TFAWS Active Thermal Paper Session

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)

A. J. Mastropietro, Pradeep Bhandari, Gajanana Birur, Hared Ochoa, Jenny Hua, Anthony Paris, Nickolas Emis, Ben Furst, David Bame, Raymond Higuera, Yuanming Liu, Paul Karlmann, Gordon Cucullu, Jacqueline Lyra, Keith Novak, Jennifer Miller, Jason Kempenaar, Matthew Redmond, Edgardo Farias, Brian Carroll, Josh Kempenaar, and Daniel Zayas

Jet Propulsion Laboratory, California Institute of Technology

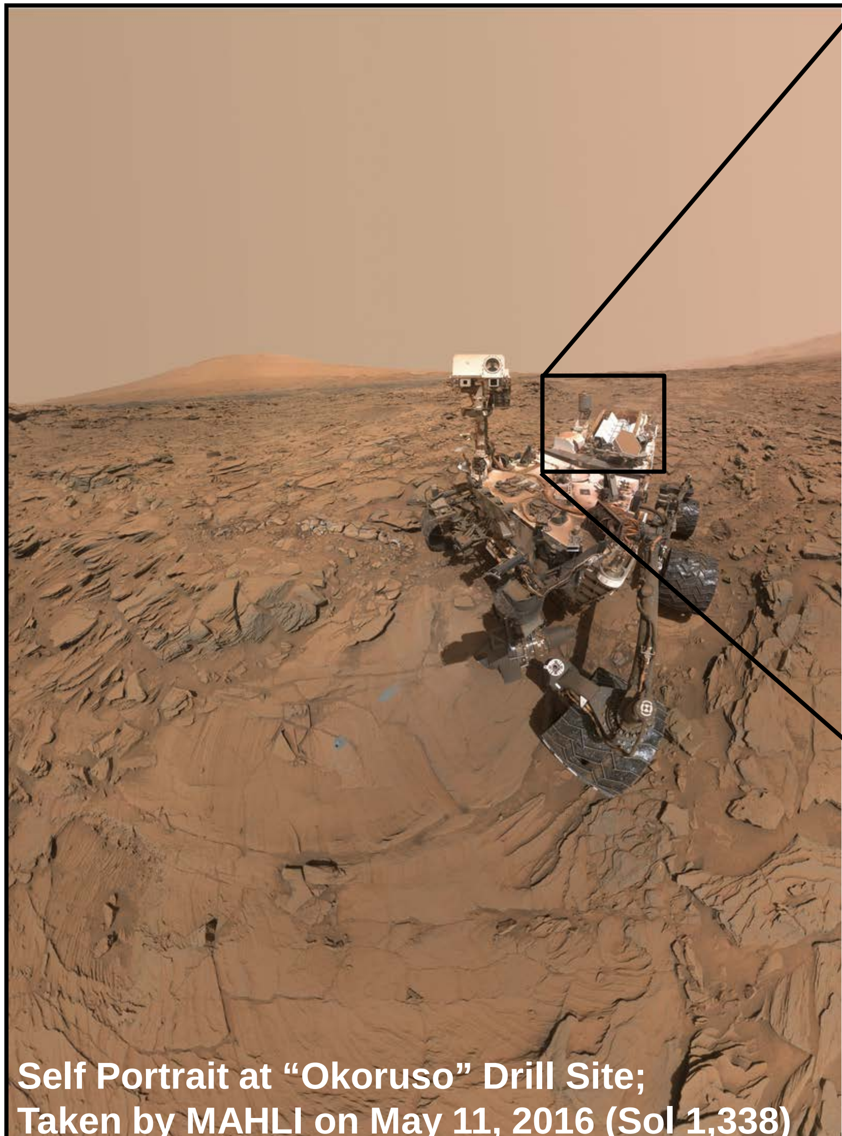
Presented By
A. J. Mastropietro

Thermal & Fluids Analysis Workshop
TFAWS 2016
August 1-5, 2016
NASA Ames Research Center
Mountain View, CA

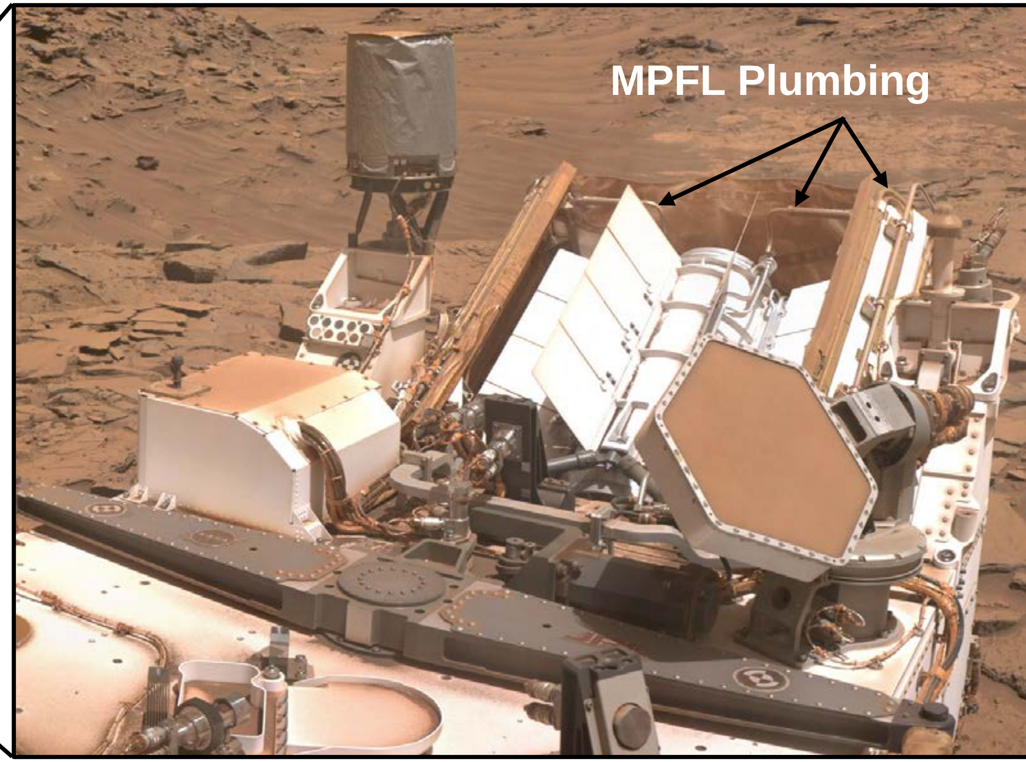
Agenda

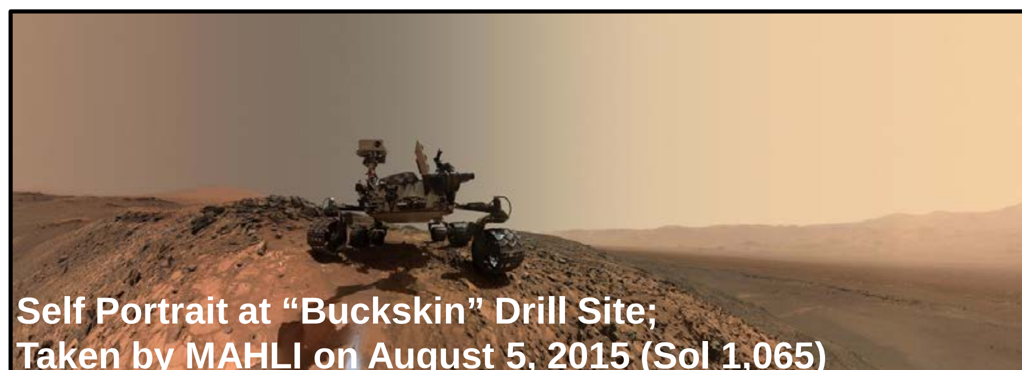
- JPL's Upcoming Mechanical Pumped Fluid Loop (MPFL) Projects: Building Upon the Recent Success of the Curiosity Rover
- MPFL Project Updates:
  - Mars 2020
  - Planned Europa Mission
  - ECOSystem Thermal Radiometer Experiment on Space Station (ECOSTRESS)
  - Orbiting Carbon Observatory (OCO-3)
  - Cold Atom Laboratory (CAL)
- Concluding Remarks

JPL's Upcoming MPFL Projects: Building upon the Recent Success of the Curiosity Rover Launched November 2011 (1/3)



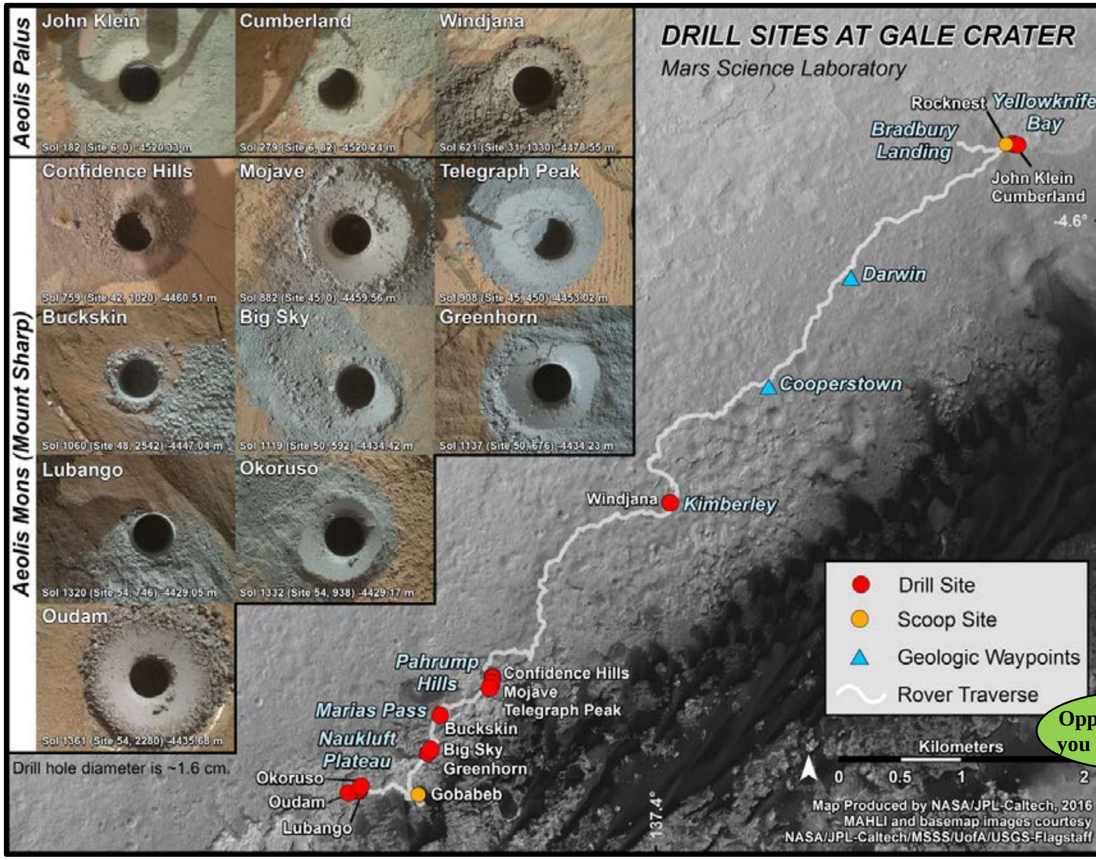
Self Portrait at "Okoruso" Drill Site;
Taken by MAHLI on May 11, 2016 (Sol 1,338)

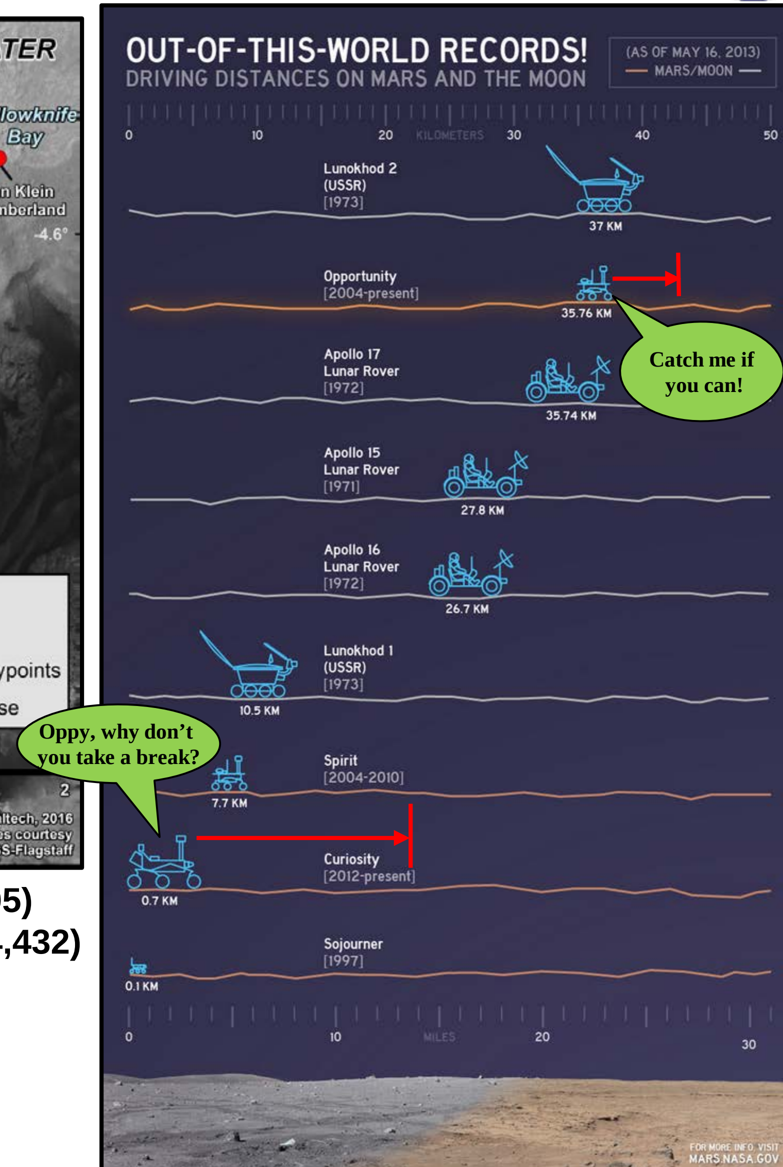




Self Portrait at "Buckskin" Drill Site;
Taken by MAHLI on August 5, 2015 (Sol 1,065)

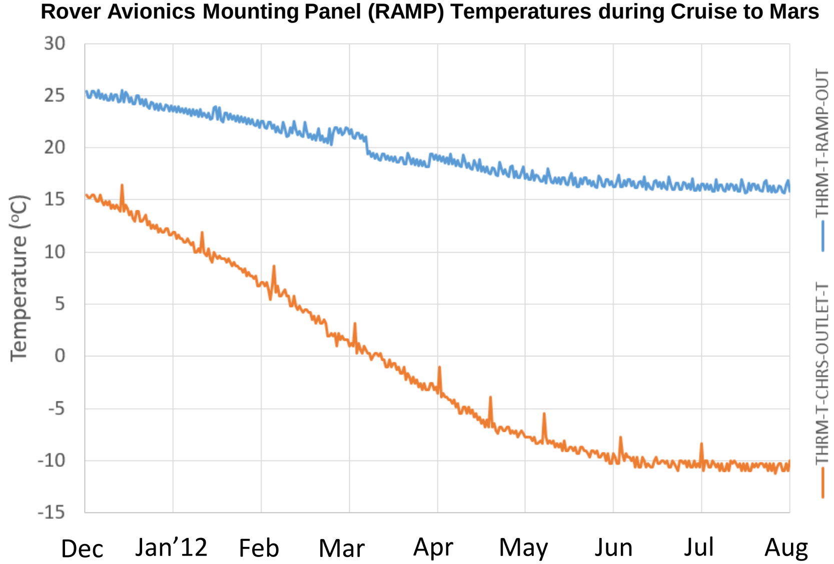
JPL's Upcoming MPFL Projects: Building upon the Recent Success of the Curiosity Rover Launched November 2011 (2/3)

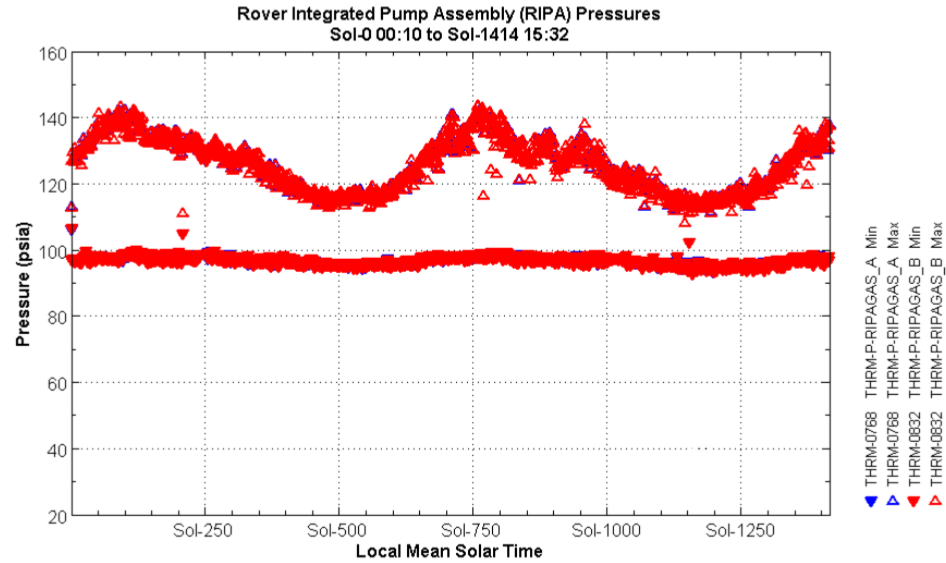


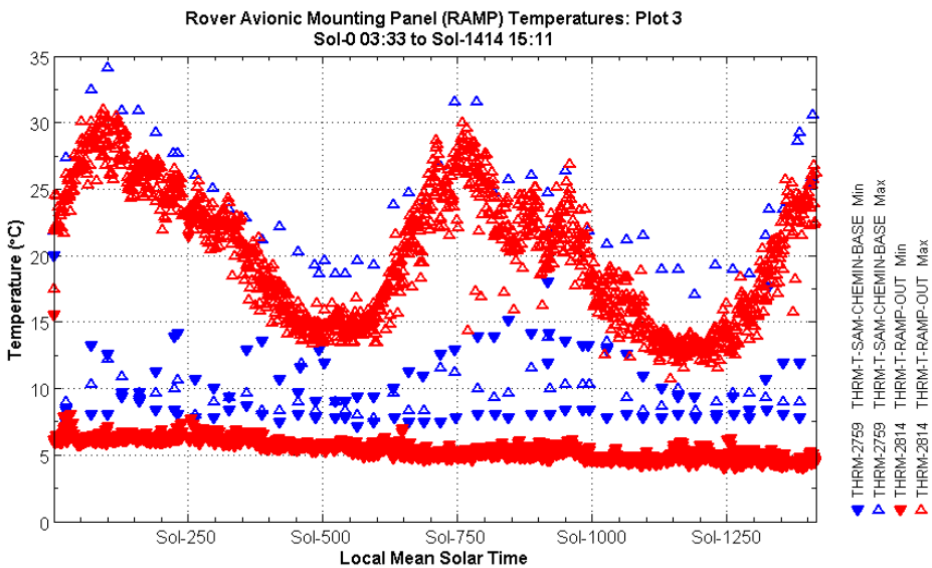


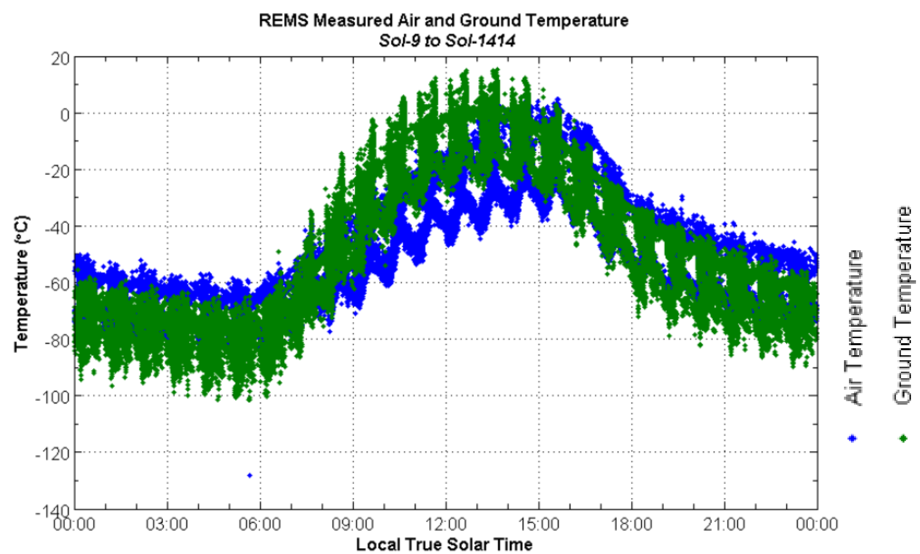
As of 7/21/2016, Curiosity Total Odometry ~13,604 m (Sol 1,405)
As of 7/12/2016, Opportunity Total Odometry ~42,940 m (Sol 4,432)

JPL's Upcoming MPFL Projects: Building upon the Recent Success of the Curiosity Rover Launched November 2011 (3/3)





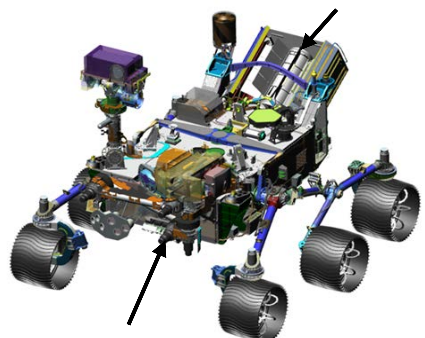


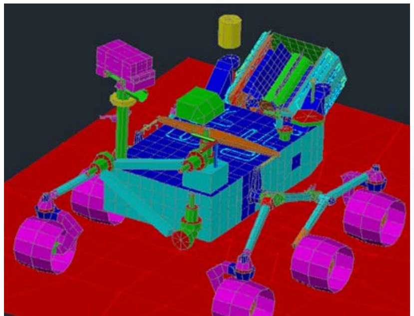


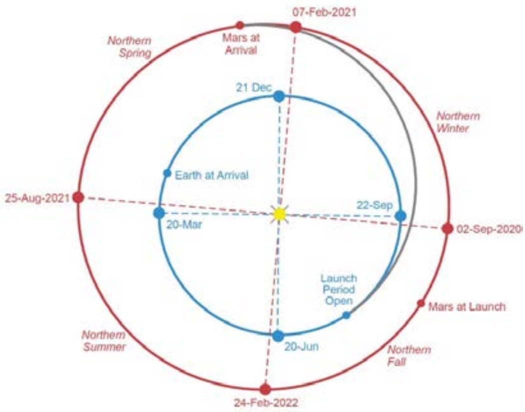
Mars 2020 Mission Thermal Requirements

Mission: Identify past environments capable of supporting microbial life, collect a returnable cache of samples using a coring system, seek signs of past microbial life in those habitable environments, and prepare for human exploration by testing oxygen production from Martian atmosphere.

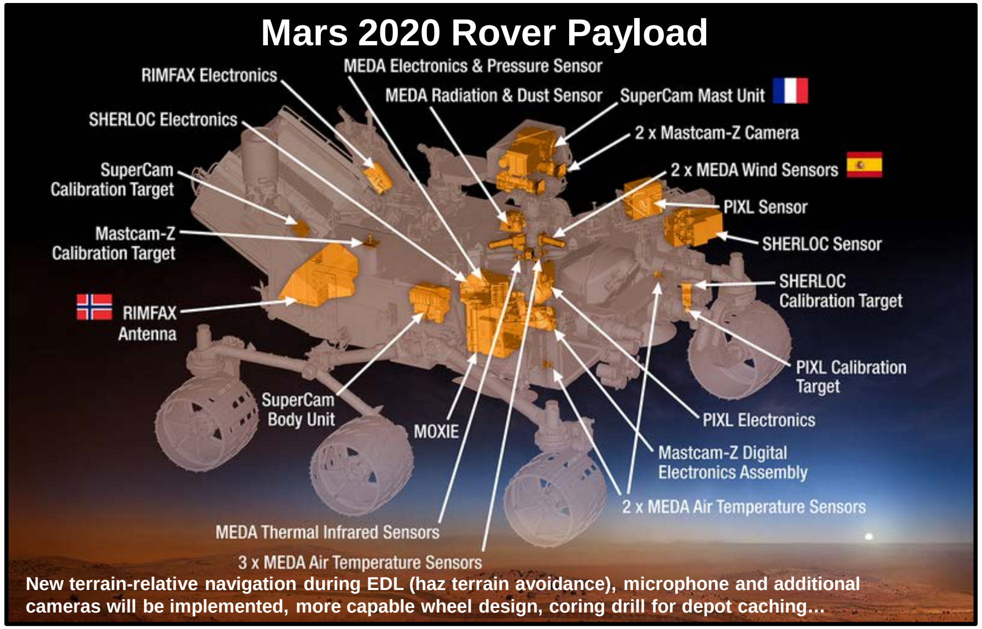
Mars 2020 Schedule	
CDR	December 2016
Rover Thermal Test	2019
Launch on Intermediate or Heavy Class Rocket	July-August 2020
Arrival at Mars	February 2021




Thermal Desktop® Model

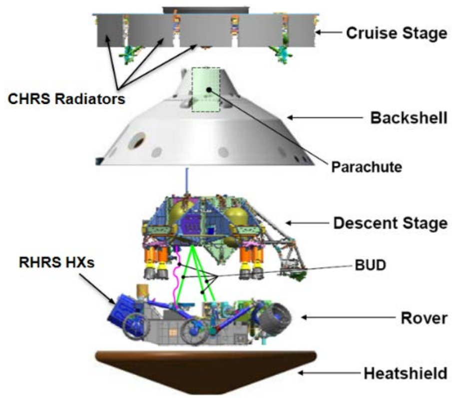


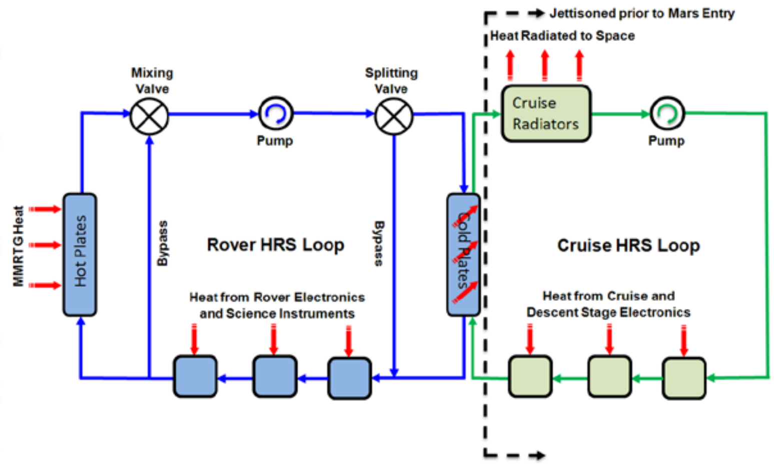
Mars 2020 Thermal Requirements/Constraints	
Allowable Flight Temperatures (AFTs)	RAMP -40°C to +50°C
Stability on Mars	RAMP maximum diurnal ΔT of 50°C
Sun Range	1 AU to 1.58 AU
Martian Thermal Environment	+/-30°C latitude: $-120^oC < T_{atm} < 13^oC$; $-124^oC < T_{grnd} < 38^oC$
Dissipation on Rover Fluid Loop	2000W MMRTG + up to 300W instantaneous electronics
Mission Life	1.5 Martian years on surface (3 Earth years + 7 months cruise)

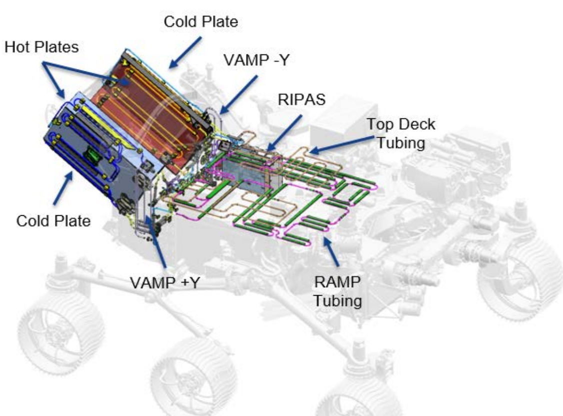


Mars 2020 MPFL Details

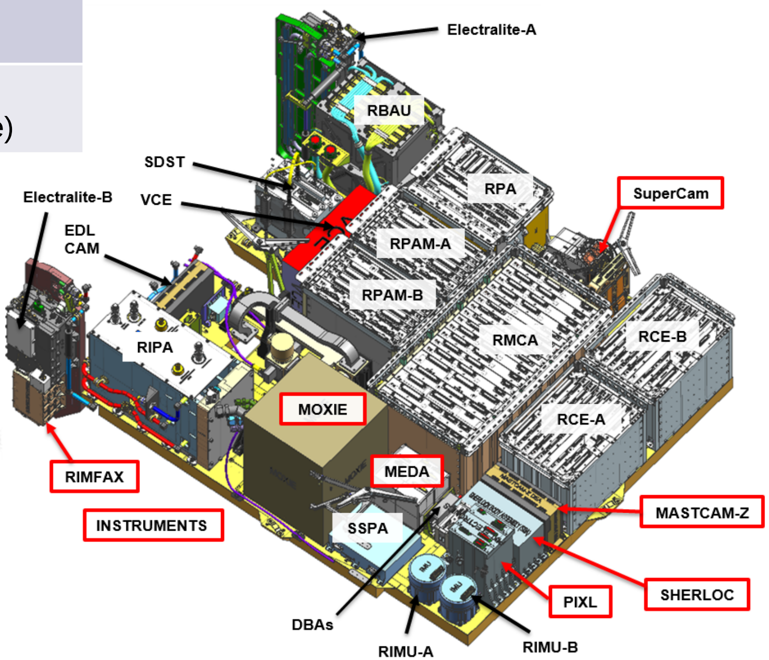
Mars 2020 Heat Rejection & Recovery System (HRS) Details	
Working Fluid	CFC-11, R-11, Freon-11, Trichlorofluoromethane
MEOP	200 psia
Flow Rates	0.75 lpm @~8.5 psid* (Rover) 1.5 lpm @~8.5 psid* (Cruise)
Expected mcp	15 W/°C (Rover) 30 W/°C (Cruise)
Reynolds Numbers	3,000-8,000 (Rover) 6,000-16,000 (Cruise)
Convection Coefficients	300-500 W/m²°C (Rover) 700-1,000 W/m²°C (Cruise)



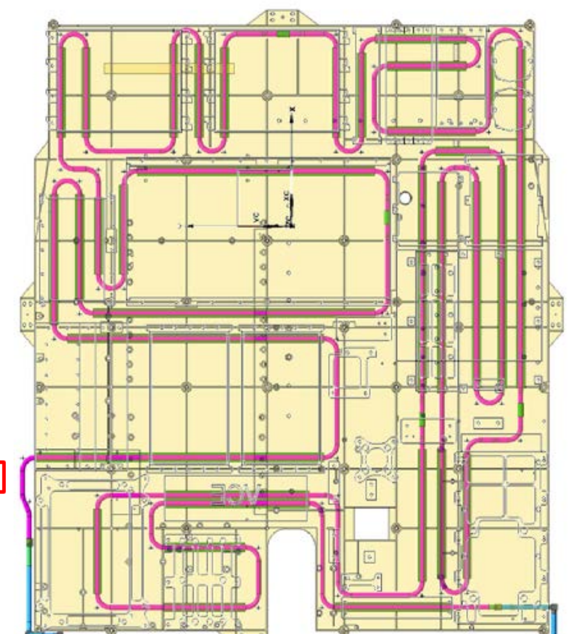




Rover HRS Loop



New RAMP Layout for Mars 2020



New RAMP HRS Routing

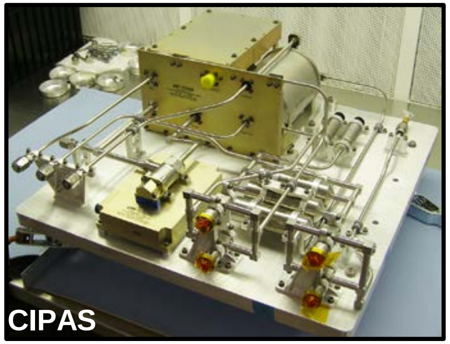
* Pressure rise external to pump package

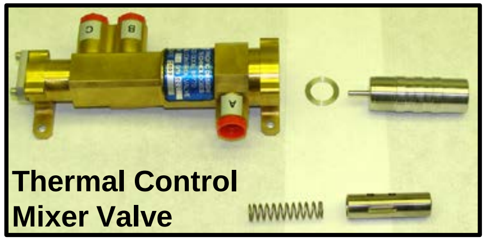
Mars 2020 Pumps and Thermal Control Valves

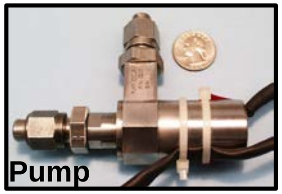
…Built upon Mars Pathfinder and Mars Exploration Rover Heritage.
Mars 2020 will implement the identical pump/valve packages flown on Mars Science Lab.

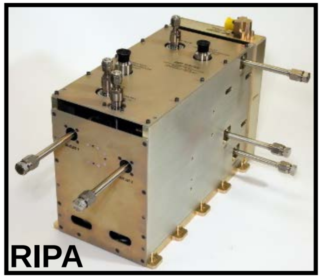
Mars 2020 Pump Details	
Pump Type	Brushless DC Centrifugal
Pump Speed	11,200 – 12,000 RPMs
Pump Package Power Draw (including electronics)	8.5 W (RIPA) @ 28V 12 W (CIPA) @ 28V
Pump Package Mass	15 kg (RIPAS) 23 kg (CIPAS)

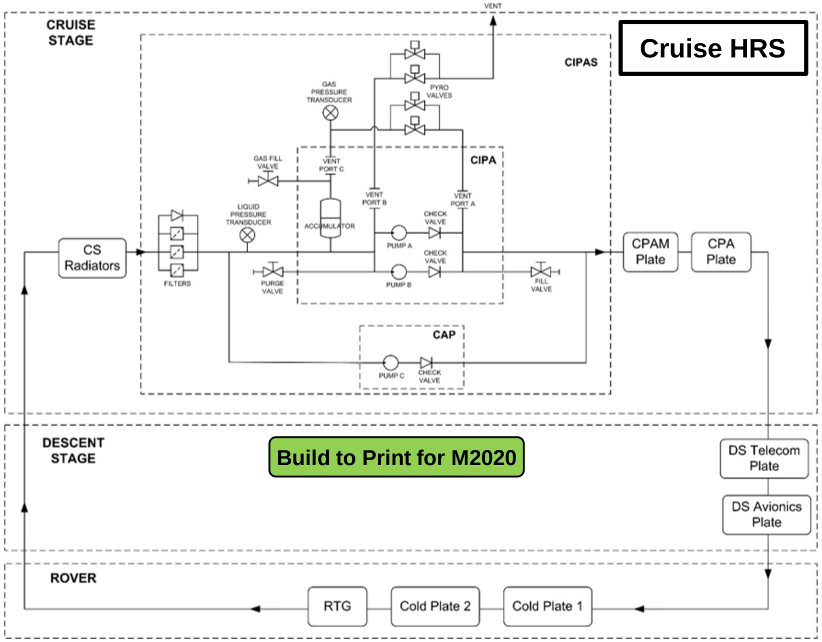
Mars 2020 Thermal Control Valve Details	
Passive Temperature Control	DC 200 Oil reservoir
Mixer Valve Setpoints	< -10ºC, 5% bypass MMRTG > +10ºC, 44% bypass MMRTG
Splitter Valve Setpoints	< +15ºC, 94% bypass radiator > +35ºC, 5% bypass radiator

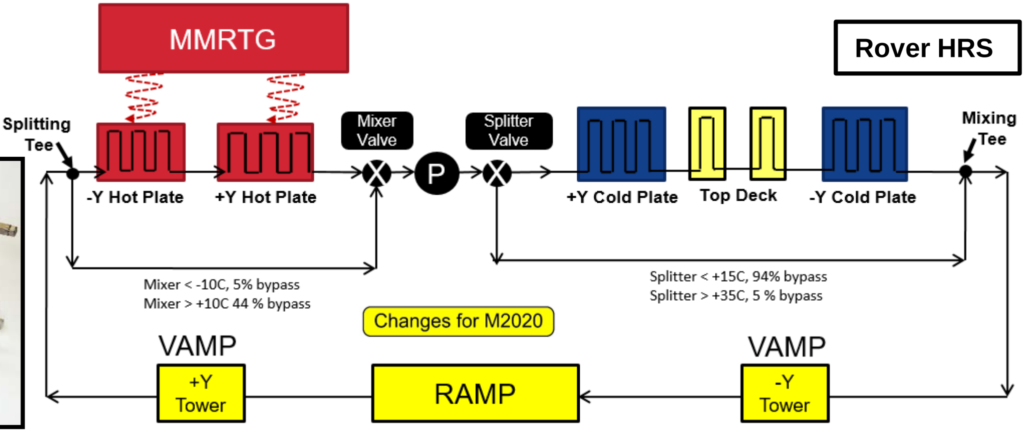

CIPAS


Thermal Control Mixer Valve


Pump


RIPA



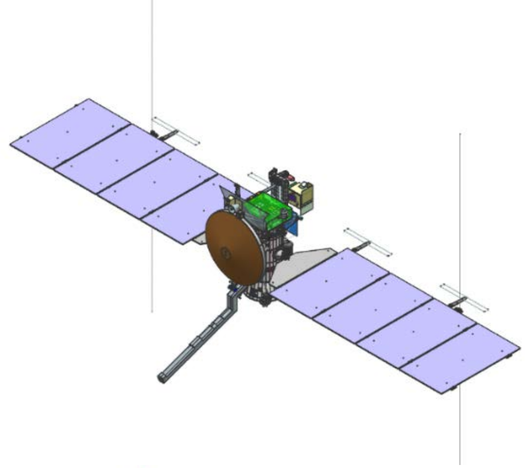


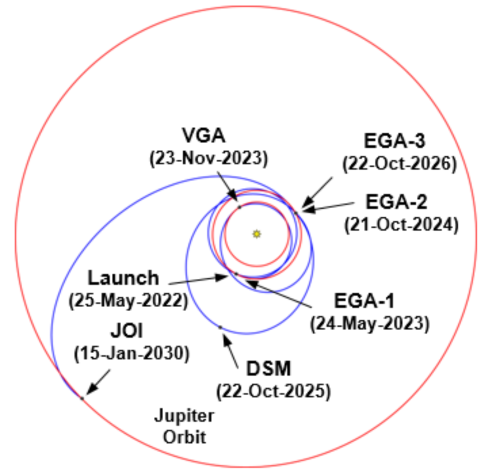
Planned Europa Mission Thermal Requirements

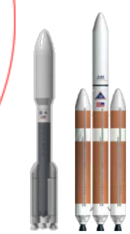
Mission: Conduct detailed reconnaissance of Jupiter's moon Europa - characterize ice shell and ocean properties, surface-ice-ocean exchange, ocean composition and chemistry, geology, and high science interest localities, as well as identify hazards for a potential future landed mission to Europa.

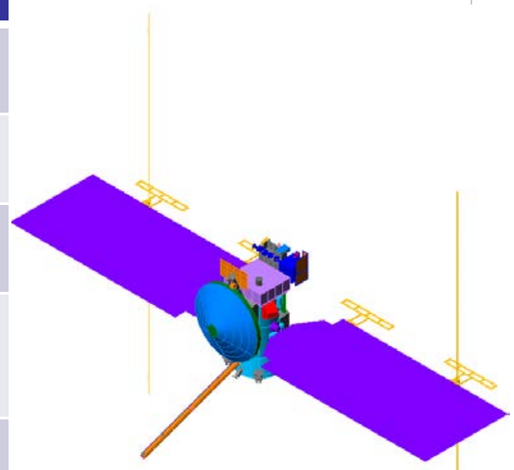
Europa Mission Tentative Schedule	
SRR	August 2016
MDR	December 2016
PDR	March 2018
CDR	May 2019
Launch	June 2022
Arrival at Jupiter (JOI)	December 2024 (SLS Direct) or February 2030 (EELV EVEEGA)

Europa Thermal Requirements/Constraints	
AFTs	Propulsion Subsystem 0ºC to +35ºC
Stability	ICEMAG E-box Interface < 1ºC/min
Sun Range	.65 AU to 5.6 AU, with max eclipse duration of 9.2 hours
Dissipation on Fluid Loop	minimum of ~360W (CBE) up to 680W (MEV) instantaneous electronics
Mission Life	11.3 years (2.6-7.6 year cruise, 3.75 year Jupiter tour with 45 Europa flybys)
Radiation	Design up to 6 Megarad



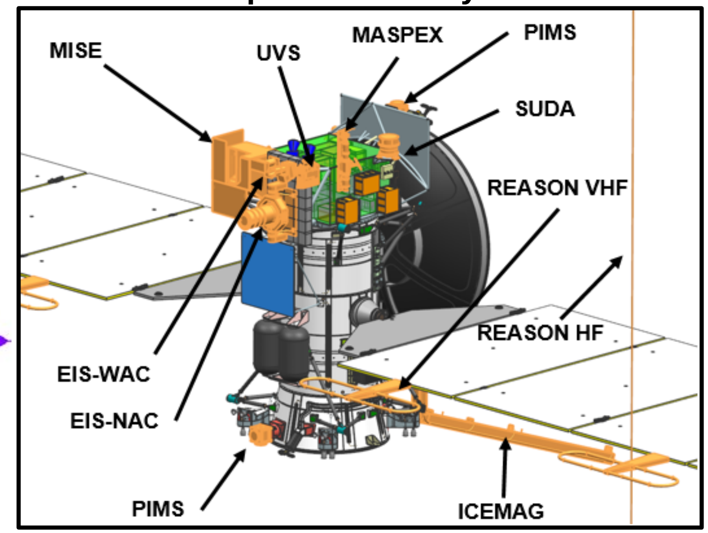






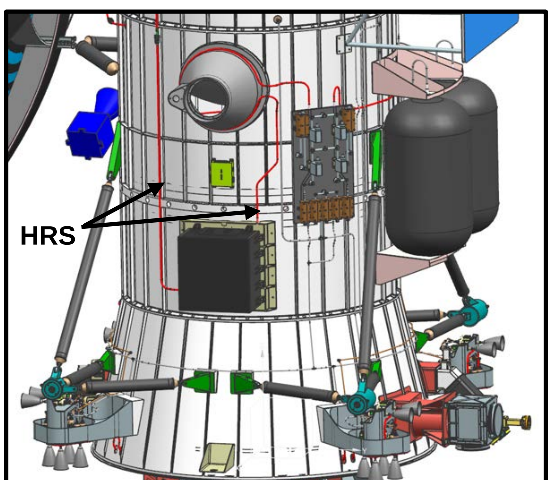
Thermal Desktop® Model

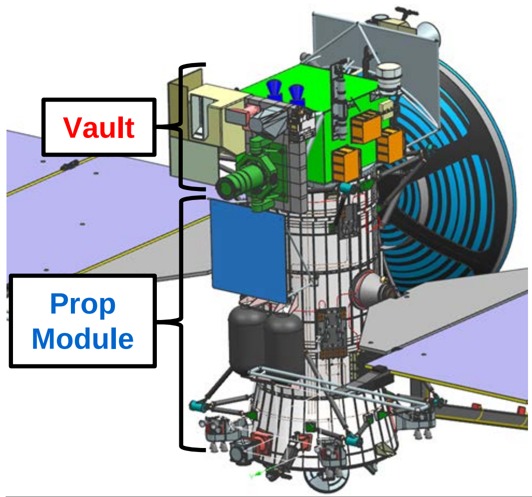
Europa Mission Payload

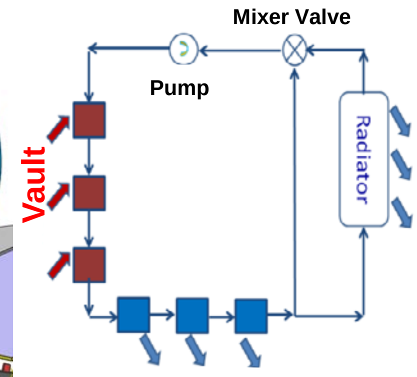


Planned Europa Mission MPFL Details

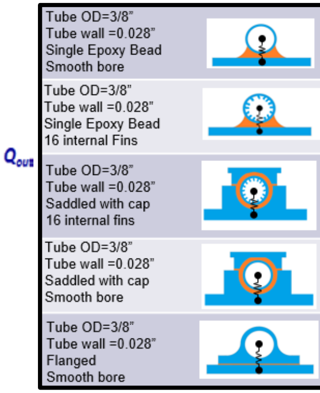
Planned Europa Heat Redistribution System (HRS) Details	
Working Fluid	CFC-11, R-11, Freon-11, Trichlorofluoromethane
MEOP	<150 psia
Flow Rates	0.75 lpm or 1.5 lpm
Expected mcp	15 W/°C or 30 W/°C
Reynolds Numbers	3,000-8,000 or 6,000-16,000
Convection Coefficients	300-500 W/m²°C or 700-1,000 W/m²°C
Pump Package	Same pump and thermal control valve technology as MER, MSL, Mars 2020

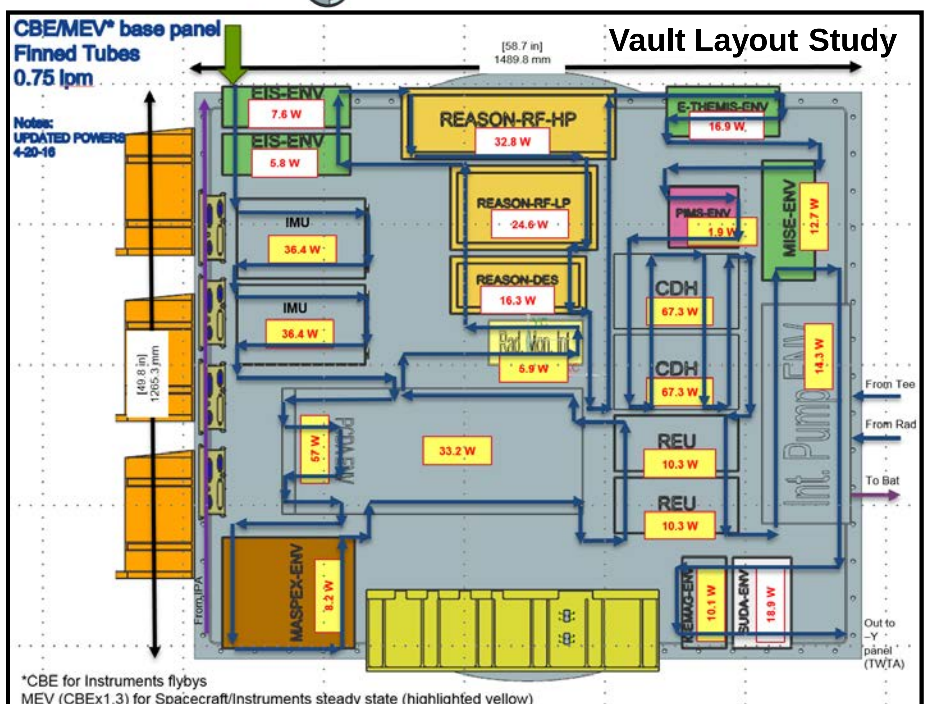


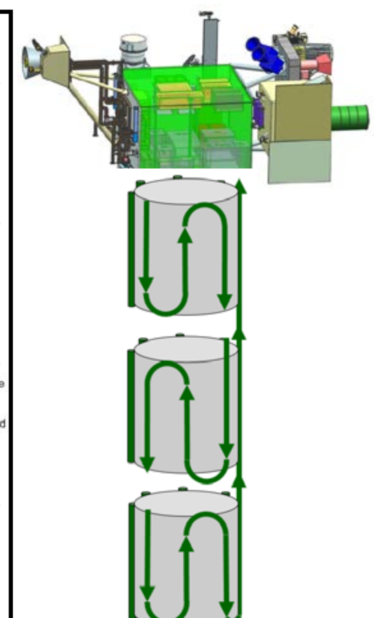




Tube Bonding Study

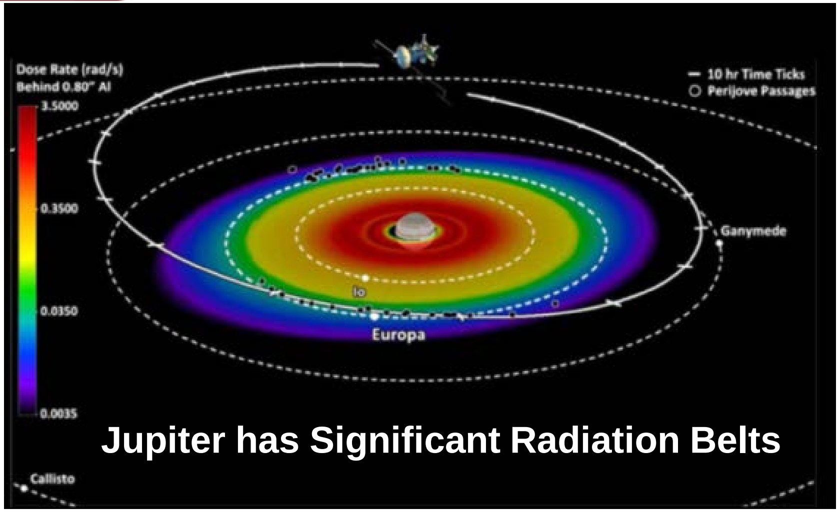






Prop Module Layout Study

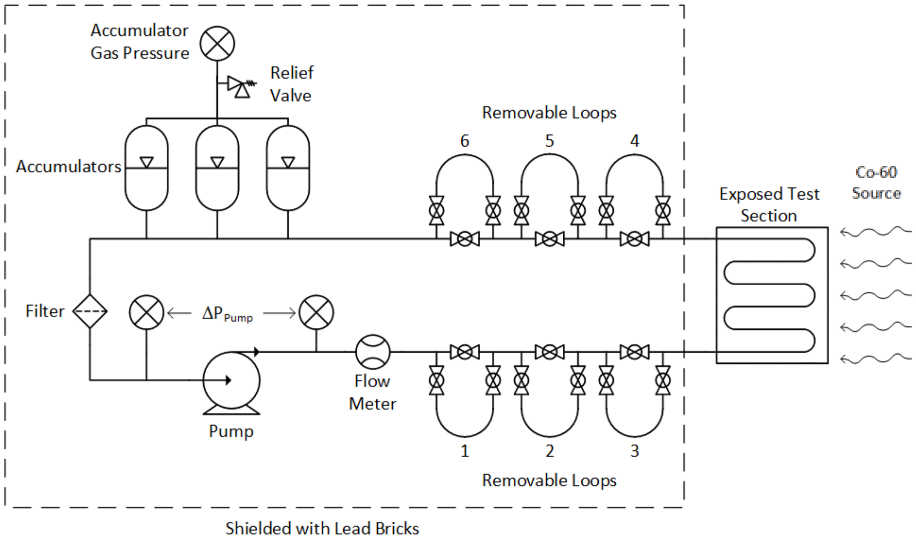
Europa Mission HRS Radiation Risk Mitigation



JPL's Europa MPFL Radiation Exposure Testbed

Highlights

- The general layout and components are similar to the anticipated flight system.
- The CFC-11 is irradiated as it flows through the test section.
- The primary flow path during testing goes through the exposed test section and the removable loops.
- The 6 removable loops are used to take fluid/tubing samples during testing.
- As of July 2016, the CFC-11 loop has been irradiated to 5.8 Megarads over the course of four three month long sessions. Total loop operation time thus far is ***~10,000 hrs***.
- Pump was characterized before and after the full radiation dose. ***No substantial changes were detected.***

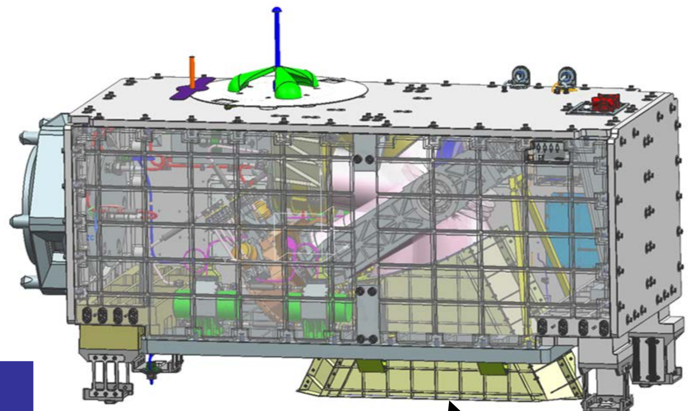


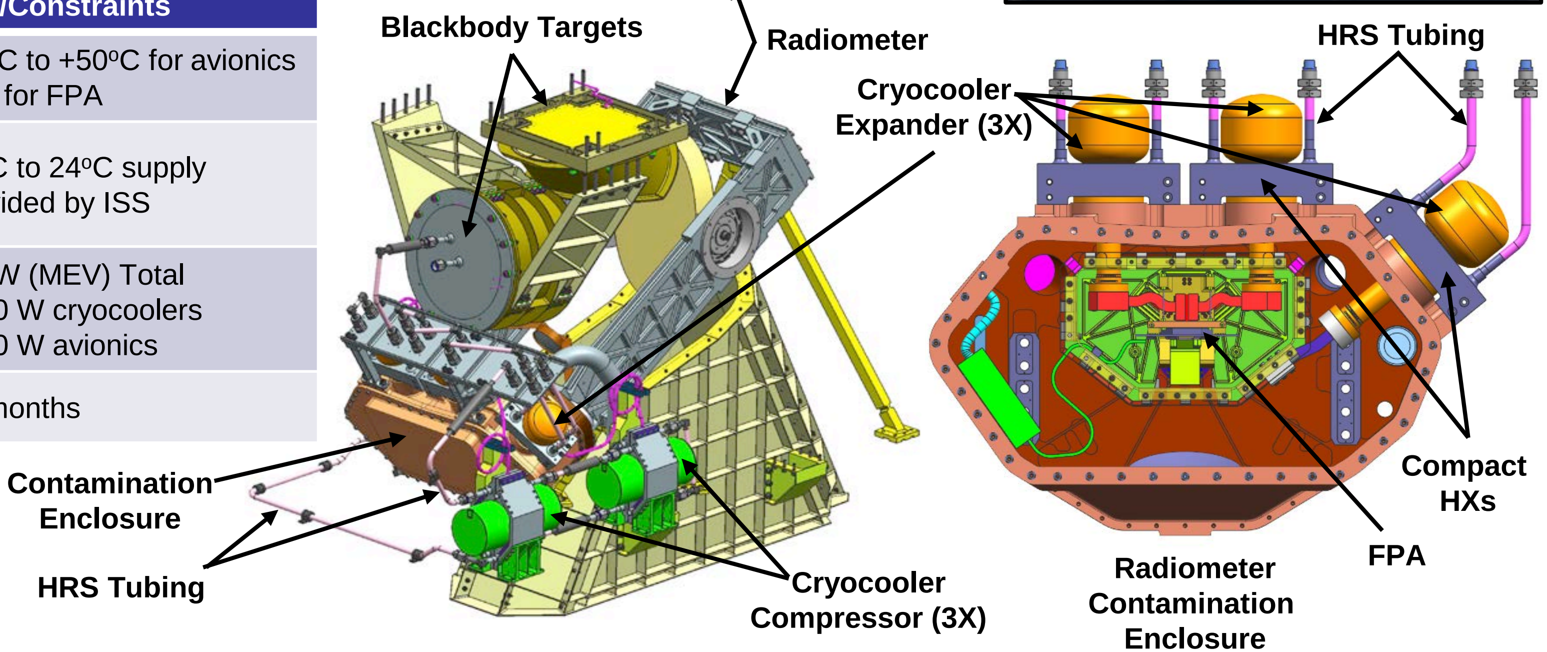
ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) Thermal Requirements

Mission: Provide critical insight into plant-water dynamics and how ecosystems change with climate via high spatiotemporal resolution thermal infrared radiometer measurements of evapotranspiration from the Japanese Experiment Module's External Facility (JEM-EF) onboard the International Space Station (ISS).

ECOSTRESS Schedule	
CDR	March 2016
Payload Thermal Test	February/March 2017
Payload Delivery	May 2017
Launch on SpaceX Falcon 9	June 2018

ECOSTRESS Thermal Requirements/Constraints	
AFTs	-20°C to +50°C for avionics 65K for FPA
JEM-EF Active Thermal Control System	16°C to 24°C supply provided by ISS
Dissipation on Fluid Loop	800W (MEV) Total –600 W cryocoolers –200 W avionics
Mission Life	13 months



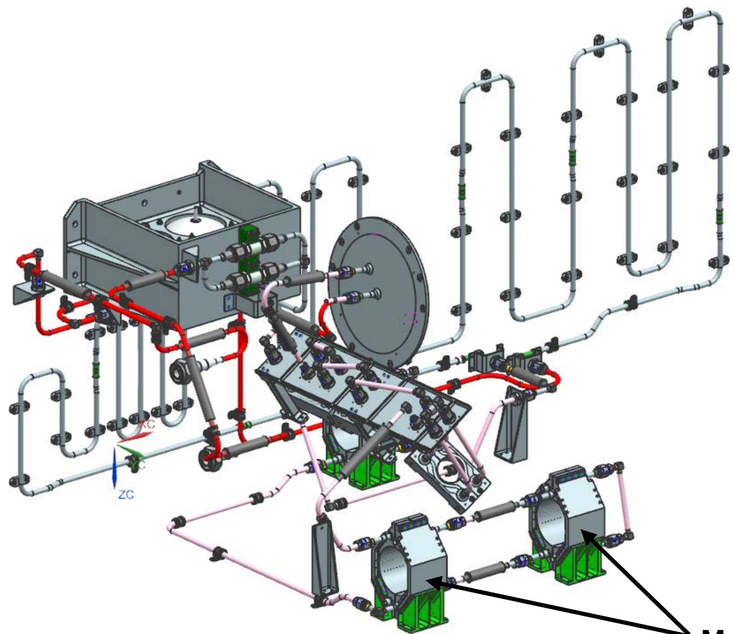


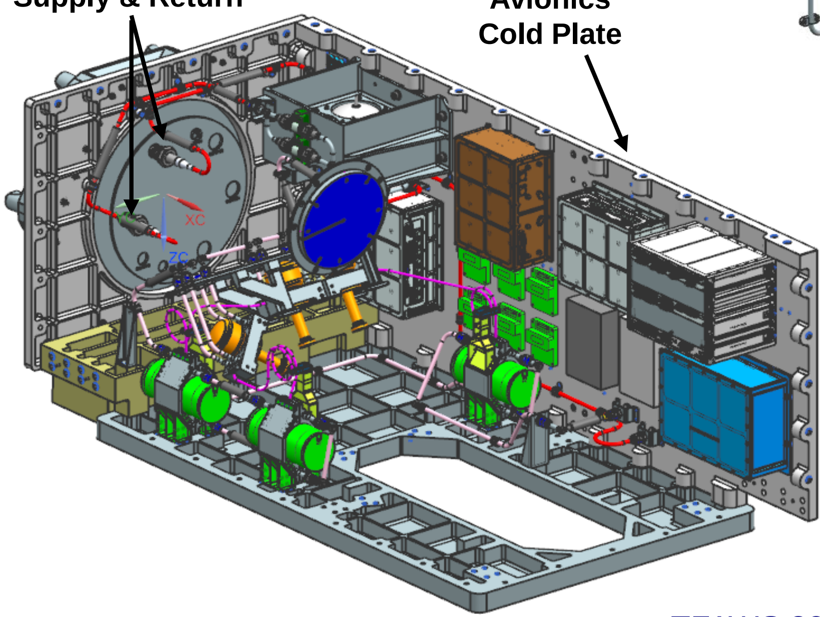
ECOSTRESS MPFL Details

The ECOSTRESS HRS is designed to remove 800 W of thermal dissipation.

- 3 pulse tube tactical cryocoolers with 12 integrated compact HXs
- 13 electronic boxes mounted on a structural/thermal panel

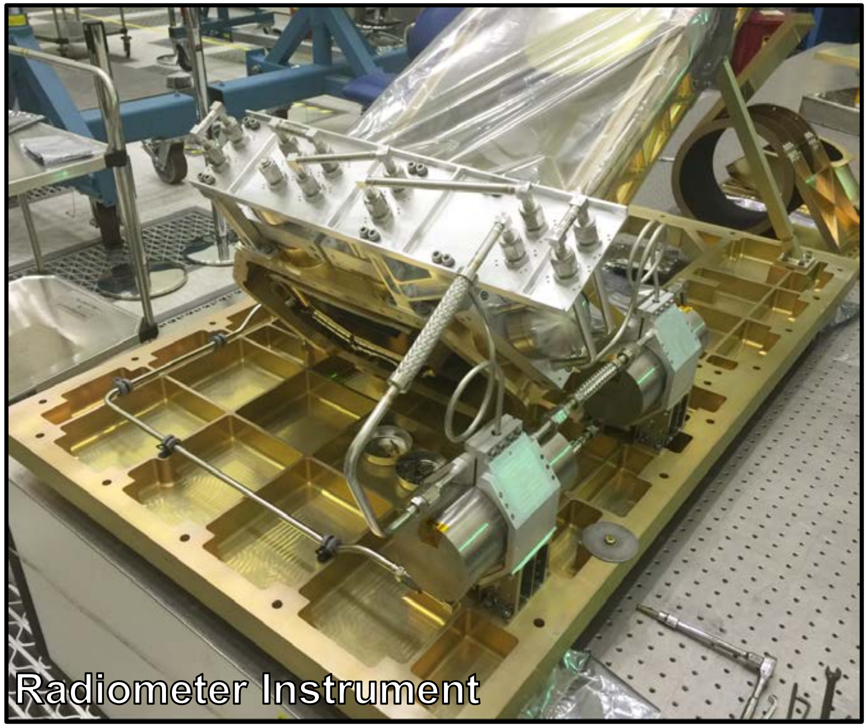
ECOSTRESS HRS Details	
Working Fluid	FC-72, Fluorinert, Perfluorohexane
MEOP	68 psia
Flow Rates	1.5 lpm @ < 8.5 psid
Expected mcp	~45 W/°C
Reynolds Numbers	~10,000
Convection Coefficients	~720 W/m²°C



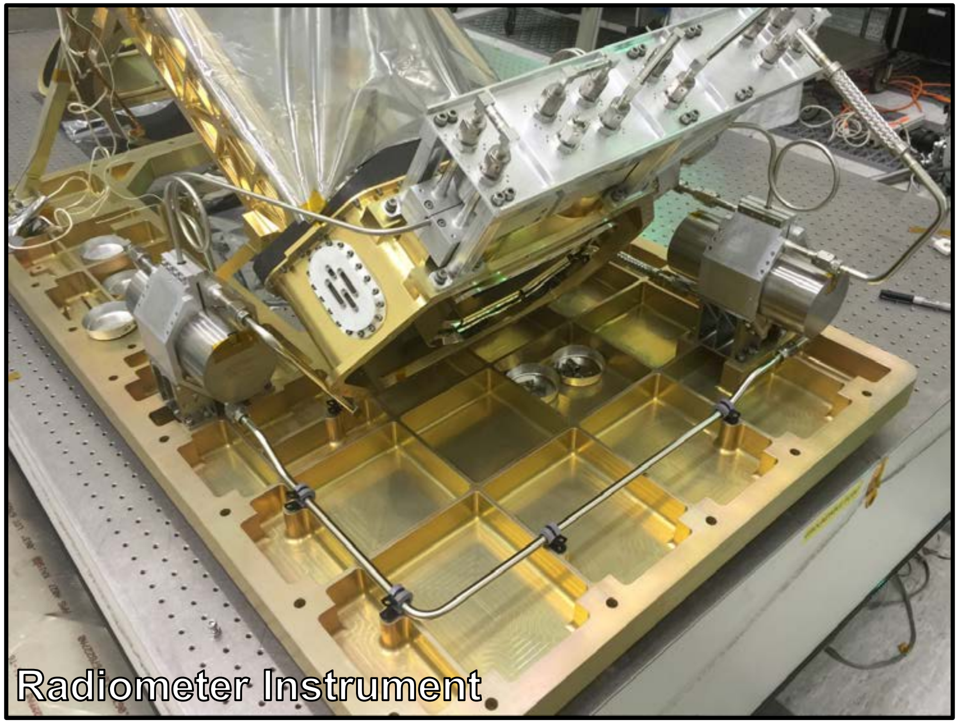


- 24 m of stainless steel tubing
- 13 compact HXs with friction stir welds
- 12 bellowed flex lines
- 4 fluid accumulators
- 125 stainless steel orbital welds
- 26 bimetal inertial welds
- 26 aluminum TIG welds
- 48 mechanical fittings

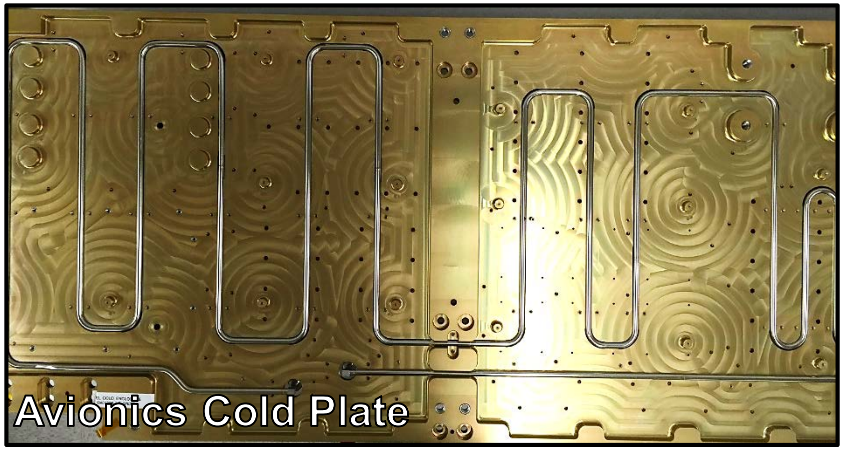
ECOSTRESS Flight Hardware



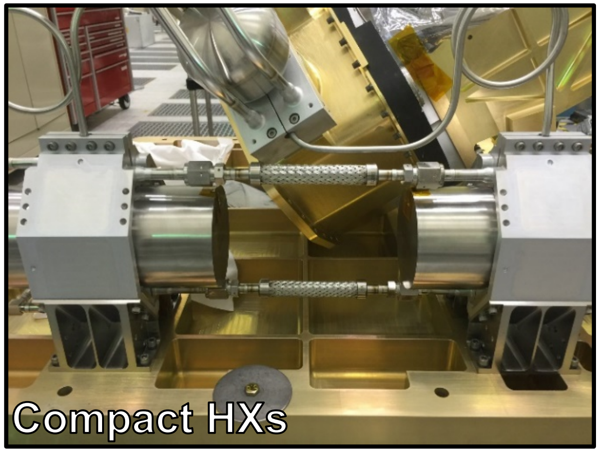
Radiometer Instrument



Radiometer Instrument



Avionics Cold Plate



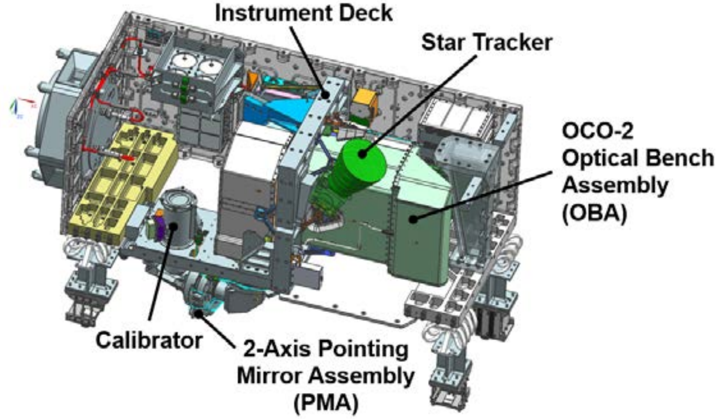
Compact HXs

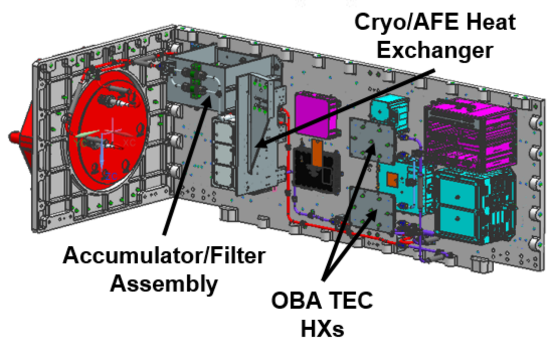
Orbiting Carbon Observatory (OCO-3)

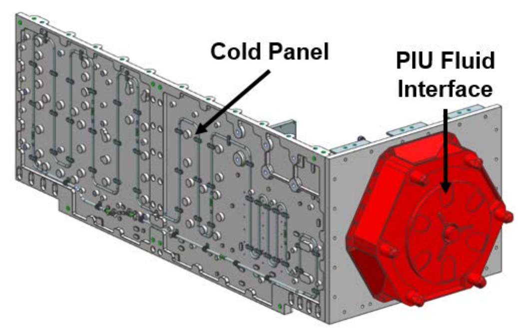
Mission: Monitor the distribution of carbon dioxide on Earth as it responds to growing population centers and changing patterns of fossil fuel combustion.

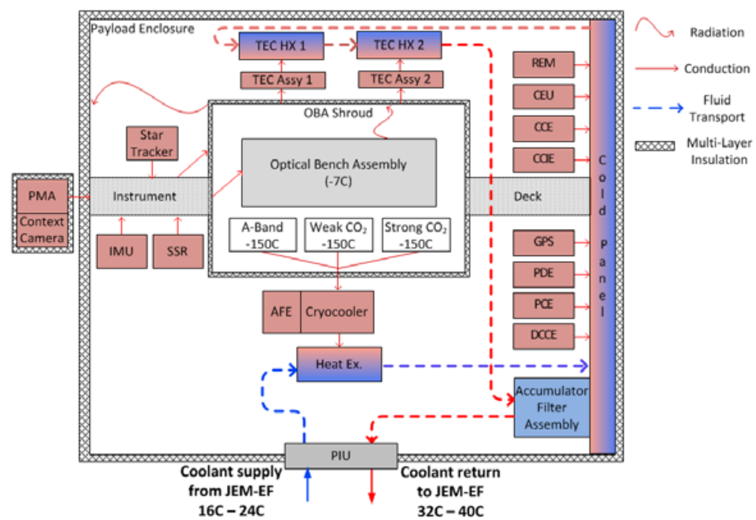
OCO-3 Schedule	
CDR	May 2016
Payload Thermal Test	February/March 2017
Payload Delivery	May 2017
Launch on SpaceX Falcon 9	September 2018

OCO-3 Thermal Requirements/Constraints	
AFTs	-20ºC to +50ºC for avionics 125K for FPA
JEM-EF Active Thermal Control System	16ºC to 24ºC supply provided by ISS
Dissipation on Fluid Loop	900W (MEV) Total
Mission Life	13 months







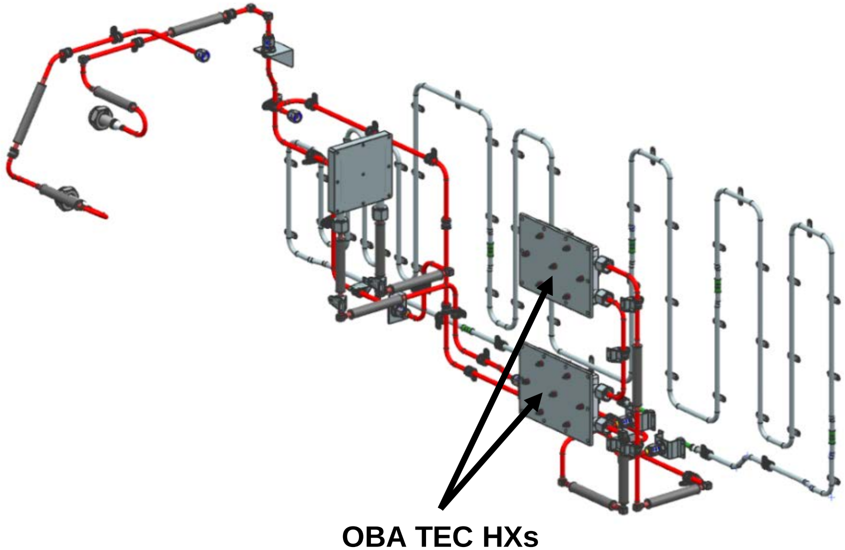


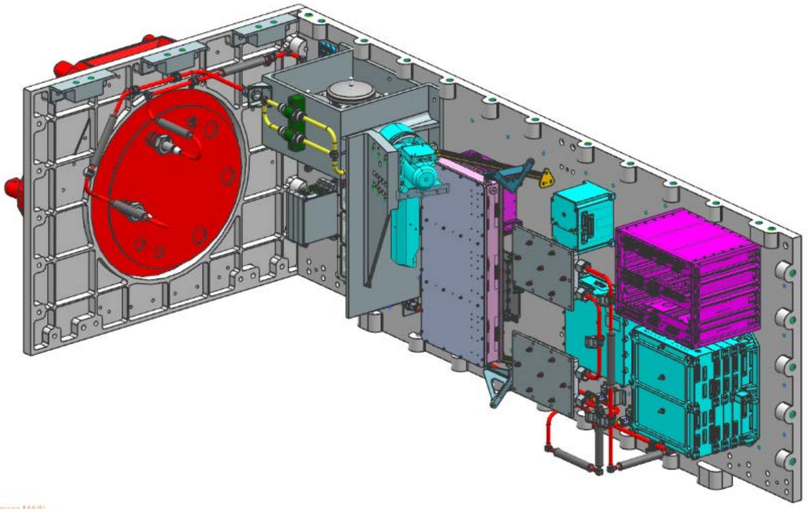
OCO-3 MPFL Details

OCO-3 HRS Details	
Working Fluid	FC-72, Fluorinert, Perfluorohexane
MEOP	68 psia
Flow Rates	1.5 lpm @ < 8.5 psid
Expected mcp	~45 W/^{o}C
Reynolds Numbers	~10,000
Convection Coefficients	~720 W/m^{2o}C

The OCO-3 HRS is designed to remove 900 W of thermal dissipation

- 1 pulse tube cryocooler with integrated tube on plate HX
- 4 thermoelectric coolers with 2 integrated compact HXs
- 8 electronic boxes mounted on a structural/thermal panel





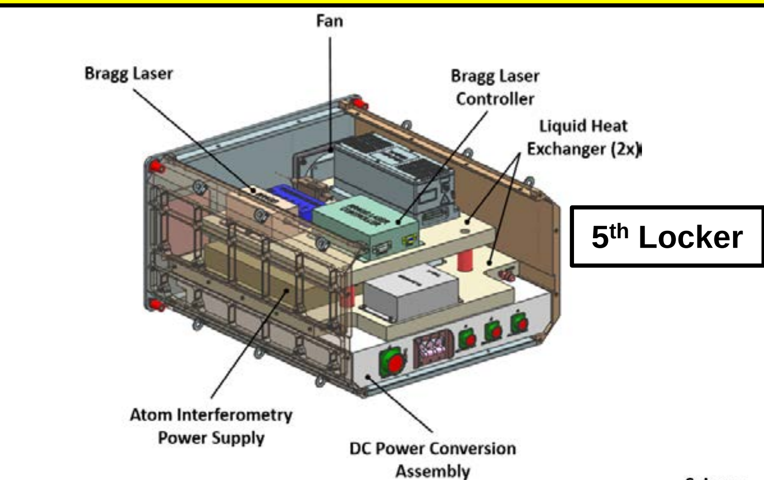
- 20 m of stainless steel tubing
- 2 compact HXs with friction stir welds
- 14 bellowed flex lines
- 4 fluid accumulators
- 100 stainless steel orbital welds
- 4 bimetal inertial welds
- 4 aluminum TIG welds
- 22 mechanical fittings

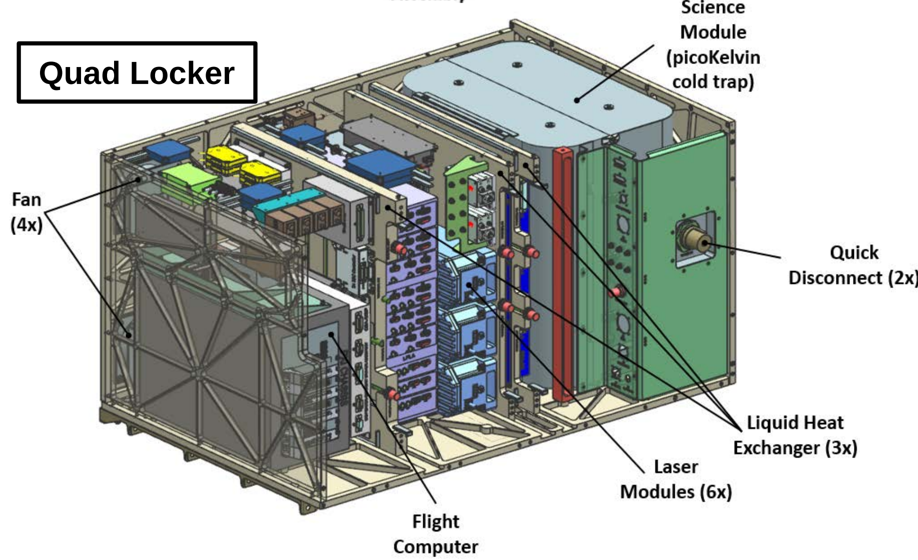
Cold Atom Laboratory (CAL)

Mission: Provide a multi-user facility for the study of ultra-cold quantum gases in the microgravity environment of the ISS using the techniques of laser, adiabatic, and evaporative cooling to create Bose-Einstein Condensates; achieve temperatures on the order of less than 100 picoKelvin with interaction times in excess of five seconds, a marked improvement over Earth-Based laboratories.

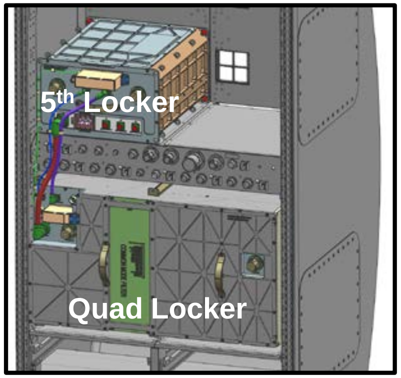
CAL Schedule	
CDR	January 2015
Thermal Ambient Test	December 2016
Launch on SpaceX Falcon 9	August 2017

CAL Thermal Requirements/Constraints	
Allowable Flight Temperatures (AFTs)	0°C to +49°C
Moderate Temperature Loop (MTL)	16°C to 23°C supply provided by ISS
Dissipation on Fluid Loop	up to 500W instantaneous electronics
Mission Life	1 year of science



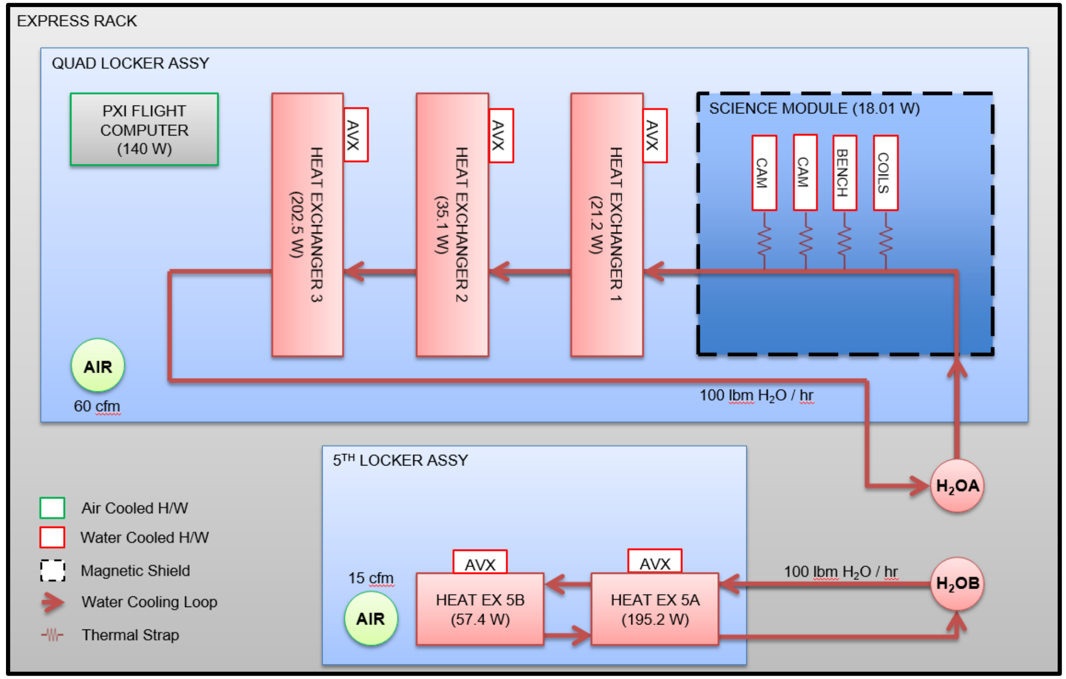


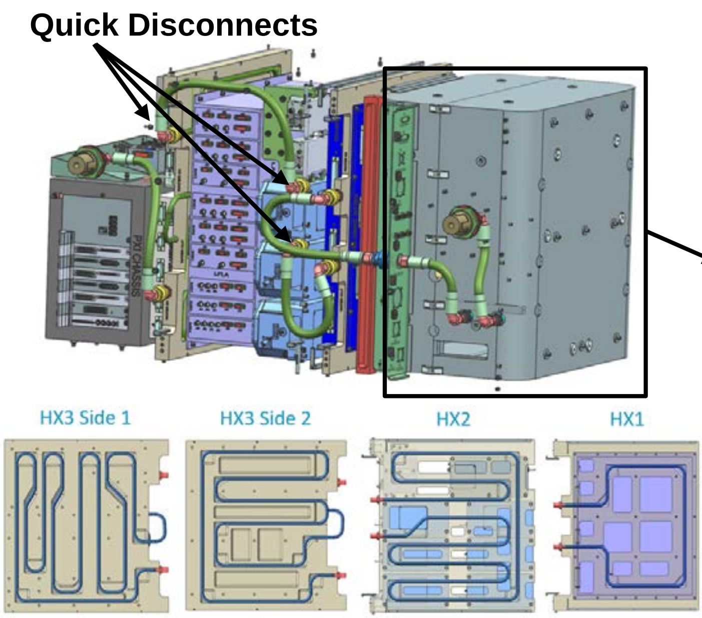
Pilot Stephen N. Frick poses by EXPRESS Rack 1 in the U.S. Lab during the STS-110 mission (2002)



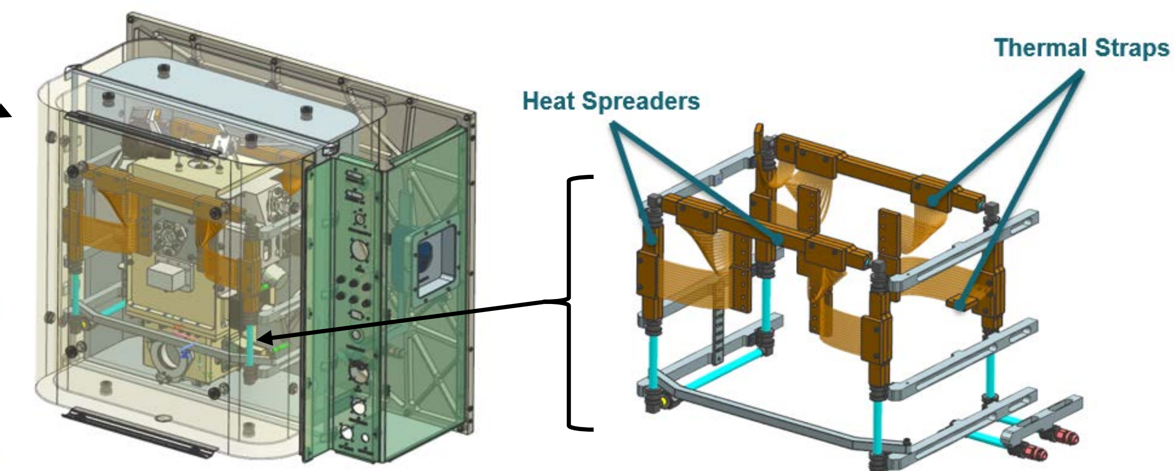
CAL MPFL Details

CAL HRS Details	
Working Fluid	DI Water
MEOP	121 psia
Flow Rates	1.5 lpm supply split into 2 loops (0.75 lpm per loop)
Expected mcp	50 W/^{o}C
Reynolds Numbers	~2,000 (laminar)
Convection Coefficients	~260 W/m^{2o}C





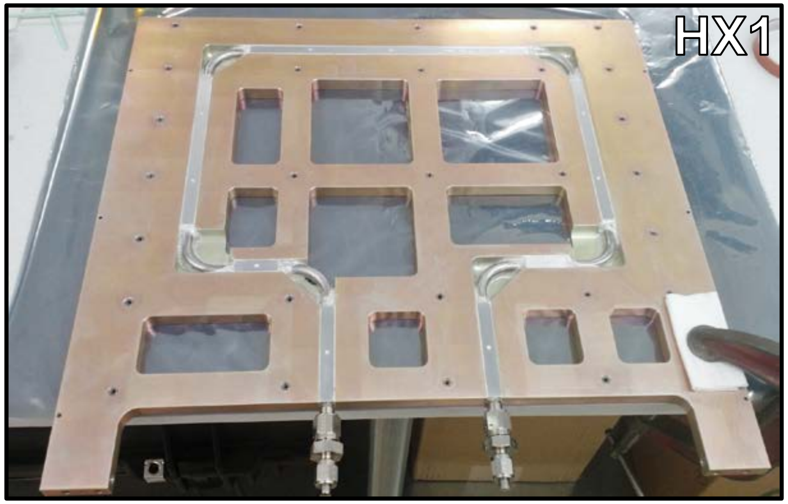
Quad Locker Assembly

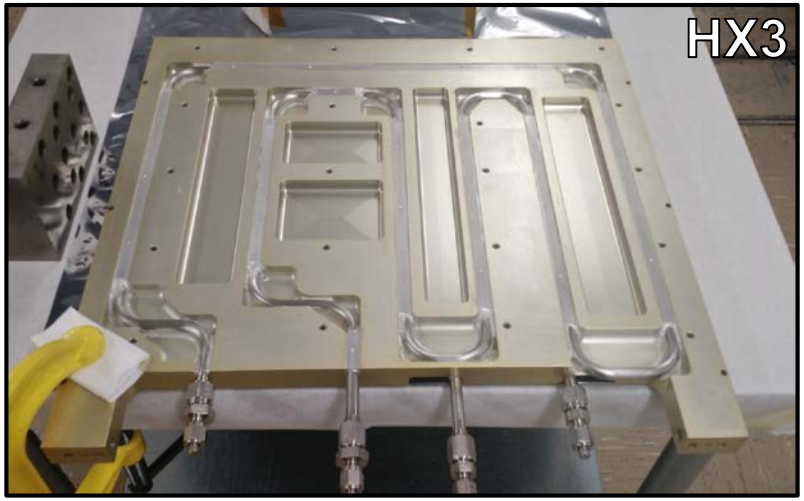


Science Module

CAL HRS Hardware

Double Sided HX





Concluding Remarks

- JPL is actively working on 5 MPFL projects – Mars 2020 and the Planned Europa Mission are still in the conceptual/design phases, and ECOSTRESS, OCO-3, and CAL are under construction marching toward their thermal tests.
- 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.
- Despite the obvious benefits, there are still lots of challenges associated with the construction of MPFLs. Each application appears to require a custom tailored approach to implementation and flight acceptance.
- While robotic and manned missions equally benefit from MPFLs, continued cross fertilization and collaborative technology development may help to streamline processes and improve reliability, while reducing complexity, hardware lead times, mass, and cost.

References

[1] Sunada, Eric, and Rodriguez, Jose, "*JPL Advanced Thermal Control Technology Roadmap*," Spacecraft Thermal Control Workshop, El Segundo, CA 2016.

[2] Wilson, Michael, "*Mars 2020 Mission Concept*," [Online] October, 2013, <http://www.nasa.gov/sites/default/files/files/3_Mars_2020_Mission_Concept.pdf>. [Accessed 30 July 2016].

[3] NASA, "*Fact Sheet: Mars 2020*," [Online] JPL, June 2015, <http://mars.nasa.gov/mars2020/files/mars2020/Mars2020_Fact_Sheet.pdf>. [Accessed 30 July 2016].

[4] NASA, "*Final Environmental Impact Statement for Mars 2020 Mission*," [Online] <https://mars.jpl.nasa.gov/mars2020/files/mep/Mars2020_Final_EIS.pdf>. [Accessed 30 July 2016]

Partial List of Acronyms

- AFT – Allowable Flight Temperature
- AU – Astronomical Unit
- BUD – Bridle Umbilical Device
- CAL – Cold Atom Laboratory
- CBE – Current Best Estimate
- CDR – Critical Design Review
- CFC-11 – Trichlorofluoromethane
- CHEMIN – Chemistry & Mineralogy
- CHRS – Cruise Heat Rejection System
- CIPA – Cruise Integrated Pump Assembly
- CIPAS – Cruise Integrated Pump Assembly System
- DI – Deionized
- DSM – Deep Space Maneuver
- ECOSTRESS – Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station
- EDL – Entry, Descent, and Landing
- EELV – Evolved Expendable Launch Vehicle
- EIS – Europa Imaging System
- E-THEMIS – Europa Thermal Emission Imaging System
- EVEEGA – Earth Venus Earth Earth Gravity Assist Trajectory
- FPA – Focal Plane Array
- HRS – Heat Rejection System, Heat Rejection & Recovery System, Heat Redistribution System
- HX – Heat Exchanger
- ICEMAG – Interior Characterization of Europa using Magnetometry
- ISRU – In-Situ Resource Utilization
- ISS – International Space Station
- JEM-EF – Japanese Experiment Module External Facility
- JOI – Jupiter Orbit Insertion
- JPL – Jet Propulsion Laboratory
- MAHLI – Mars Hand Lens Imager
- MASPEX – Mass Spectrometer for Planetary Exploration/Europa
- MDR – Mission Design Review
- MEDA – Mars Environmental Dynamics Analyzer
- MEOP – Maximum Expected Operating Pressure
- MER – Mars Exploration Rover
- MEV – Maximum Expected Value
- MISE – Mapping Imaging Spectrometer for Europa
- MMRTG – Multi Mission Radioisotope Thermoelectric Generator
- MOXIE – Mars Oxygen ISRU Experiment
- MPFL – Mechanical Pumped Fluid Loop
- MSL – Mars Science Laboratory
- NAC – Narrow Angle Camera
- OCO – Orbiting Carbon Observatory
- OBA – Optical Bench Assembly
- PDR – Preliminary Design Review
- PIMS – Plasma Instrument for Magnetic Sounding
- PIXL – Planetary Instrument for X-ray Lithochemistry
- RAMP – Rover Avionics Mounting Plate
- REASON – Radar for Europa Assessment and Sounding: Ocean to Near-Surface
- REMS – Rover Environmental Monitoring Station
- RHRS – Rover Heat Rejection & Recovery System
- RIMFAX – Radar Imager for Mars' Subsurface Exploration
- RIPA – Rover Integrated Pump Assembly
- RIPAS – Rover Integrated Pump Assembly System
- SHERLOC – Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals
- SLS – Space Launch System
- SRR – System Requirements Review
- SUDA – Surface Dust Mass Analyzer
- TEC – Thermoelectric Cooler
- TIG – Tungsten Inert Gas
- UVS – Ultraviolet Spectrograph
- VAMP – Vertical Avionics Mounting Plate
- WAC – Wide Angle Camera

Questions?

Additional Acknowledgments

- Danny Lok, ASL
- Bruce Williams, APL
- Jeff Kelley, APL
- Stuart Hill, APL
- Nick Keyawa, JPL
- Matthew Horner, JPL
- Sasha Eremenko, JPL
- Matthew Spaulding, JPL

Backup