JPL Advanced Thermal Control Technology Roadmap

a presentation to

Spacecraft Thermal Control Workshop
The Aerospace Corporation, El Segundo California
March 20, 2018

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NASA Jet Propulsion Laboratory
California Institute of Technology

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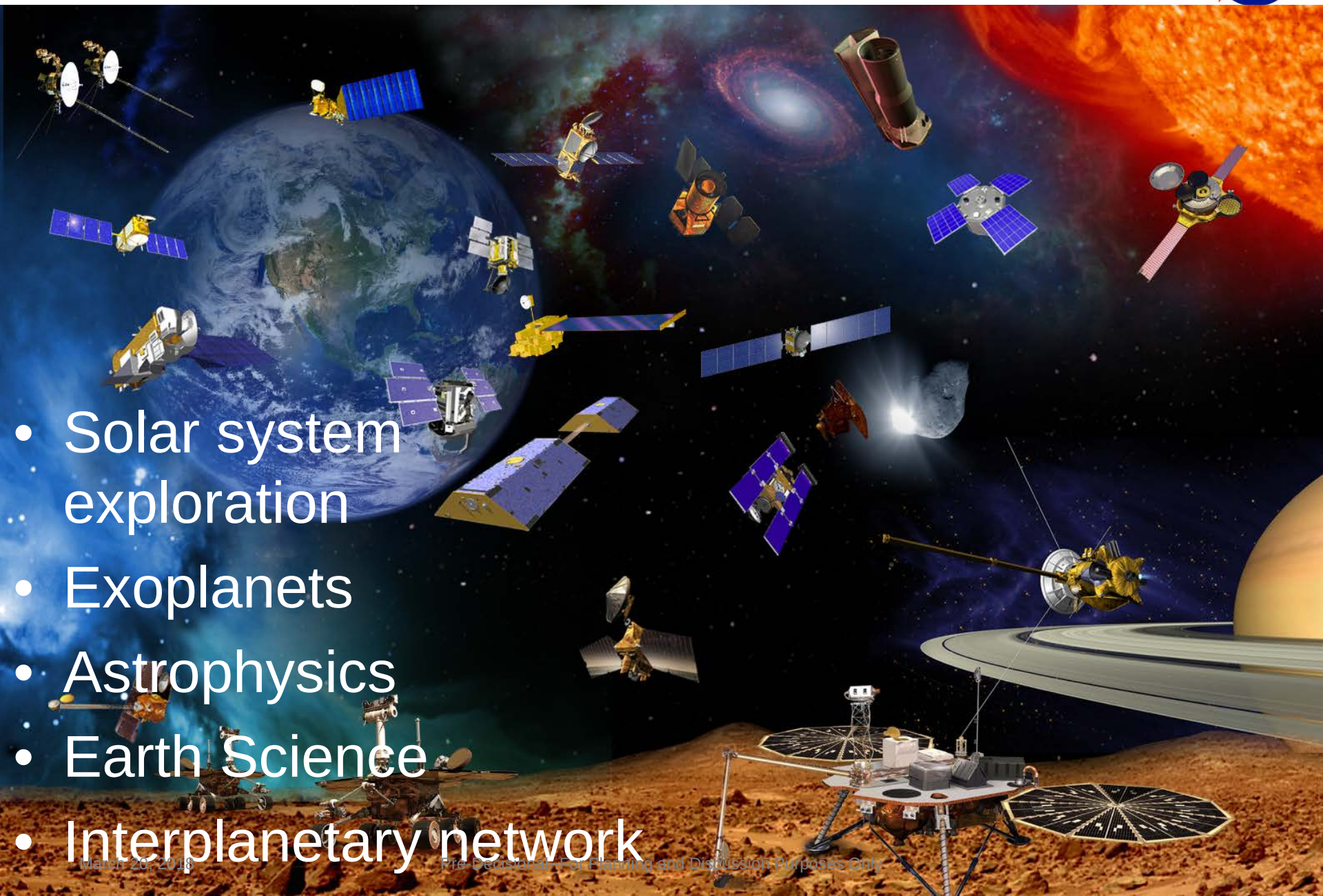
Introduction to NASA JPL

- Federally (NASA)-owned “Federally-Funded Research and Development Center” (FFRDC)
- University (Caltech)-operated
- 6,000+ employees (mostly Caltech)
- > 100 acres

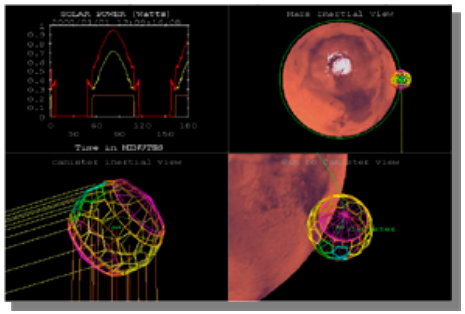
JPL's focus is *robotic* space exploration



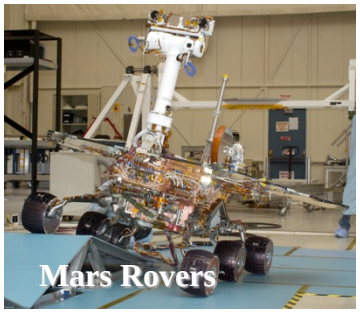
- Solar system exploration
- Exoplanets
- Astrophysics
- Earth Science
- Interplanetary network

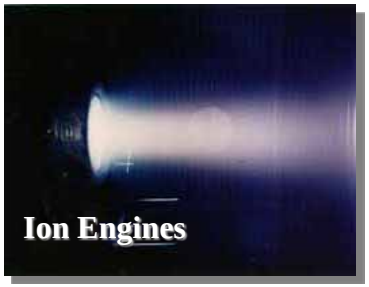
End-to-end capabilities

Project Formulation - Team X

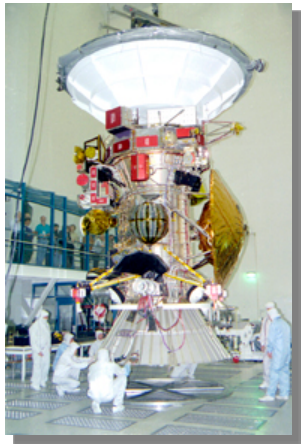


Mission Design

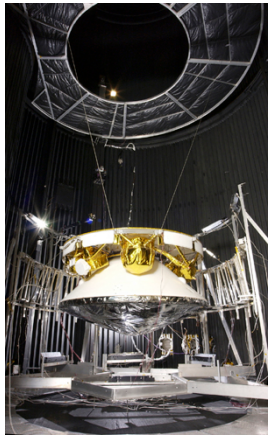




Spacecraft Development



Integration and Test



Environmental Test

Real Time Operations

Outline

- Current and proposed flight projects
  - Status from the thermal subsystem perspective
- JPL/NASA mission roadmap
- Thermal technology challenges

Current and proposed projects

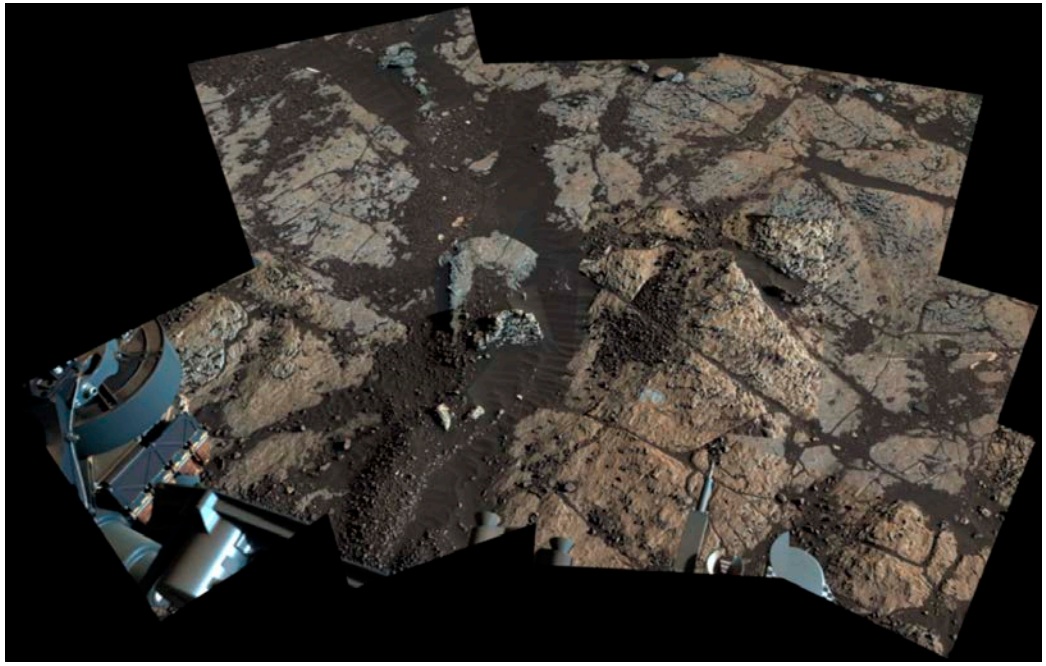
Status from the thermal subsystem perspective

Jet Propulsion Laboratory
California Institute of Technology

Curiosity Rover—Thermal Status

(Courtesy of Kurt Gonter, Curiosity Rover Thermal Operations Engineer)

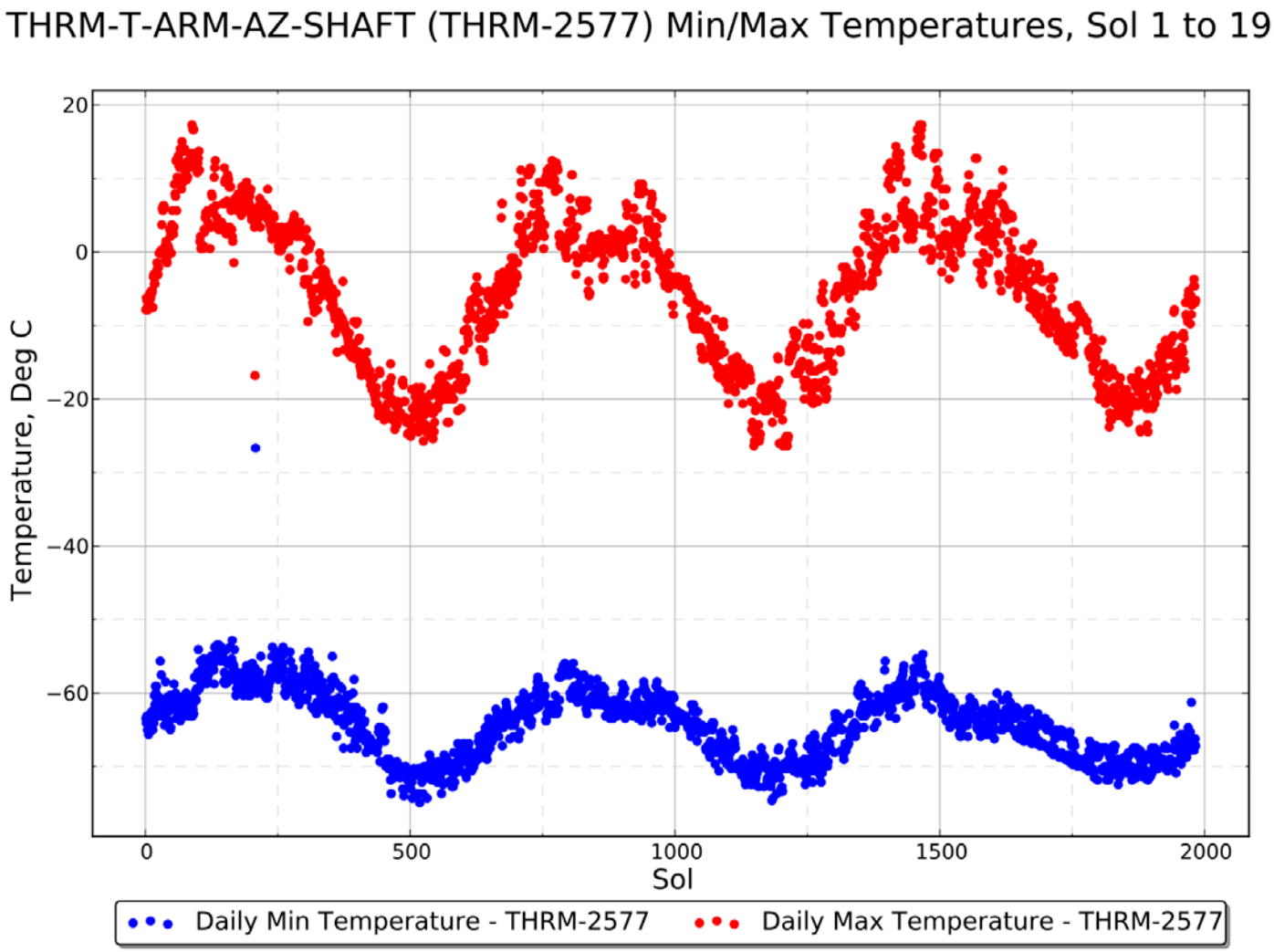
- Total odometry: 18,408m
- RTG output nominal at ~88-92 W_e.
- Thermal performance remains excellent.



Curiosity Rover—Thermal Status

(Courtesy of Gordon Cucullu, Thermal/Fluid Systems & Mission Operations Group Supervisor)

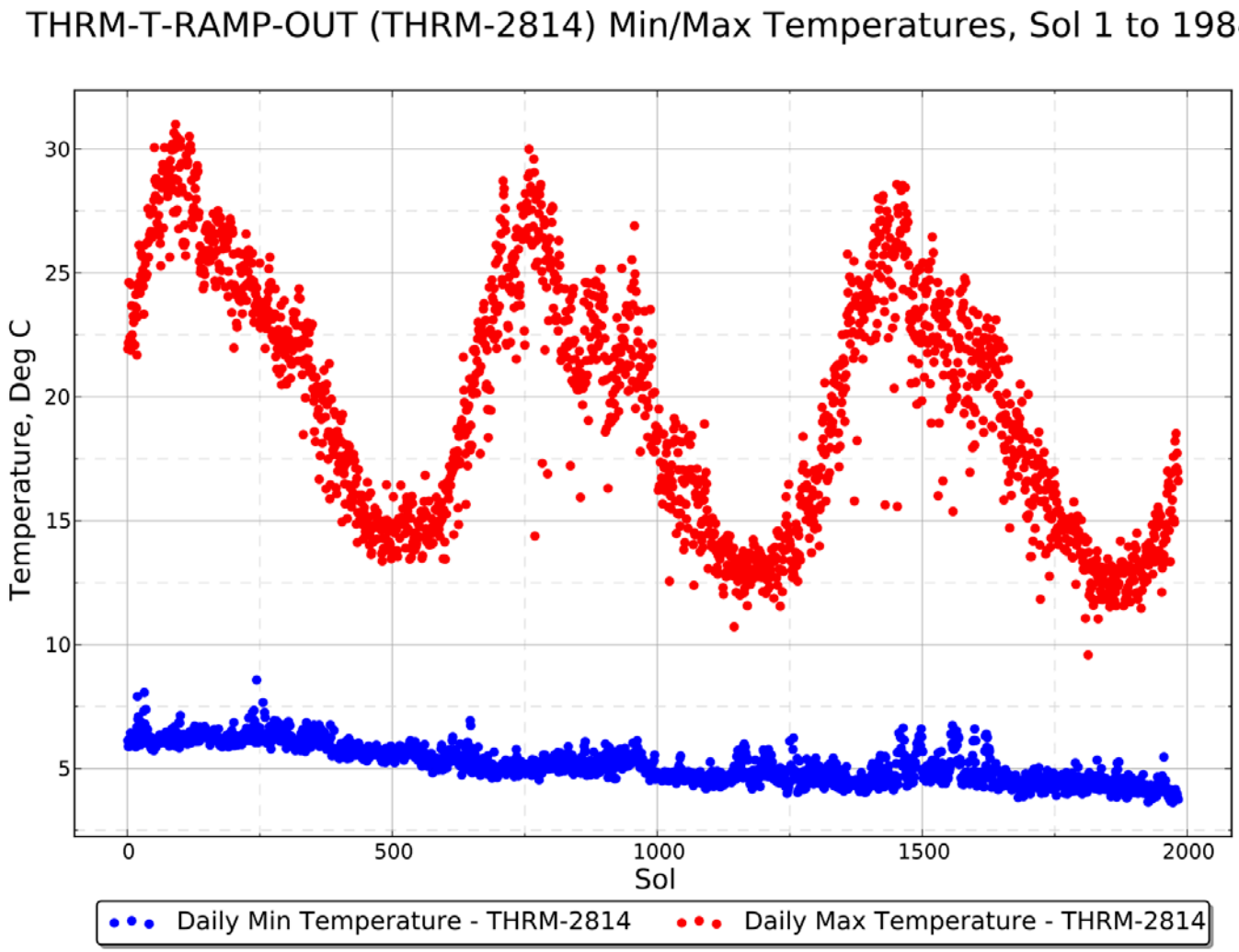
Robotic Arm (RA) Shoulder Mounting Bracket Temperatures



Curiosity Rover—Thermal Status

(Courtesy of Gordon Cucullu, Thermal/Fluid Systems & Mission Operations Group Supervisor)

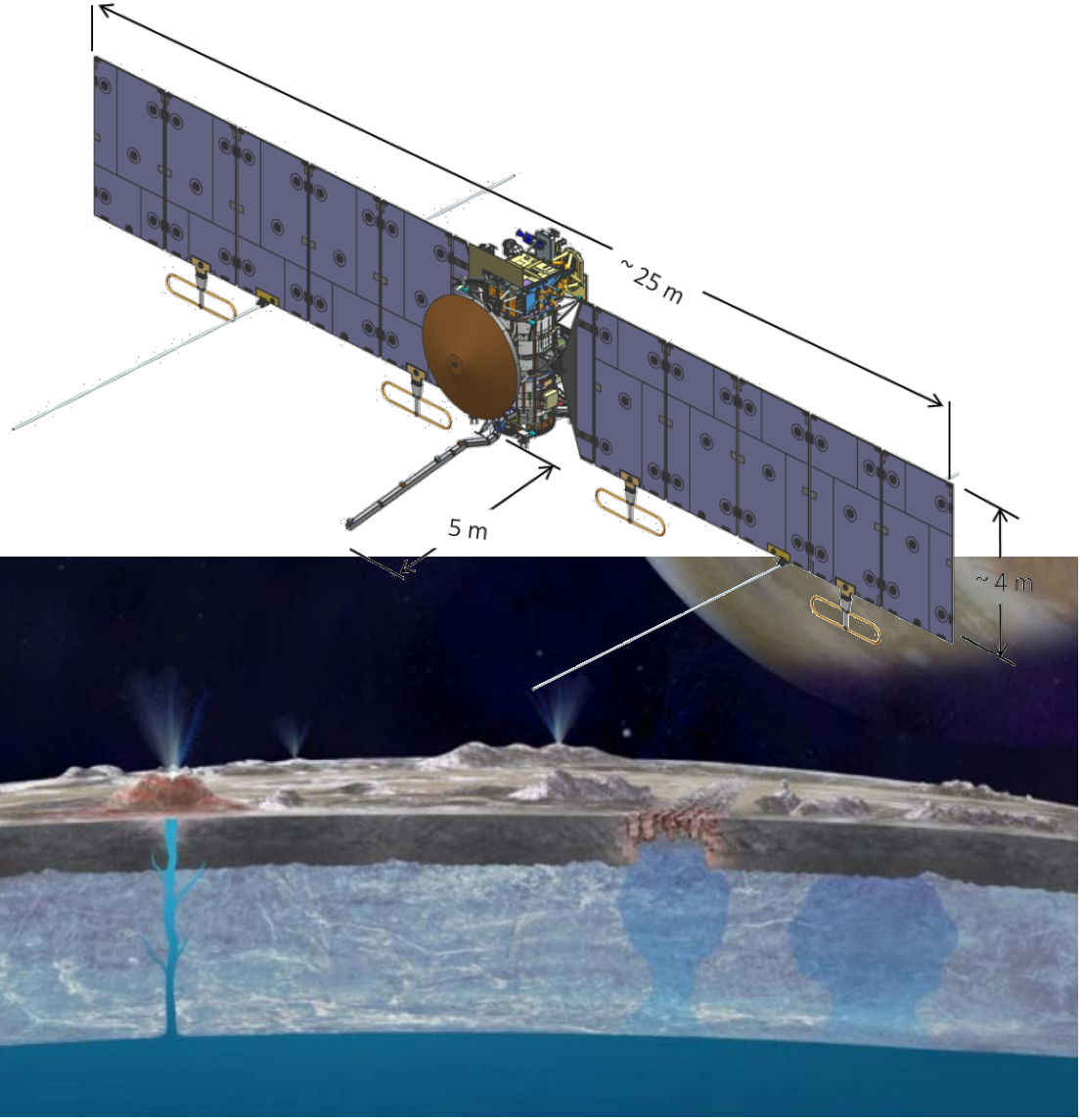
Rover Avionics Mounting Panel (RAMP) Temperatures



Europa Clipper Mission

(Courtesy of Dr. Tony Paris, JPL Europa Thermal)

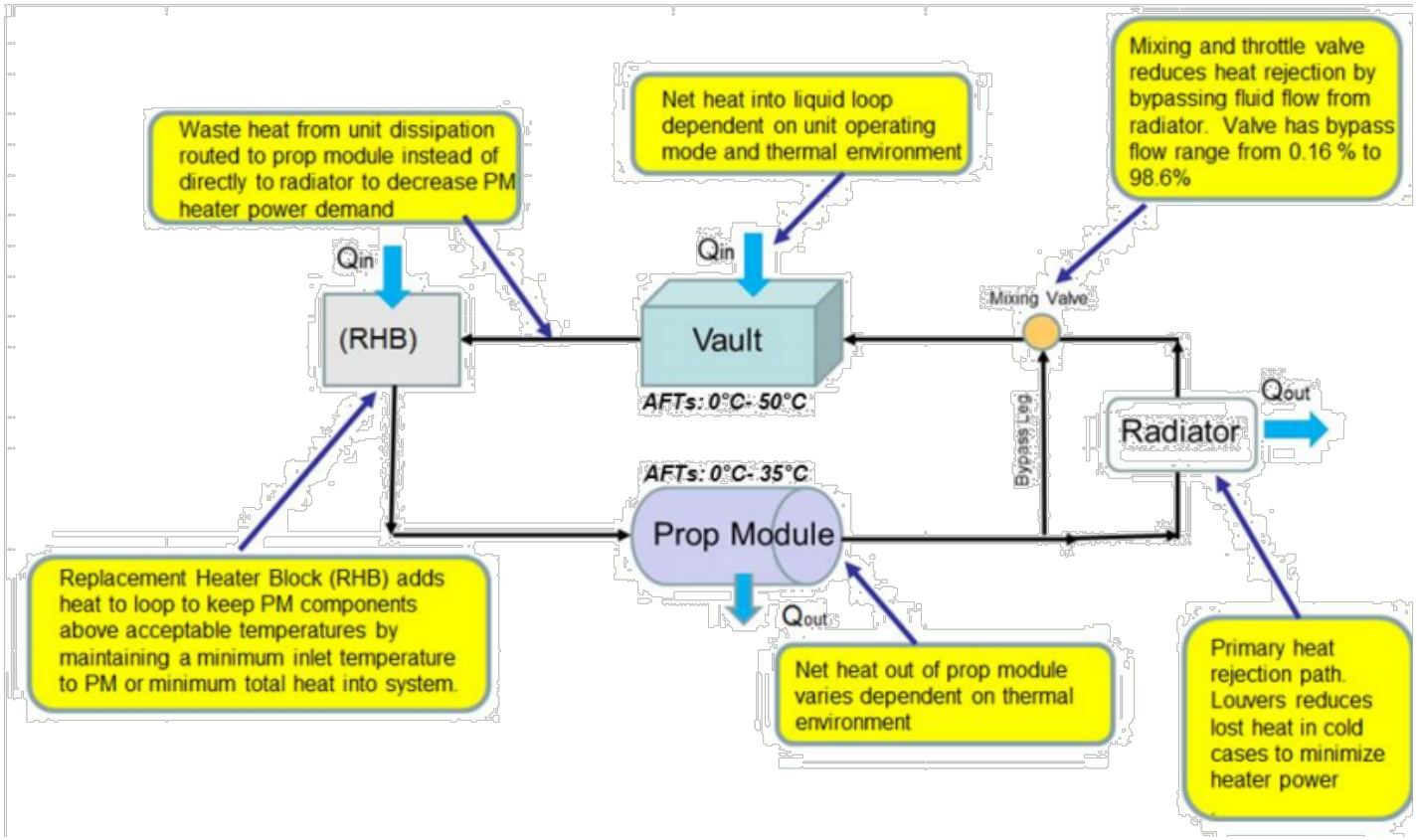
- From Jupiter orbit, perform a detailed investigation of the giant planet's moon Europa -- a world that shows strong evidence for an ocean of liquid water beneath its icy crust and which could host conditions favorable for life.
- Constraints for the spacecraft design include limited electrical power for heating, long mission lifetime, and tolerance for high radiation environments.

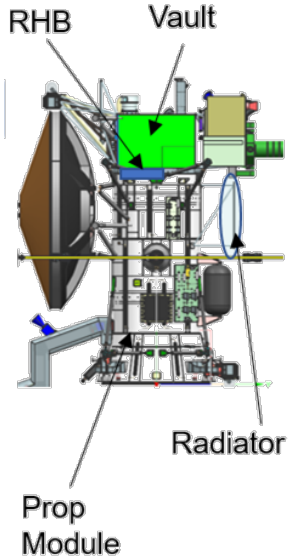


Planned Europa Clipper Mission

(Courtesy of Dr. Tony Paris, JPL Europa Thermal Lead)

- Thermal architecture
  - Single-phase, mechanically pumped fluid loop
  - Redistributes waste heat
  - System is being developed and tested for survivability in the Jovian environment

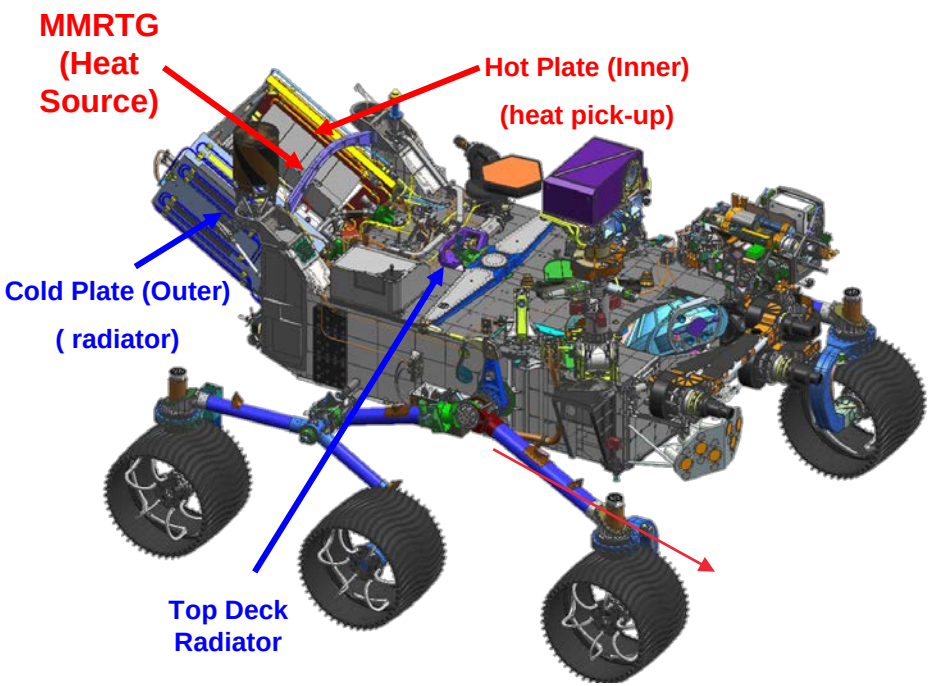


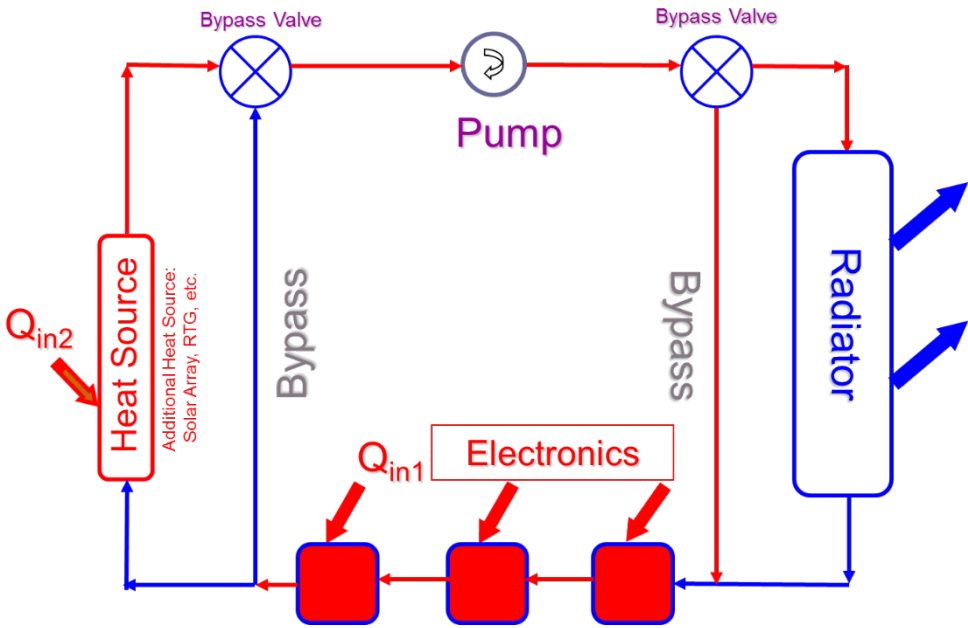


Mars 2020 Rover

(Courtesy of Jason Kempenaar, M2020 Surface Thermal Lead)

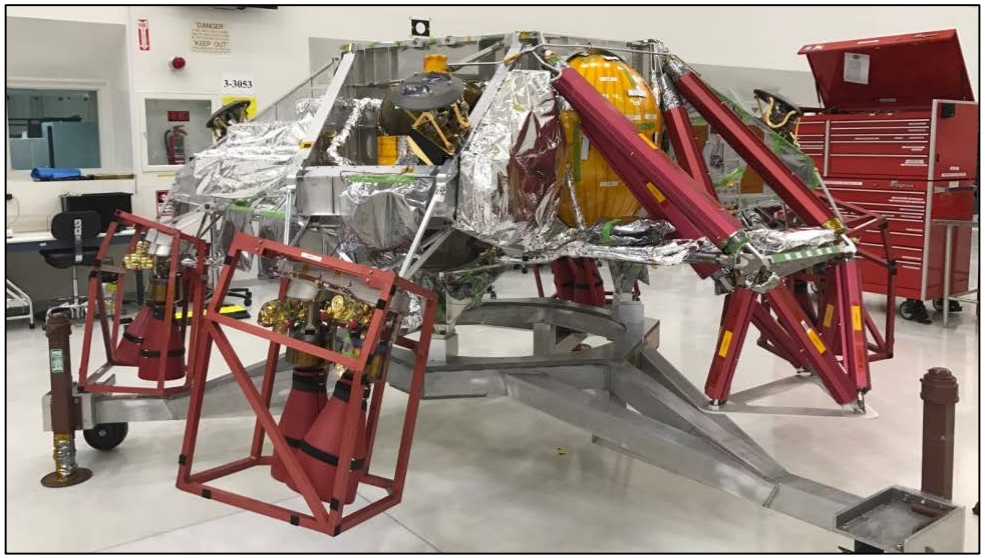
- Key functions of M2020 Rover Heat Rejection System (RHRS):
  - Removal of waste heat from rover during Cruise phase of mission
  - Removal of waste heat from rover and MMRTG during hot part of the day
  - Recovery of waste heat from MMRTG during the cold part of the day
  - Thermally couple RAMP masses to create large effective thermal mass to reduce temperature swings
- RHRS fluid tubes are embedded in RAMP to remove or add heat to keep the science and engineering hardware at safe operating and survival temperatures





Pumped Fluid Loop Based Thermal *Bus* Architecture
(Supply as well as Reject Heat)

Mars 2020 Descent and Cruise Stage Status



Mars 2020 Descent Stage

- Primary structure and propulsion system assembly complete
  - Includes propulsion thermal and harness
- HRS interconnect lines installed
- ATLO work begins March 2018!
  - Begins with installation of electronics and system harness

Mars 2020 Cruise Stage

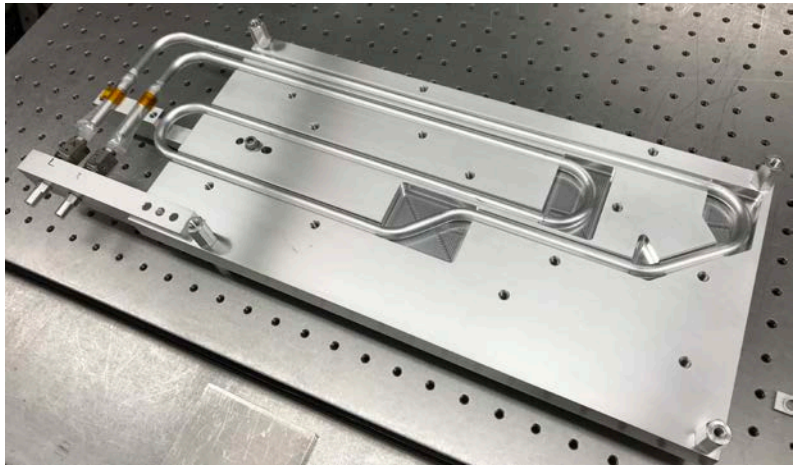
- Primary structure and propulsion system assembly complete
  - Propulsion thermal and harness in progress
- HRS including interconnect lines and radiators in progress
- ATLO work begins May 2018

Mars 2020 Rover HRS Status

Lots of Heat Rejection System Hardware being delivered already!!

Top Deck HRS Tubing being bonded

RAMP Tube Assembly



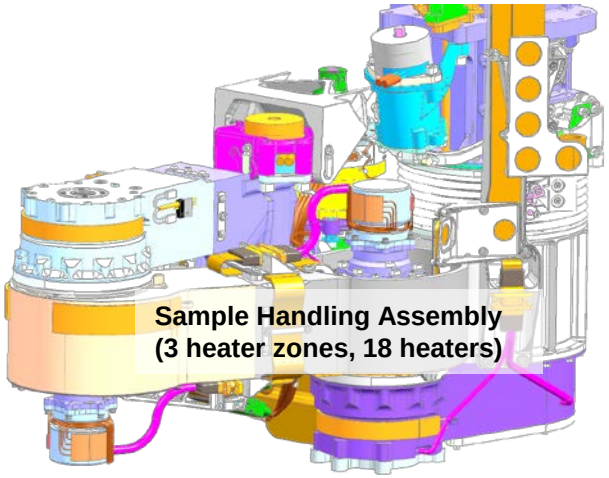
VAMP Tube Assembly

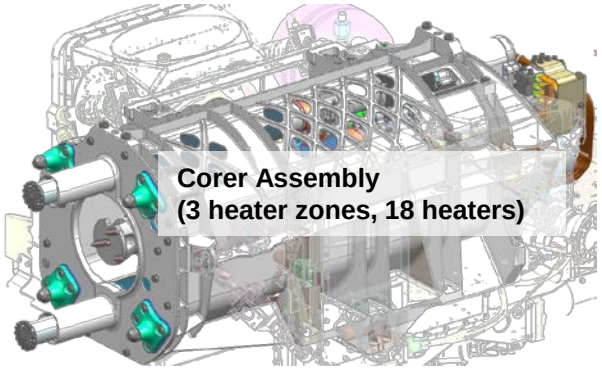
MMRTG HX Tubes

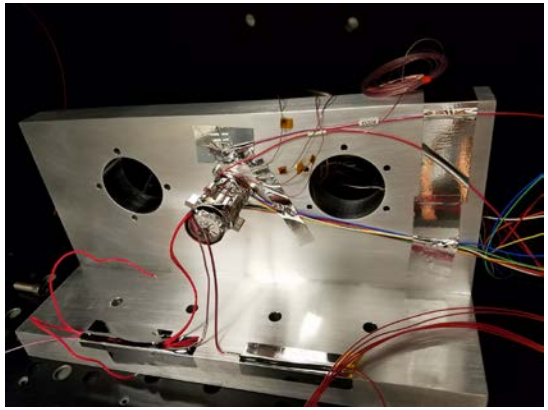
Mars 2020 Rover Sample Caching System Thermal Status

- Thermal Design for SCS Hardware completed in April 2017 with over 50 unique heaters designs to warmup actuators and mechanisms
- All SCS heaters procured and ready for install
- Heater Installations on EM hardware has began
- Motor thermal characterization (with internal Instrumentation) completed for 2 motor types and motor models correlated

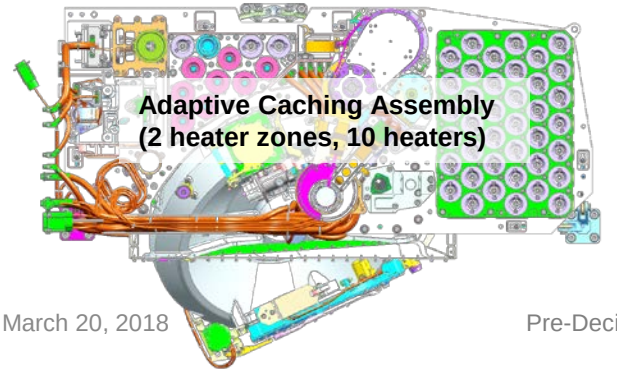
Heater Installation EM Robotic Arm Actuators

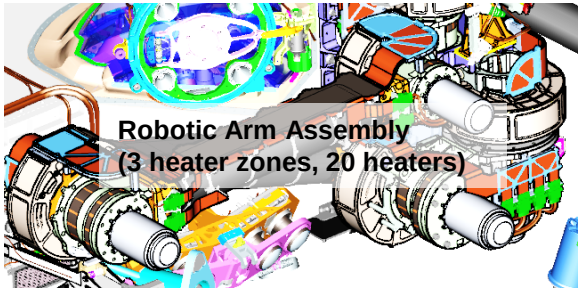






M32 Motor Thermal Characterization

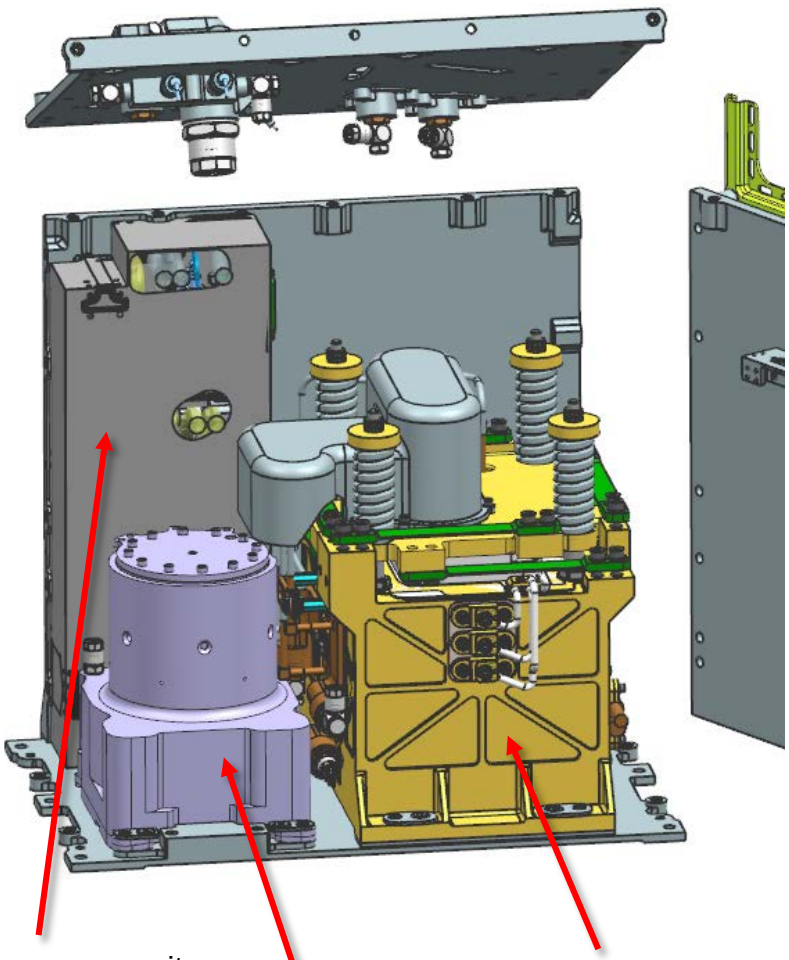




Mars Oxygen ISRU Experiment (MOXIE)

(Courtesy of Asad Aboobaker and Jenny Hua, MOXIE Thermal team)

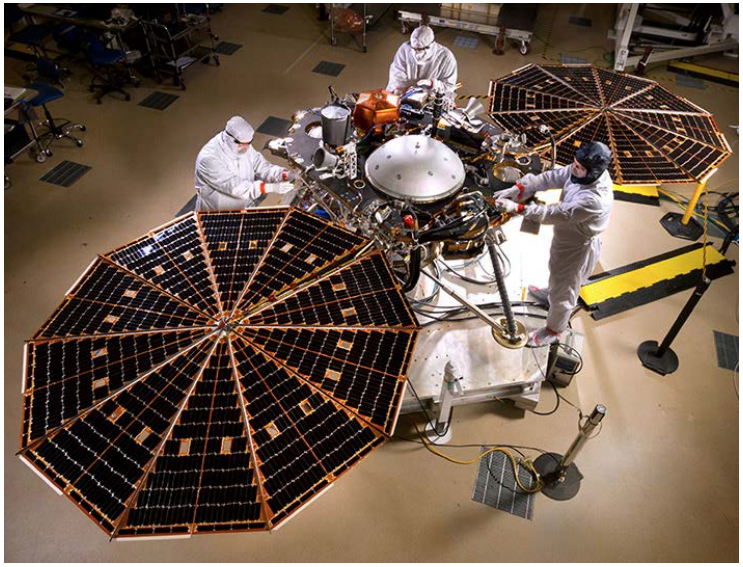
- ISRU tech demo for M2020 – goal is to demonstrate oxygen production from Martian CO_2 atmosphere using Solid Oxide Electrolysis technology
- Mounted inside M2020 rover body on RAMP, atmosphere intake via externally-mounted filter assembly
- Electrolysis stack (approx. 50 x 50 x 100mm) must operate at ~800° C, limited volume and heater power available
  - High temperature creates materials challenges: need superalloys, ceramics
  - Using Min-K and JPL aerogel composite insulations, ~20-30mm thick
  - Approximately 75 W heater power @ 800° C
- High thermal power (~300 W during oxygen production, for up to 2 hours) into Rover HRS
  - MOXIE operations restricted during high-temperature periods
  - Must ensure no harm to Rover or other components mounted to RAMP
- Currently integrating MOXIE flight hardware



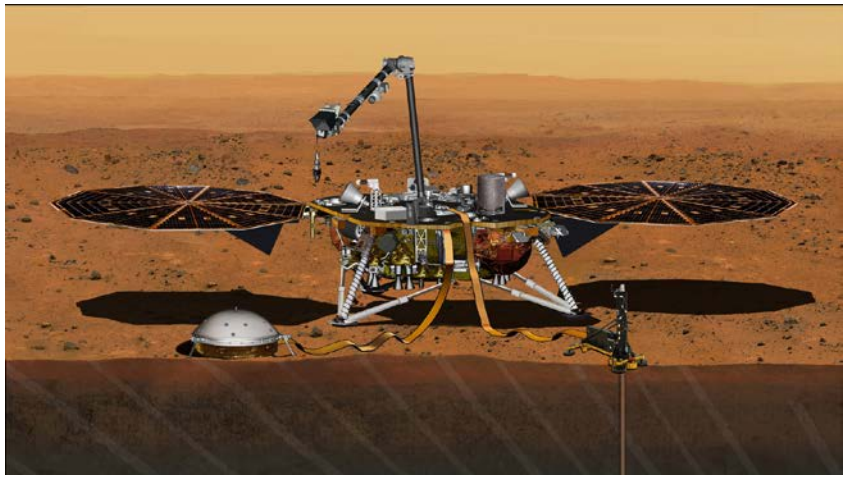
Mars InSight Lander (Scheduled for May 2018 Launch)

Science Goals and Objectives:

- Understand the formation and evolution ofterrestrial planets through investigation of theinterior structure and processes of Mars by
  - Determining the size, composition and physical state(liquid/solid) of the core.
  - Determining the thickness and structure of the crust.
  - Determining the composition and structure of the mantle.
  - Determining the thermal state of the interior.
- Determine the present level of tectonic activity andmeteorite impact rate on Mars.
  - Measure the magnitude, rate and geographical distribution of internal seismic activity
  - Measure the rate of meteorite impacts on the surface.
- LM responsible for spacecraft, integration, test, launch operations and mission operations support. CNES would manage, integrate and deliver the SEIS, and DLR would build and deliver HP3 . Centro de Astrobiología (CAB) of Spain will supply wind and air temperature sensors.

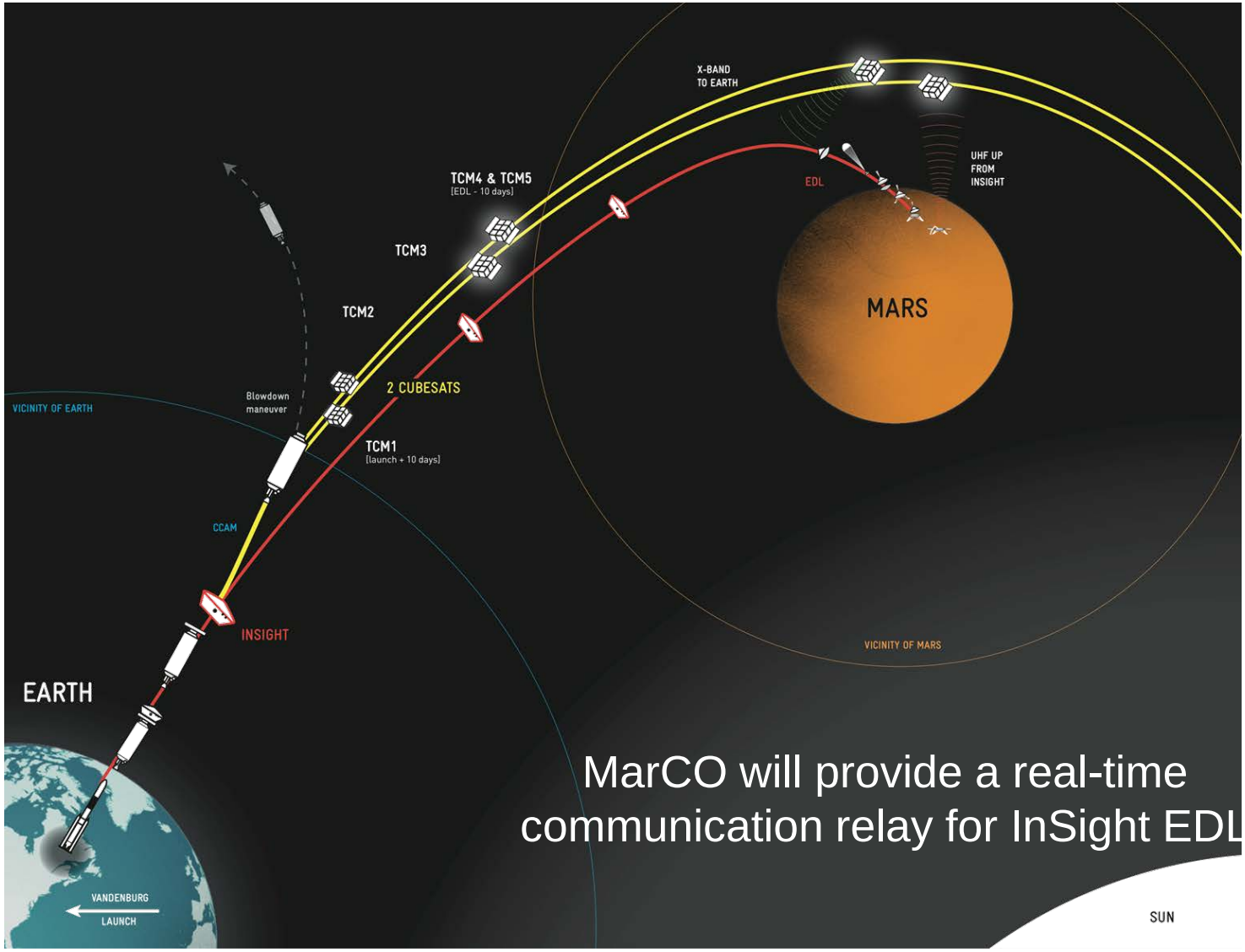


(Image courtesy of Lockheed Martin)



Mars CubeSat Orbiter (MarCO)

(Courtesy of Daniel Forgette, MarCO Thermal Lead)

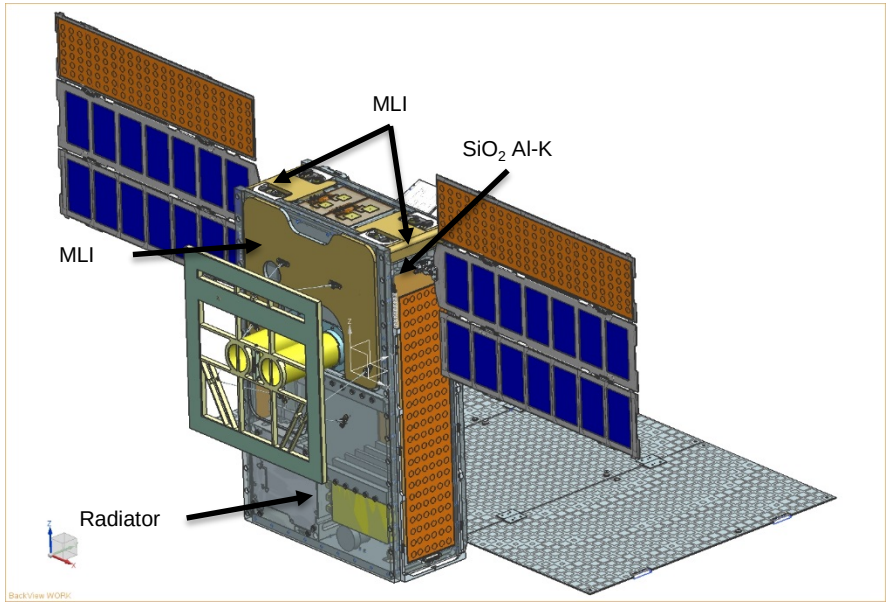


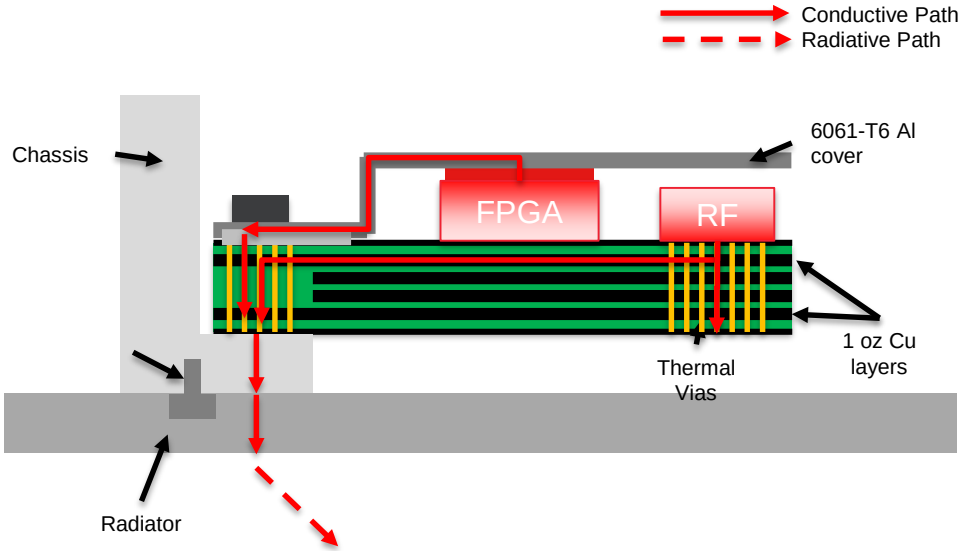
MarCO will provide a real-time communication relay for InSight EDL

Mars CubeSat Orbiter (MarCO)

(Courtesy of Daniel Forgette, MarCO Thermal Lead)

- Transponder with high power density
  - Dedicated thermal PWB Cu layers
  - Custom Al thermal cover for FPGA
  - High conductance chassis
- Radiator sized for S.S. -10°C operation at 15 W
- Capability for ~ 3 hours transmit time
- SiO2 Al-K closeout on small non-radiator surfaces
  - Reduces solar heat load near Earth
  - Reduces SC heat loss near Mars

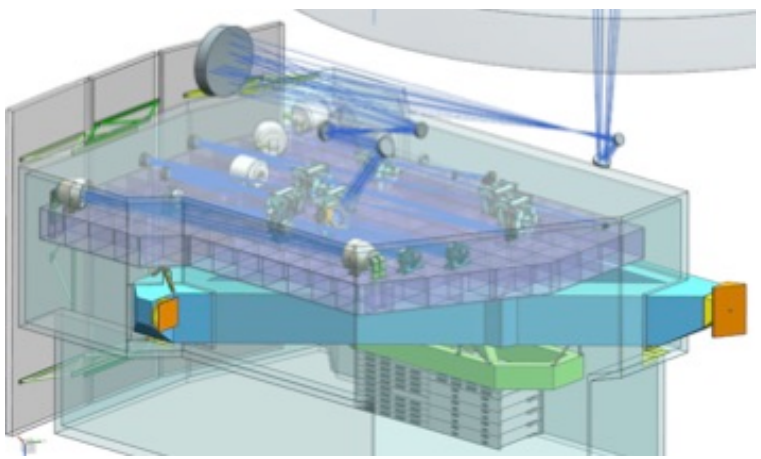




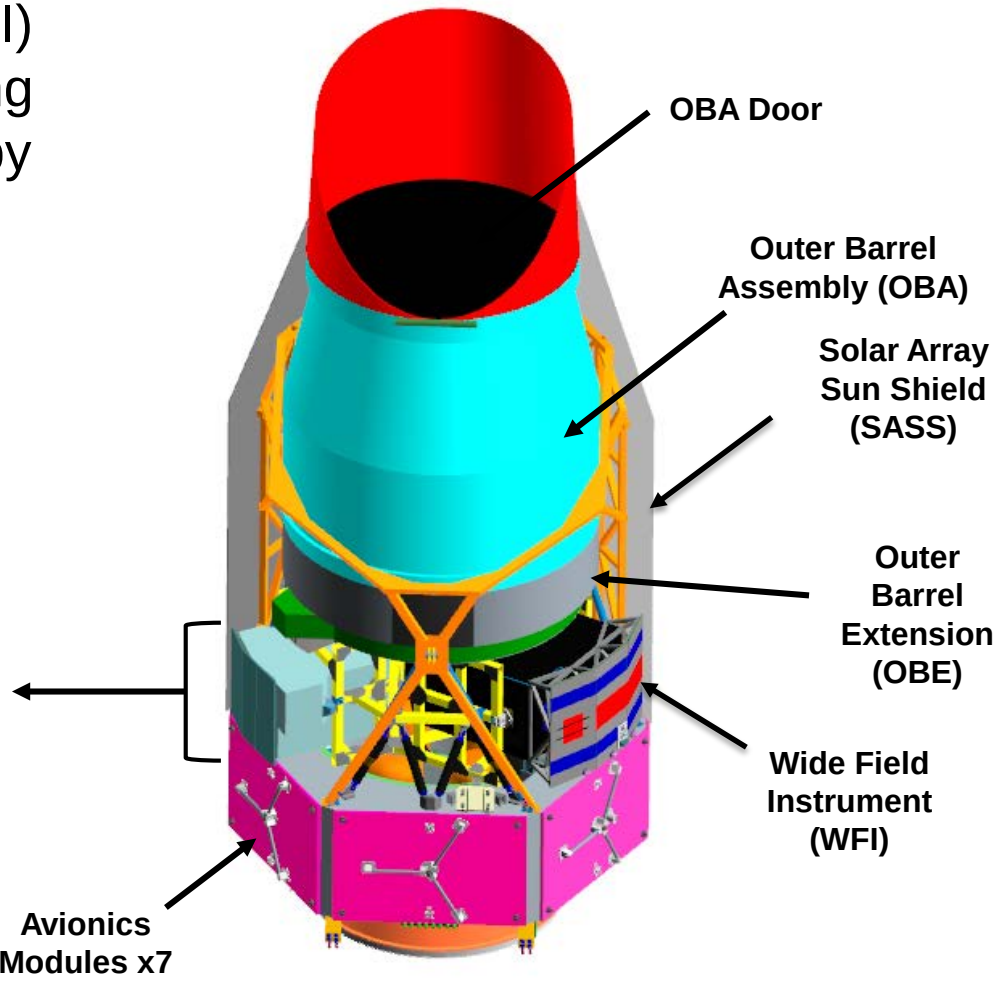
WFIRST/AFTA Exo-Planet Finder

(Courtesy of Gary Kuan, JPL WFIRST/AFTA Systems Engineer & Hung Pham, JPL Thermal Lead)

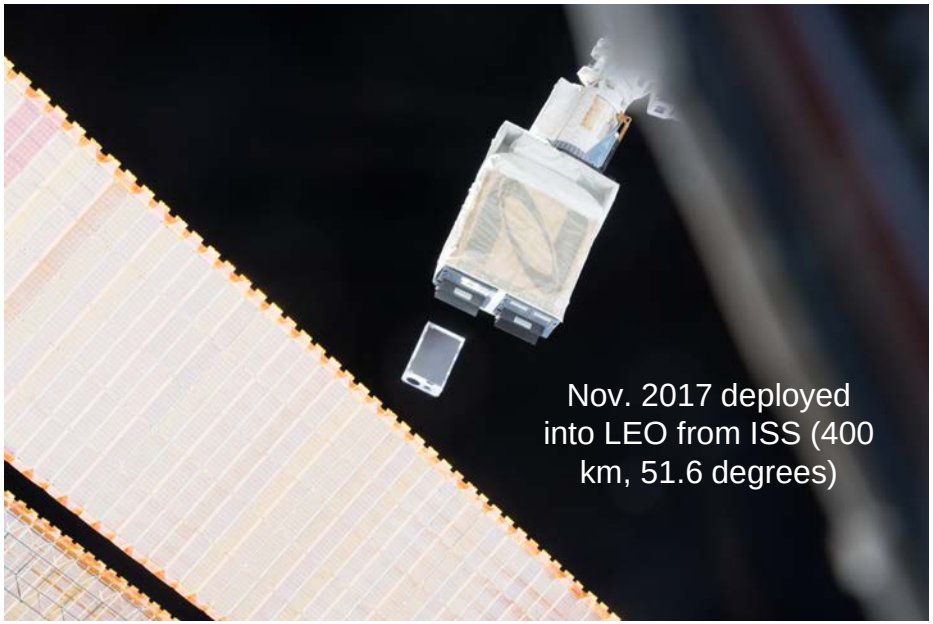
- Coronagraph Instrument (CGI) provides high contrast imaging and integral field spectroscopy in support of exoplanet and debris disk science.



Coronagraph Instrument (CGI)



ASTERIA (Courtesy of Dr. Colin Smith, ASTERIA Thermal Lead)



ASTERIA is a *technology demonstration* mission to advance capabilities in technology areas that *enable photometric studies of astrophysical phenomena* using CubeSats.

Mission Objectives

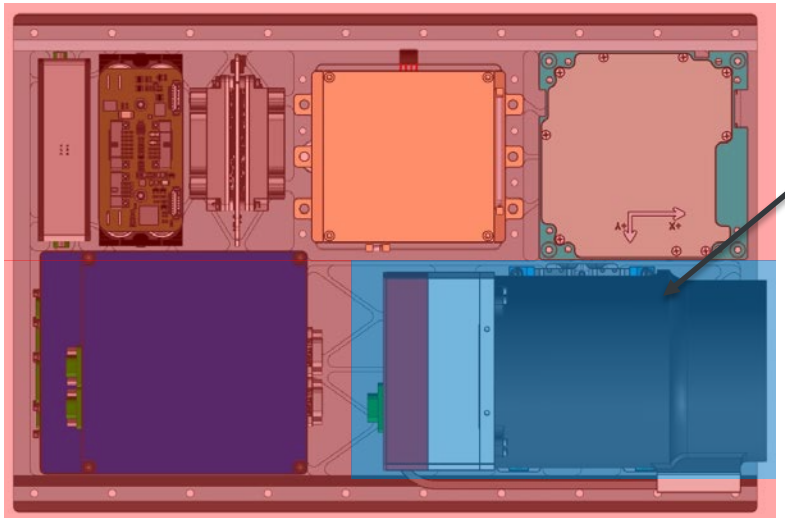
1. Demonstrate high precision line-of-sight pointing
2. **Demonstrate high precision focal plane temperature control (L1 requirement is repeated $\pm 10\ mK$ temperature stability during 20-minute observations)**
3. Conduct photometric measurements of astrophysical sources on an opportunistic basis – PI is Sara Seager from MIT

Overview of flight data

- Spacecraft thermal control
  - Entire spacecraft thermal control system is operating as designed
  - All temperatures within allowable flight temperatures with margin
  - All observed absolute temperatures and orbital temperature variations are expected
- Precision focal plane temperature control
  - Tested multiple configurations (2-stage vs 1-stage, temperature setpoints, sensor selection), and control system is working well
  - Multiple data sets show compliance L1 focal plane thermal control requirement

Asteria Thermal control architecture

(Courtesy of Dr. Colin Smith, ASTERIA Thermal Lead)



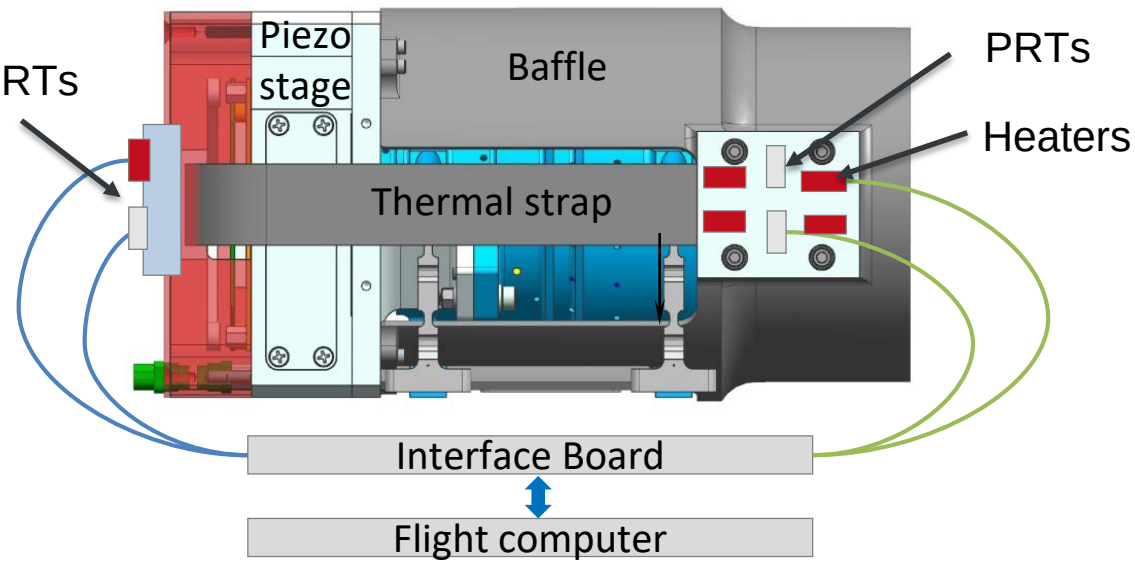
Spacecraft Bus and Payload Electronics Assembly: poor thermal stability

Optical Telescope Assembly is thermally isolated from the spacecraft chassis

To minimize thermal disturbance, the telescope does not point towards earth or sun

Imager power dissipation radiated to environment through baffle

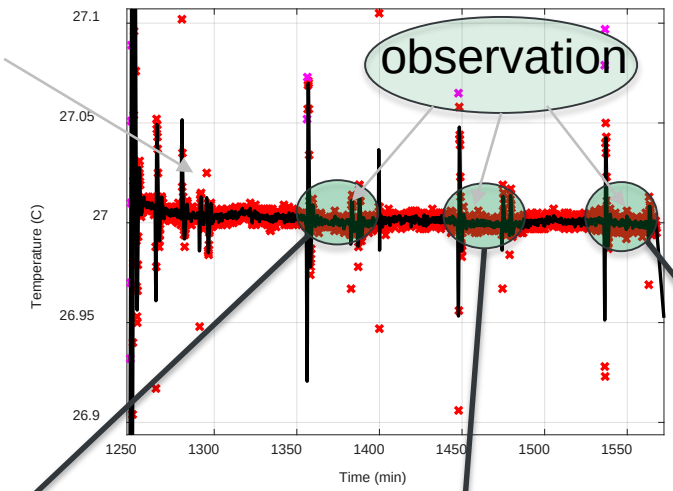
Optical Telescope Assembly

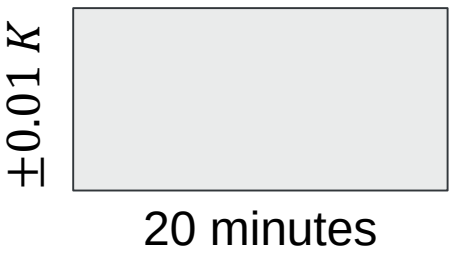


- Heat moved from imager to baffle through thermal strap
- 2-stages of active thermal control
- Interface board reads PRTs, supplies heater power and communicates with flight computer hosting PID algorithm

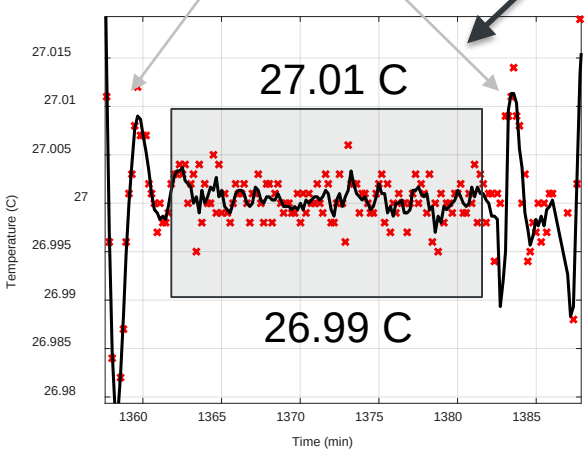
ASTERIA Focal Plane Temperature Control – Sample of Flight Data (Courtesy of Dr. Colin Smith, ASTERIA Thermal Lead)

Red X is raw temperature measurement, black curve is 60 second window-average

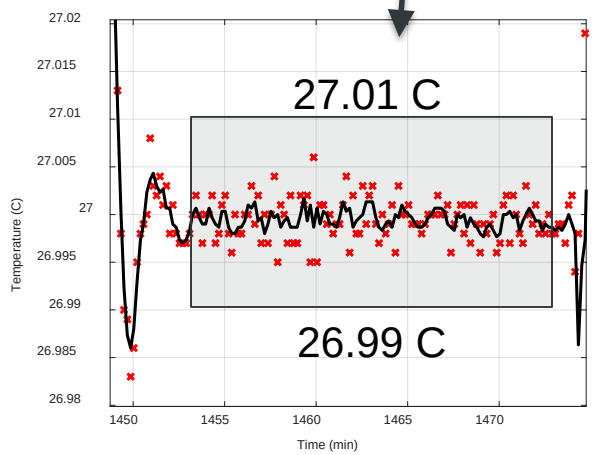




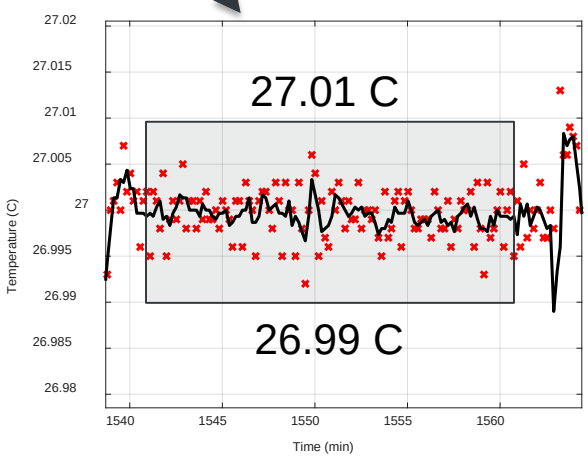
The camera is restarted at these times (not control instability)



±0.01 K control for > 20 min



±0.01 K control for > 20 min



±0.01 K control for > 20 min

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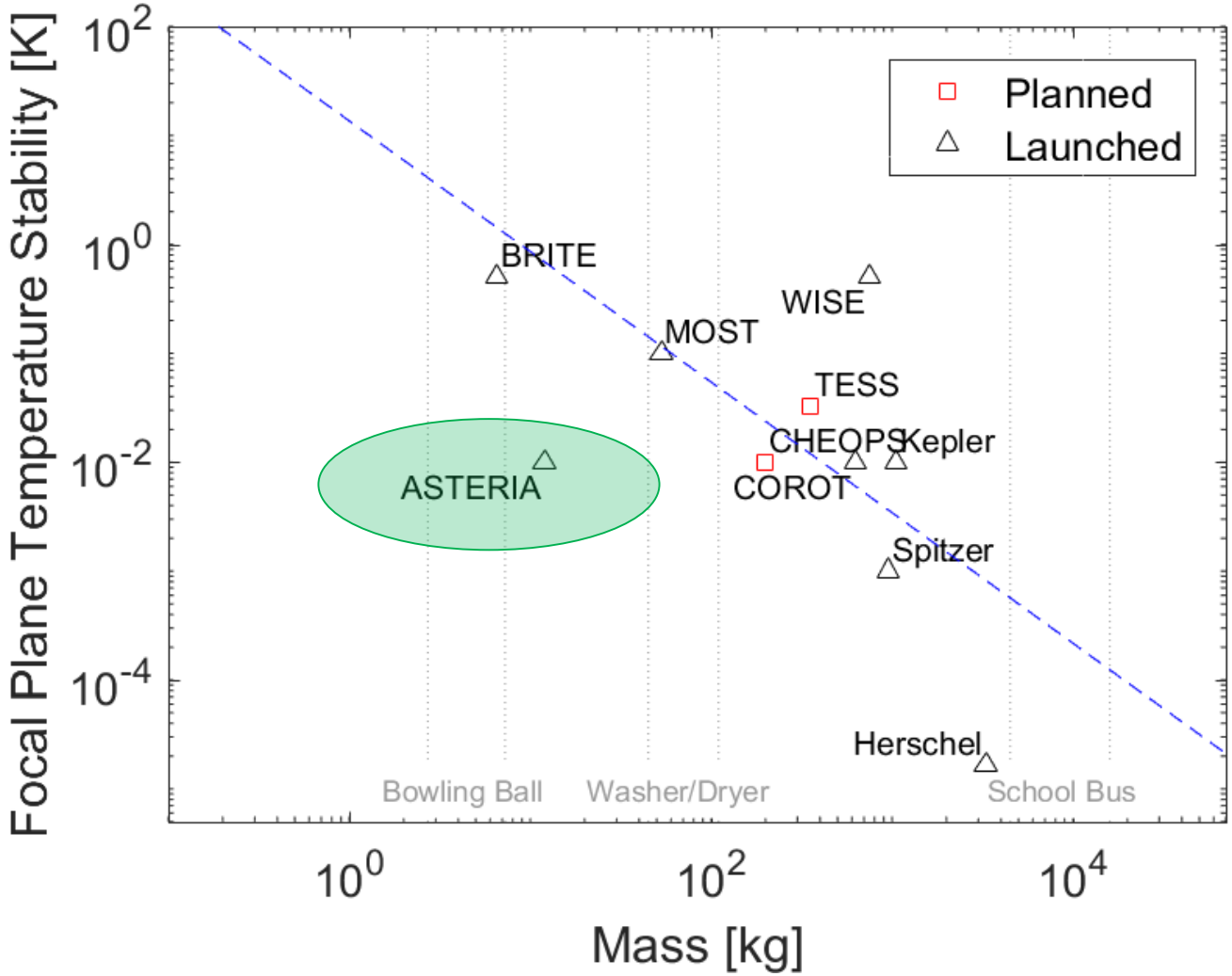
ASTERIA focal plane temperature control in context



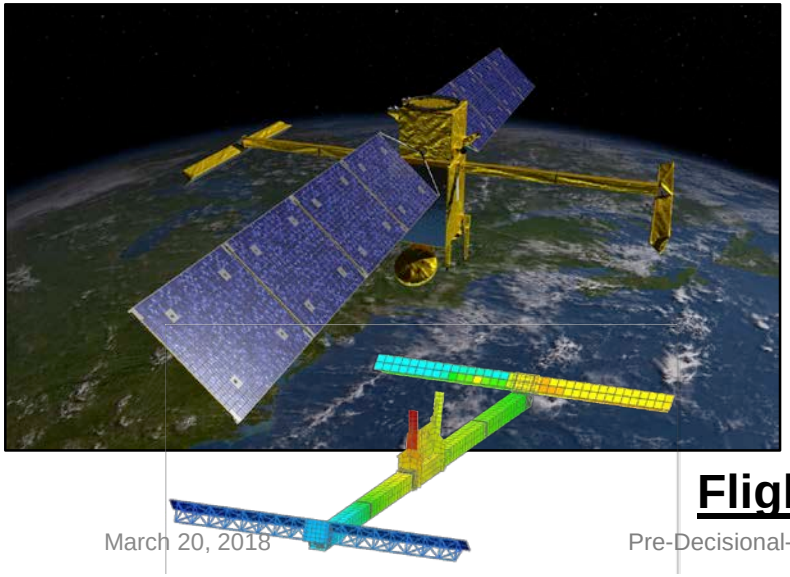
Surface Water Ocean Topography Mission

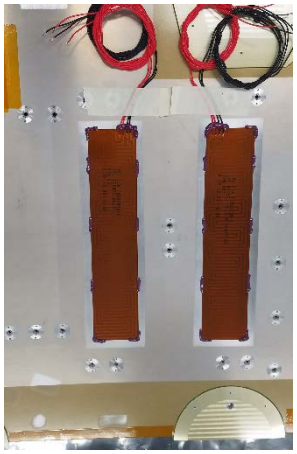
(Courtesy of Ruwan Somawardhana, JPL SWOT Thermal Lead)

- SWOT's mission objective is to characterize ocean topography to a spatial resolution as low as 15 km and provide a global inventory of surface water
  - Joint partnership between NASA and CNES
- Challenging combination of thermal requirements
  - Co-location requirements
  - >1000 W peak thermal dissipation
    - Heat fluxes as high as ~75 kW/m^2
  - Stability requirements as low as 0.05°C/min
- Thermal control subsystem utilizes a wide array of thermal hardware including LHPs, CCHPs, AlBeMet doublers, heaters, temperature sensors, MLI, mechanical thermostats, and surface finishes including 'tiger striping' to meet requirements
- Project Status:
  - CDR cycle successfully complete
  - Hardware fabrication in progress for majority of hardware
  - Integration and testing has started for a few items
  - Surface finish application qualification in-work

Flight EIK Thermal Pallet

Embedded CCHPs in structural plate;
provides direct contact of CCHPs to instrument electronics (source) and LHP Evaporator (sink)





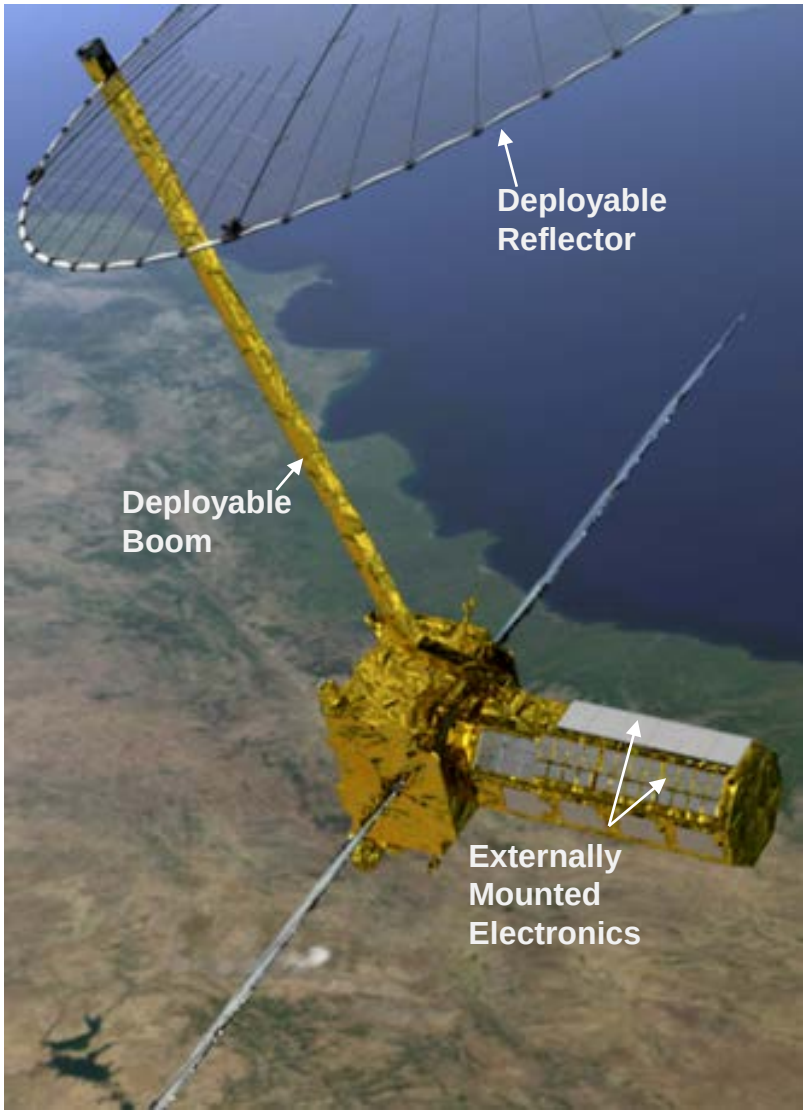
LHP Piece-Part Fabrication

Flight Installs of Heaters

NASA-ISRO Synthetic Aperture Radar (NISAR)

(Courtesy of Frank Kelly, JPL NISAR Thermal Lead)

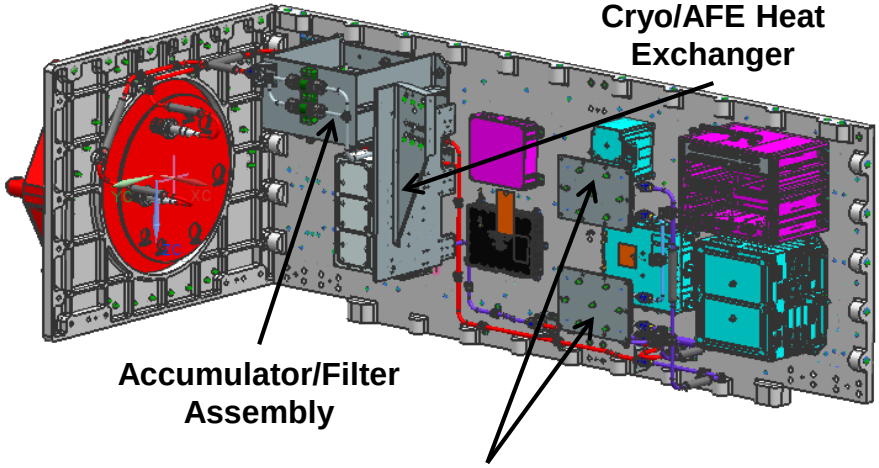
- The NISAR Mission
  - NASA-ISRO Synthetic Aperture Radar
  - NISAR will measure surface motion over span of 12 days to study:
    - Ice Sheet Collapse
    - Earthquakes
    - Volcanoes
    - Landslides
- Thermal Challenges
  - Thermal environment
    - In order for the Instrument to observe both North and South Poles the Instrument is required to operate both sun facing and space facing
  - Externally mounted boxes
    - Due to space limitations and cable length requirements, the majority of the Instrument electronics are mounted to the exterior of the Instrument with radiators built into the high dissipation boxes
  - Deployable boom for the Radar
    - A segmented boom that deploys in orbit
    - Thermal control and analysis required for each of the five deployment phases
  - Deployable reflector
    - ASTRO Northrop Grumman will be supplying a deployable 12m aperture radar mounted on the deployable boom
- The NISAR Thermal System utilizes traditional thermal control materials and hardware for a largely passive thermal design
  - Passive components
    - Radiative coatings/PRTs/Thermistors/MLI/Thermal Isolation
  - Active Components
    - Kapton Heaters/Mechanical Thermostats

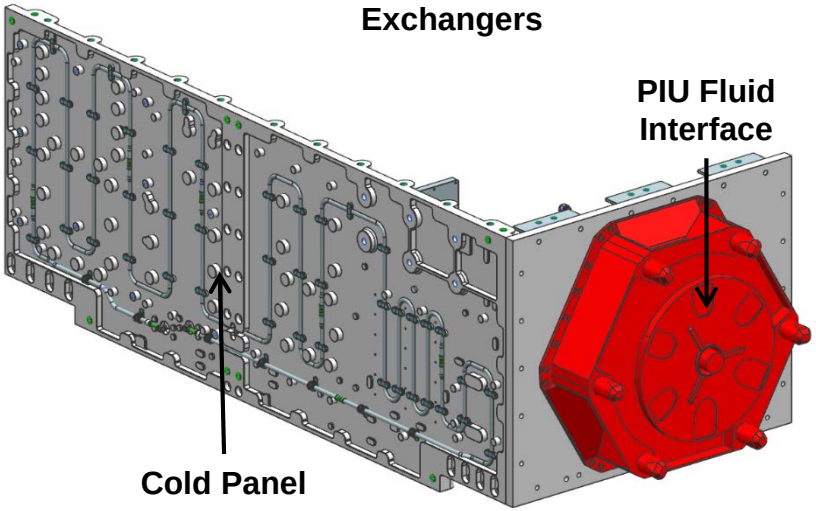


Orbiting Carbon Observatory-3

(Courtesy of Josh Kempenaar, OCO-3 Thermal Lead)

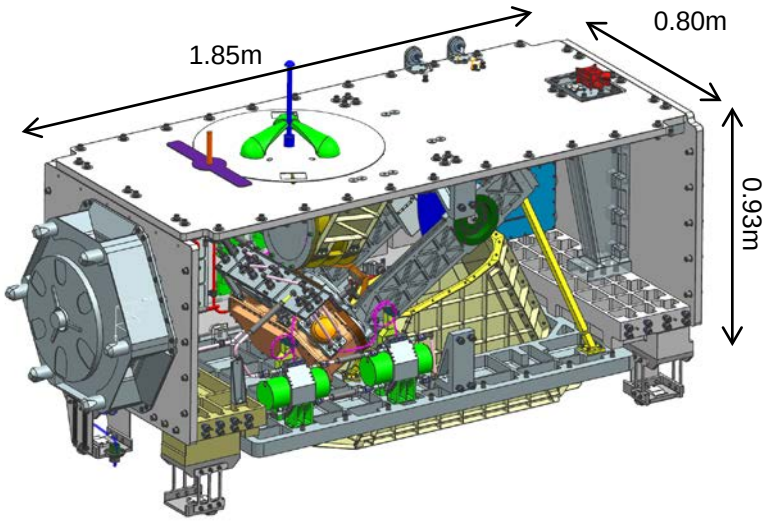
- The thermal control system utilizes the JEM-EF Active Thermal Control System (pumped fluid loop)
- Four thermoelectric coolers cool the Optical Bench Assembly (OBA)
- Two heat exchangers (HXs) remove heat from four thermoelectric coolers (2 per HX)
- A “Cold Panel” provides structure and heat rejection for electronics
- Accumulators compensate for decreases in fluid density during transit
- Fluid filters provide compliance with JEM-EF ATCS usage
- Operational heaters provide thermal stability for AFE, OBA, and PMA

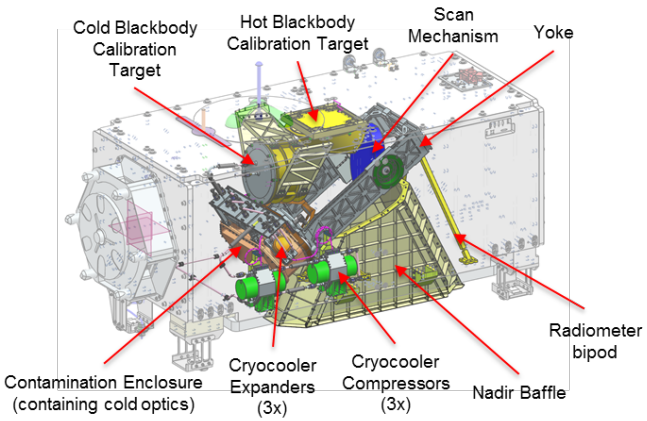


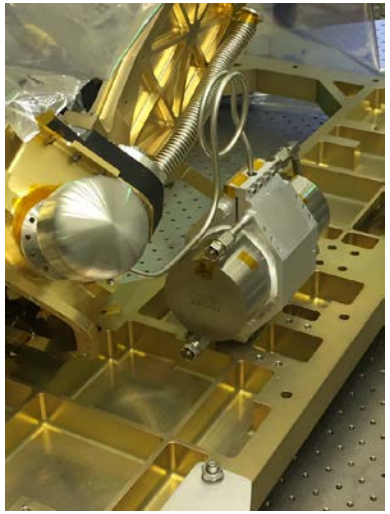


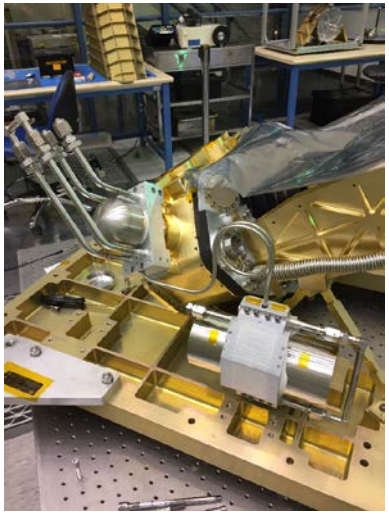
ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)

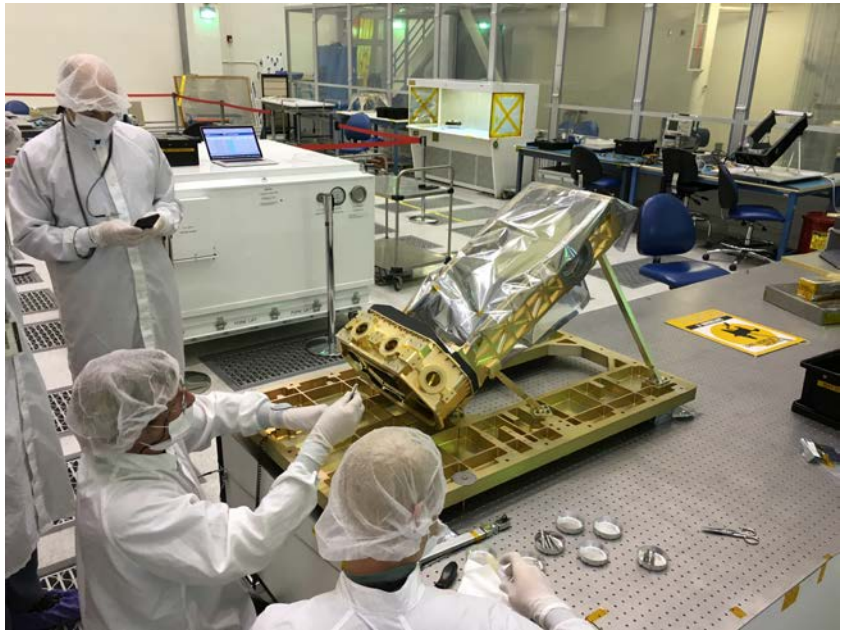
(Courtesy of Jose Rodriguez, JPL Cryogenic Systems Engineering Group Supervisor)

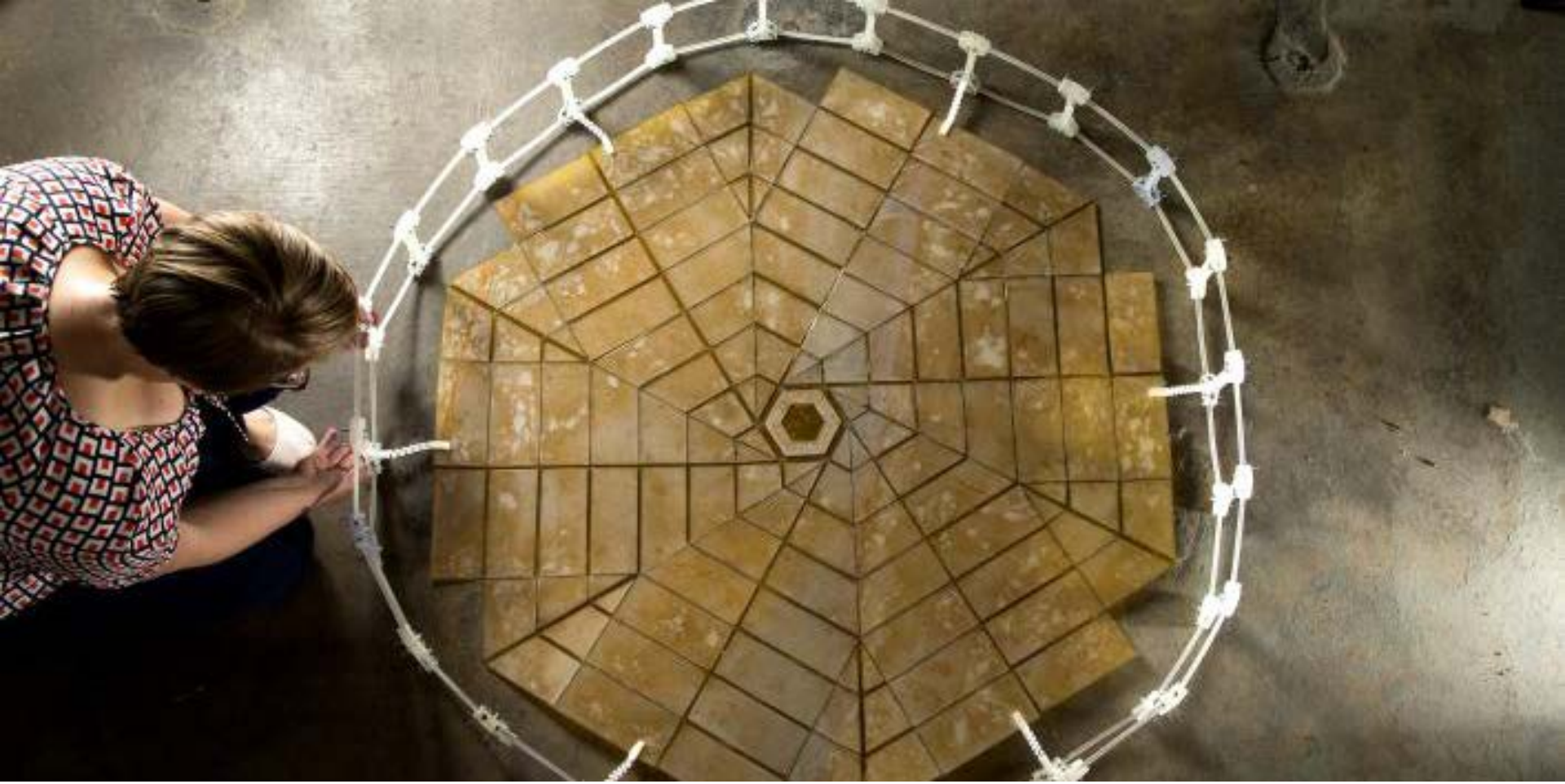












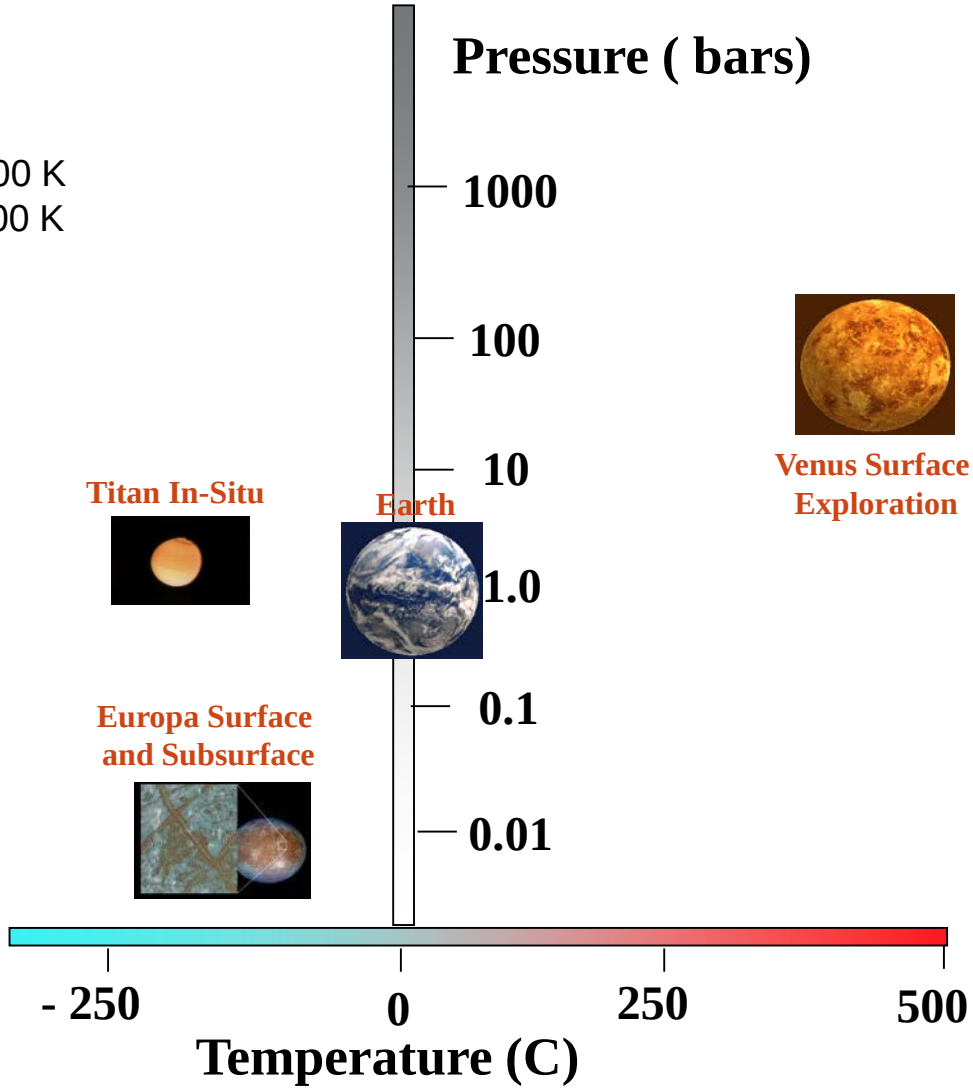
Thermal Technology Challenges

Jet Propulsion Laboratory
California Institute of Technology

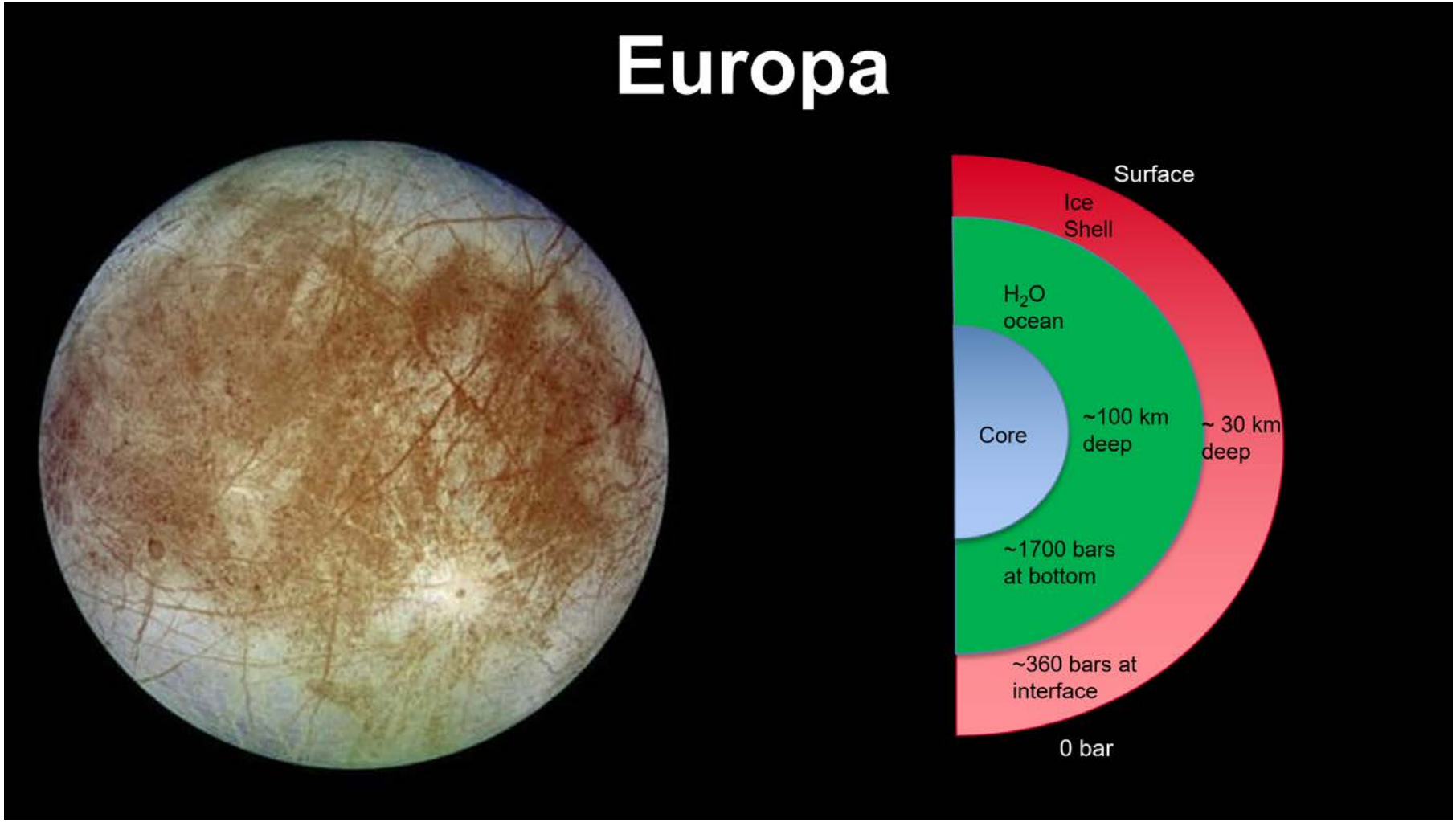
TCS Challenge: Missions to Extreme Environments

Challenge: Extreme Environments

Lunar Diurnal: 100 to 400 K
Mars Diurnal: 150 to 300 K



Example of a Far-Term TCS Challenge



Mission pulls on thermal technology

SMD Div.	Mission	Timeframe	Thermal Challenges	Technology Focus
Planetary Science	Ocean Worlds exploration of ice and under-ice oceans	Far-term	Extreme cold temperature and pressure; management of nuclear power source; isothermal skins	Actively pumped two-phase thermal control
	Venus landers (long duration)	Far-term	High temp. and press. environment; mngmt of nuclear power source	Closed-cycle heat pump (two-phase)[1]
	Venus landers (1-2 day surf. life)	Mid-term	High temp. and press. environment	Expendable two-phase thermal control
	Solar-powered outer planet missions	Mid-term	Waste heat reclamation over multiple interfaces and long distances	Actively pumped two-phase thermal control
	Low-power, long-duration diurnal, non-nuclear landers	Mid-term	Surviving the long night with minimal energy available for heating	Heat switch; variable heat rejection radiator
	Cryogenic Sample Return	Mid-term	Maintaining sample at cryogenic temp throughout EDL	Two-phase thermal control
Earth Science	LIDAR, InSAR	Mid-term Near-term	High heat fluxes; isothermal phase electronics; reflect array thermal stability	Single-phase (near-term) and two-phase (mid-term) pumped loops; RF transparent MLI
	Science Stations	Mid-term Far-term	Many concurrent payloads with total dissipations > 15 kW	Single-phase (near-term); Two-phase (far-term) thermal control
Astrophysics	Planet Finders	Far-term	Thermal stability over long integration times	Two-phase thermal control

[1]Not included on JPL Roadmap and relies on NASA GRC Stirling-based heat pump

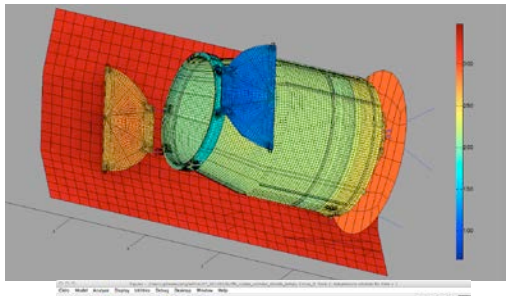
Cross-cutting technology pushes

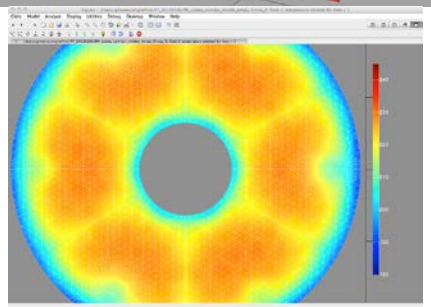
Cross-cutting trends	Timeframe	Thermal Challenges	Technology Pushes
Small-Spacecraft	Near-term	Higher spacecraft heat densities requiring heat transfer across deployables	Actively pumped single-phase systems
	Mid-term	Same as above but also with higher heat fluxes and need for instrument isothermicity	Actively pumped two-phase thermal systems
Additive Manufacturing for Heat Transfer Devices	Mid-term	How to take advantage of this flexibility in features offered by additive manufacturing	Thermal optimization design tools
Enhanced Operability	Mid-term	Surface mission operability is often limited by the thermal subsystem	More efficient heating of actuators; pseudo-real-time thermal modeling; weather-based predictive modeling

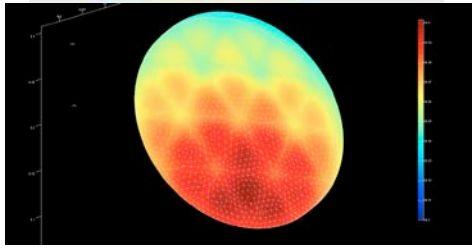
Challenge: Thermal Design Validation by Analysis Cielo Toolkit Development

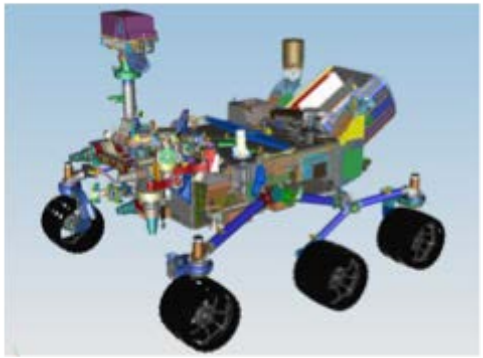
(Courtesy of Mike Chainyk, Cielo Developer)

- Cielo is a finite-element based, multidisciplinary, parallel toolkit that enables high-fidelity, fundamentally-integrated thermal, structural, and optical aberrations analysis of precision deployable systems
  - "Nonderivative Technology" developed under 5-year R&TD Strategic Initiative by in-house team formerly from industry
  - Distributed client server paradigm (MATLAB client, OpenMP-based parallel network server)
  - Continued development and application in a variety of projects, from pre-Phase A demonstrators to rapid-turnaround challenges
- Cielo is enabling "In The Loop" model-driven operations development for MSL
  - Operations currently rely on static "heater tables" for scenario planning
  - Development of each heater table currently requires:
    - Over a year of effort
    - Hundreds of simulations
    - Coordination of both internal and external (vendor) teams, each using separate subsystem models
  - Cielo enables "Full-Up", common system modeling to:
    - Create heater tables "on demand"
    - Increase daily, and overall, science return
    - Improve power use efficiency and maximize safe battery draw-down
    - Enable future anomaly detection, investigation, and mission life extension



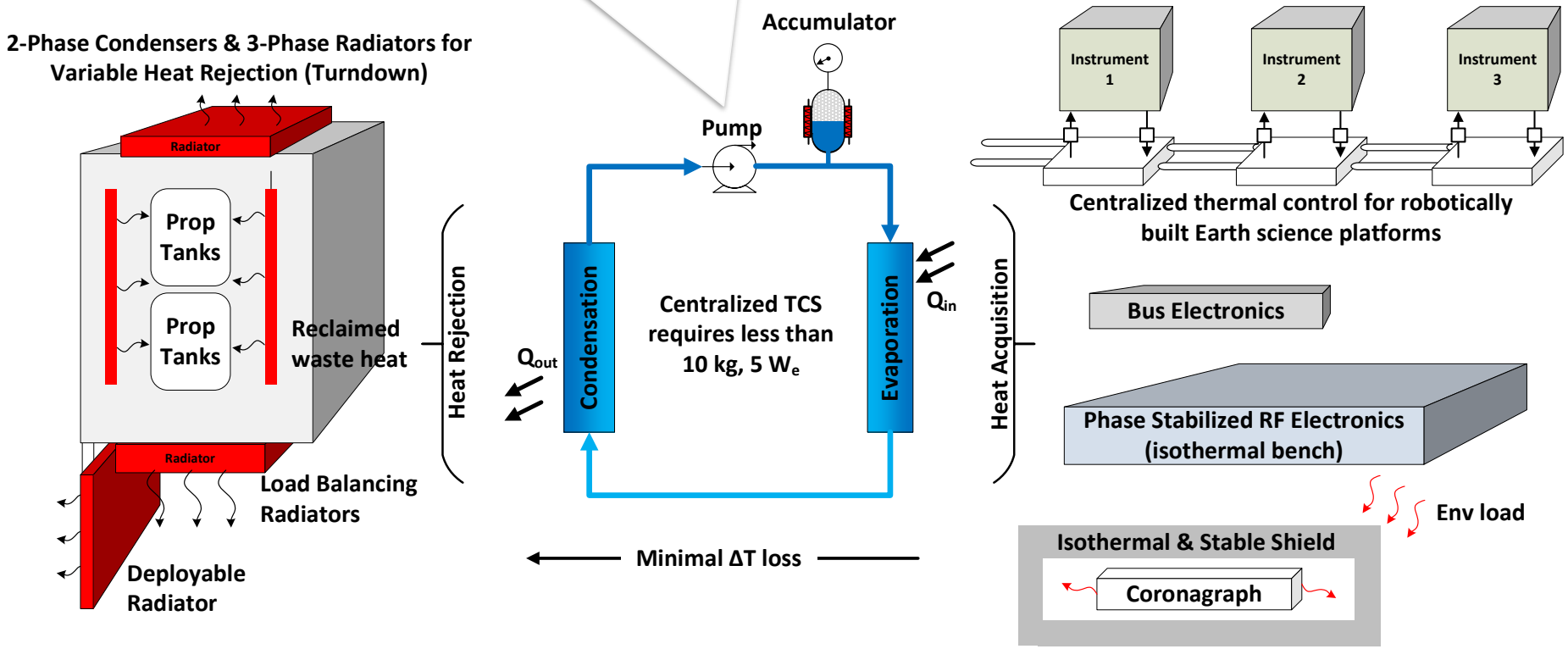






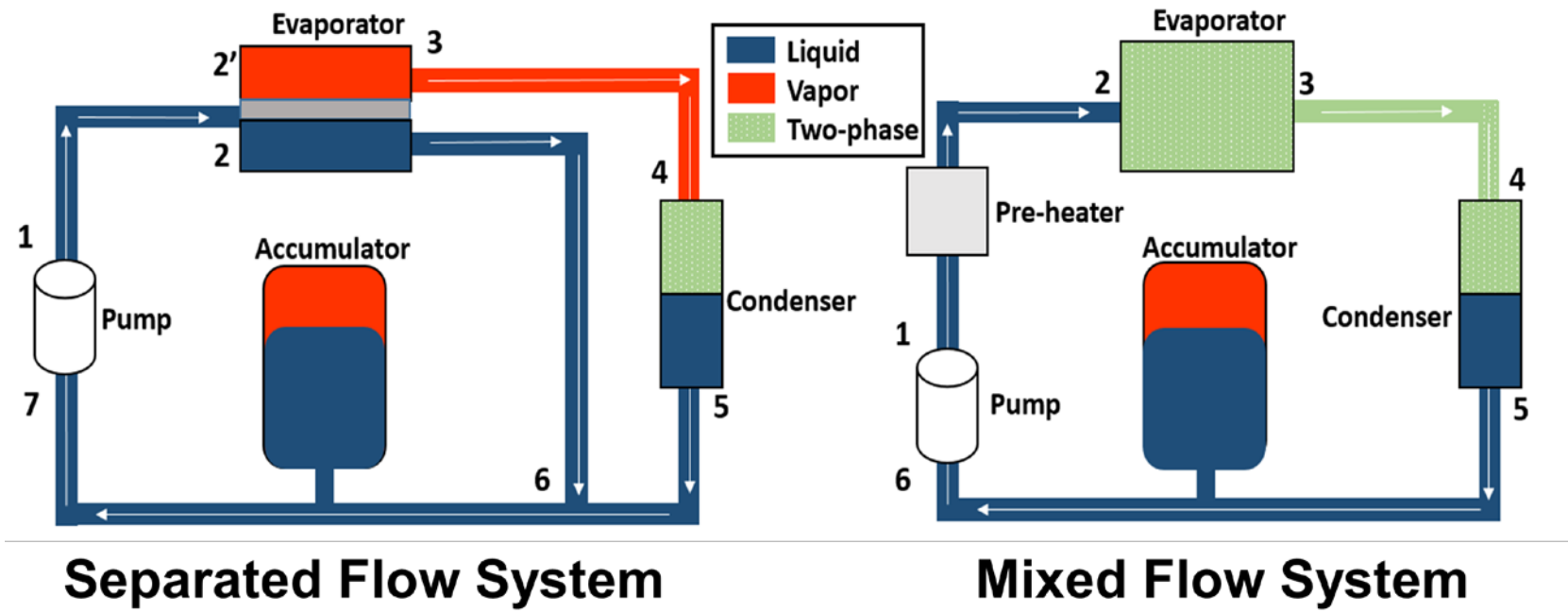
Two-Phase Thermal Control System Concept for Outer Planet Exploration

A mechanical pump is used for small to large spacecraft to provide the required pressure and phase management control authority



Mechanically Pumped Two-Phase Thermal Control

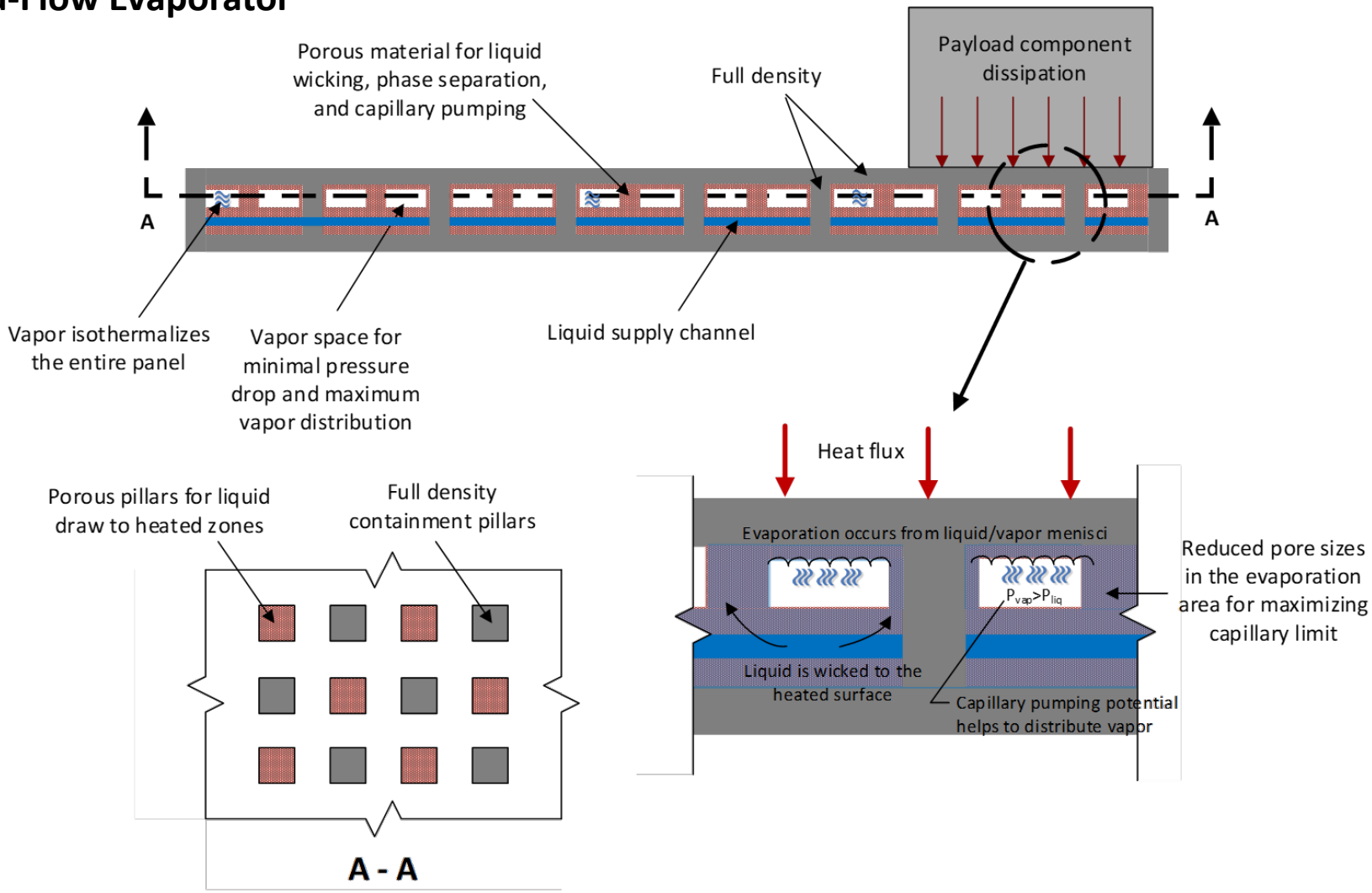
Loop architecture study using integrated phase separation within evaporator



Two-phase loop architecture based on porous-media phase separator/evaporator (JPL investigation, Eric Sunada/Ben Furst)

Mechanically Pumped Two-Phase Thermal Control

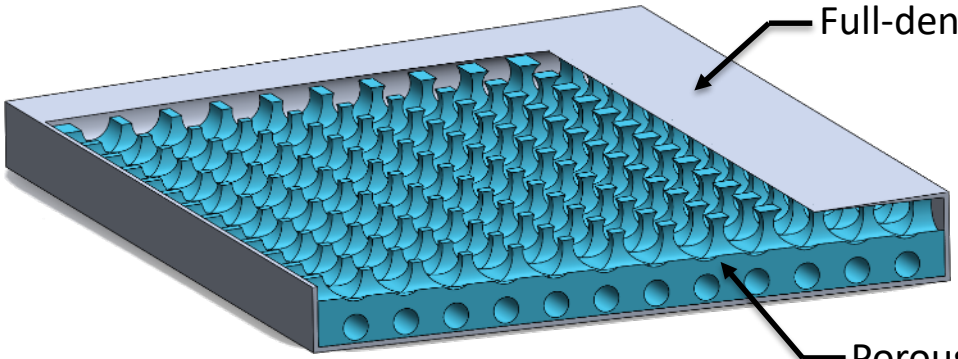
Separated-Flow Evaporator



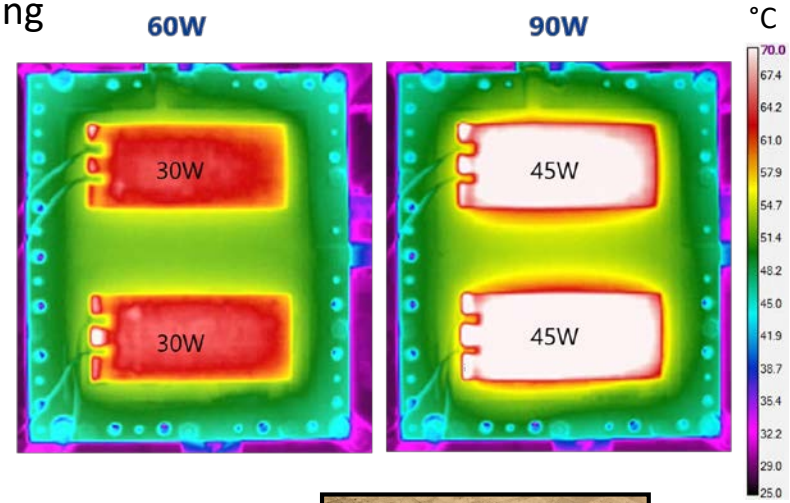
JPL investigation, Eric Sunada/Ben Furst

Mechanically Pumped Two-Phase Thermal Control

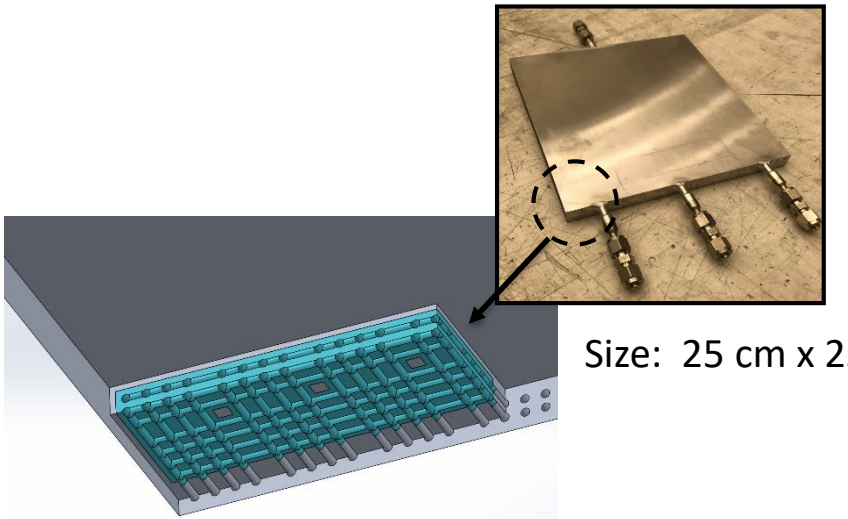
Separator-Flow Evaporator Utilizing Additive Manufacturing



Monolithicly-built 3-D printed evaporator for JPL two-phase pumped fluid loop



3-D printed aluminum wick with water



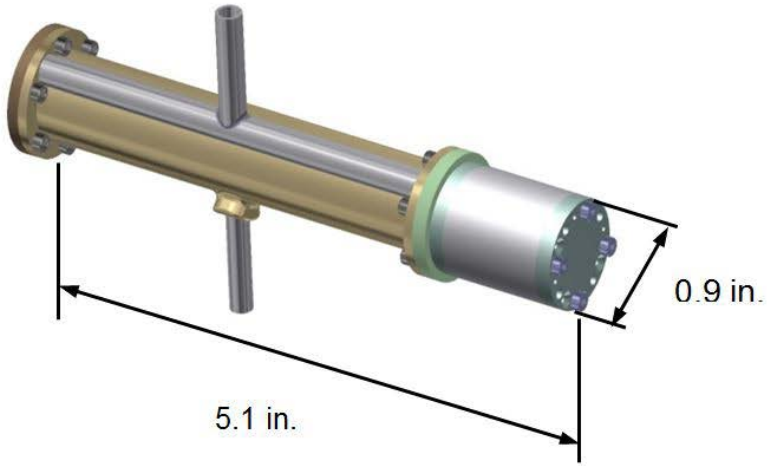
Size: 25 cm x 25 cm

JPL investigation, Eric Sunada/Ben Furst

An Efficient, Reliable, Vibration-Free Refrigerant Pump for Space Applications

SBIR Ph II Proposal # S3.07-7413—Creare LLC, PI: Dr. Weibo Chen

- Significance of the innovation
  - An innovative refrigerant pump to enable reliable refrigerant circulation in two-phase pumped loops
  - Long-life, vibration-free bearing technology for reliable operation
  - Unique pumping mechanism for low Net Positive Suction Head (NPSH), preventing cavitation in impeller and bearing liquid film
  - Efficient operation for low flow rate and high pressure rise
- Benefits
  - Compact, lightweight, and low pumping power
  - Ultra-reliable
  - No exported vibration
- Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)



Pump Performance

ΔP =10 psid

$\dot{V}$ = 2 cc/s

$W_{electrical}$ = 1.6 W

M = 198 g

Speed: 12,000 rpm

NPSH: 0.2 psi

NASA SBIR/STTR Technologies

S3.06-8949 - A Two-Phase Pumped Loop Evaporator with Adaptive Flow Distribution for Large Area Cooling

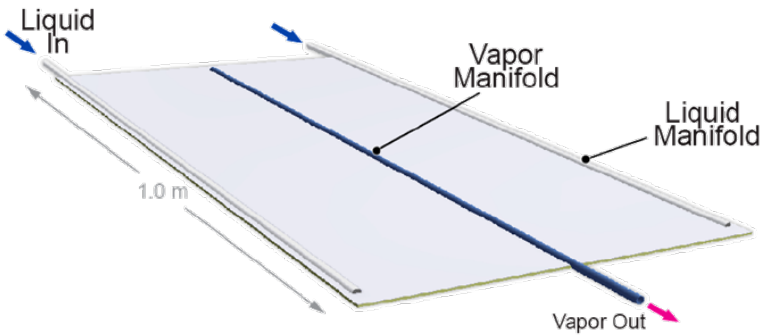
PI: Weibo Chen
Creare, LLC - Hanover, NH

Identification and Significance of Innovation

Large spacecraft need a reconfigurable thermal control system to cool multiple instruments and reject heat through multiple radiators
A microgravity-compatible evaporator having a large cooling area to maintain the temperatures of multiple electronics and instruments
--Very large cooling area to accommodate a large number of loads with different heat flux densities, power levels, sizes, and shapes
--Adaptive flow distribution ability to prevent dryout
--Unique design to provide strong structural support for covers
Benefits

--Uniform cooling temperature with spatial variation <0.2 K
--Simplify vehicle level system integration
--Reduce pumping power by reducing liquid recirculation
--Lightweight and low liquid holdup
--Microgravity compatible operation

Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)



Technical Objectives and Work Plan

Technical Objectives
Reliable fabrication and assembly processes for lightweight evaporator
High-fidelity evaporator design model
Stable and isothermal operation with highly nonuniform heat flux distribution
Gravity-insensitive operation
Phase II Work Plan
Fabrication process optimization and separate effects testing
Evaporator design analysis
Evaporator fabrication
Evaporator thermal performance testing
-- Challenging heat flux distribution and different orientations

NASA Applications

- Thermal control system for spacecraft to Saturn's moon Enceladus
- Two-phase pumped loops for future remote sensing science missions, including Surface Water and Ocean Topography (SWOT)
- Two-phase pumped loops for large spacecraft with a large number of instruments

Non-NASA Applications

- Two-phase thermal control systems in commercial and military satellites, aircraft, and vehicles
- Thermal management systems for high-power electronics systems

Firm Contacts

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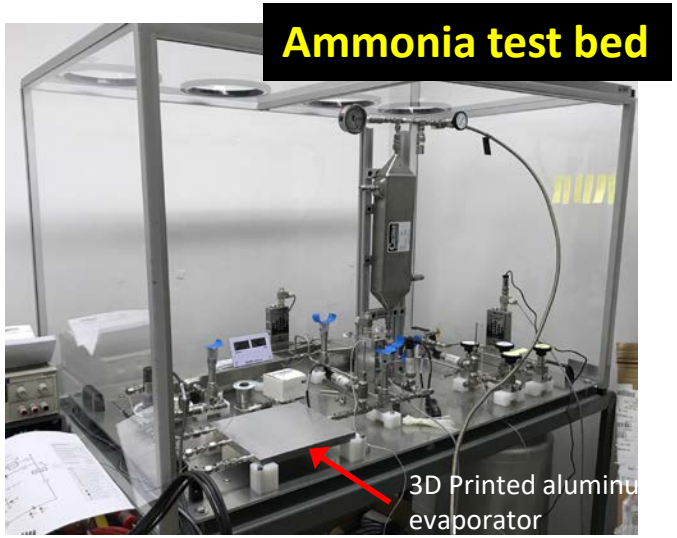
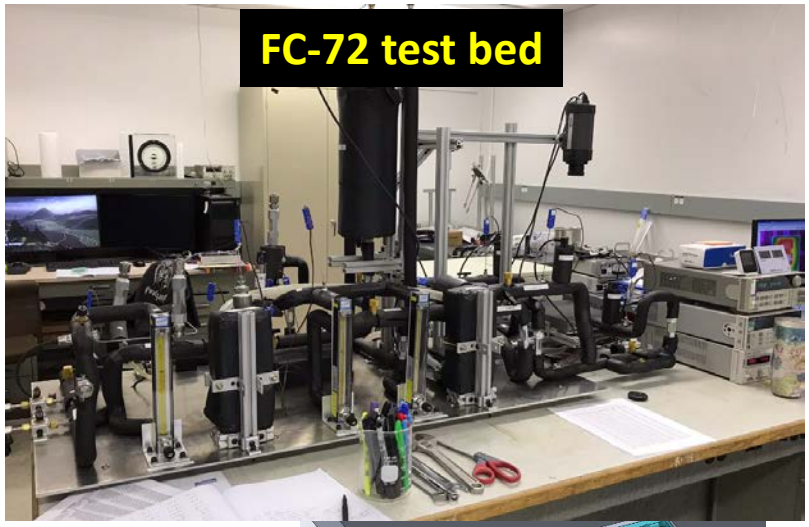
Creare, LLC
16 Great Hollow Road
Hanover, NH, 03755-3116
PHONE: (603) 643-3800
FAX: (603) 643-4657

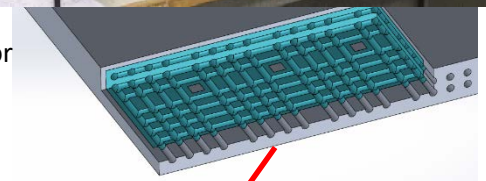
Mechanically Pumped Two-Phase Thermal Control

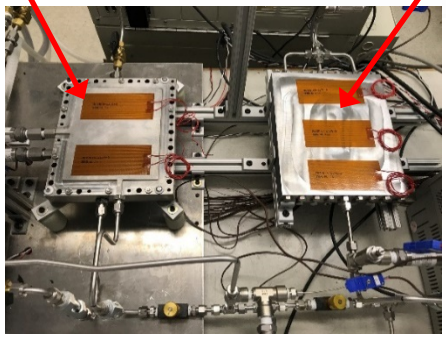
Two-Phase Test Beds at JPL





316 Stainless evaporator with 3D printed wick



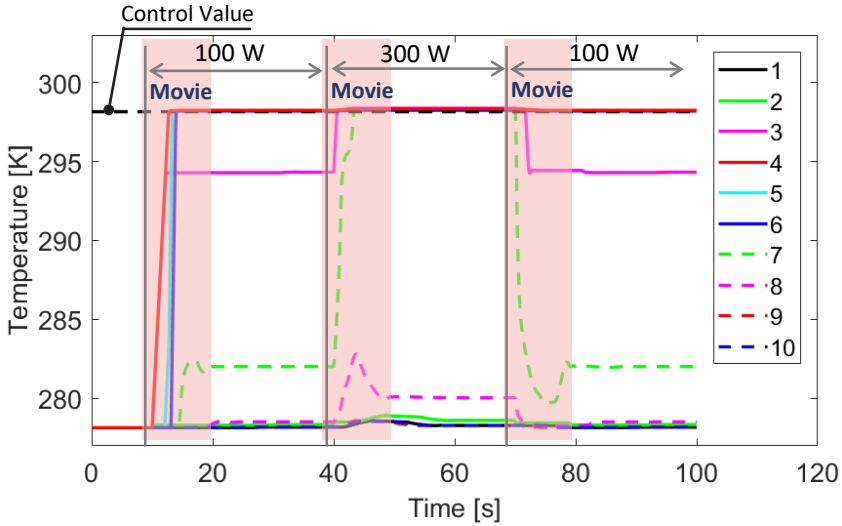


3D Printed aluminum evaporator

JPL Internal Investigation—Eric Sunada/Ben Furst

Mechanically Pumped Two-Phase Thermal Control

Two-Phase Loop System Model Development



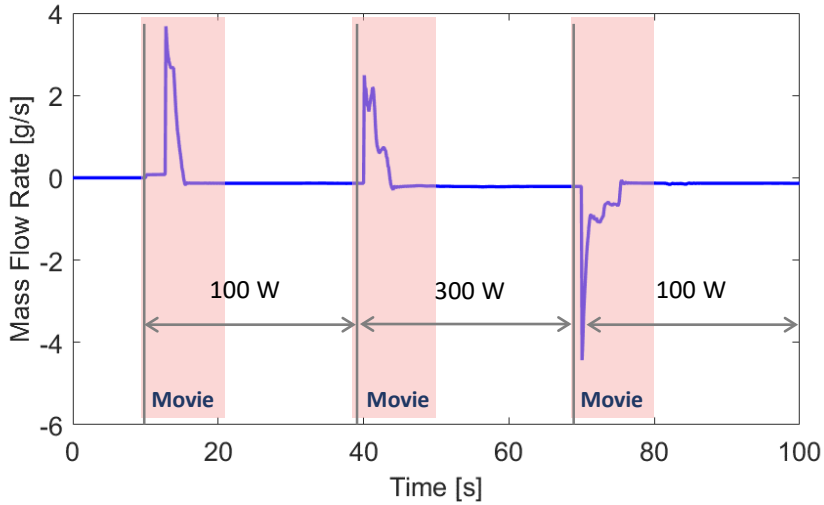
Temperature History

- Temperature in the evaporator increases linearly until vapor generation
- Loop is activated at two-phase flow initiation and Evaporator temperature is maintained at the control value
- Two-phase region and temperature change with heat input variation

JPL Internal Investigation—Takuro Daimaru

Mechanically Pumped Two-Phase Thermal Control

Two-Phase Loop System Model Development



Mass Flow Rate into Accumulator

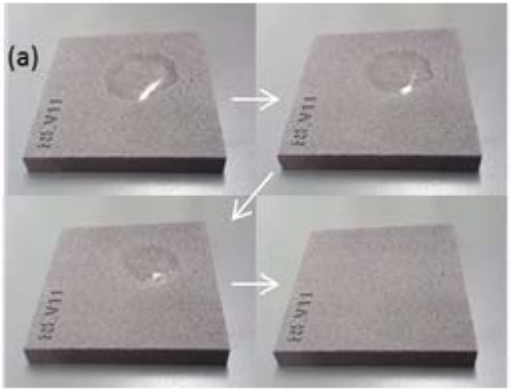
- Mass flow rate into accumulator changes due to heat input variation
- Liquid flow into accumulator when heat input increased
- Liquid flow out of accumulator when heat input decreased

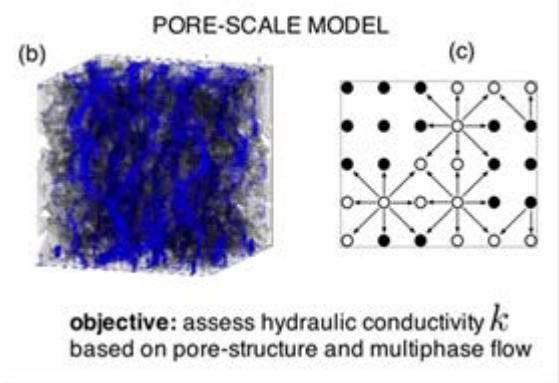
JPL Internal Investigation—Takuro Daimaru

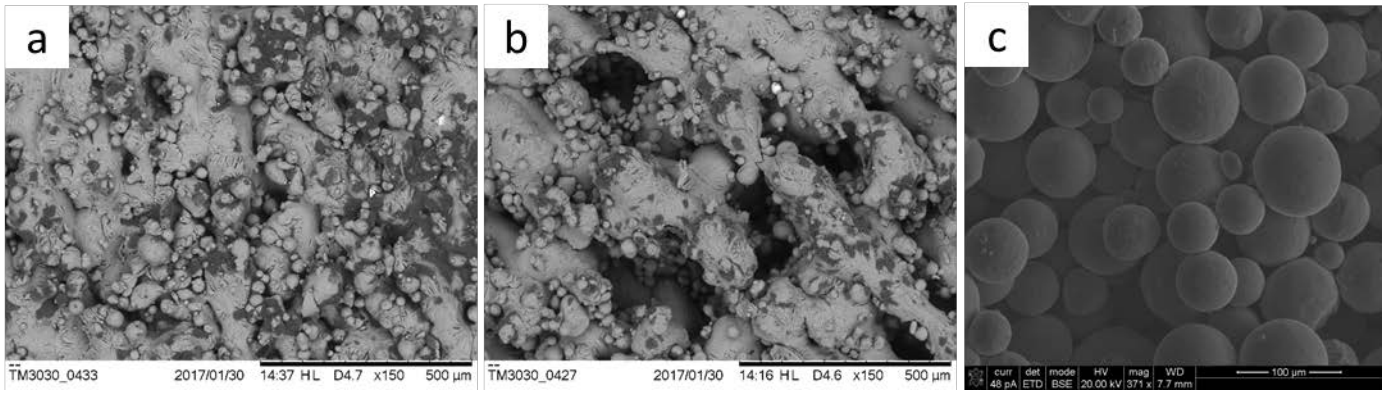
Mechanically Pumped Two-Phase Thermal Control

Multi-Phase Flow in Porous Media using Lattice-Boltzmann Modeling

- Predictive design tools are necessary to exploit JPL's capability for 3D printing of variable porosity structures
- Developing Lattice Boltzmann Modeling techniques based on 3D CT Scans of sample builds
- Goal is to develop constitutive equations for use in higher-level models







Additively manufactured alum. wick with an energy density of (a) 22 J/mm³ and (b) 7 J/mm³, both with estimated porosity of ~46%. (c) Ti wick made through a different additive process, with porosity ~ 50%

Caltech/JPL Internal Investigation—Prof. Jose Andrade, CIT Co-PI; Scott Roberts, JPL Co-PI

Passive Two-Phase Thermal Technology Development

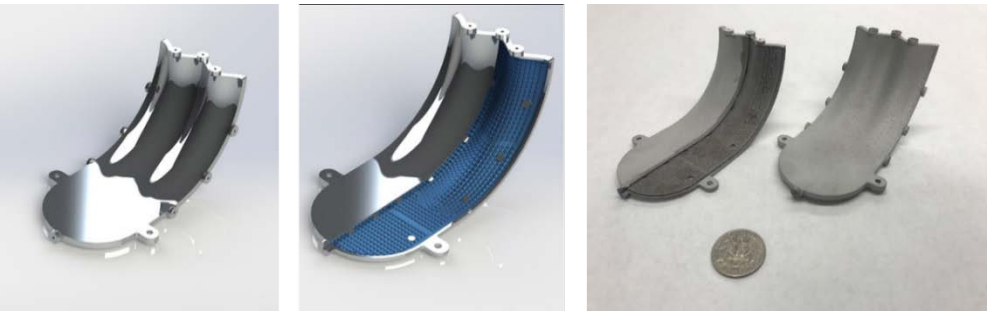
Ben Furst, Vapor Chamber PI
Takuro Daimaru, Oscillating Heat Pipe PI

Jet Propulsion Laboratory
California Institute of Technology

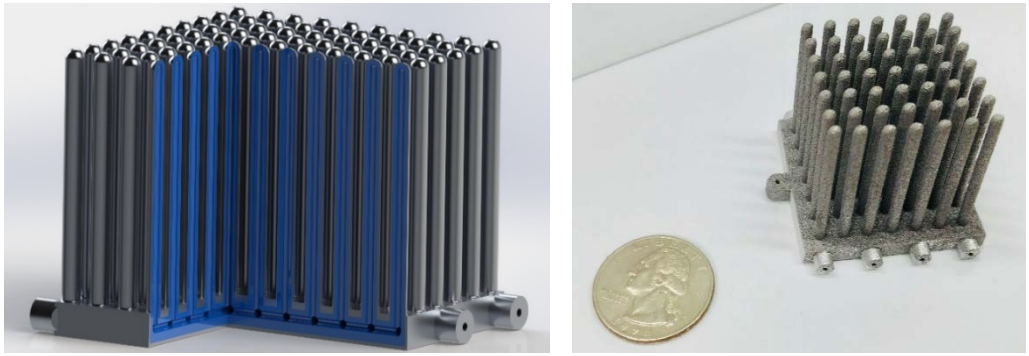
Passive Two-Phase Thermal Control

Vapor Chamber Development

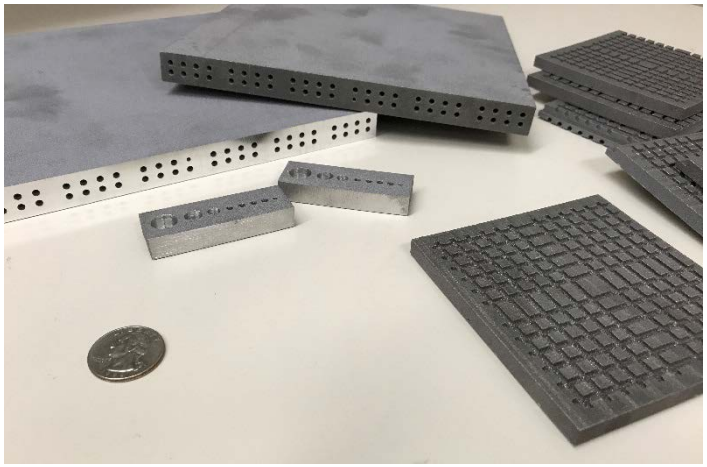
- 3D printed two-phase vapor chambers capable of conformal shapes



Additively manufactured vapor chamber with complex 3D geometry (left/center shows the CAD, right shows the fabricated part). This unit was designed at JPL. It is currently undergoing testing



An additively manufactured heat sink with integrated heat pipes and vapor chamber. The cutaway (right) shows the integrated wicking structure (blue) and channels for vapor flow of the heat pipes/vapor chamber.

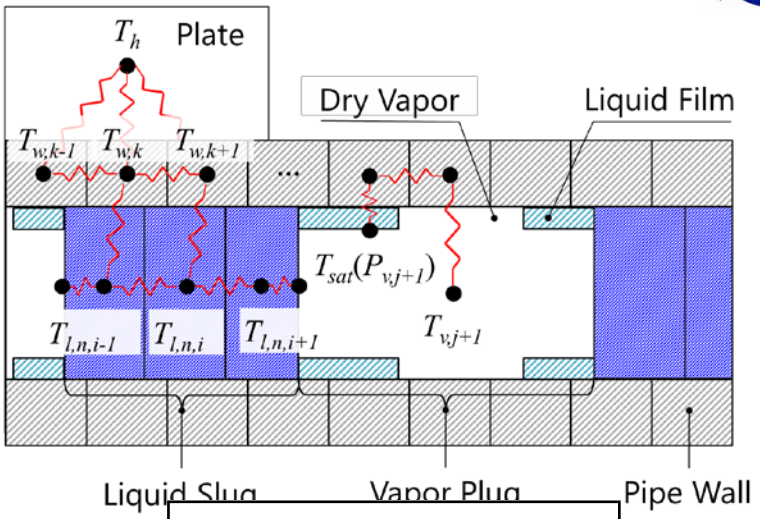


Several additively manufactured units with integral wick structure. The wicking properties of these coupons were well characterized under the current project.

JPL Internal Investigation—Ben Furst, PI

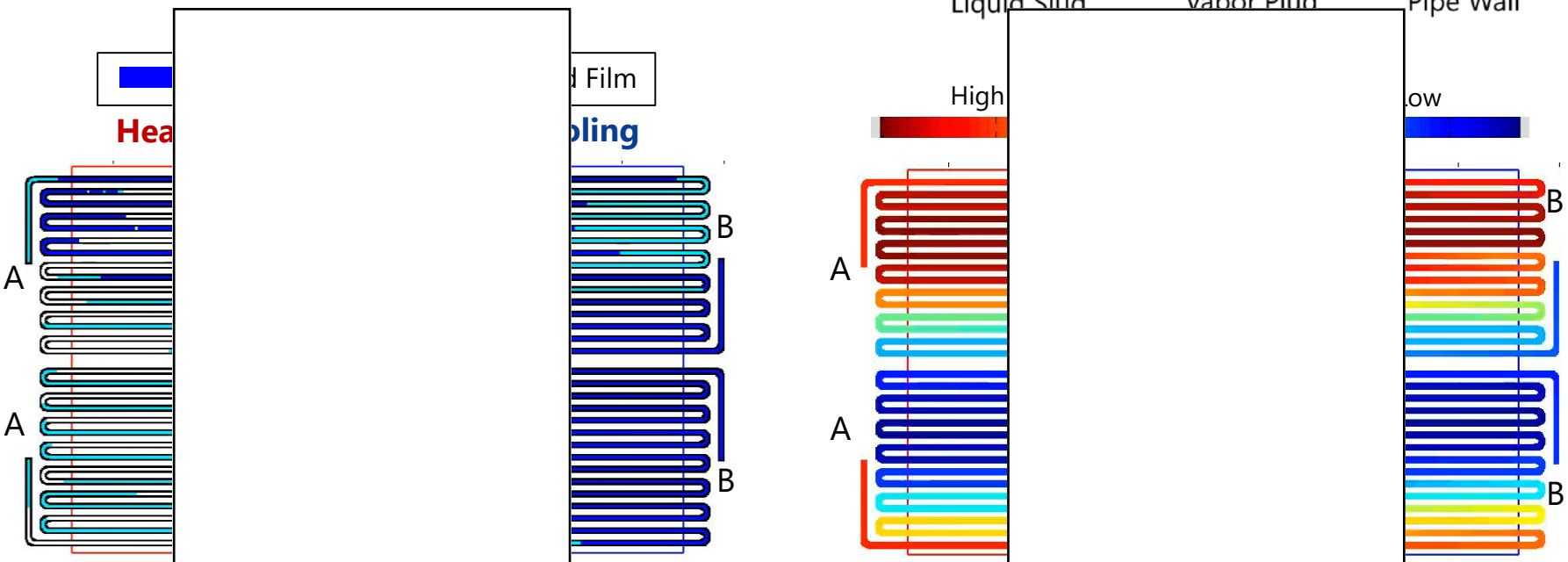
Passive Two-Phase Thermal Control

Numerical Simulation of Oscillating Heat Pipes



Assumptions

- Flow regime is slug flow, uniform along radial direction
- Temperature and pressure within each vapor segment is uniform
- Thickness of liquid film surrounding vapor is constant

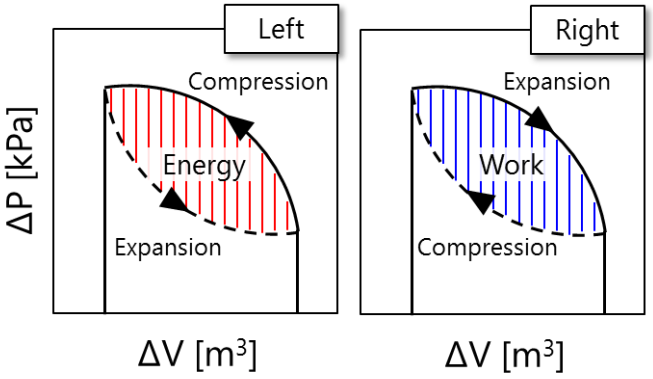


al Investigation—PI, Takur

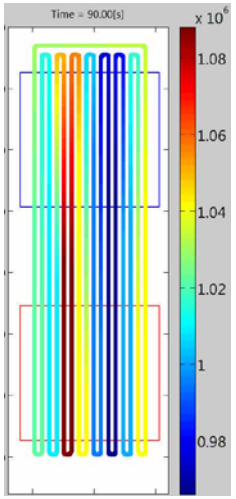
Passive Two-Phase Thermal Control

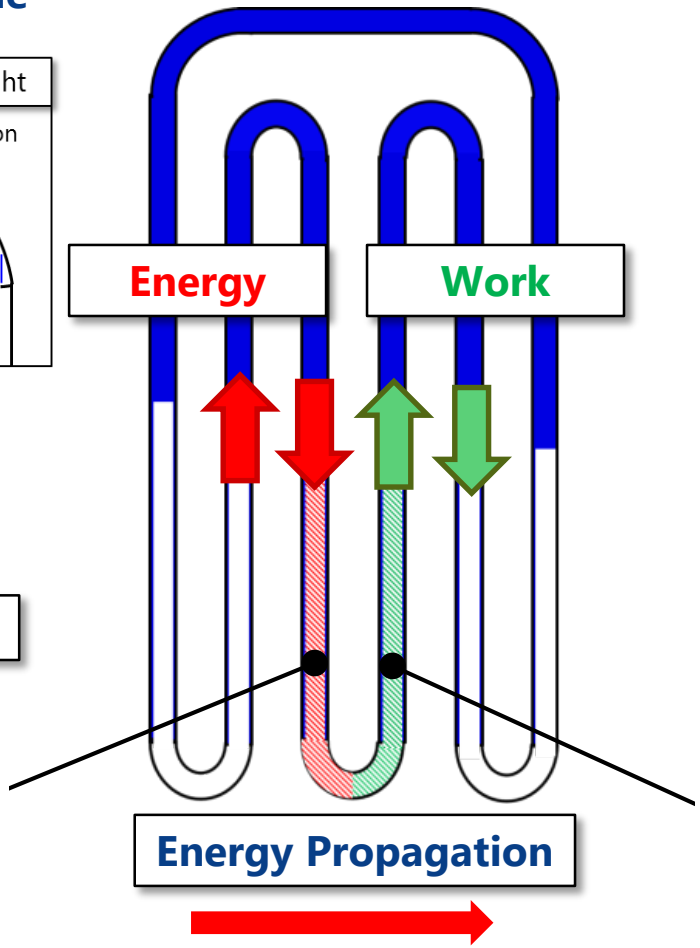
Research in Oscillating Heat Pipe Phenomena

Direction of Thermal Cycle

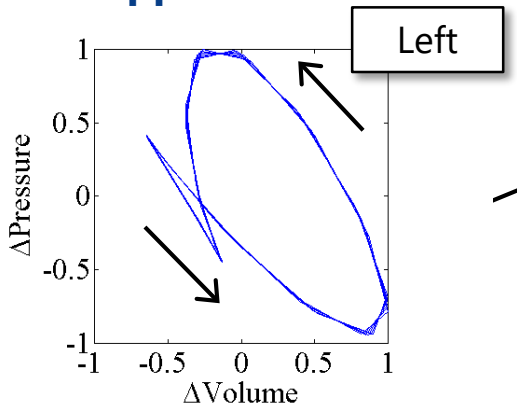


Pressure Field in OHP

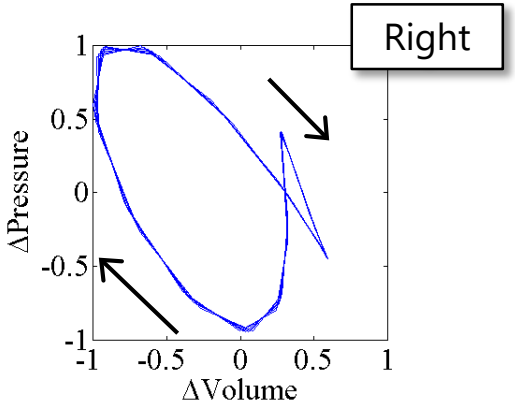




Upper Channel



Lower Channel



Obtaining Energy

Direction of Pressure Propagation

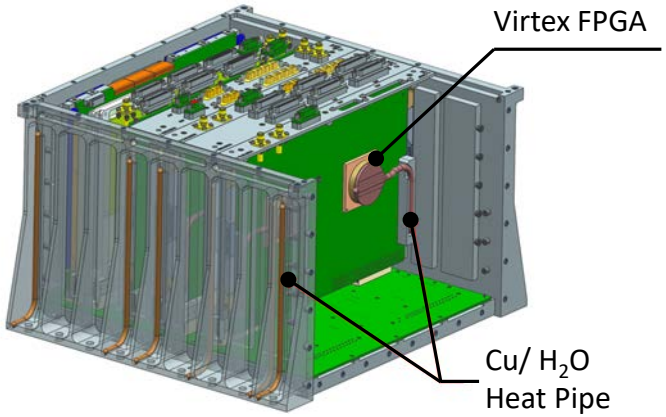
Work to Next Liquid

Passive Two-Phase Thermal Control

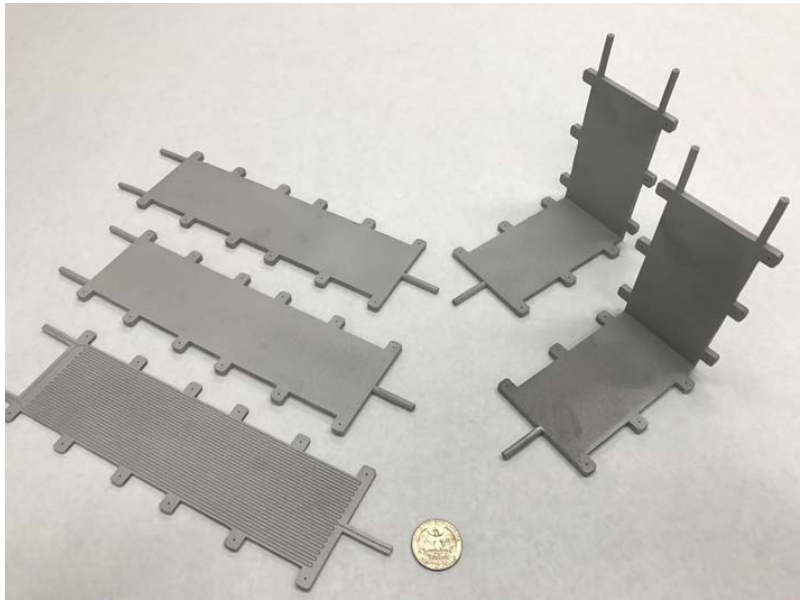
Oscillating Heat Pipe Application Prototyping

Multi-Functional OHP System

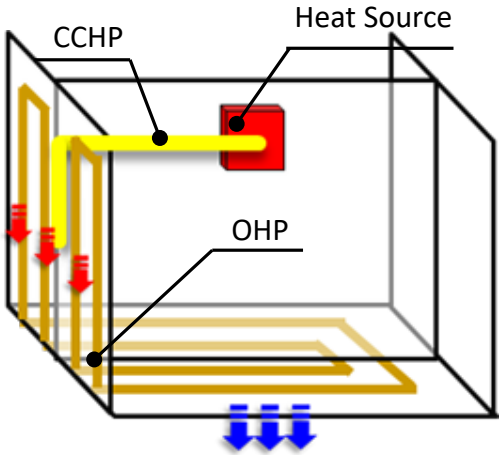
- 3D printed OHPs
- Integrated thermal-structural chassis with 2D heat transfer
- Capable of handling fluxes of 100's W/cm^2 due to evaporation and forced convection



Current electronic chassis TCS uses Cu/H2O CCHPs



3D Printed aluminum OHPs



OHPs integrated directly in the structure permit more efficient heat transfer

JPL Internal Investigation—PI, Takuro Daimaru

Single-Phase Pumped Fluid Loop Developments

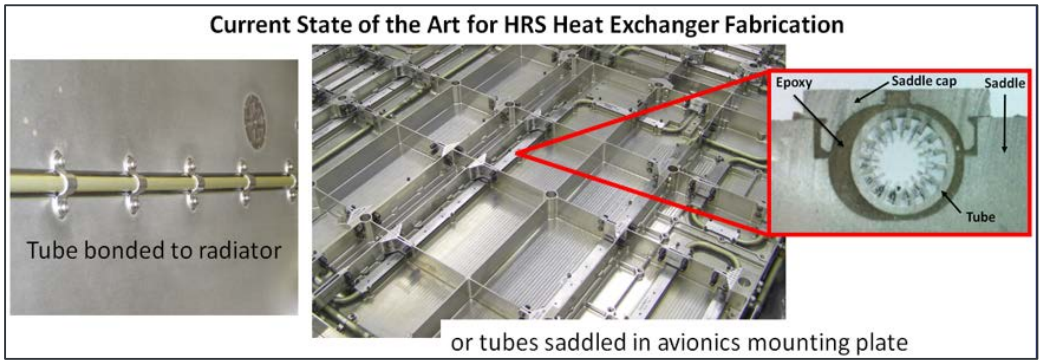
A.J. Mastropietro

Jet Propulsion Laboratory
California Institute of Technology

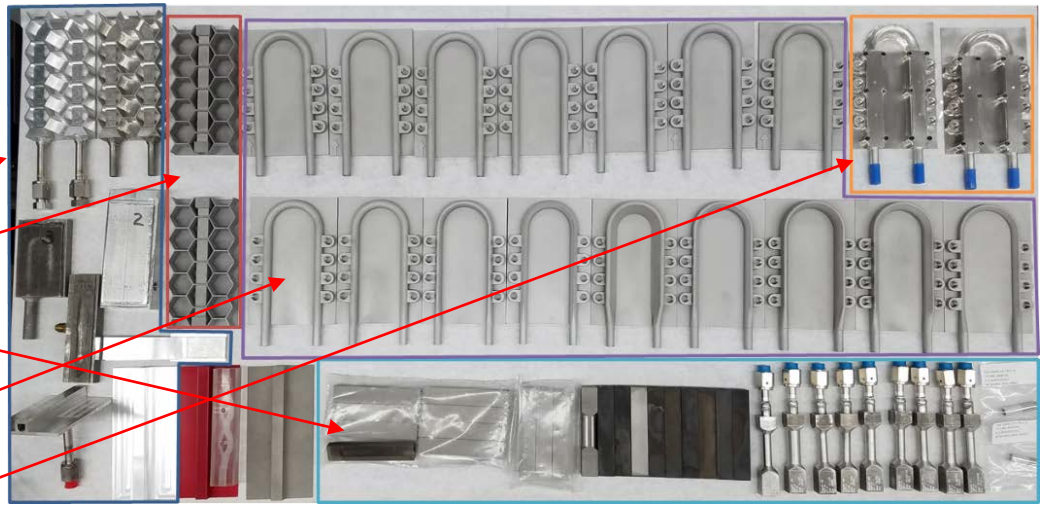
Single-Phase Fluid Loop Technology Advancement

3-D Printed Aluminum Cold Plates for Single-Phase Fluid Systems

- Desire to explore alternate ways of producing complicated HX parts using additive manufacturing instead of traditional tube on plate designs:
- Direct Metal Laser Sintering (DMLS)
- Ultrasonic Additive Manufacturing (UAM)
- Reduce cost and lead time for manufacturing
- Minimize part count, and mass while increasing reliability, and enhancing thermal performance



- ✓ Ultrasonic Additively Manufactured (UAM) HX and burst specimens.
- ✓ Investment cast demonstration HX with integrated isogrids.
- ✓ Titanium, 316 stainless steel, and $AlSi_{10}Mg$ burst pressure specimens.
- ✓ $AlSi_{10}Mg$ flow test articles with varying interior and external geometries.
- ✓ Traditionally manufactured (machined & epoxied) HX plates.



JPL Internal Investigation—A.J. Mastropietro, PI

Single-Phase Fluid Loop Technology Advancement

3-D Printed Aluminum Cold Plates—Test Articles

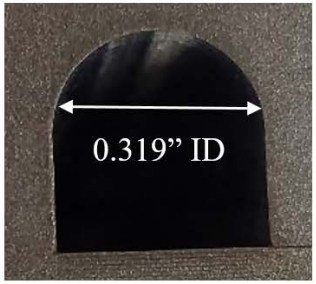
Five test samples were used:

1. Epoxied smooth tubing
2. Epoxied finned tubing
3. UAM U-shaped tubing

(Al 6061, K = 159 W/m-K)

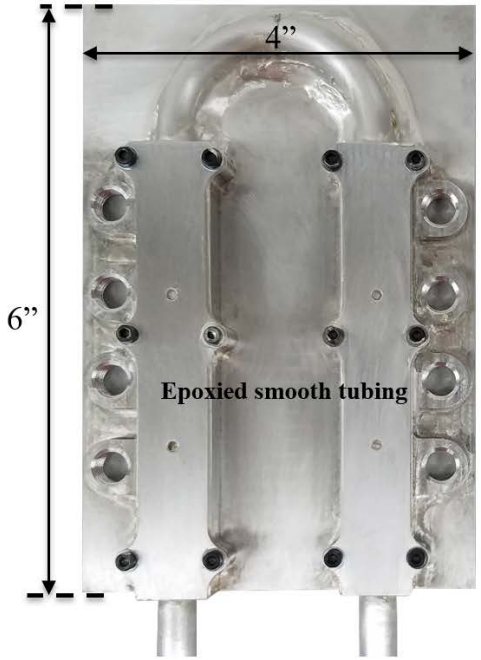
4. DMLS smooth tubing
5. DMLS spiral tubing

($AlSi_{10}Mg$, K = 125 W/m-K)



U-shaped UAM

- 0.028" Wall Thickness
- 0.12" Web Thickness

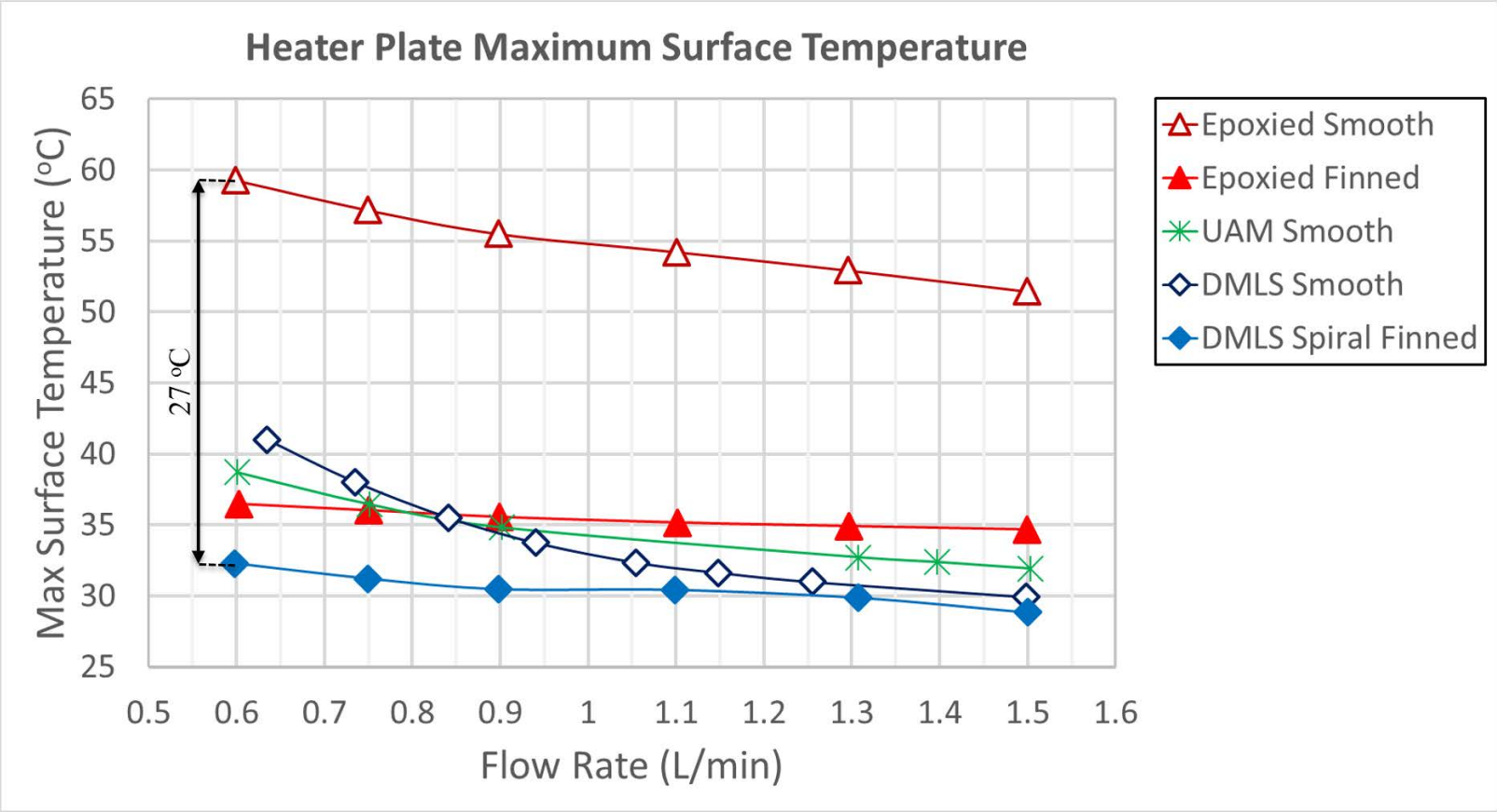


JPL Internal Investigation—A.J. Mastropietro, PI

Single-Phase Fluid Loop Technology Advancement

3-D Printed Aluminum Cold Plates—Test Results (1/2)

- 52 Watts
- FC-72 working fluid

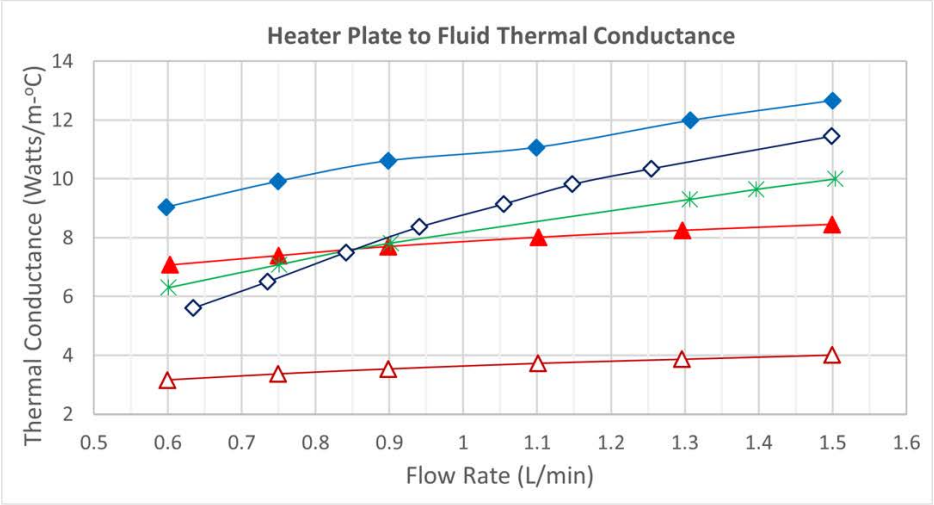


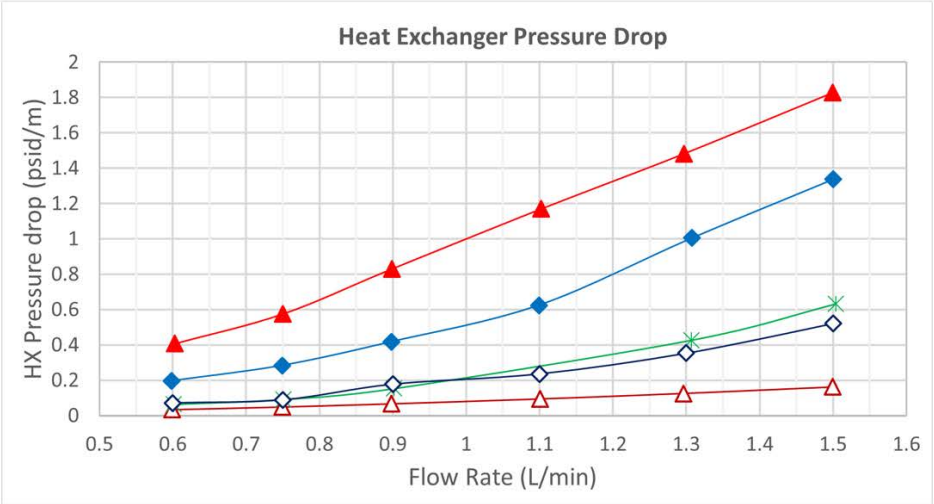
JPL Internal Investigation—A.J. Mastropietro, PI

Single-Phase Fluid Loop Technology Advancement

3-D Printed Aluminum Cold Plates—Test Results (2/2)

- 52 Watts
- FC-72 working fluid





JPL Internal Investigation—A.J. Mastropietro, PI

Cryogenics Systems Engineering Group

(Courtesy of Jose Rodriguez, JPL Cryogenic Systems Engineering Group Supervisor)

Engineering & Research Capabilities

Microcoolers for space and Mars landed missions. Challenge: Low Power Efficiency, High Cost and Poor Reliability. POC: Drs. Jose I. Rodriguez, Dean Johnson, Ian McKinley

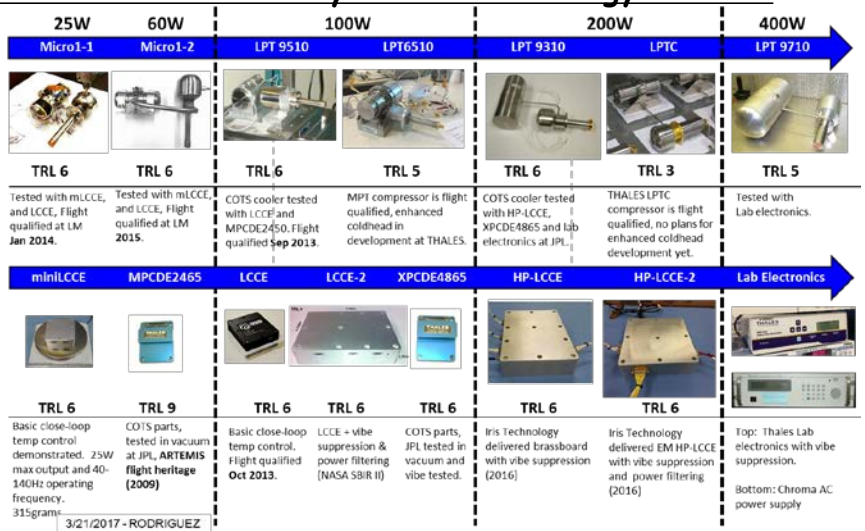
Architecting multi-stage passive cooling systems for LEO and outer planetary missions. Challenge: Solar Power Missions with Large Solar Arrays, Extreme Environments, Materials, Reliability and High Cost. POC: Dr. Jose I. Rodriguez, Doug Bolton, Perry Ramsey

Pulse tube cryocooler technology advancements for cooling to 40K. Challenge: Complex Pulse Tube Designs, Thermodynamic Modelling, CFD Analysis, Materials. POC: Dr. Dean Johnson

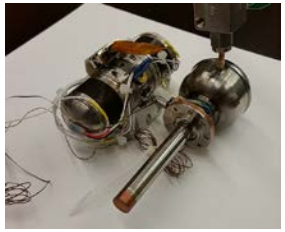
Cryogenic technology development and infusion on future remote sensing science instruments. Challenge: High Development Costs, TRL6 High Qualification Costs, Materials and Reliability. POC: Drs. Jose I. Rodriguez, Perry Ramsey, Ian McKinley

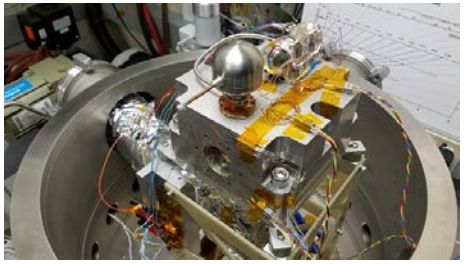
Flight qualification and characterization testing of cryocooler systems for space flight instruments. Challenge: High Cost and Maintenance of Special Test Equipment and Flight Certified Facilities. POC: Dr. Dean Johnson

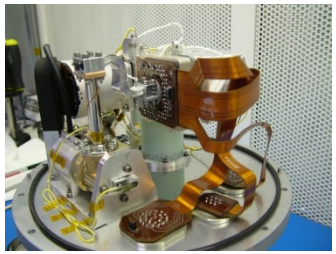
Low Cost Pulse Tube Cryocooler Technology- Status



Microcoolers for Space and Mars Landed Missions

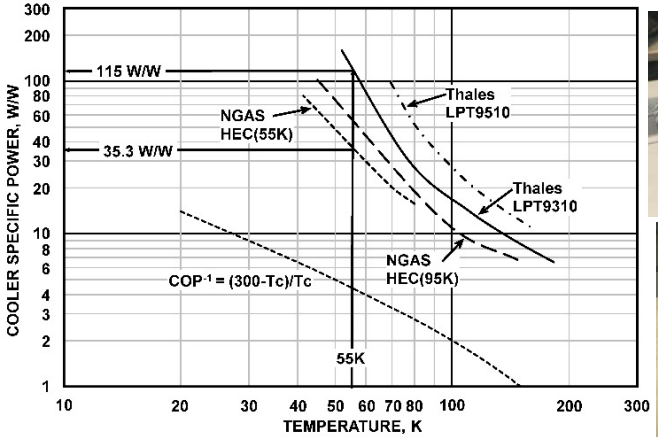


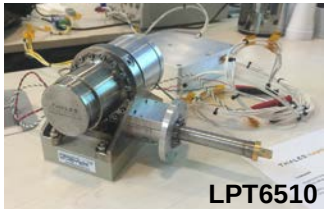


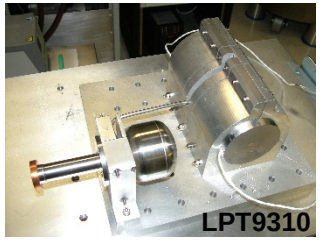


Small form factor and less than 500g microcoolers enable efficient cryogenic cooling for CubeSats and compact science instruments

Characterization Testing of Cooler technologies







Targeting strategic improvements to increase thermodynamic efficiency

Cryogenics Systems Engineering Group

Long-life Space Cryocooler Operating Experience

	Cooler / Mission	Hours/Unit	Comments
	Air Liquide Turbo Brayton (ISS MELFI 190K)	85,600	Turn on 7/06, Ongoing, No degradation
	Ball Aerospace Stirling		
	HIRDLS (60K 1-stage Stirling)	83,800	8/04 thru 3/14, Instr. failed 2008; Data turned off 3/14
	TIRS cooler (35K two-stage Stirling)	27,900	Turn on 3/6/13, Ongoing, No degradation
	Creare Turbo Brayton (77K NICMOS)	57,000	3/02 thru 10/09, Off, Coupling to Load failed
	Fujitsu Stirling (ASTER 80K TIR system)	141,700	Turn on 3/00, Ongoing, No degradation
	JPL Sorption (PLANCK 18K JT (Prime & Bkup))	27,500	FM1 (8/10-10/13 EOM); FM2 failed at 10,500 h
	Mitsubishi Stirling (ASTER 77K SWIR system)	137,500	Turn on 3/00, Ongoing, Load off at 71,000 h
	NGAS (TRW) Coolers		
	CX (150K Mini PT (2 units))	161,600	Turn on 2/98, Ongoing, No degradation
	HTSSE-2 (80K mini Stirling)	24,000	3/99 thru 3/02, Mission End, No degrad.
	MTI (60K 6020 10cc PT)	141,600	Turn on 3/00, Ongoing, No degradation
	Hyperion (110K Mini PT)	133,600	Turn on 12/00, Ongoing, No degradation
	SABER on TIMED (75K Mini PT)	129,600	Turn on 1/02, Ongoing, No degradation
> 14 yrs →	AIRS (55K 10cc PT (2 units))	121,600	Turn on 6/02, Ongoing, No degradation
> 12 yrs →	TES (60K 10cc PT (2 units))	102,600	Turn on 8/04, Ongoing, No degradation
	JAMI (65K HEC PT (2 units))	91,000	4/05 to 12/15, Mission End, No degrad.
	GOSAT/IBUKI (60K HEC PT)	63,300	Turn on 2/09, Ongoing, No degradation
	STSS (Mini PT (4 units))	52,800	Turn on 4/10, Ongoing, No degradation
> 2 yrs →	OCO-2 (HEC PT)	14,900	Turn on 8/14, Ongoing, No degradation
	Himawari-8 (65K HEC PT (2 units))	12,800	Turn on 12/14, Ongoing, No degradation
	Oxford/BAe/MMS/Astrium/Airbus Stirling		
	ISAMS (80 K Oxford/RAL)	15,800	10/91 thru 7/92, Instrument failed
	HTSSE-2 (80K BAe)	24,000	3/99 thru 3/02, Mission End, No degrad.
	MOPITT (50-80K BAe (2 units))	138,600	Turn on 3/00, lost one disp. at 10,300 h
	ODIN (50-80K Astrium (1 unit))	132,600	Turn on 3/01, Ongoing, No degradation
	AATSR on ERS-1 (50-80K Astrium (2 units))	88,200	3/02 to 4/12, No Degrad, Satellite failed
	MIPAS on ERS-1 (50-80K Astrium (2 units))	88,200	3/02 to 4/12, No Degrad, Satellite failed
	INTEGRAL (50-80K Astrium (4 units))	118,700	Turn on 10/02, Ongoing, No degradation
	Helios 2A (50-80K Astrium (2 units))	96,600	Turn on 4/05, Ongoing, No degradation
	Helios 2B (50-80K Astrium (2 units))	58,800	Turn on 4/10, Ongoing, No degradation
	SLSTR (50-80K Airbus (2 units))	1,400	Turn on 3/16, Ongoing, No degradation
	Planck (4K JT using 2 Astrium Comp.)	38,500	5/09 thru 10/13, Mission End, No Degrad.
	Raytheon ISSC Stirling (STSS (2 units))	52,800	Turn on 4/10, Ongoing, No degradation
	Rutherford Appleton Lab (RAL)		
	ATSR 1 on ERS-1 (80K Integral Stirling)	75,300	7/91 thru 3/00, Satellite failed
	ATSR 2 on ERS-2 (80K Integral Stirling)	112,000	4/95 thru 2/08, Instrument failed
	Sumitomo Stirling Coolers		
	Suzaku (100K 1-stg)	59,300	7/05 thru 4/12, Mission End, No degradation
	Akari (20K 2-stg (2 units))	39,000	2/06 to 11/11 EOM, 1 Degr., 2nd failed at 13 kh
	Kaguya GRS (70K 1-stg)	14,600	10/07 thru 6/09, Mission End, No degradation
	JEM/SMILES on ISS (4.5K JT)	4,500	Turn on 10/09, Could not restart at 4,500 h
	Sunpower Stirling		
	RHESSI (75K Cryotel)	124,600	Turn on 2/02, Ongoing, Modest degradation
	CHIRP (CryoTel CT-F)	19,700	9/11 to 12/13, Mission End, No degradation

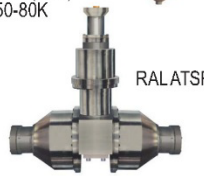
Creare NICMOS

NGAS (TRW) Mini PT

NGAS (TRW) AIRS PT

NGAS (TRW) HEC PT

Astrium (BAe) 50-80K


RAL ATSR

Sunpower RHESSI

Ross 05/18/16

Cryogenics Systems Engineering Group

(Courtesy of Jose Rodriguez, JPL Cryogenic Systems Engineering Group Supervisor)

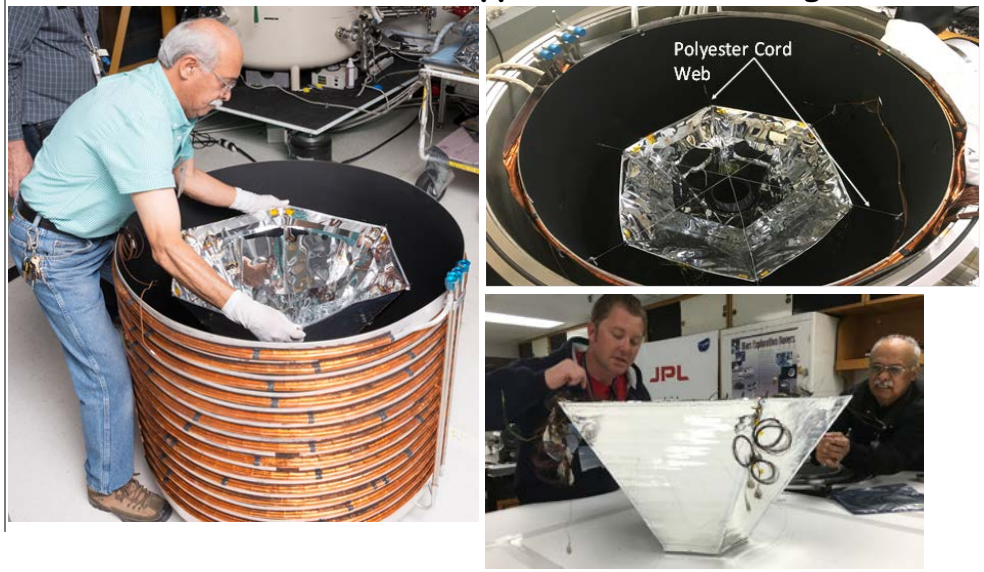
Cryocooler Performance Characterization Testing

MISE Cryocooler Life-Test Laboratory

Flight Cryocooler Testing Lab

Orbiting Carbon Observatory-2 (OCO-2): Mission will collect precise global measurements of carbon dioxide (CO_2) in the Earth's atmosphere utilizing a single instrument with 3 high-resolution, grating spectrometers (0.765 µm O_2 A-band, 1.61 µm "weak" CO_2 band, and 2.06 µm "strong" CO_2 band). Single-stage High Efficiency Cooler (HEC) cools all three focal planes to 120K. Variable conductance heat pipes are used to transport the cooler waste heat to the outboard radiators.

SPHEREx 1/4 Scale Prototype Thermal Testing



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