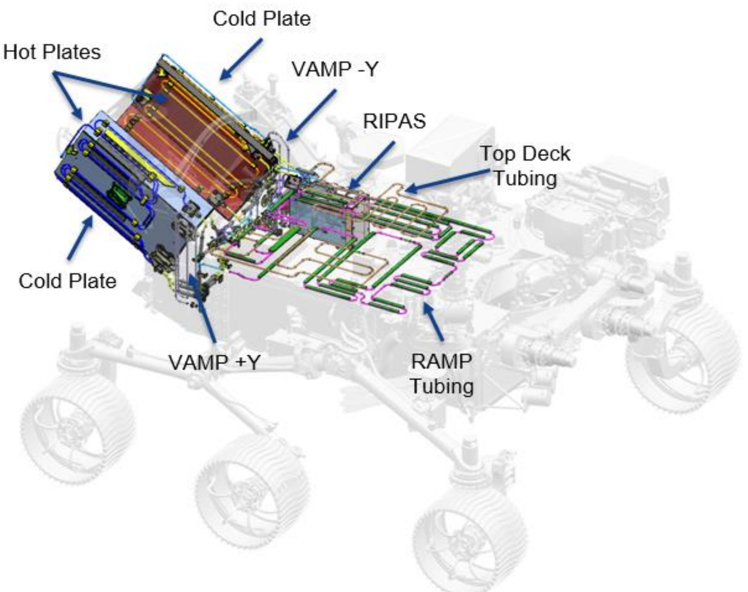
NASA Development of Complex Heat Exchangers Leveraging Additive Manufacturing

A. J. Mastropietro, Dr. Scott Roberts, Dr. Douglas Hofmann, Dr. Elham Maghsoudi, and Simon Luong

Jet Propulsion Laboratory, California Institute of Technology

5/25/2017

Presented By
A. J. Mastropietro



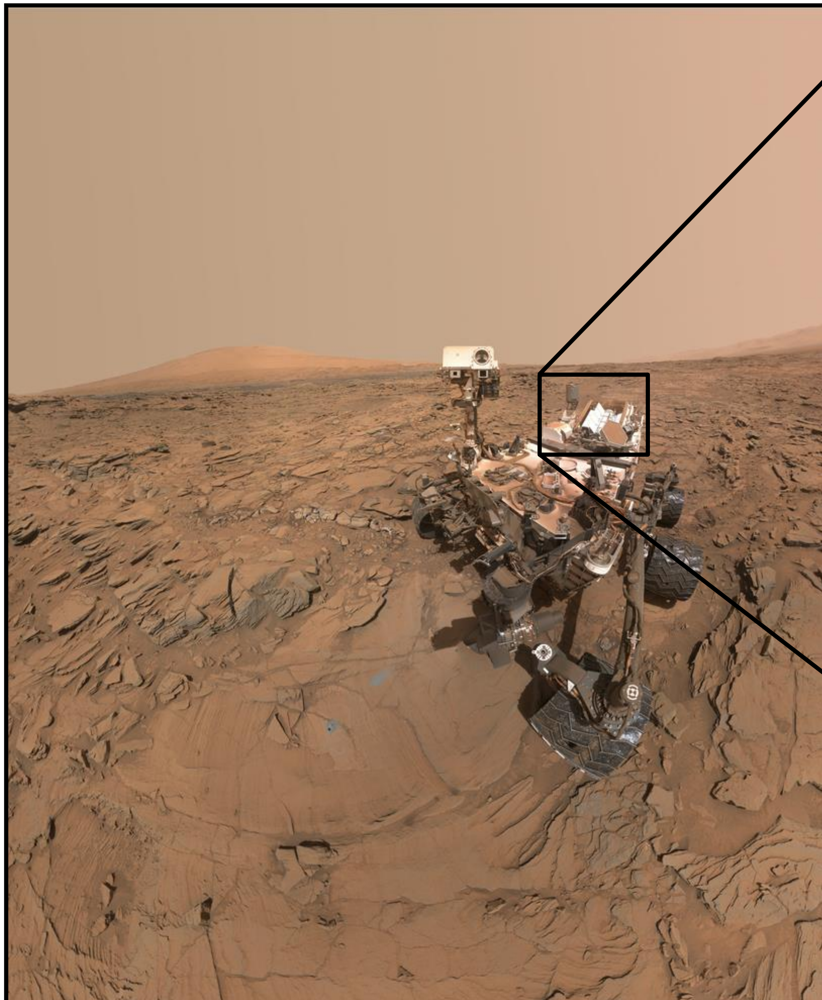
Mars 2020 Rover

Agenda

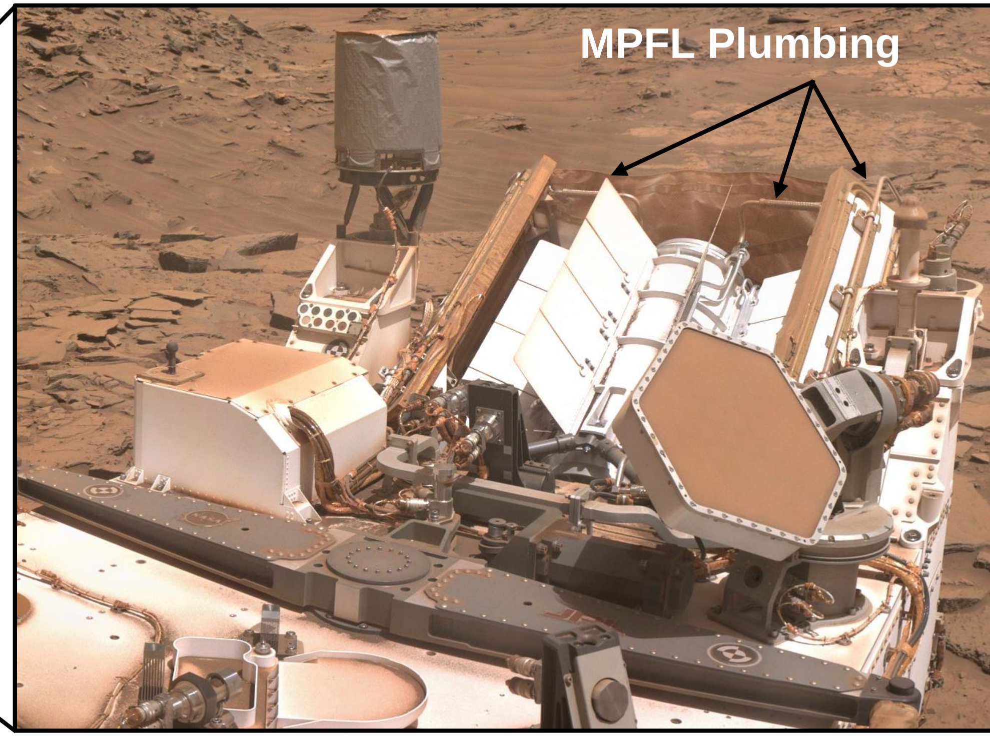
- Why is JPL interested in Additive Manufacturing of Heat Exchangers?
- Mechanical Pumped Fluid Loop (MPFL) Heritage and Upcoming Missions
- Current State of the Art for Heat Exchanger (HX) Fabrication at JPL
- Considered 2 Types of Aluminum Additive Manufacturing: UAM vs. DMLS
- Ultrasonic Additive Manufacturing (UAM)
  - 2014 JPL Spontaneous R&TD - Feasibility of UAM HXers
  - 2015 SBIR Phase I Study of UAM HX Fabrication
  - 2016 SBIR Phase II Study of UAM HX Fabrication
- Future Work
- Concluding Remarks
- References
- Acknowledgement

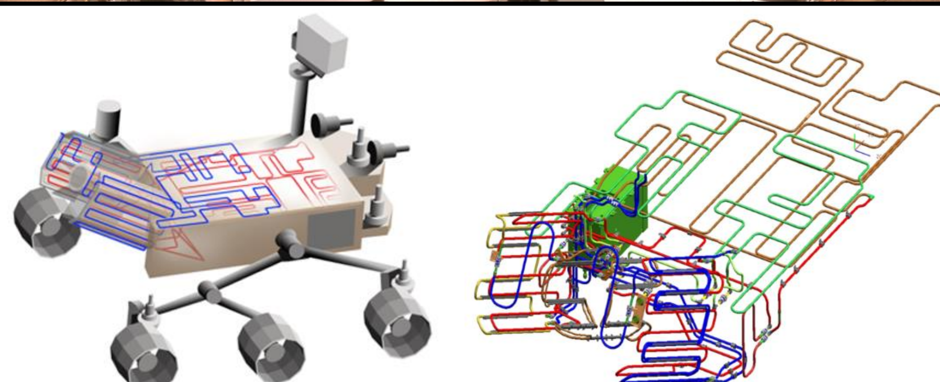
Why is JPL interested in Additive Manufacturing of Heat Exchangers?

Single-Phase Mechanical Pumped Fluid Loop (MPFL) thermal control architecture on last few Mars flagship missions including the Curiosity Rover launched November 2011 has been very successful!



Self Portrait at "Okoruso" Drill Site; Taken by MAHLI on May 11, 2016 (Sol 1,338)

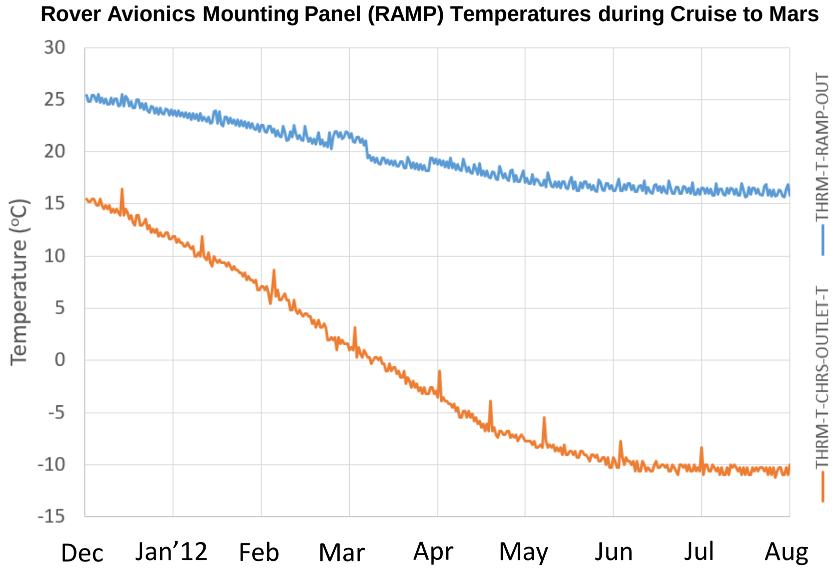


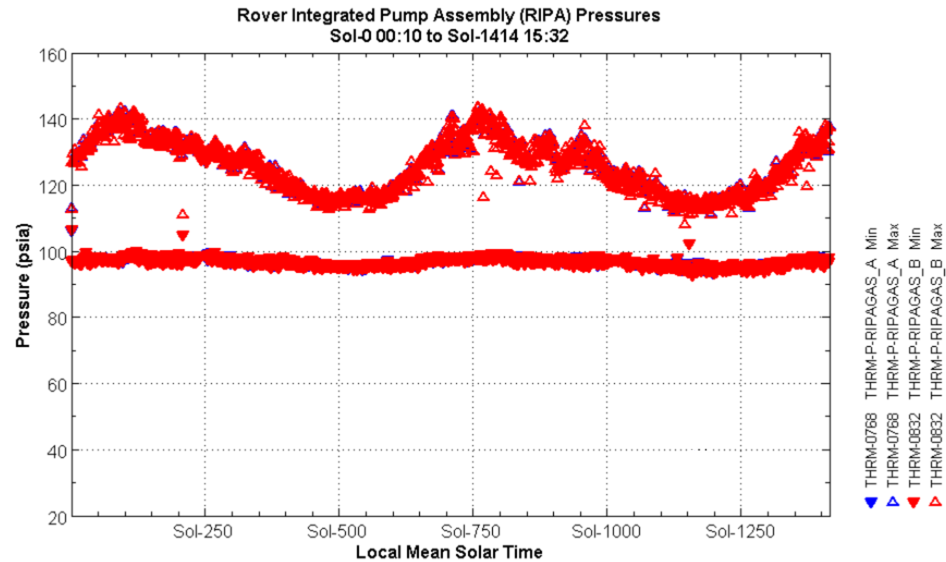


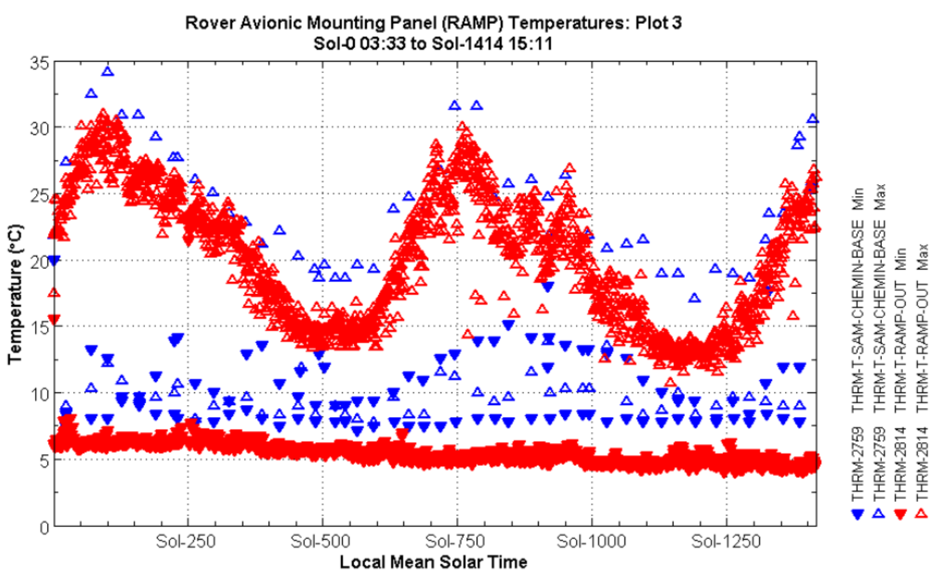
Curiosity has 9 HXers

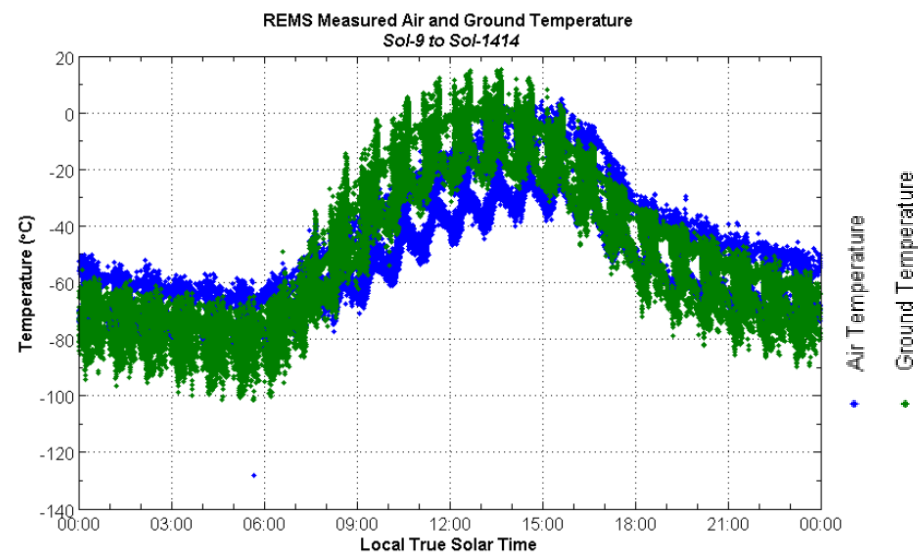
JPL's Upcoming MPFL Projects Are Building upon the Recent Success of the Curiosity Rover Launched November 2011

MPFL thermal control architecture very resilient despite dynamic thermal environments!



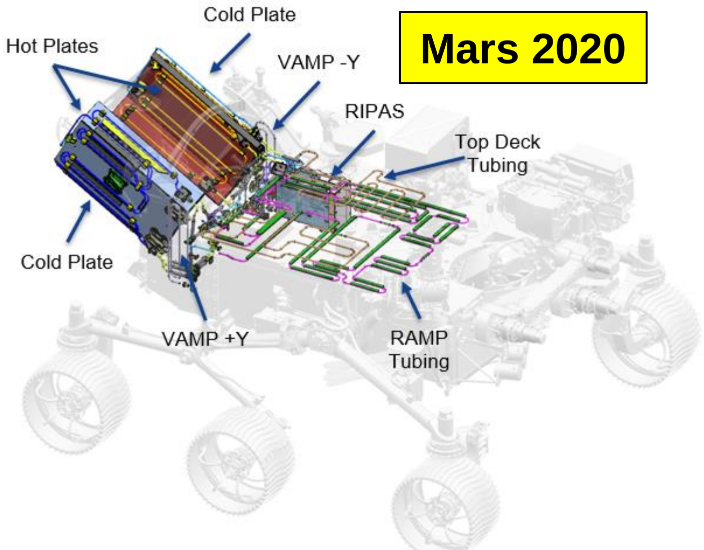






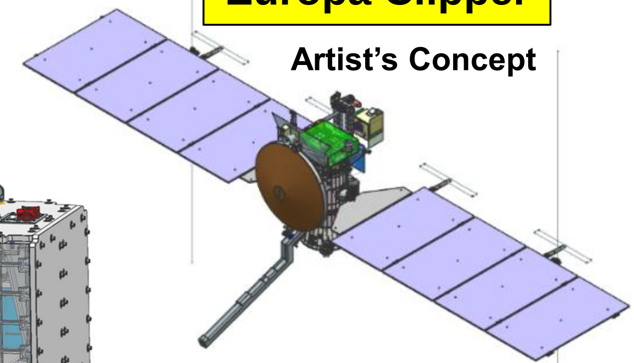
5 Upcoming JPL Missions with a MPFL Architecture[1,2]

Mars 2020

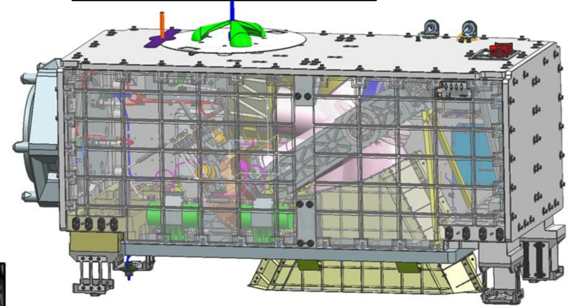


Planned Europa Clipper

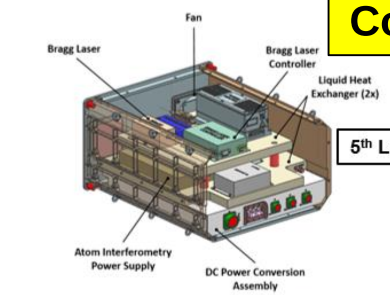
Artist's Concept

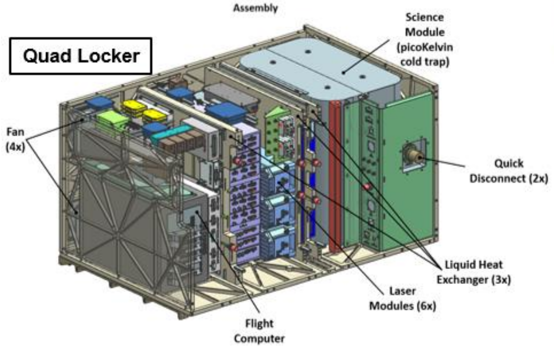


ECOSTRESS

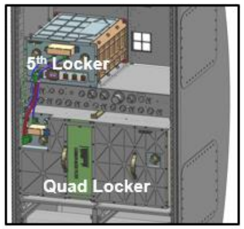


Cold Atom Lab

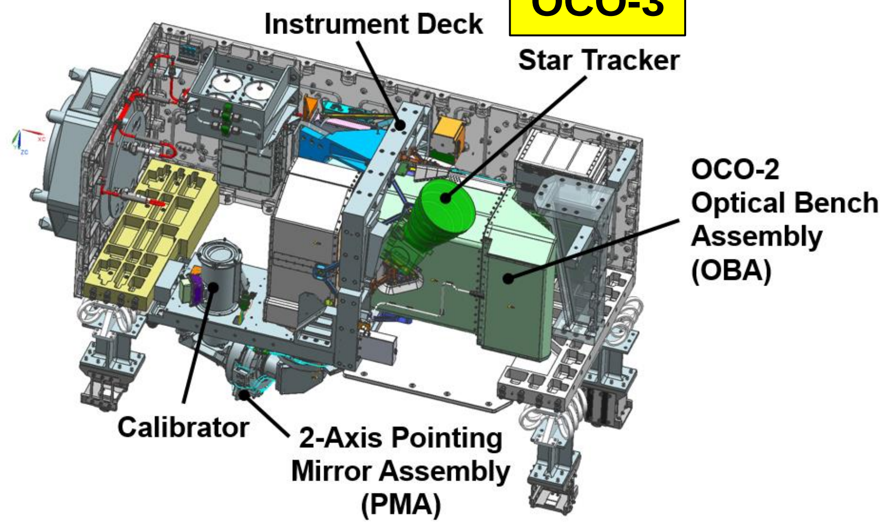




Pilot Stephen N. Frick poses by EXPRESS Rack 1 in the U.S. Lab during the STS-110 mission (2002)

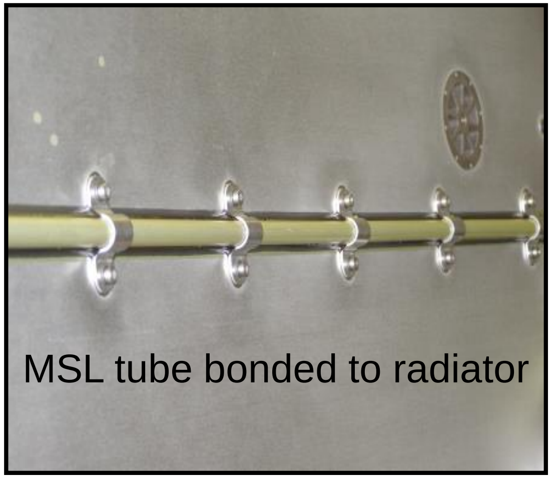


OCO-3

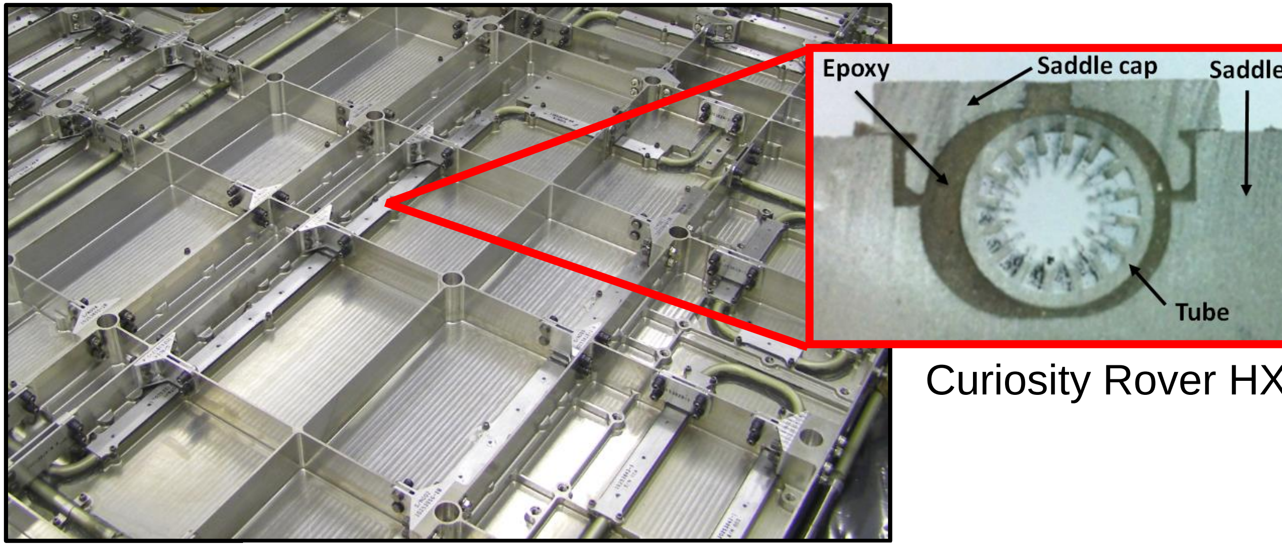


Current State of the Art for HX Fabrication at JPL

Epoxy bonded Al tubes on Al structures with or without saddles…



MSL tube bonded to radiator

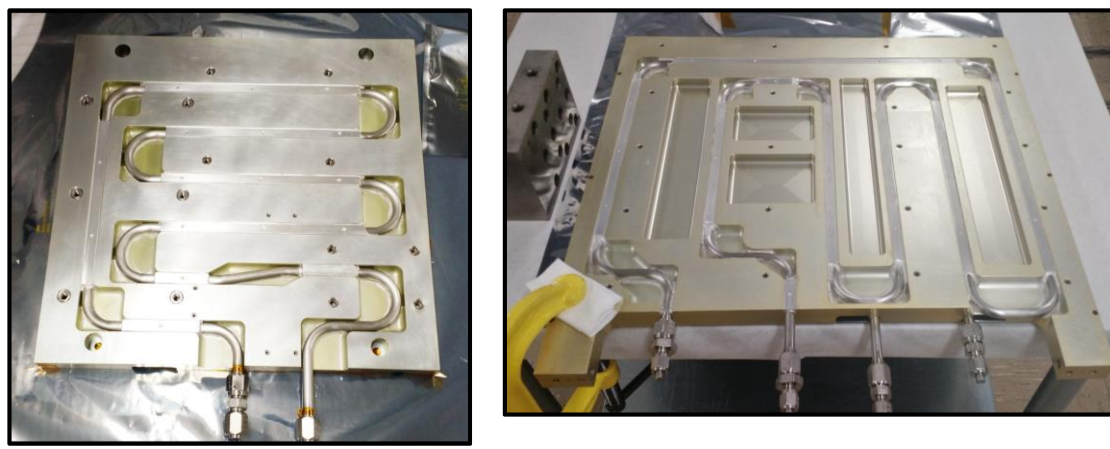


Curiosity Rover HX

- All touch labor
- Long lead times
- Very expensive
- Epoxy bond diminishes thermal performance & increases mass

Perfect application for metal Additive Manufacturing?

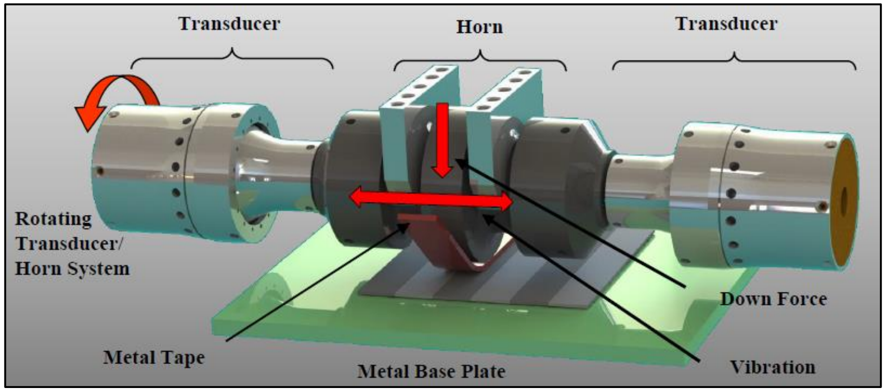
or tubes saddled in avionics mounting plate



Cold Atom Lab HXers

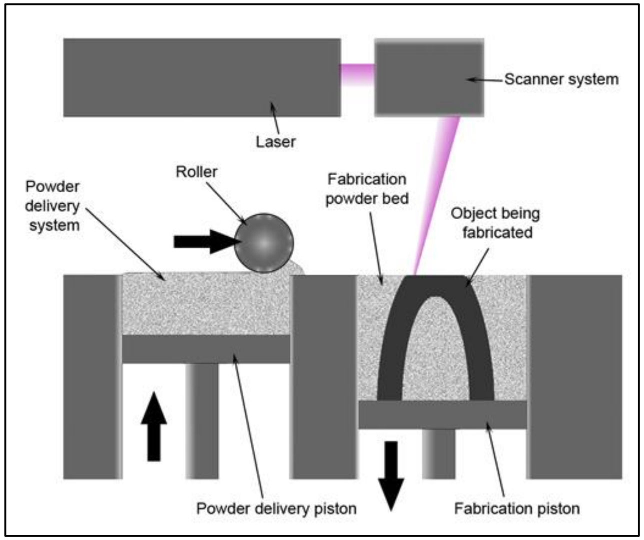
Considered 2 Types of Al Additive Manufacturing: UAM vs. DMLS

Ultrasonic Additive Manufacturing (UAM)



- Creates net-shape solid parts using <u>low temperature</u> solid state ultrasonic metal welding and CNC contour milling
- <u>6ft x 6ft x 3ft</u> build size permissible
- 15 to 30 cubic inch per hour print rate
- Tolerances within +/- 0.0005 inch
- Al 6061, Al 7075, copper, titanium, etc.
- Dissimilar metal joining (i.e., Cu-Al, Ti-Al, SS-Al)

Direct Metal Laser Sintering (DMLS)

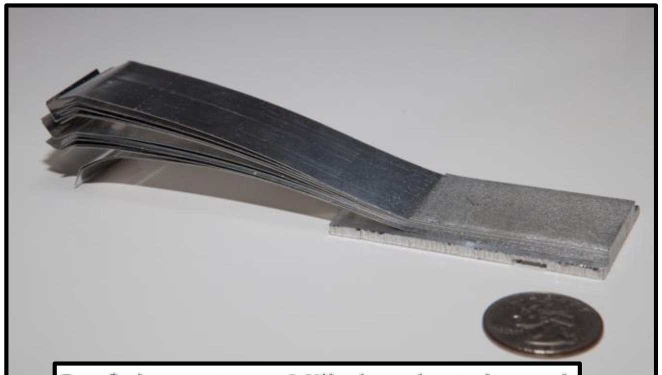


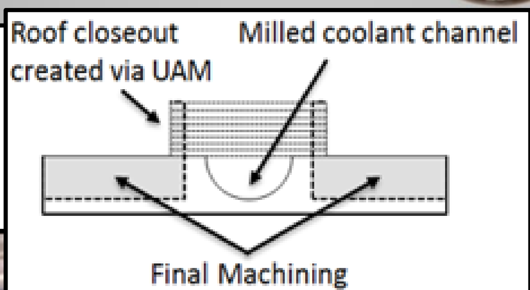
- High temperature, full melting welding
- 10 in x 10 in x 13 in build size
- 0.4 to 1.8 cubic inch per hour print rate
- Tolerances within +/- 0.002 inch
- $AlSi_{10}Mg$, Ti 6-4, SS 316L, Inconel 625, SS 17-4 PH
- Multiple unique parts can be built at same time minimizing cost

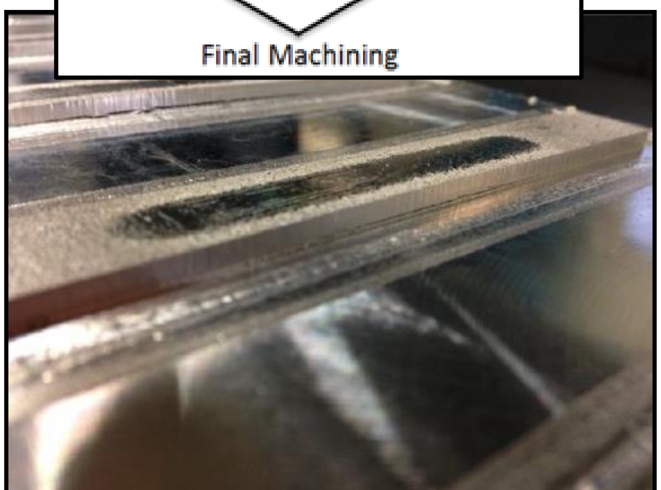
This presentation will not cover JPL's recent DMLS effort, see Ref. 3. which covers thermal performance improvements

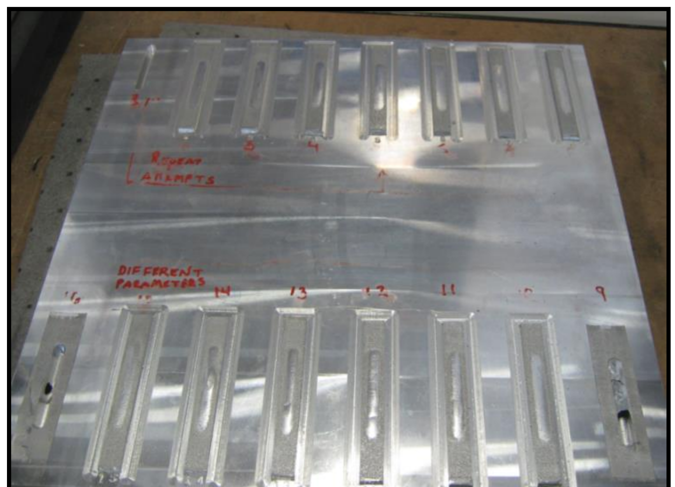
2014 JPL Spontaneous R&TD Investigates Feasibility of UAM HX^4

Early study focused on hermeticity of Al 6061 foil strips (“tape”) consolidated over single pass coolant channels without support material… **(burst pressure>800psi, He leak rate < 4E-8 scc/s)**

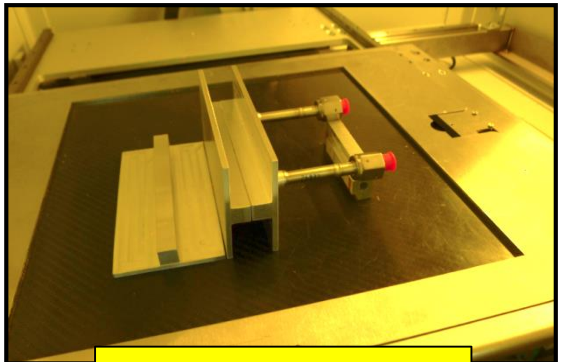




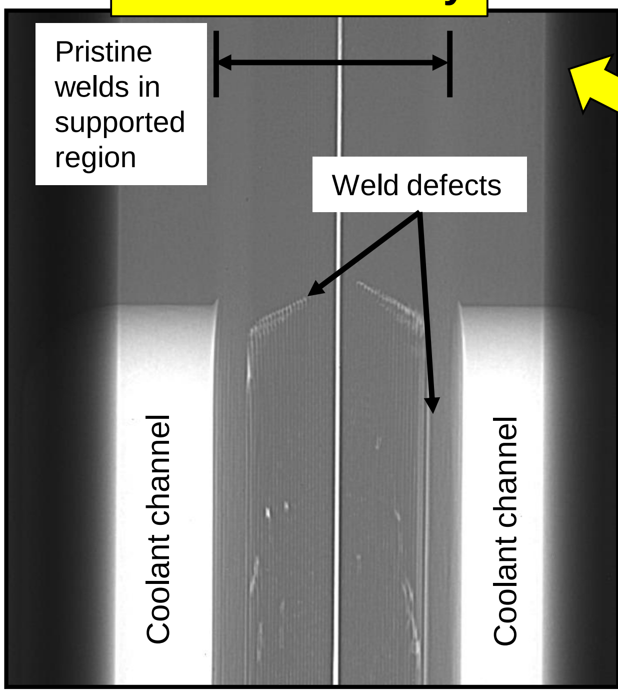




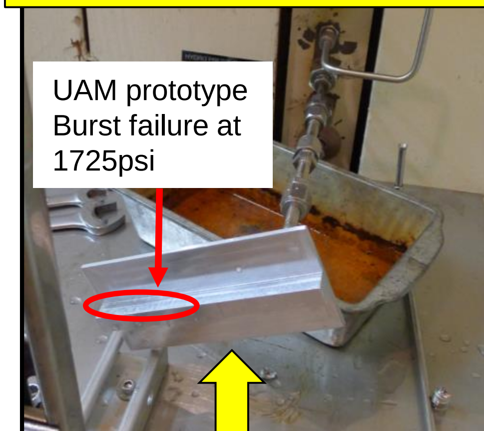
2014 JPL Spontaneous R&TD Investigates Feasibility of UAM HX^4

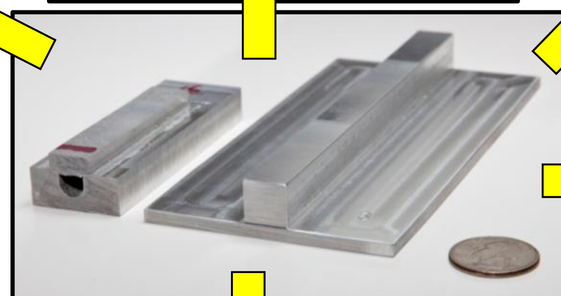


Feinfocus X-Ray

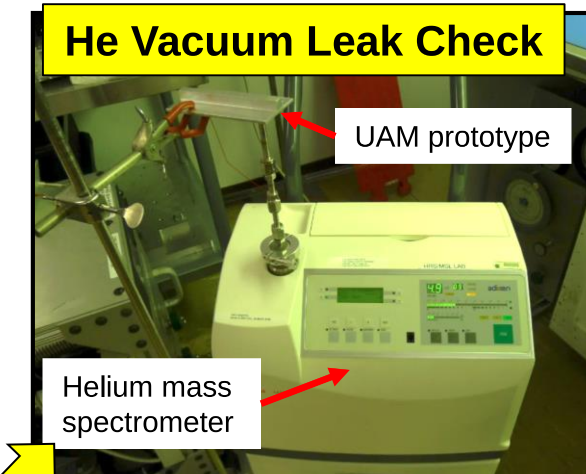


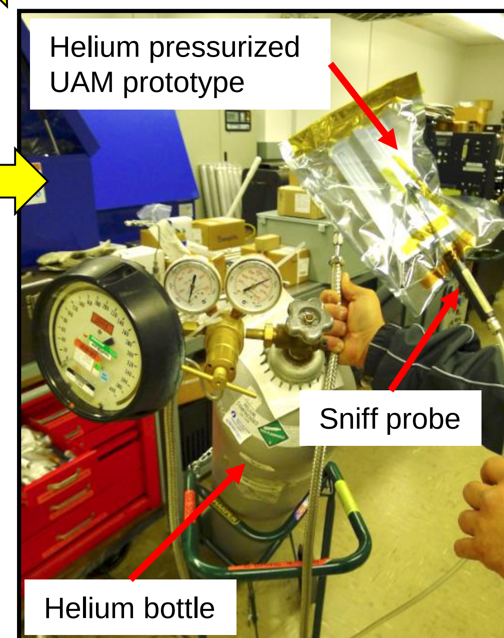
Hydrostatic Burst Test



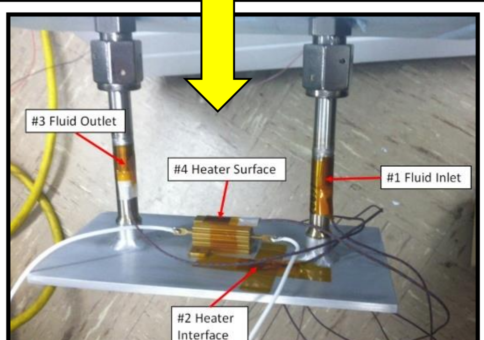


He Vacuum Leak Check





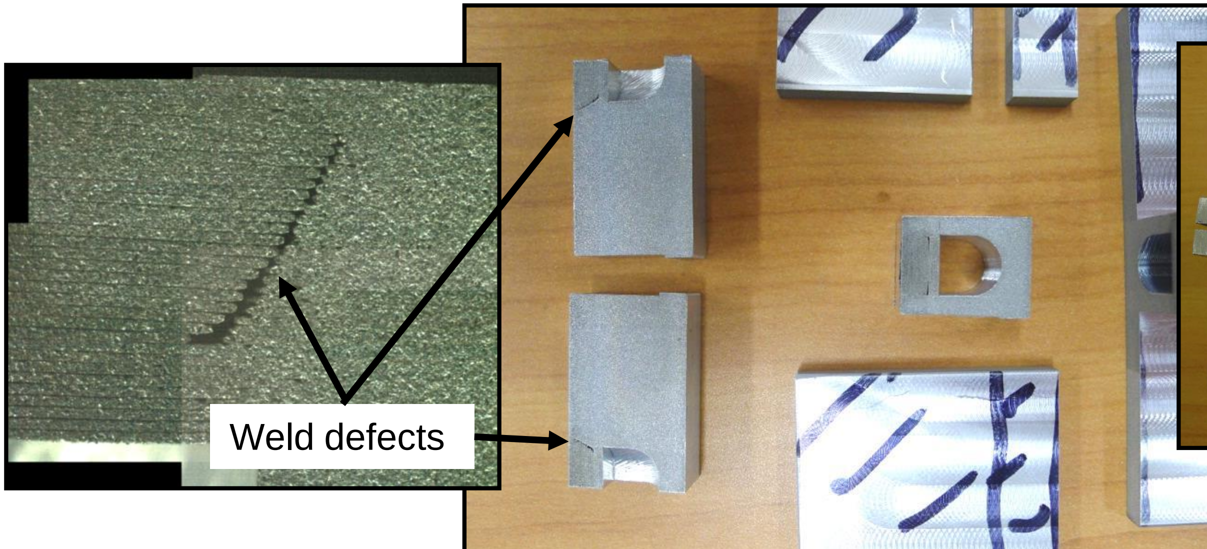
He Pressure Sniff Leak Test



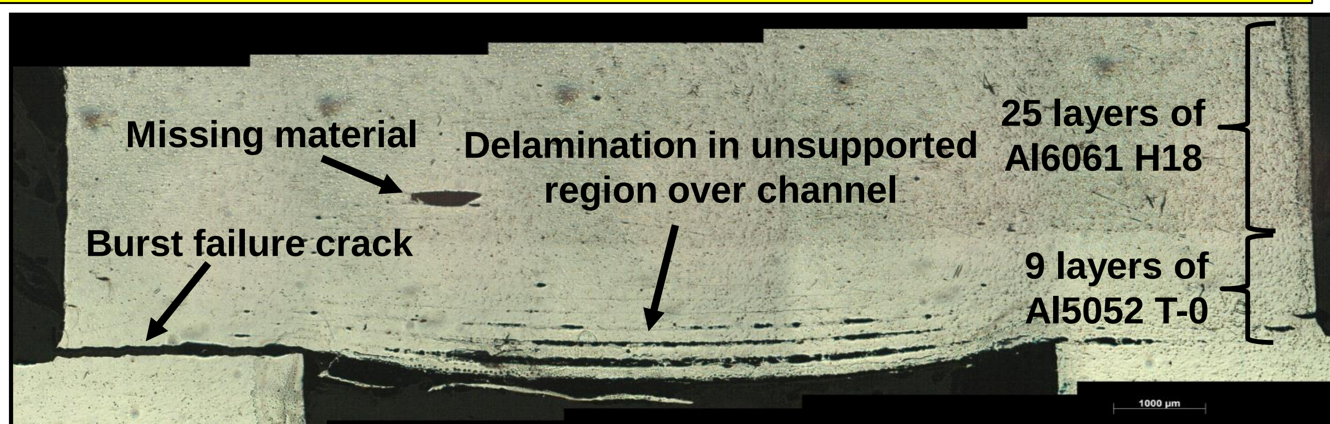
CFC-11 Thermal Flow Test

2014 JPL Spontaneous R&TD Investigates Feasibility of UAM HX^4

Post burst testing cross section and magnification reveals internal weld defects and incomplete consolidation especially over unsupported channel, corroborating x-rays…



BUT the part did pass burst > 800 psi and He leak rate < 5E-9 scc/s

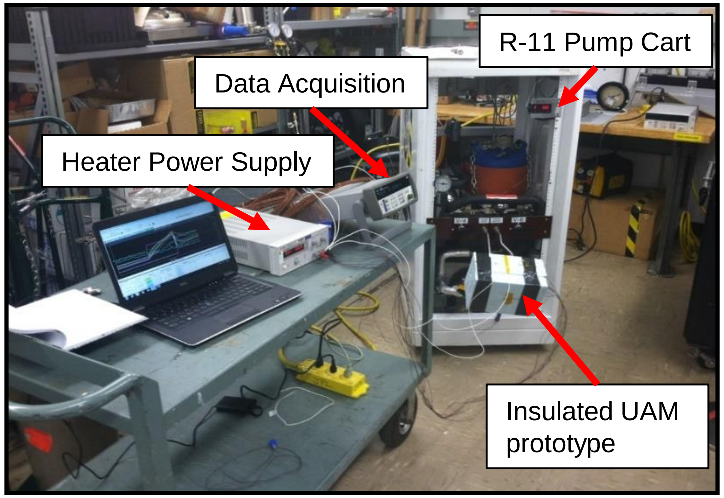


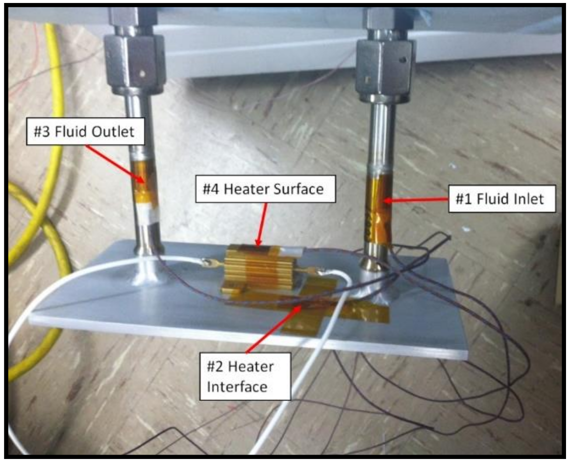
2014 JPL Spontaneous R&TD Investigates Feasibility of UAM HX[4]

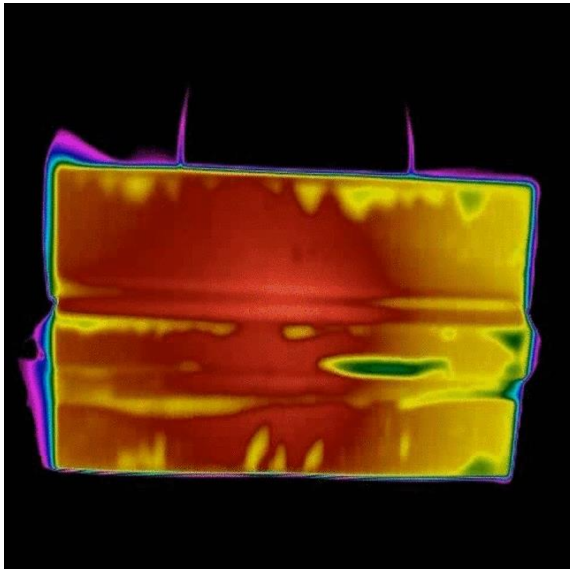
Despite some internal defects, determined UAM HX Feasible!

- Proof of concept demonstrated & <u>hermeticity requirements met</u>
- UAM consolidation over supported regions metallurgically sound
- Defects were observed in the consolidated layers over unsupported spans - concerning from a crack propagation perspective; support material such as Cerrobend was recommended for further study
- Started investigating different cross sectional geometry for double pass design with Hot Isostatic Press (HIP) post-weld under a 2015 SBIR Phase I with Sheridan Solutions LLC


UAM prototypes in different phases of testing and machining





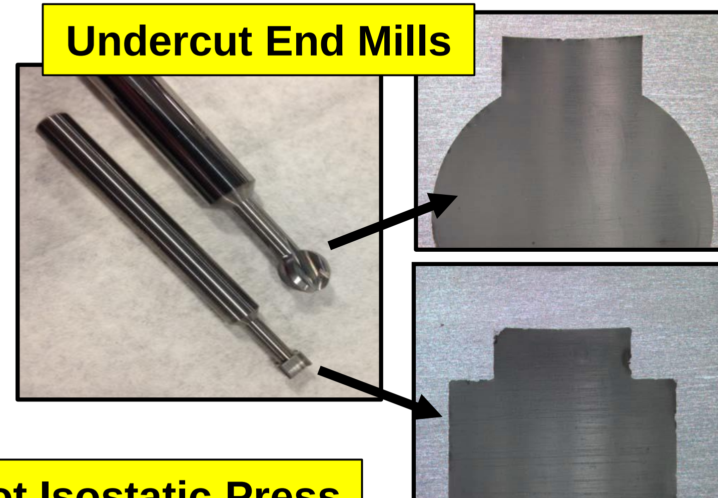


2015 SBIR Phase I UAM HX Recap

Although support material recommended, still a desire to attempt a clean build without it; concern was support material removal and working fluid compatibility with residual…

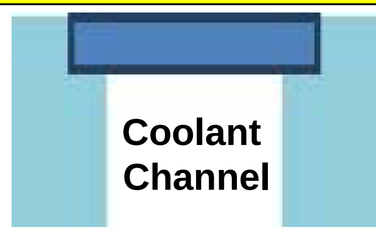
- Investigated undercut end mills and custom channel roof inserts (with and without fins) - both proven feasible, HIPing also shown to have significant increase in burst pressures
- Double pass "J" geometry explored with positive hermetic results; foil "sheet" implemented rather than "tape" as vacuum methods improved

Undercut End Mills



Double Pass Study

Custom Roof Insert



Finned Inserts

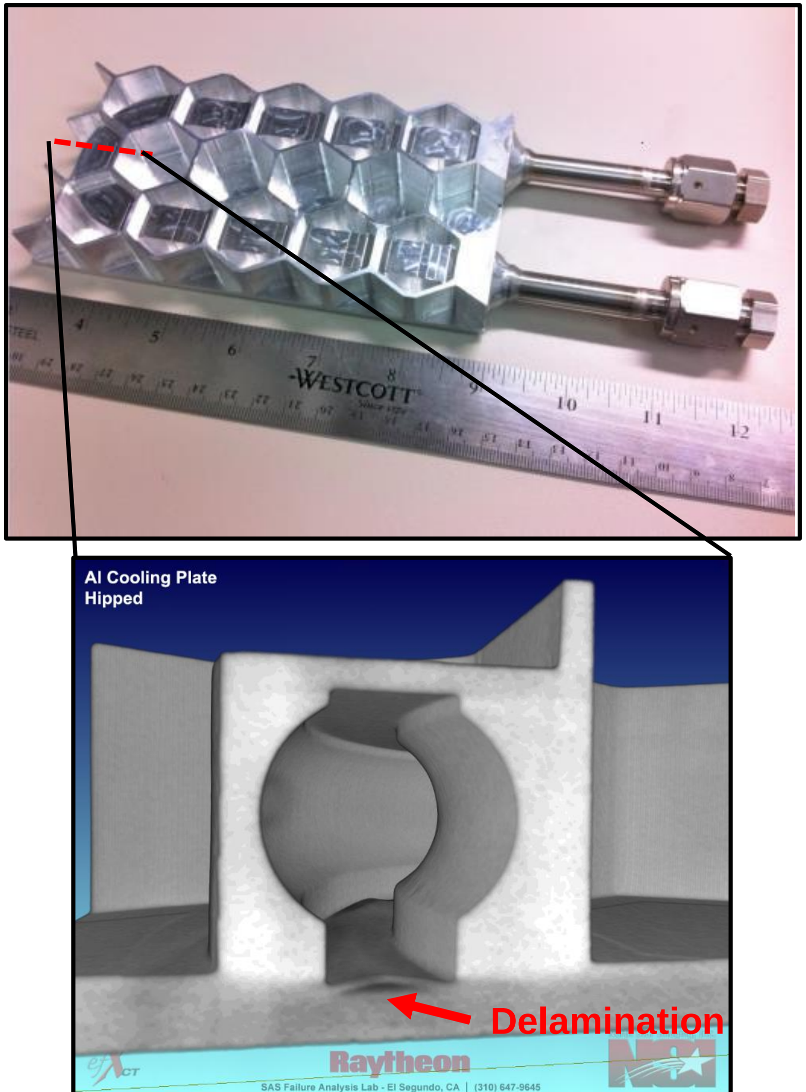
Hot Isostatic Press

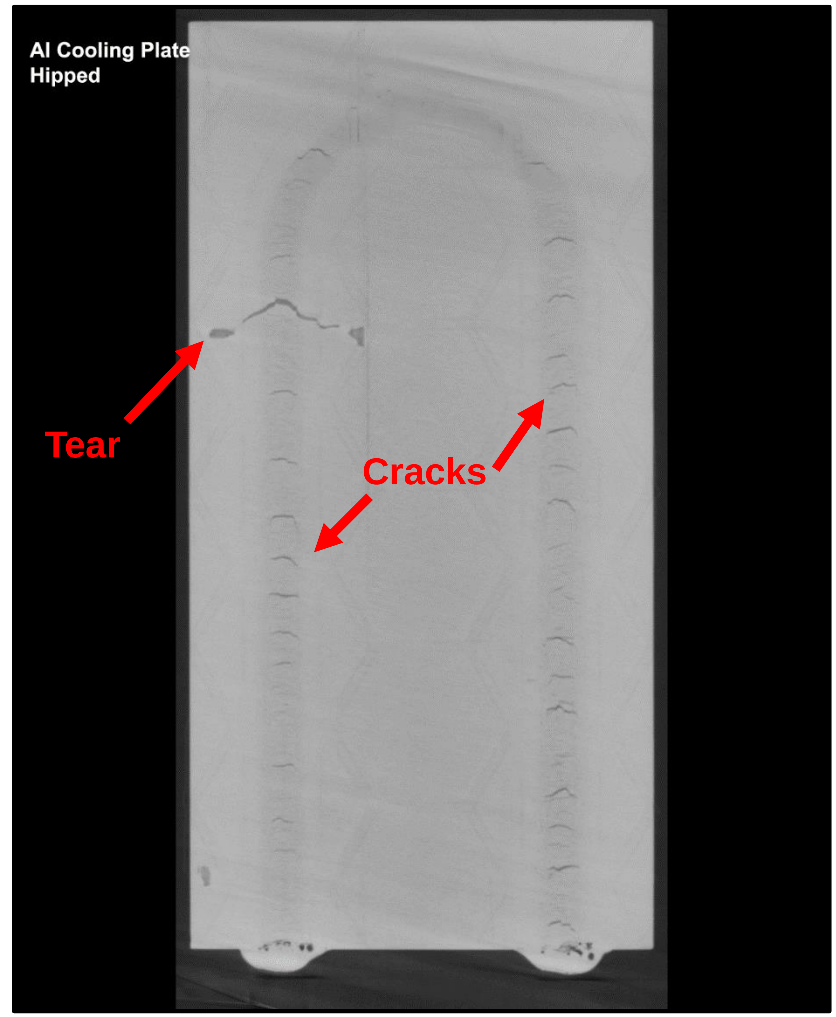
Sample	HIP ?	Background (std.cc/sec)	Leak Rate from top (std.cc/sec)	Pressure Test Results (psi)	
T0.1 (6061 T0 Al)	YES	5.20E-10	4.40E-10	2643	240%
T0.3 (6061 T0 Al)		3.50E-10	3.30E-10	1098	
T0.5 (6061 T0 Al)		6.50E-10	4.50E-10	1351	
T0.7 (6061 T0 Al)		5.5E-10	2.8E-10	1204	
T6.1 (6061 T6 Al)	YES	5.4E-10	3.9E-10	1500	133%
T6.3 (6061 T6 Al)		8.0E-11	5.4E-10	1126	
T0.2 (6061 T0 Al)	YES	3.0E-10	2.4E-10	3049	290%
T0.4 (6061 T0 Al)		3.6E-10	2.7E-10	1048	
T0.6 (6061 T0 Al)		4.5E-10	3.2E-10	1221	
T0.8 (6061 T0 Al)		4.2E-10	3.6E-10	1153	

Images Courtesy of Sheridan Solutions LLC

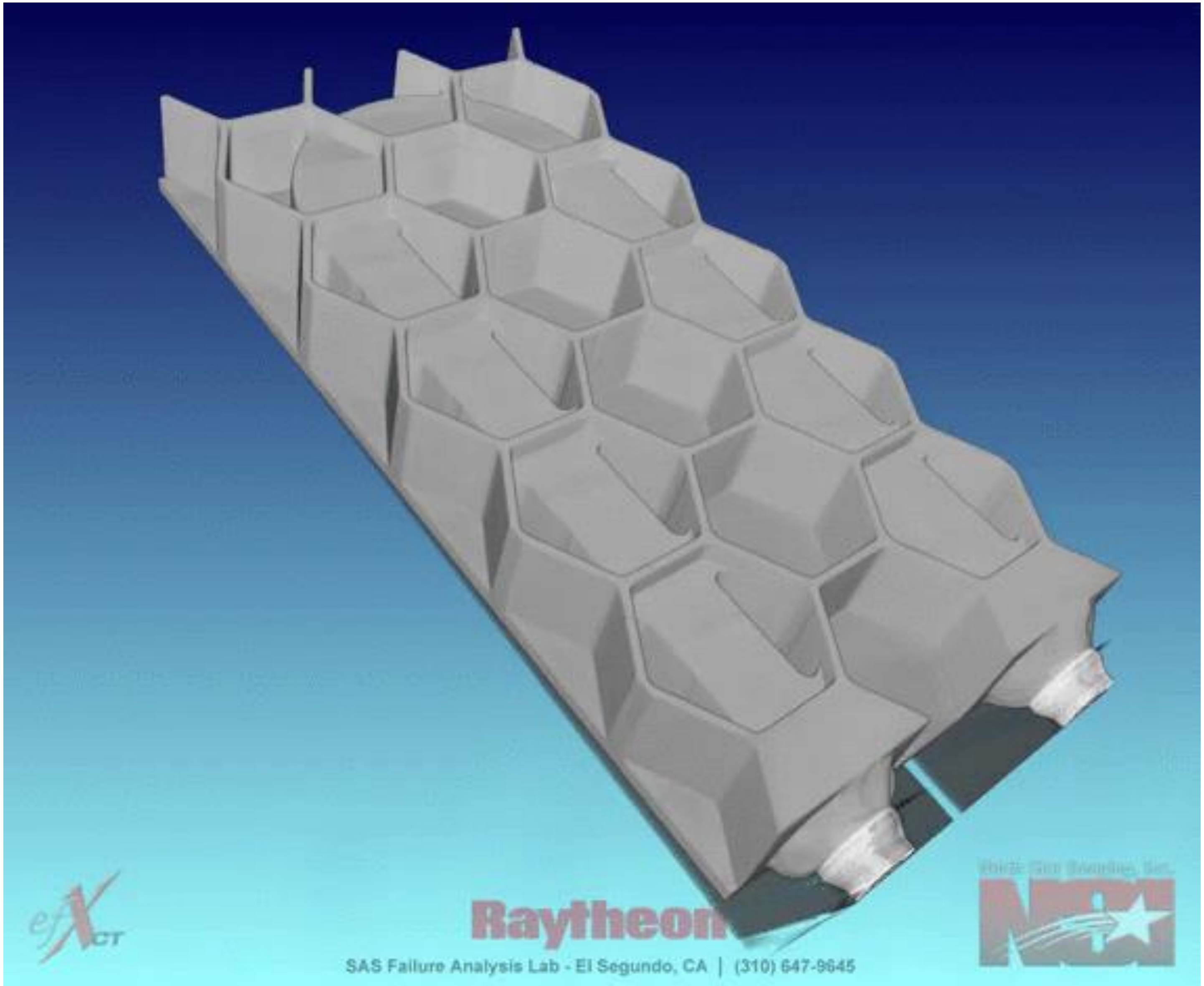
CT Scan of 2015 SBIR Phase I UAM HX Prototype

While UAM HX without support material proved to be hermetic and robust, internal defects above channels still revealed cracking along first layer & widespread delamination in U bend





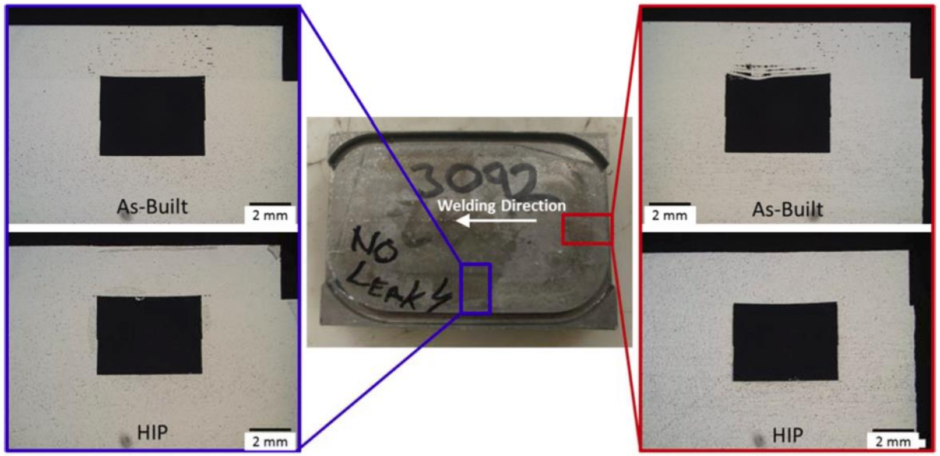
CT Scan of 2015 SBIR Phase I UAM HX Prototype



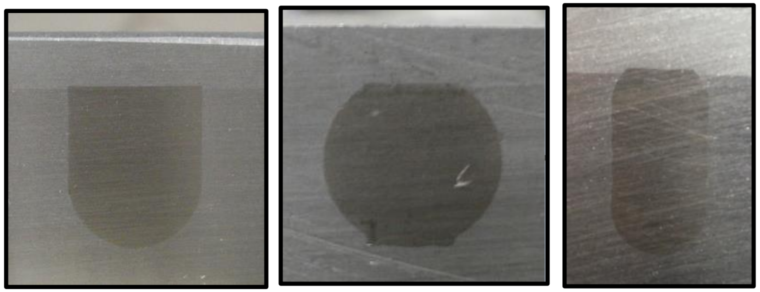
2016 SBIR Phase II UAM HX Study To Date

So… support material & cross section geometry revisited; HIP process improved–channel widths less than 0.2” seem to not require support material if HIPed; channels greater than 0.2” benefit from both support material and HIP

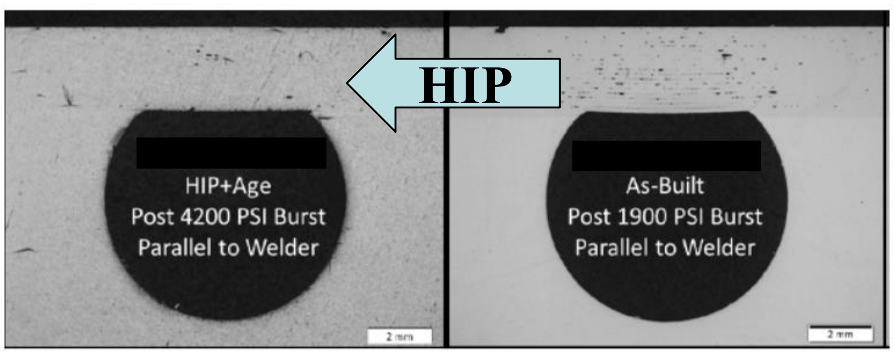
Design of Experiments,
0.2”, Square, No Support Material



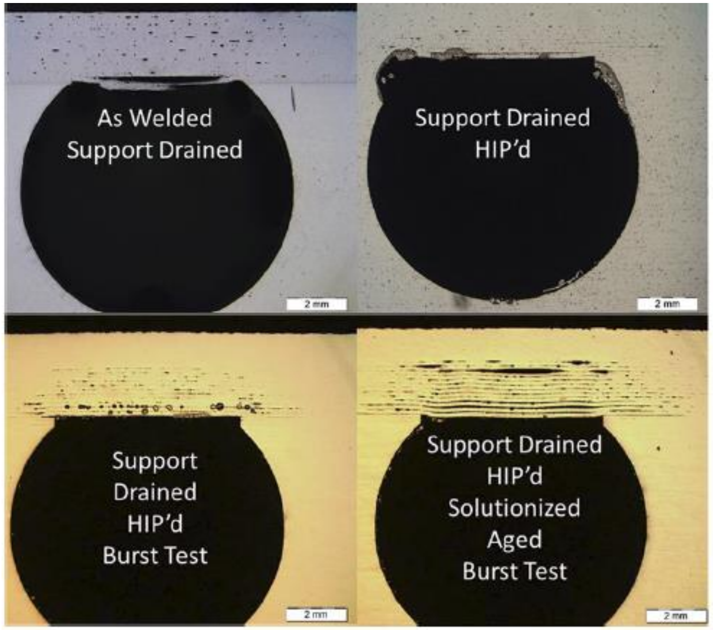
Various Cross Sections & Support Materials



0.38”, Undercut ball, Support Material

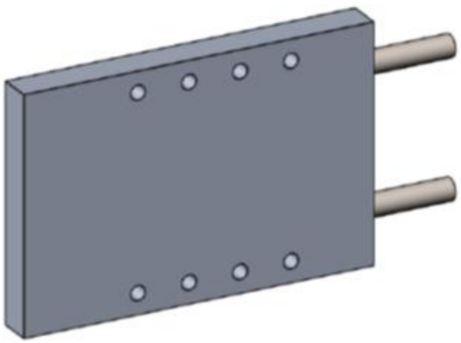


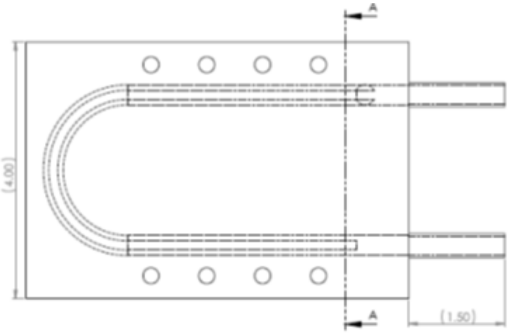
Support Material Removed Post Weld



Images Courtesy of Sheridan Solutions LLC

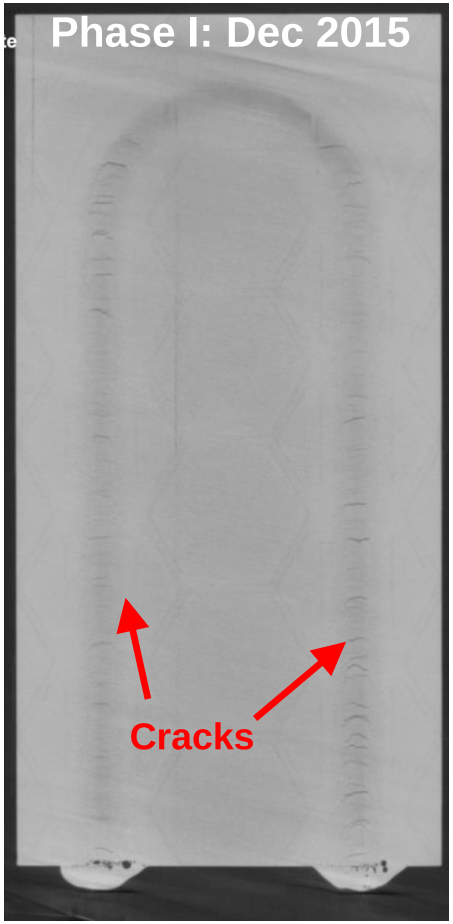
CT Scan of 2016 SBIR Phase II UAM HX Prototype





CT Scan Comparison: Dec 2015 vs. May 2017

Excellent Progress! – much better control of all consolidation layers

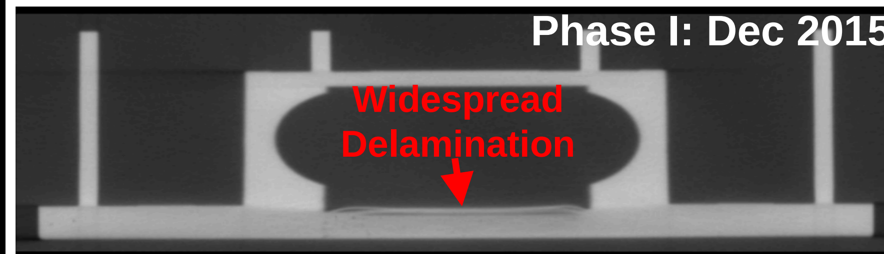


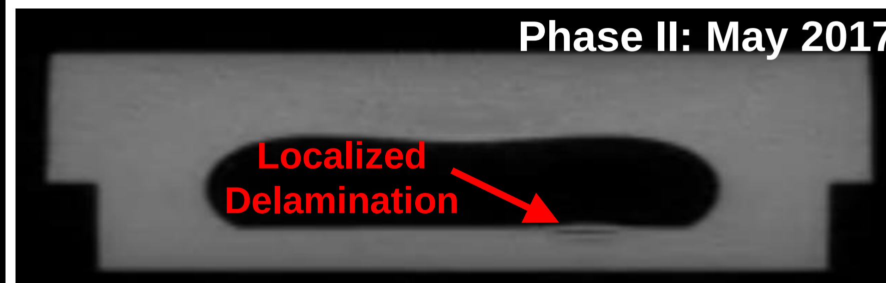
6061 Al
Sheet and Tape
No support material
HIP

6061 Al
All Sheet
Water soluble support material
HIP

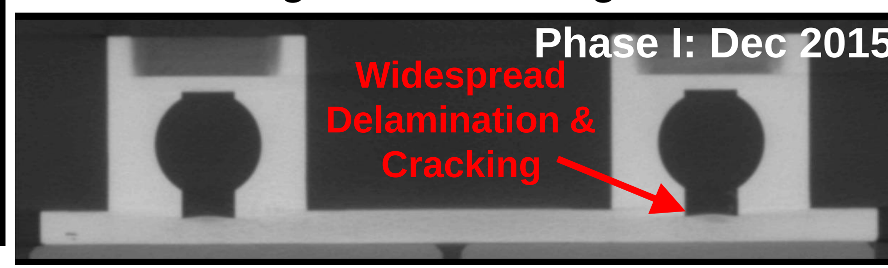
Phase II Images Courtesy of Mark Norfolk

U Bend Channel Segments



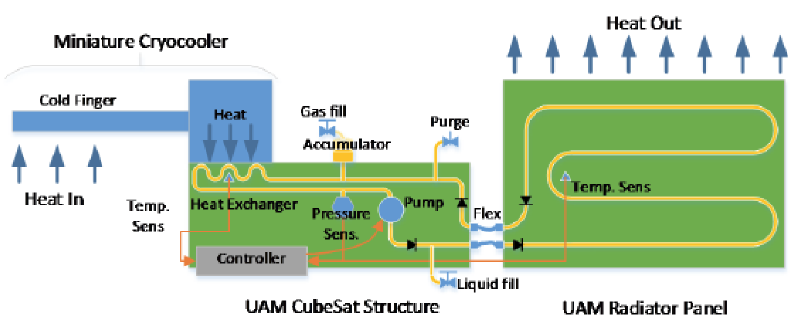


Straight Channel Segments

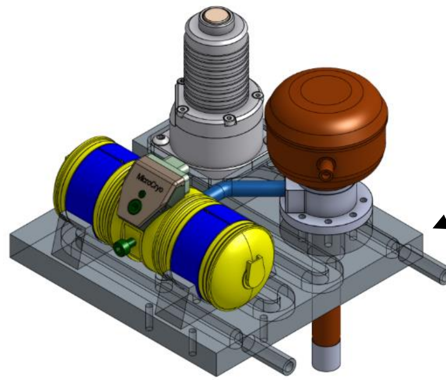


Additional UAM HX Investigation: Active CryoCubeSat

JPL Smallsat Partnership with Dr. Charles Swenson of Utah State University – leverage AM to enable miniature MPFL accommodation of small cryocoolers for Smallsat IR science missions

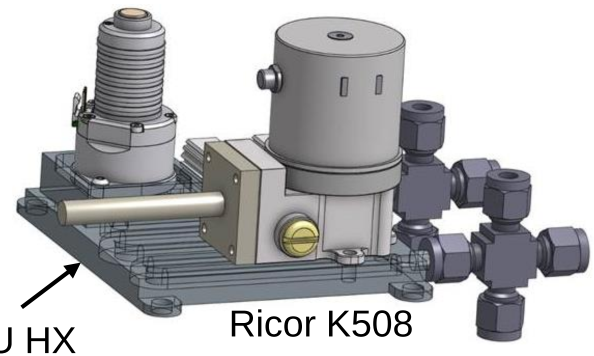


Conceptual Diagram of the Active CryoCubeSat Testbed



Lockheed Micro Cryocooler

1U HX

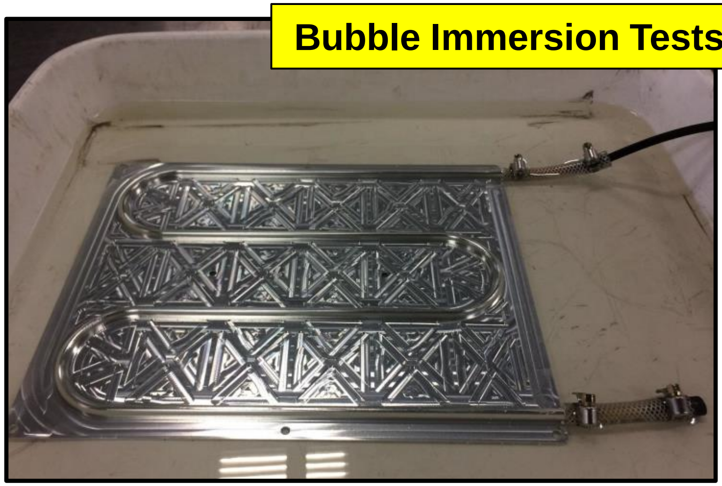


Ricor K508

~3U X 2U Radiator Panel

4 Pass UAM Radiator

Bubble Immersion Tests – No Leaks!



1U HX Prototype

H/W Images Courtesy of Mark Norfolk

Future Work

- Demonstrate UAM HXers still leak tight post thermal cycle and random vibration testing
  - The goal is to get this technology as close to TRL 6 as possible by next year so that it's more likely future JPL missions (i.e. the planned Europa Clipper) can capitalize on it
- Development of test coupons for B-basis design allowables may ultimately be required for flight infusion
  - Note CalRAM has done this for electron beam powder bed fusion of Ti 6Al-4V
- Build more challenging prototypes
  - Perform more metallurgy, NDE, & DE
- Blend small DMLS HX part into a larger UAM HX part
- Investigate blended metal HXers (Cu-Al, Al-SS)
- Fly, Fly, Fly!

Concluding Remarks

- Due to repeatedly successful implementations on NASA Flagship Class Missions, single phase MPFLs are becoming more common place at JPL. We are expecting the business base to grow and thus we are continuing to invest in MPFL relevant technology development.
- Aluminum Additive Manufacturing, namely UAM, is definitely worth leveraging for fabrication of complex liquid cold plate HXers.
  - What are typically very expensive, highly unique, and long lead time assemblies requiring all touch labor can be reduced to single part count using more reliable automatic milling and welding for a fraction of the cost and time.
- SBIR funded projects can be incredibly successful when you have the right motivated team attempting to develop something that both NASA and Industry can equally benefit from.

References

[1] Sunada, Eric, and Rodriguez, Jose, "*JPL Advanced Thermal Control Technology Roadmap*," Spacecraft Thermal Control Workshop, El Segundo, CA 2017.

[2] Mastropietro, A. J., Bhandari, Pradeep, Birur, Gajanana, et. al., "*Summary and Status of 5 Mechanical Pumped Fluid Loop (MPFL) Projects Currently in Process at the Jet Propulsion Laboratory (JPL) for the Planned Europa Mission, Mars 2020, Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), Orbiting Carbon Observatory (OCO-3), and Cold Atom Lab (CAL)*," Thermal and Fluids Analysis Workshop (TFAWS), Mountain View, CA, August 2016.

[3] Maghsoudi, Elham, Mastropietro, A. J., Roberts, Scott, and Kinter, Bradley, "*Experimental Thermal Performance Comparison of 3D Printed Aluminum Heat Exchangers vs Traditionally Manufactured Heat Exchangers*," Spacecraft Thermal Control Workshop (STCW), El Segundo, CA, March 2017.

[4] Mastropietro, A. J., Pauken, Michael, Hofmann, Douglas, D'Agostino, Saverio, "*Ultrasonic Additive Manufacturing (UAM) of Heat Rejection System (HRS) Heat Exchangers*," Innovative Spontaneous Concept R&TD, Annual Report to JPL's R&TD Program Office, 2014.

Acknowledgements

Part of the development described was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors would like to thank NASA's Space Technology Mission Directorate SBIR PMO and its Small Spacecraft Technology PMO as well as JPL's Internal R&TD Program Office for enabling this work. The authors also wish to thank the following individuals for their invaluable support: Gregory Davis, Timothy O'Donnell, Nickolas Emis, Eric Sunada, Gordon Cucullu, Fred Hadaegh, Saverio D'Agostino, Michael Pauken, Abdullah Aljabri, Bryan Mcenerney, Raymond Higuera, Brian Carroll, Sandro Torres, Bradley Kinter, Stefano Cappucci, Thomas Ackermann, Israel Morado, and John Sheridan, Mark Norfolk, Adam Hehr, Justin Wenning, Cam Benedict, Brian Miracle, Hilary Johnson, Jay Belle Isle, Josh George, Gary Paelicke, Luke Snider of Sheridan Solutions & Fabrisonic LLC, and Dr. Charles Swenson, and Lucas Anderson of Utah State University.

Questions?

Backup

Partial List of Acronyms

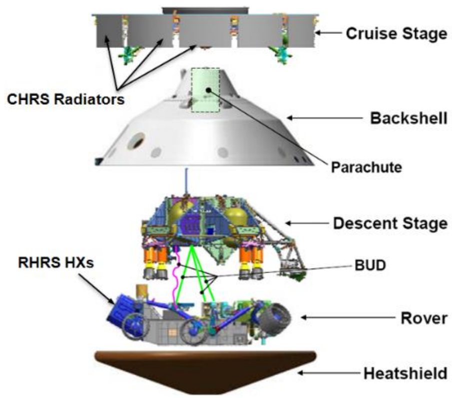
- Al - Aluminum
- AM – Additive Manufacturing
- CAL – Cold Atom Laboratory
- CFC-11 – Trichlorofluoromethane, Freon-11
- CHEMIN – Chemistry & Mineralogy
- CNC – Computer Numerical Controlled
- DC – Direct Current
- DMLS – Direct Metal Laser Sintering
- ECOSTRESS – Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station
- He – Helium
- HIP – Hot Isostatic Press
- HRS – Heat Rejection System
- HX – Heat Exchanger
- ISS – International Space Station
- JEM-EF – Japanese Experiment Module External Facility
- JPL – Jet Propulsion Laboratory
- MAHLI – Mars Hand Lens Imager
- MPFL – Mechanical Pumped Fluid Loop
- MSL – Mars Science Laboratory
- NASA – National Aeronautics and Space Administration
- NDE – Non Destructive Evaluation
- OBA – Optical Bench Assembly
- OCO – Orbiting Carbon Observatory
- PMO – Program Management Office
- PS&S – Propulsion, Safety, & Sustainment
- RAMP – Rover Avionics Mounting Plate
- R&TD – Research & Technology Development
- REMS – Rover Environmental Monitoring Station
- RIPA – Rover Integrated Pump Assembly
- RIPAS – Rover Integrated Pump Assembly System
- SAM – Surface Analysis at Mars
- SS – Stainless Steel
- UAM – Ultrasonic Additive Manufacturing
- VAMP – Vertical Avionics Mounting Plate

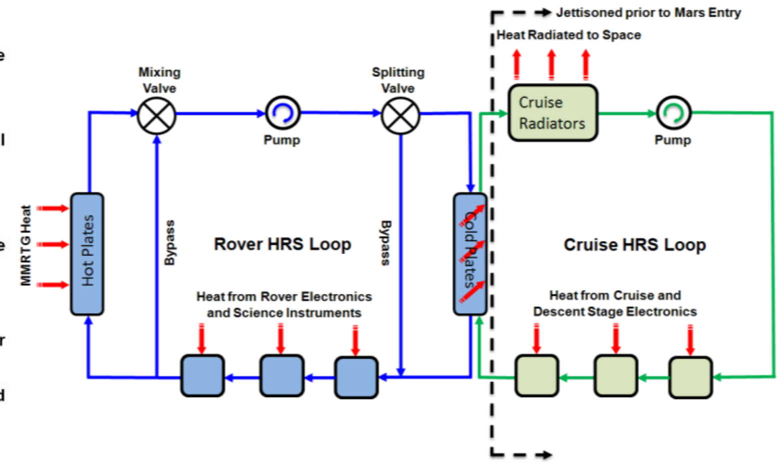
Summary

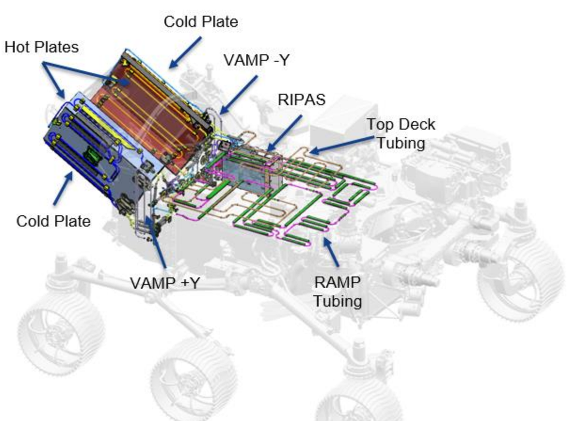
MPFL Parameter	Mars 2020	Planned Europa	ECOSTRESS	OCO-3	CAL
AFTs	RAMP -40°C to +50°C	Propulsion Module 0°C to 35°C	Avionics -20°C to + 50°C FPA 65K	Avionics -20°C to + 50°C FPA 125K	Avionics 0°C to 49°C
Dissipation on Loop	2000W MMRTG + 300 W Electronics	360W (CBE) to 680W (MEV)	800 W (MEV)	900 W (MEV)	up to 500W
Working Fluid	CFC-11	CFC-11	FC-72	FC-72	DI Water
MEOP	200 psia	< 150 psia	68 psia	68 psia	121 psia
Flow Rates	0.75lpm (Rover) 1.5 lpm (Cruise)	0.75 lpm **or** 1.5 lpm	1.5 lpm	1.5 lpm	0.75 lpm
Estimated Line Length	59.7m (Rover) 73m (Cruise)	86m	25m	21.4m	2m
Pressure Drop	<8.5psid (Rover) <8.5psid (Cruise)	< 8.5 psid	<8.5 psid	<8.5 psid	<2.9 psid
Expected Mcp	15 W/C (Rover) 30 W/C (Cruise)	15 W/°C **or** 30 W/°C	45 W/°C	45 W/°C	50 W/°C
Reynolds Numbers	3,000-8,000 (Rover) 6,000-16,000 (Cruise)	3,000-8,000 **or** 6,000-16,000	10,000	10,000	2,000
Convection Coefficients	300-500 W/m^2°C (Rover) 700-1,000 W/m^2°C (Cruise)	300-500 W/m^2°C **or** 700-1,000 W/m^2°C	720 W/m^2°C	720 W/m^2°C	260 W/m^2°C
As Filled Volume	4.3L (Rover) 6.5L (Cruise)	6.3L	2.2L	2L	0.8 L
Mission Life	3.6 Years	11.3 Years	13 Months	13 Months	1 Year

Mars 2020 MPFL Details

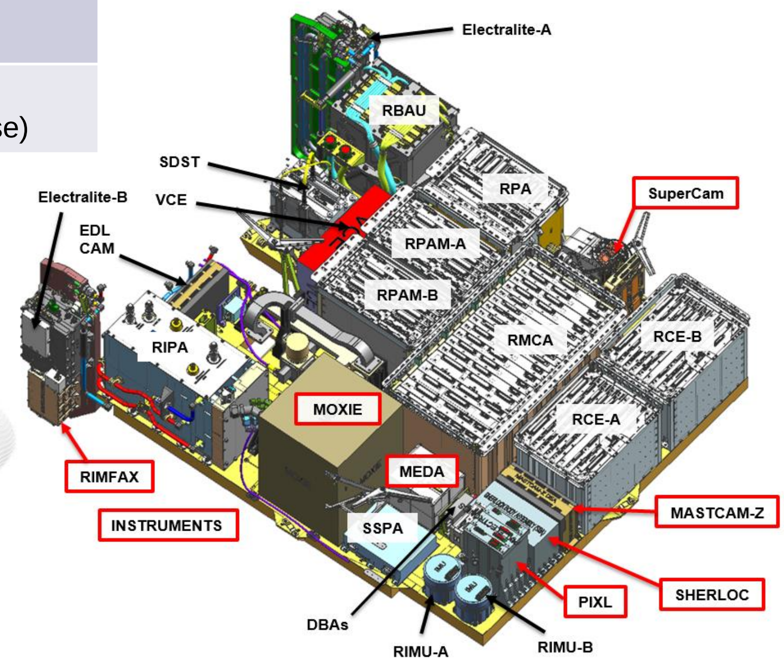
Mars 2020 Heat Rejection & Recovery System (HRS) Details	
Working Fluid	CFC-11, R-11, Freon-11, Trichlorofluoromethane
MEOP	200 psia
Flow Rates	0.75 lpm @~8.5 psid* (Rover) 1.5 lpm @~8.5 psid* (Cruise)
Expected mcp	15 W/^{o}C (Rover) 30 W/^{o}C (Cruise)
Reynolds Numbers	3,000-8,000 (Rover) 6,000-16,000 (Cruise)
Convection Coefficients	300-500 W/m^{2o}C (Rover) 700-1,000 W/m^{2o}C (Cruise)



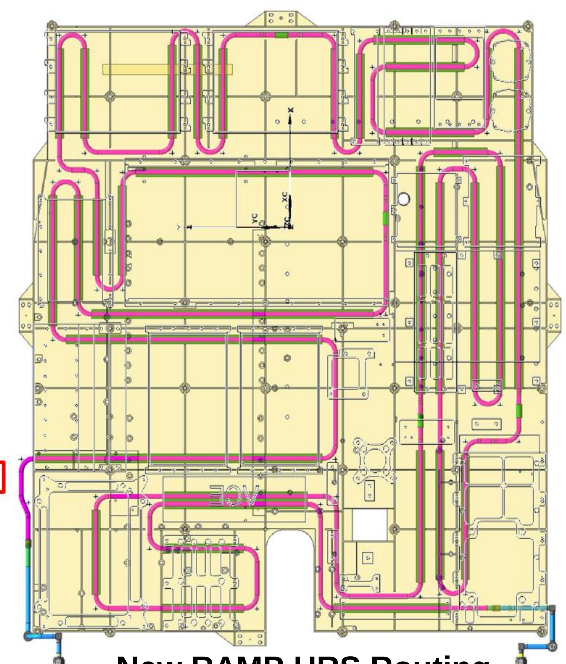




Rover HRS Loop



New RAMP Layout for Mars 2020



New RAMP HRS Routing

* Pressure rise external to pump package