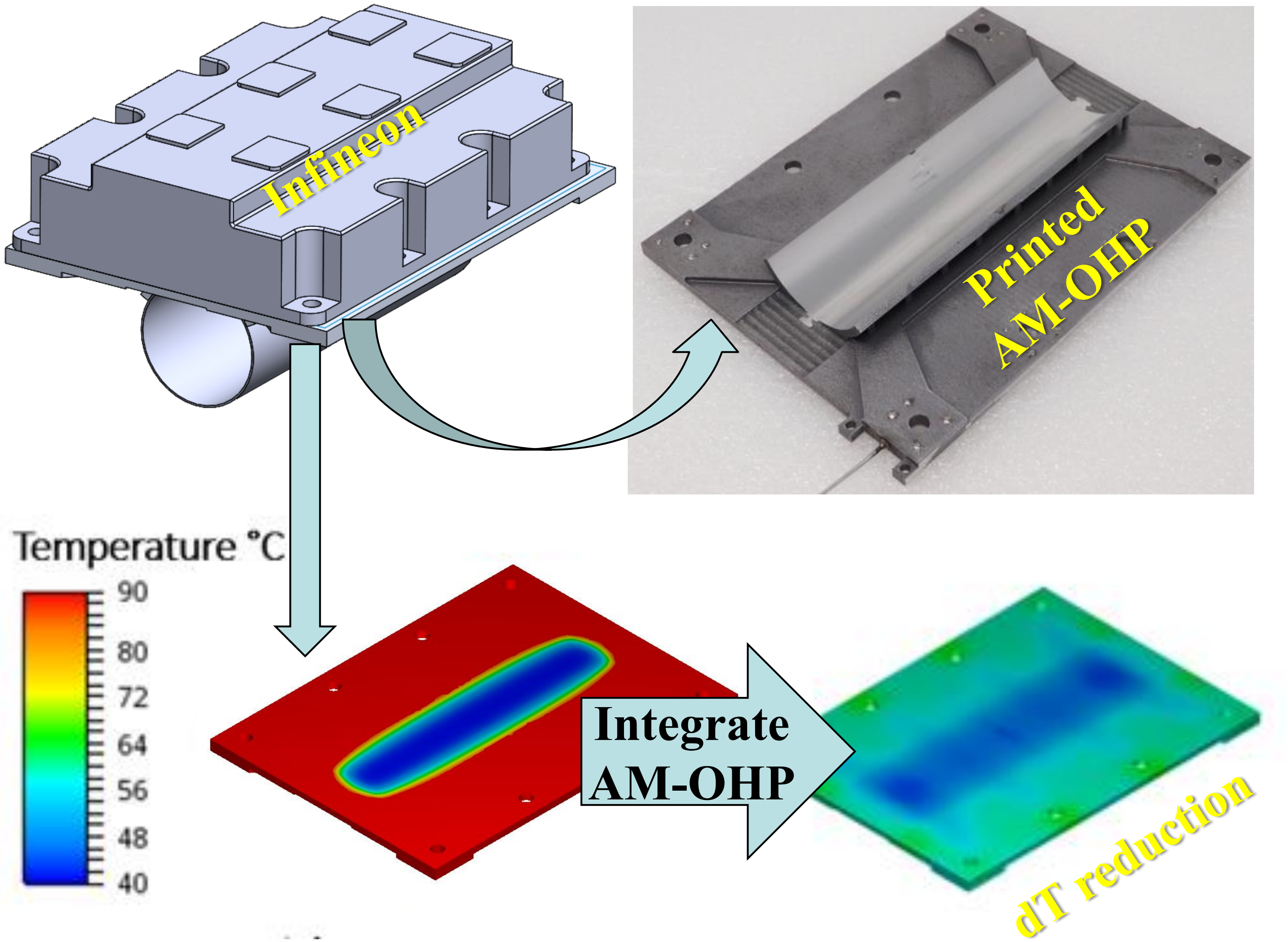


Statistical data of PDIV values at different pressures and temperatures for both 3.3kV and 4.5kV IGBT modules for performance assessment (10 samples based on 240 tests)

AM-OHP enables higher voltage (and thus power) device by limiting peak temperature:

- NPS selection of 3.3kV IGBT based partially on PDIV limit at 120C temperature (at 100kPa, left)
- If circuit breaker could be assumed to never exceed 60C through heat rejection enabled by AM-OHP, then 4.5kV IGBT would have same PDIV
- Potential change to 4.5kV IGBT to increase performance by 37%

Scope of Work

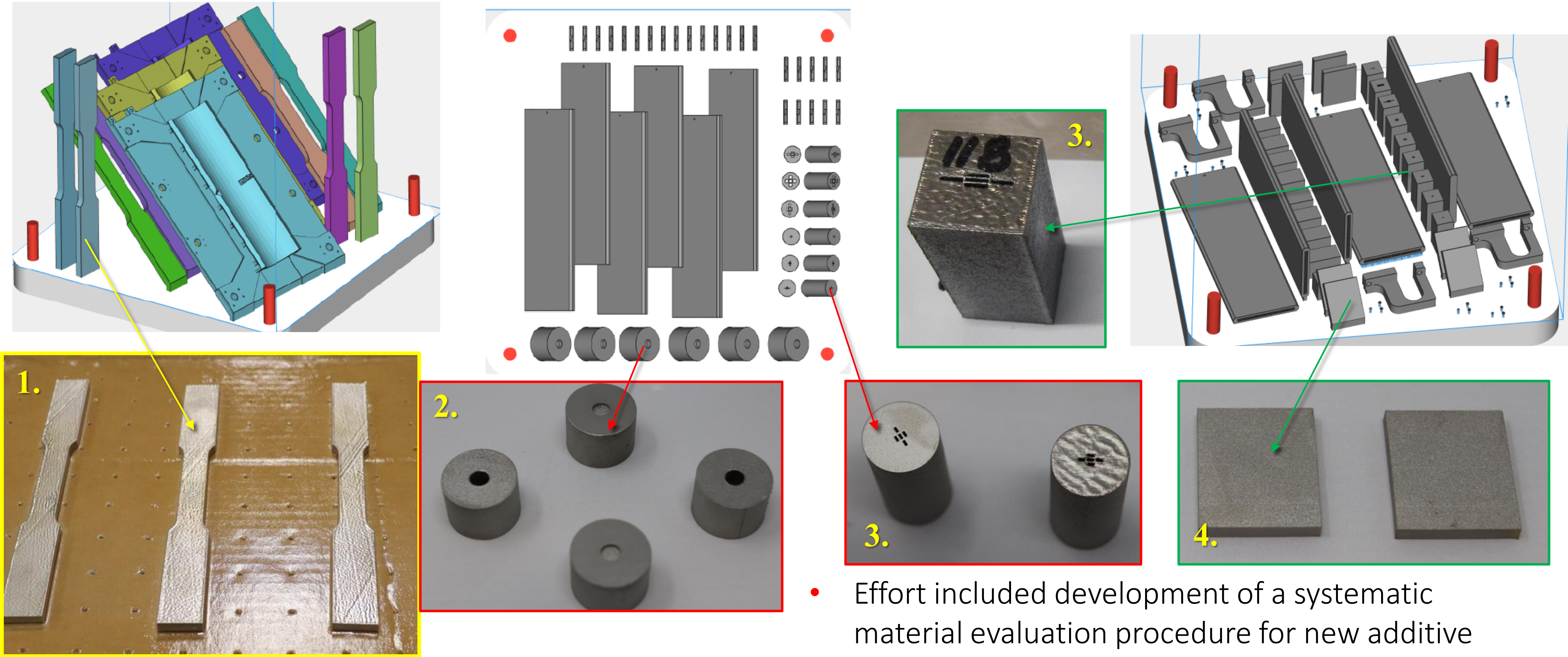


- In previous phase of work, performed under NASA Phase I SBIR (80NSSC21C0339) and summarized at Spacecraft Thermal Control Workshop 2022, ThermAvant performed analytical work (bottom left) to determine appropriate form factor of AM-OHP (center top).

- Focus of this presentation
  - MRL scale up to application form factor
  - Scale up to 5kW, 4kW/kg thermal test

MRL Development

Development of Standard Material Evaluation Procedure

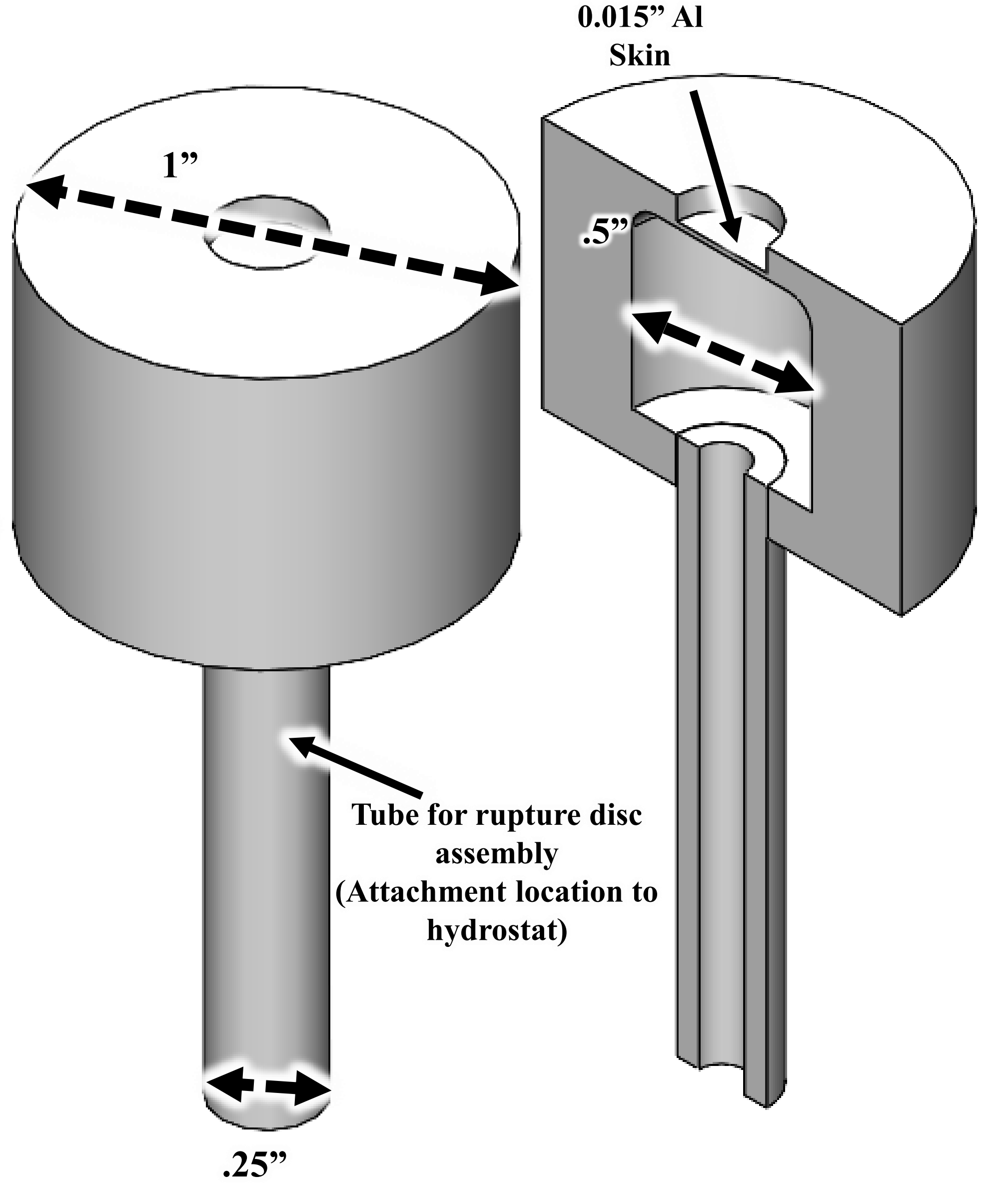


- Effort included development of a systematic material evaluation procedure for new additive materials for OHP fabrication

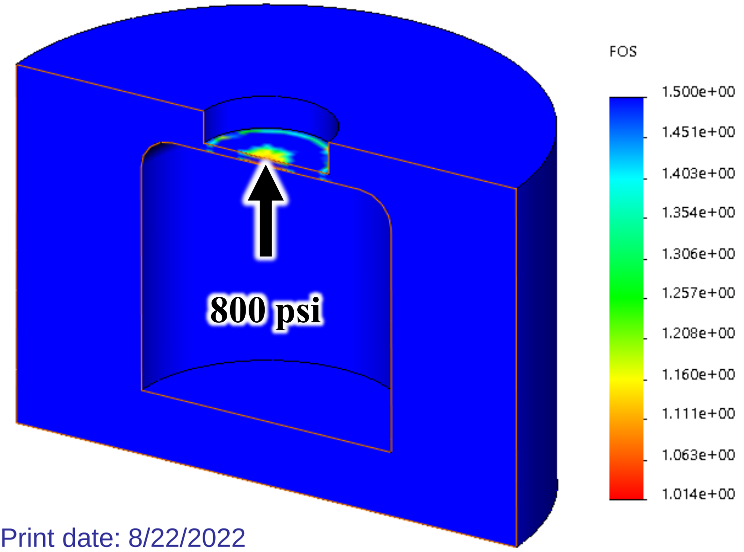
MRL Development

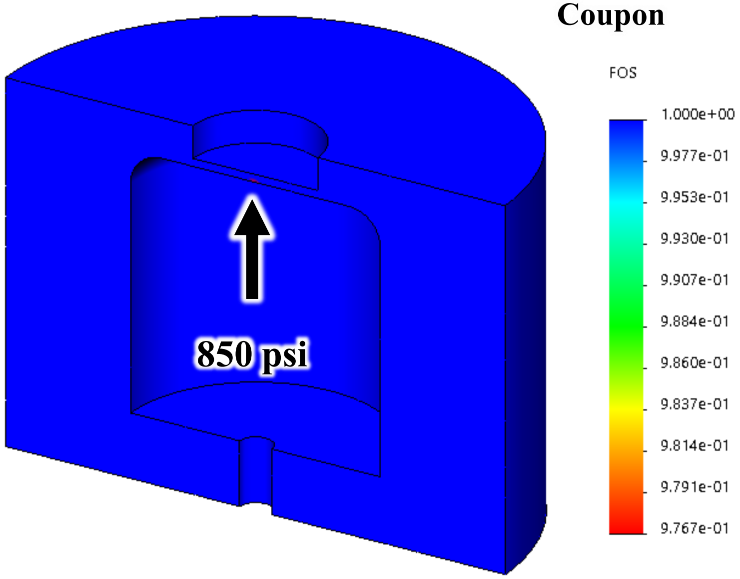
2. Burst Pressure Testing - analysis

- Attach .25” OD aluminum tube to hydrostatic pressure test stand
- Apply 750 psi pressure to burst coupon
- Hold burst coupon at 750 psi for 5 minutes and check for leaks
- Increase pressure of hydrostat in 50 psi increments, burst coupon if it was T4 6061 would begin to fail above 825 psi
- Record point at which leaking beings on burst coupon and note location where leak occurs
- Hold at 50 psi increments for 5 minutes
- Static Stress Analysis below for reference



Burst Coupon





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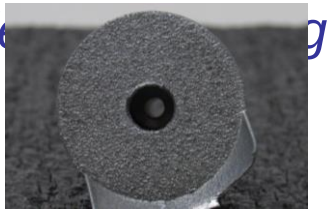
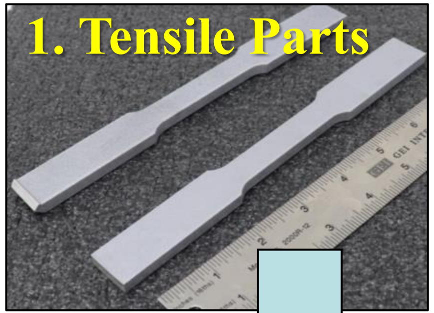
MRL Development

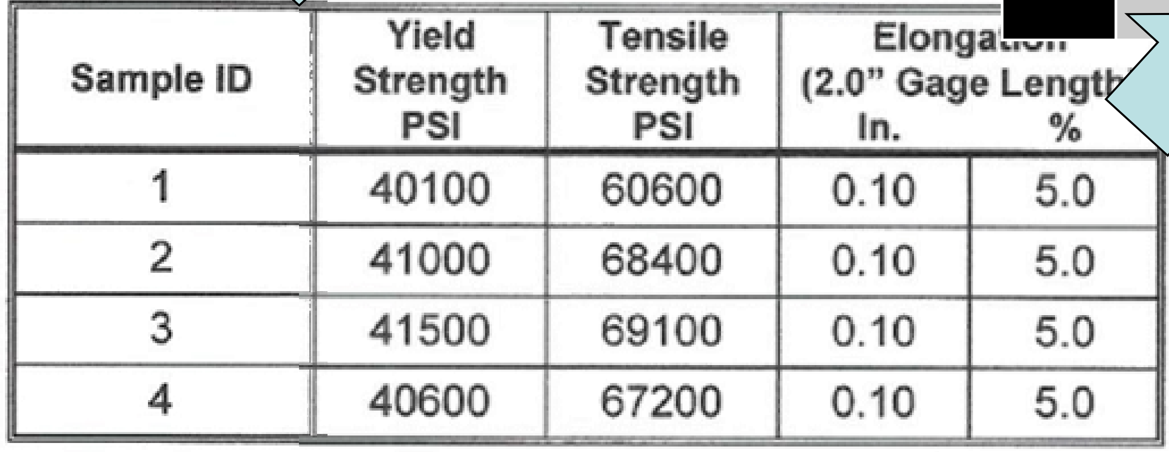



2. Burst Coupons

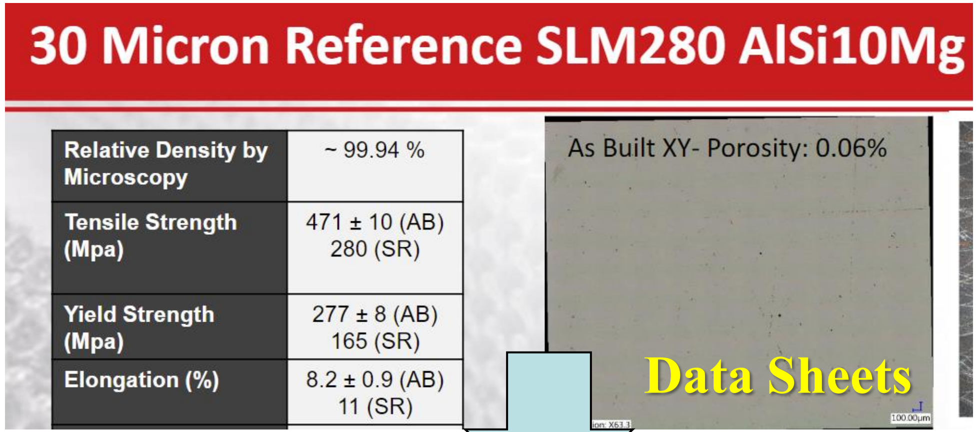
Sample #	Rupture Pressure [psi]
1	3,700
2	3,500
3	3,800
4	3,800
5	3,500
6	3,800



1. Tensile Parts



Sample ID	Yield Strength PSI	Tensile Strength PSI	Elongation (2.0" Gage Length) In.	%
1	40100	60600	0.10	5.0
2	41000	68400	0.10	5.0
3	41500	69100	0.10	5.0
4	40600	67200	0.10	5.0

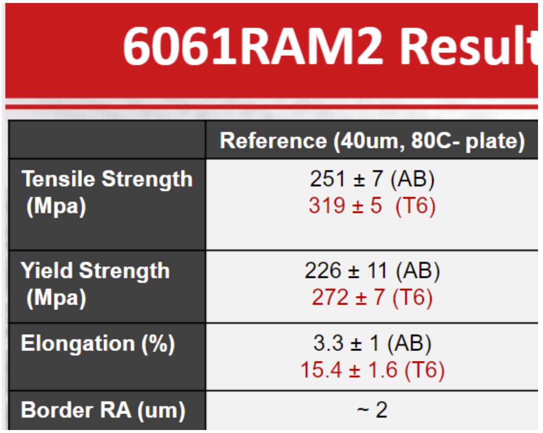


30 Micron Reference SLM280 AlSi10Mg

Relative Density by Microscopy	~ 99.94 %
Tensile Strength (Mpa)	471 ± 10 (AB) 280 (SR)
Yield Strength (Mpa)	277 ± 8 (AB) 165 (SR)
Elongation (%)	8.2 ± 0.9 (AB) 11 (SR)

As Built XY- Porosity: 0.06%

Data Sheets



6061RAM2 Result

	Reference (40um, 80C- plate)
Tensile Strength (Mpa)	251 ± 7 (AB) 319 ± 5 (T6)
Yield Strength (Mpa)	226 ± 11 (AB) 272 ± 7 (T6)
Elongation (%)	3.3 ± 1 (AB) 15.4 ± 1.6 (T6)
Border RA (um)	~ 2

	Al 6061 T4	Al 6061 T6	Datasheet AlSi10Mg	Rupture Testing Data AlSi10Mg	ASTM A370-21 Tensile Testing AlSi10Mg
UTS	241 MPa	310 MPa	454 MPa	450 MPa	418 MPa to 476 MPa (0, 45, 90 print orientations)

Key take-away:

- AlSi10Mg as-built (AB) outperforms Al 6061 T6 bulk properties
- Al 6061 as-built underperforms AlSi10Mg

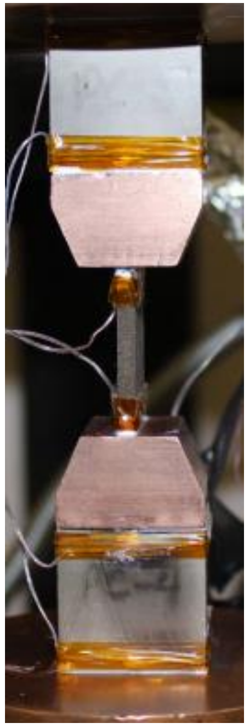
MRL Development

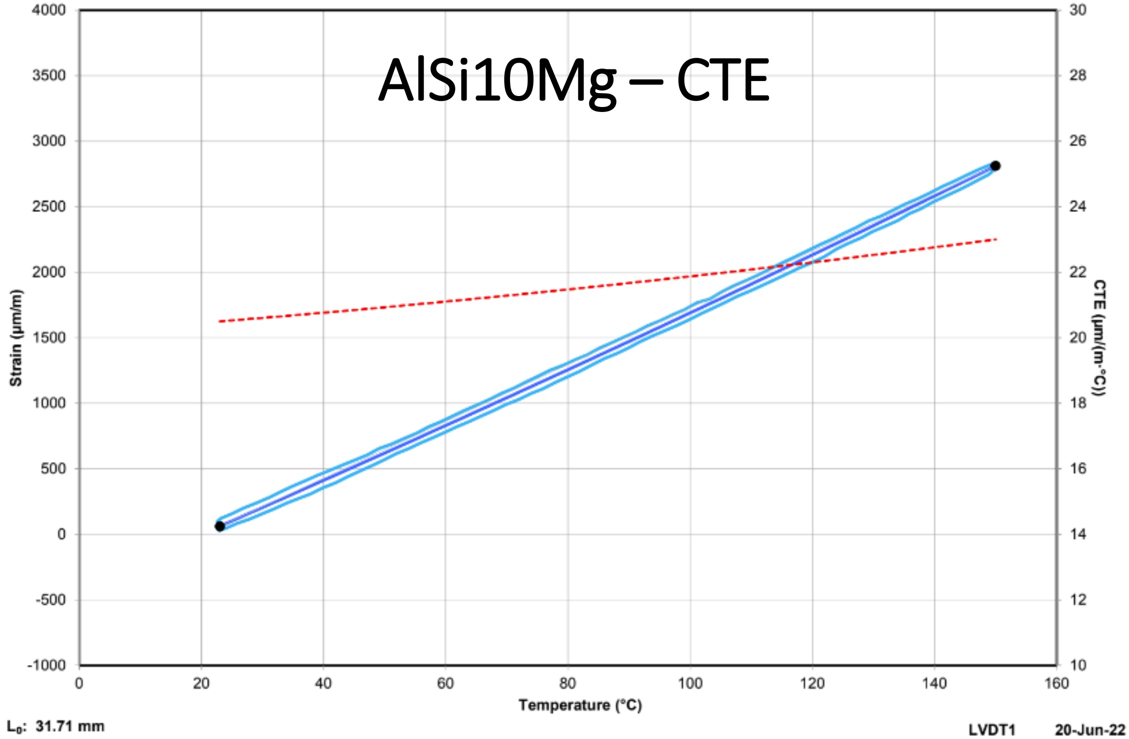
4. Material Testing

- AlSi10Mg – Density, Thermal k

Specimen ID	Temperature (°C)	Average Thermal Diffusivity (cm^2/s)	Specific Heat (J/(kg·K))	Density B311 (kg/m^3)	Average Thermal Conductivity (W/(m·K))
A1	23	0.490	832	2670	108
	150	0.514	923		126
A2	23	0.515	881	2670	120
	150	0.521	982		136
B1	23	0.522	847	2670	117
	150	0.547	924		125
B2	23	0.521	867	2670	127
	150	0.538	911		125


4. Material Eval. Parts

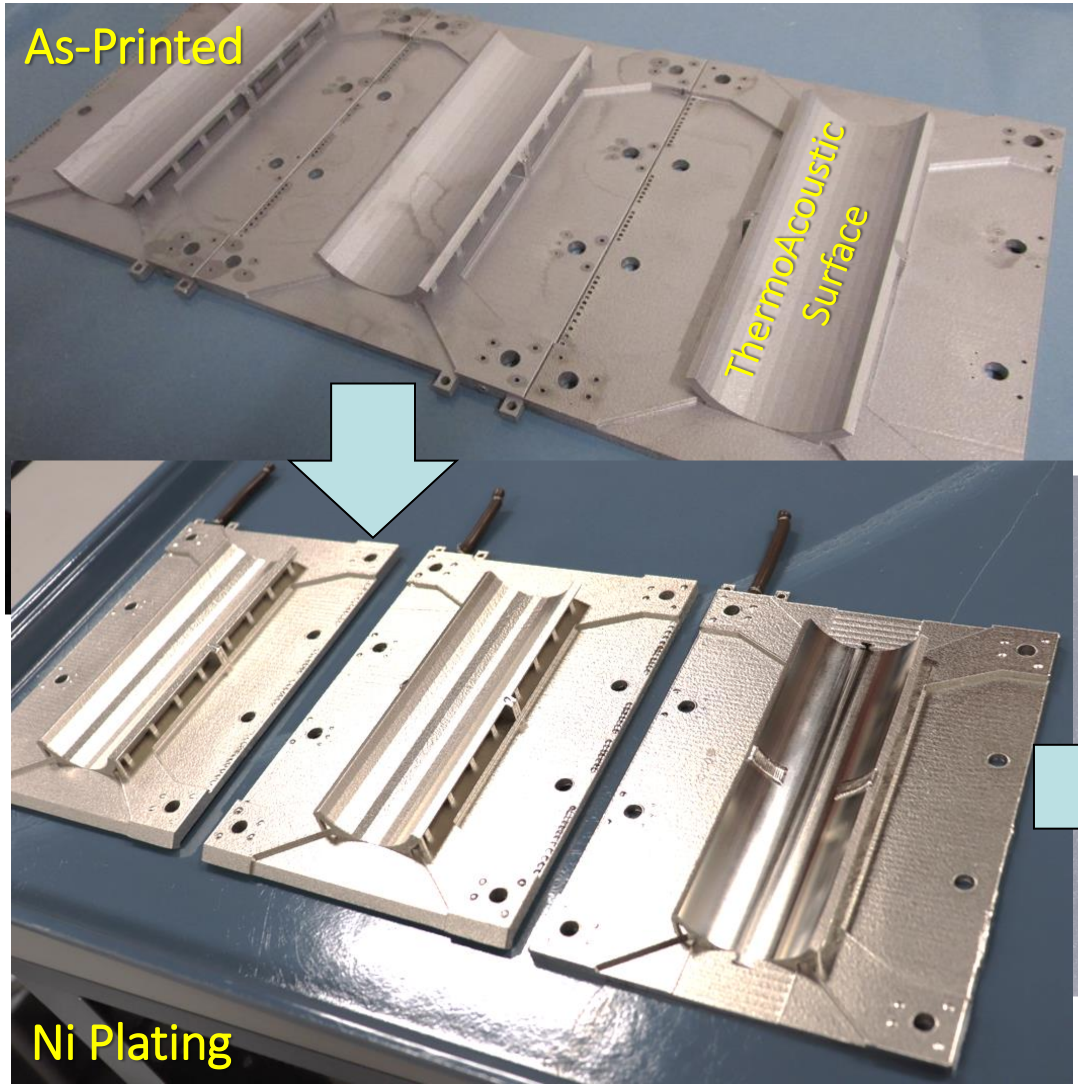



AlSi10Mg – CTE

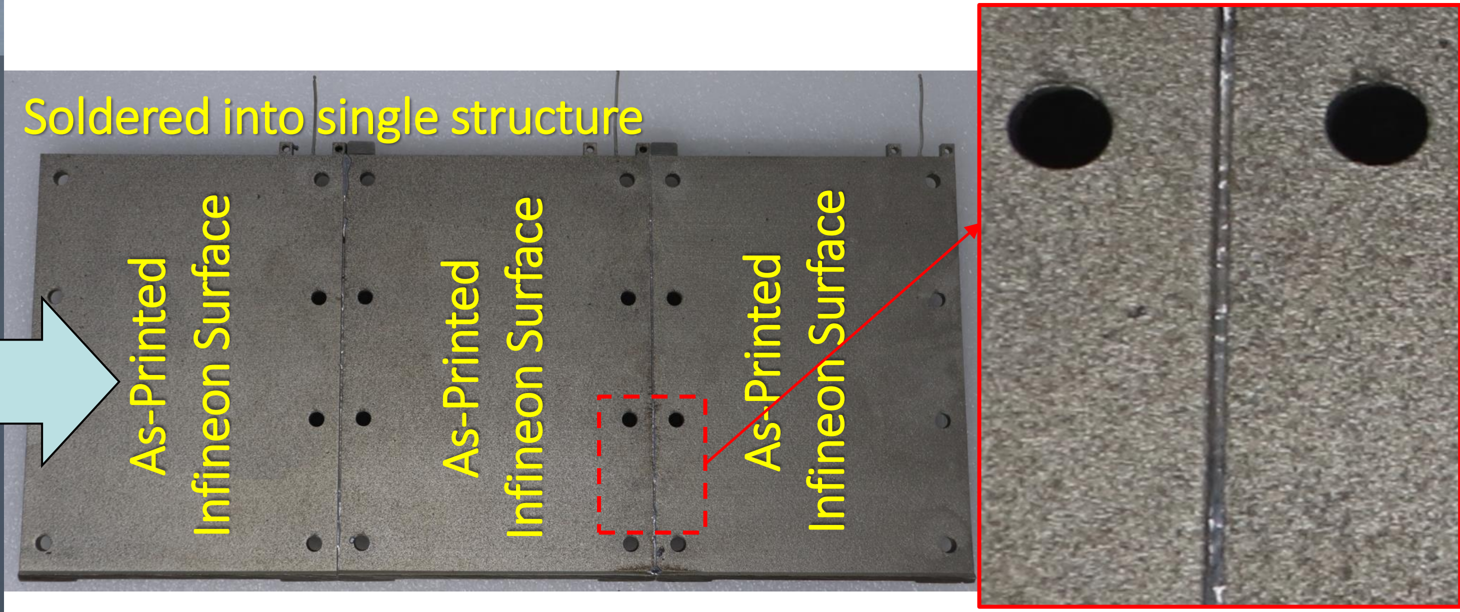
- Note anisotropy of thermal k with print orientation (A vs B) and measurement direction (1 vs 2)
- As such, print orientation is significant element of OHP design

MRL Development

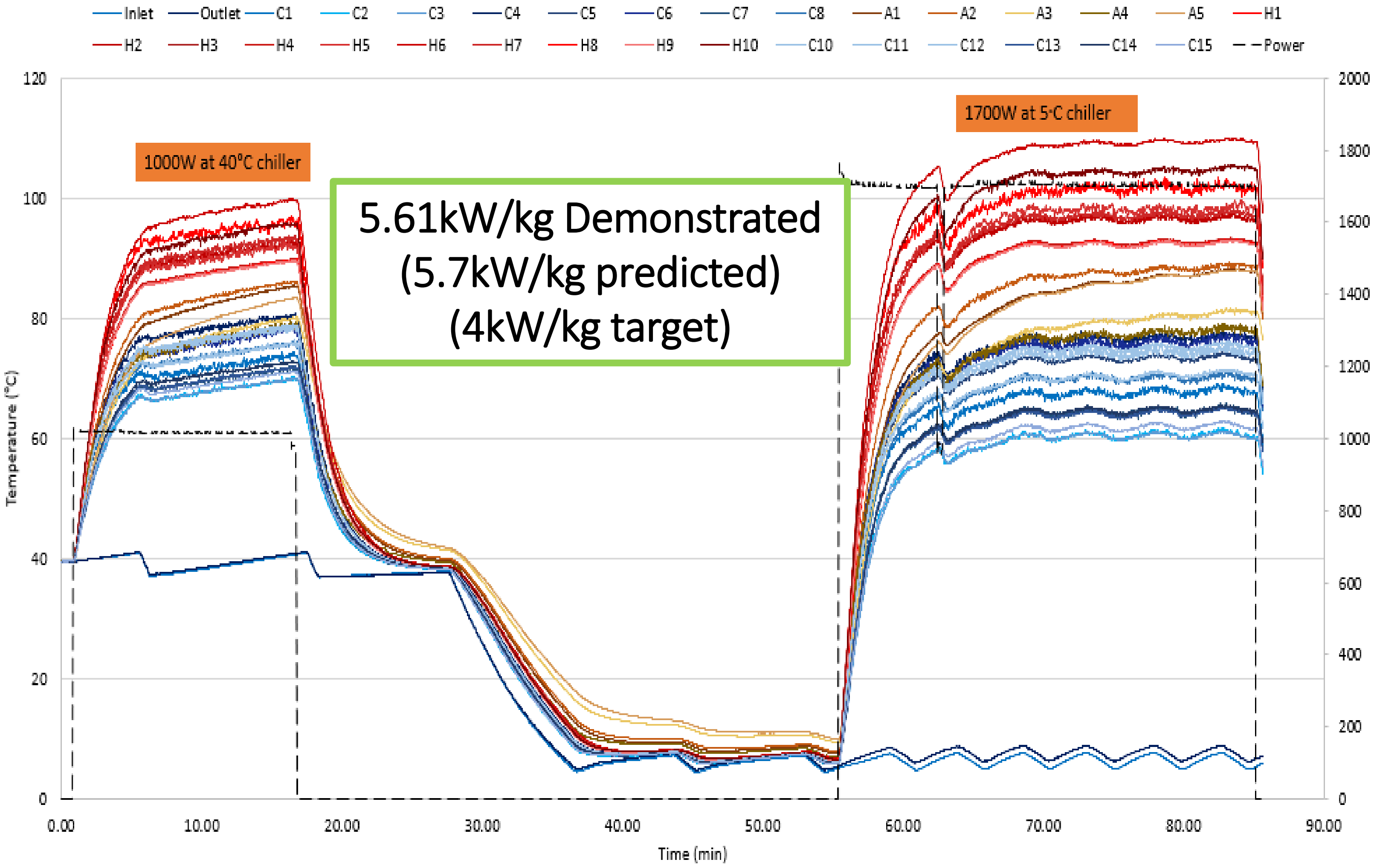
5. Final Part Fabrication



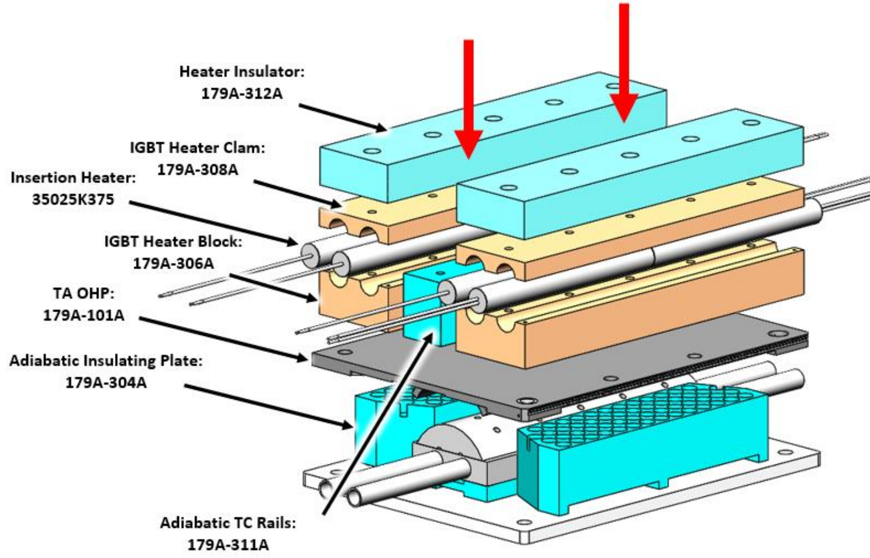
- ThermAvant has demonstrated large scale highly thermally conductive substrates beyond print bed size through joining subscale (in this case 1/3 scale) components by soldering and welding.

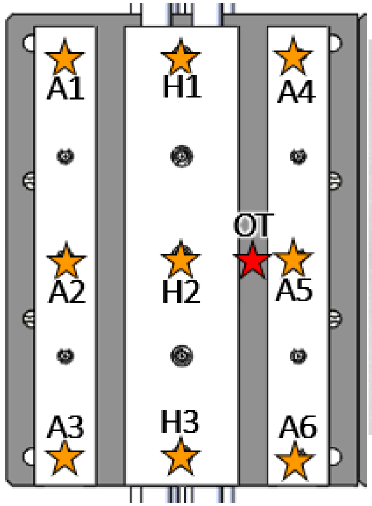


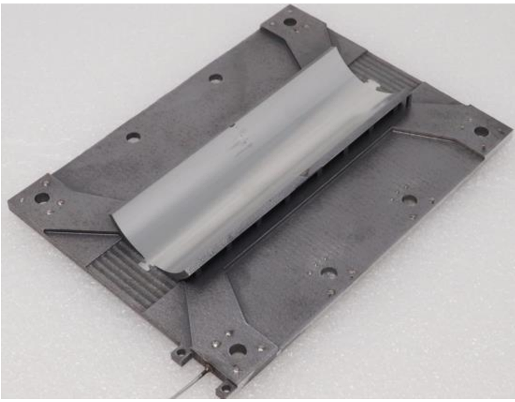
Thermal Testing



5.61kW/kg Demonstrated
(5.7kW/kg predicted)
(4kW/kg target)



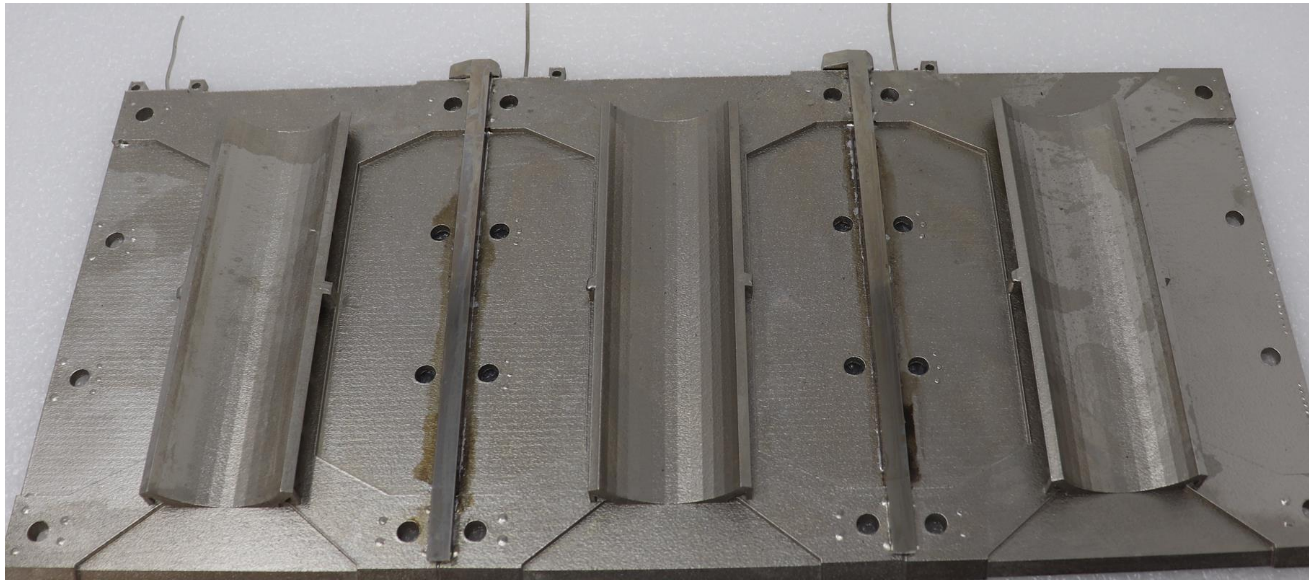


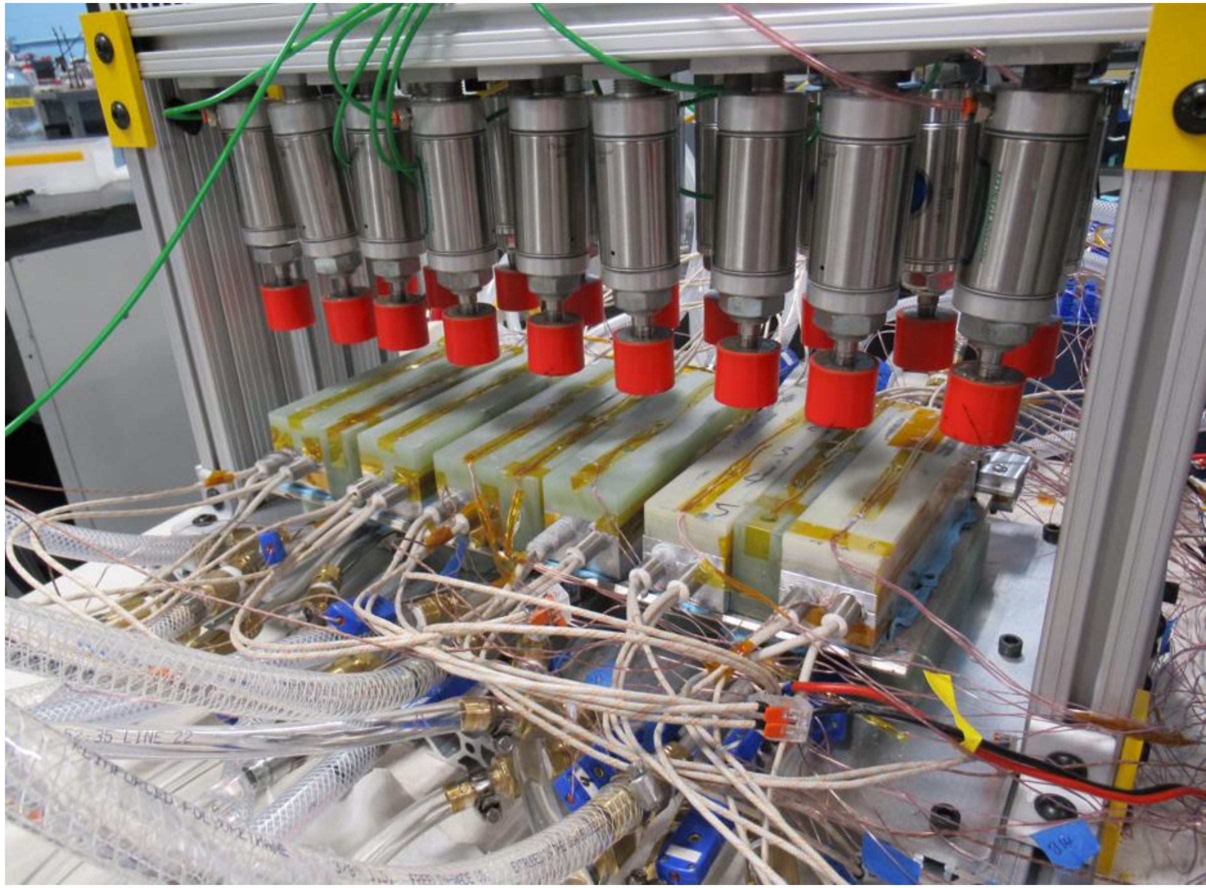


Thermal Testing

Full Scale Part Failure

- Full scale parts (below) tested on 7kW testbed (right), unable to demonstrate stable functionality. Believed due to printing issue on this print run.
- Single unit tested on 7kW testbed confirms capability of testbed
- Minor instrumentation offset in cold plate temperature observed, but not driving issue





Concluding Remarks

- Additive manufacturing enables rapid prototyping of OHPs concepts (on the order of 3 weeks instead of 3 months!)
- Additive manufacturing enables previously cost prohibitive form factors and channel routing (simplified engineering design as well)
- OHP technology enables low thermal resistance heat sink for fault management systems in electric aircraft at power levels required for large electrified aircraft (1MW & above)
- Active associated Phase II SBIR with NASA is working to leverage additive learning to high temperature materials (e.g., 316SS, Inconel 625) to demonstrate OHP application to turbofan cooling.
- With this demonstration of fault management systems cooling, ThermAvant’s past experience with battery thermal management, ThermAvant’s past experience with thermal skin heat rejection enhancement, and the active Phase II mentioned above, ThermAvant will be well positioned to provide OHP solutions for a variety of electric aircraft thermal management needs.