JPL Advanced Thermal Control Technology Roadmap - 2012

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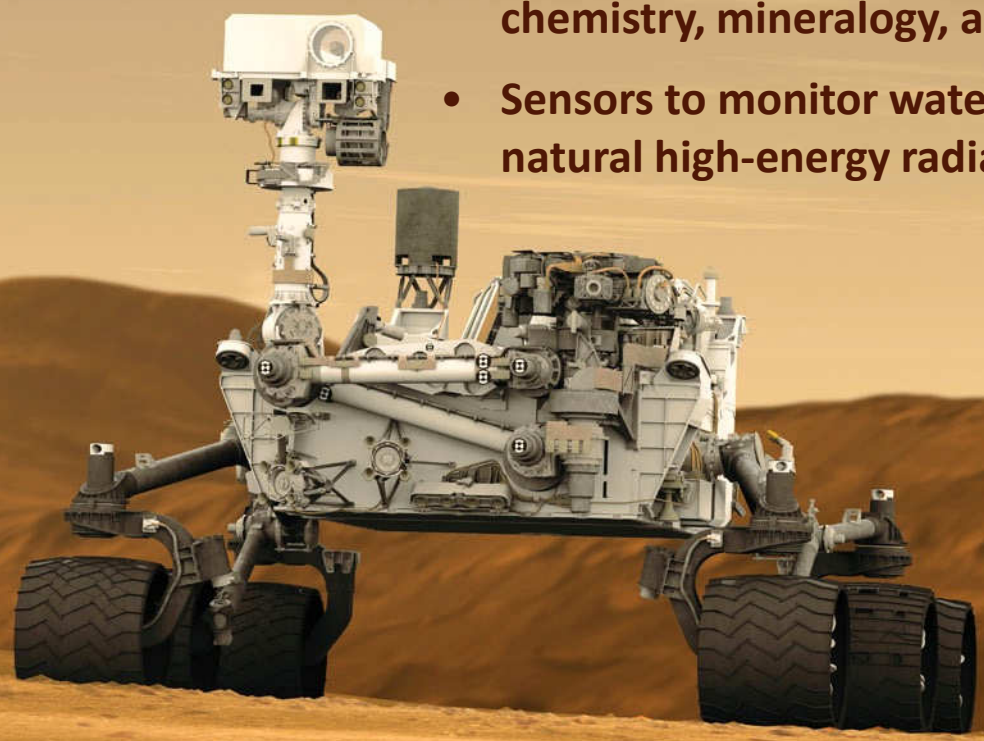
Curiosity's Capabilities

A Robotic Field Geologist

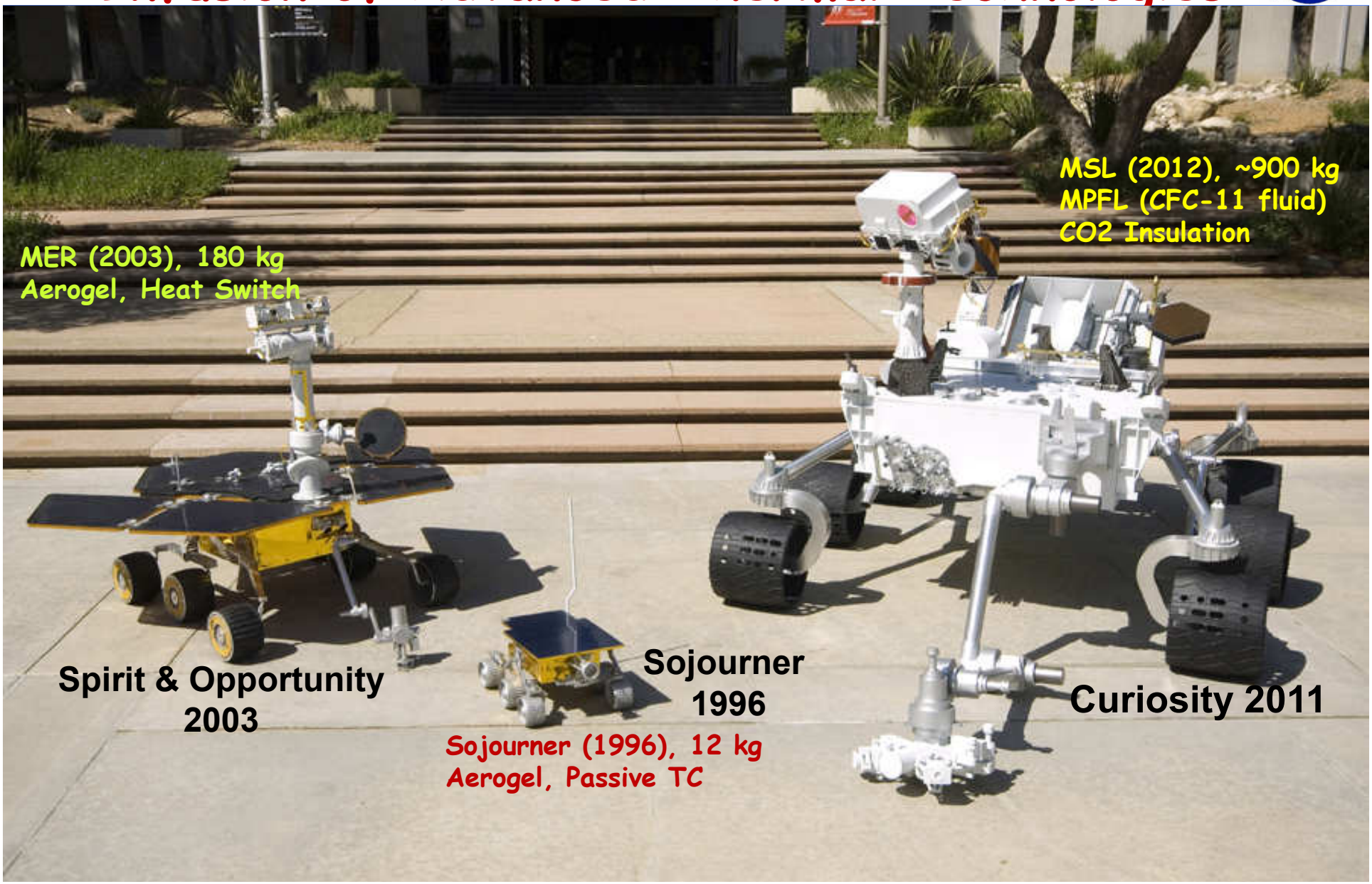
- Long life, ability to traverse many miles over rocky terrain
- Landscape and hand-lens imaging
- Ability to survey composition of bedrock and regolith

A Mobile Geochemical and Environmental Laboratory

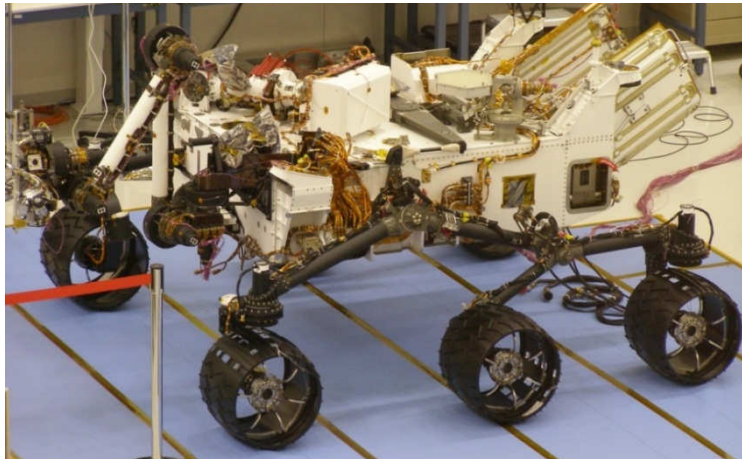
- Ability to acquire and process dozens of rock and soil samples
- Instruments that analyze samples for chemistry, mineralogy, and organics
- Sensors to monitor water, weather, and natural high-energy radiation



Rover Family Portrait –
Infusion of Advanced Thermal Technologies



Mars Science Laboratory Rover



Thermal Challenges

- Large thermal loads, ~2 kWt
- Long life on Mars, 2 Earth years
- MMRTG thermal management during launch, cruise, EDL, & Martian surface
- High heat flux and tight temperature requirements of science instruments and engineering equipment

Thermal Architecture

- MPFL based thermal design for cruise & surface ops
- CFC-11 chosen to meet -100 C to +100 C fluid loop temperature requirement
- Passive thermal valves modulate flow through radiator and heat exchangers

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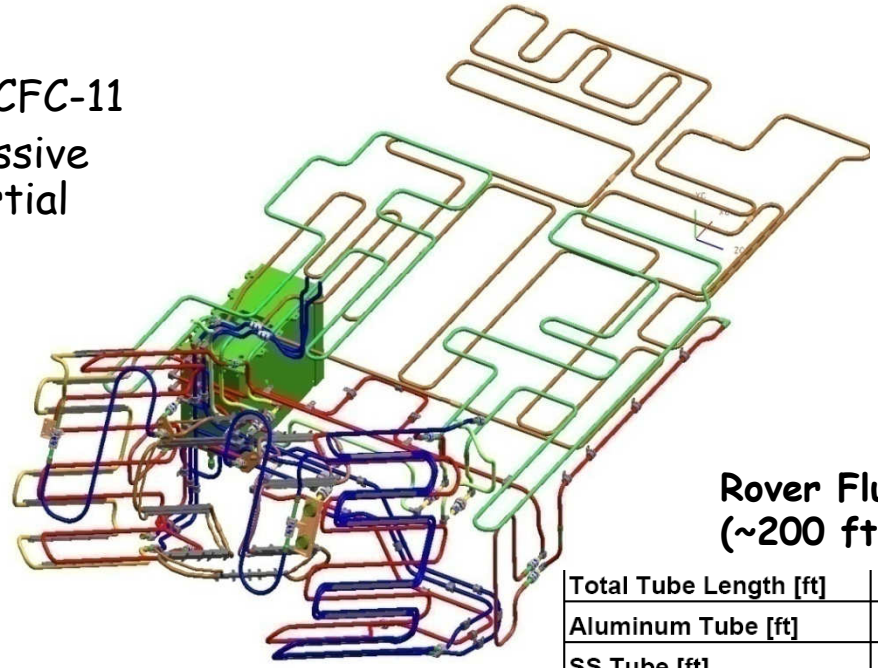
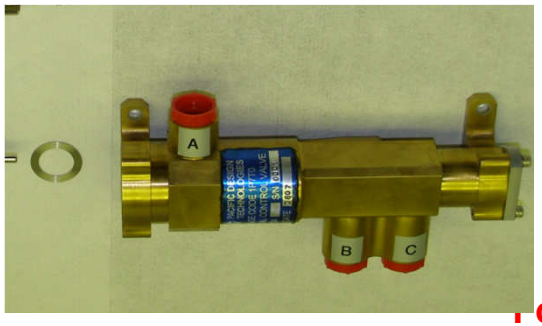
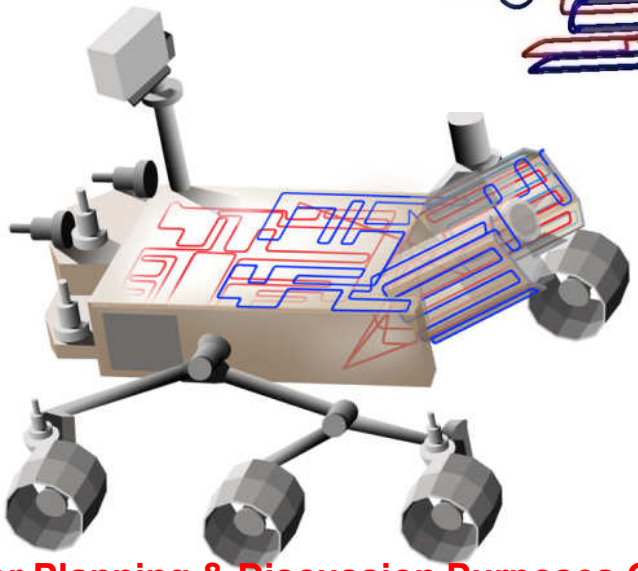
MSL Focused Technology Development

- **Pump Life Testing:** 20 C to 120 C
- **Long-term Chemical tests:** >100 C in CFC-11
- **Thermal valves & Mech. Fittings:** Passive flow valves, OmniSafe VCR joints, inertial welds, flex tubes
- **Working fluids:**
  - CFC-11, Galden HT-170







Rover Fluid Loop (~200 ft tubes)

Total Tube Length [ft]	188
Aluminum Tube [ft]	149
SS Tube [ft]	28
Flex Line [ft]	11
Flex Bellows	30
Bi-Metal Joints	18
Aluminum Unions	12
Micro Elbows	47
Ominsafe Glands	42
Other SS Components	0
SS Orbital Welds	155
Aluminum Hand Welds	42
SS-AL Inertial Welds	18
Mechanical Fittings	21

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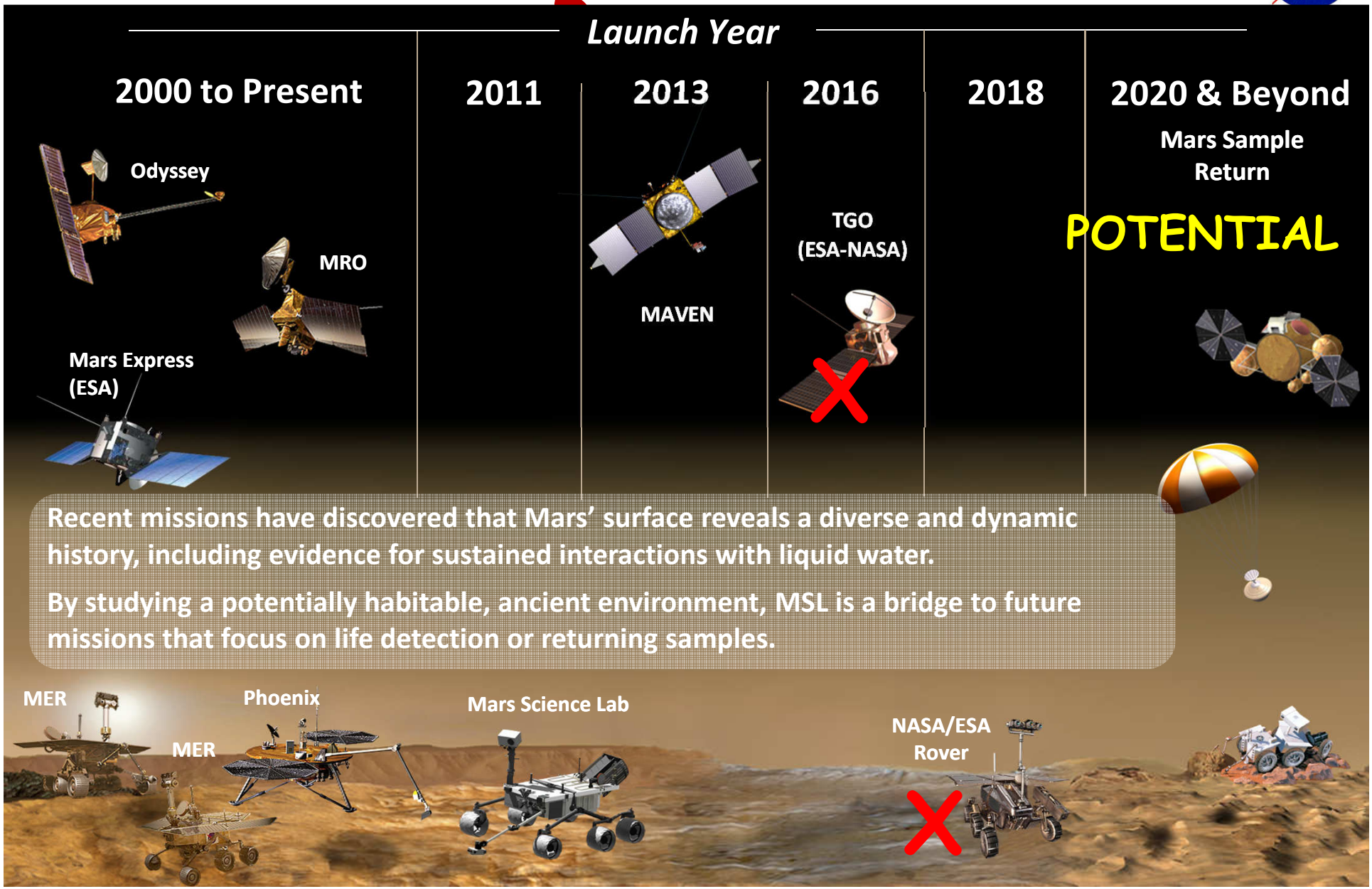
MSL Rover Thermal Team

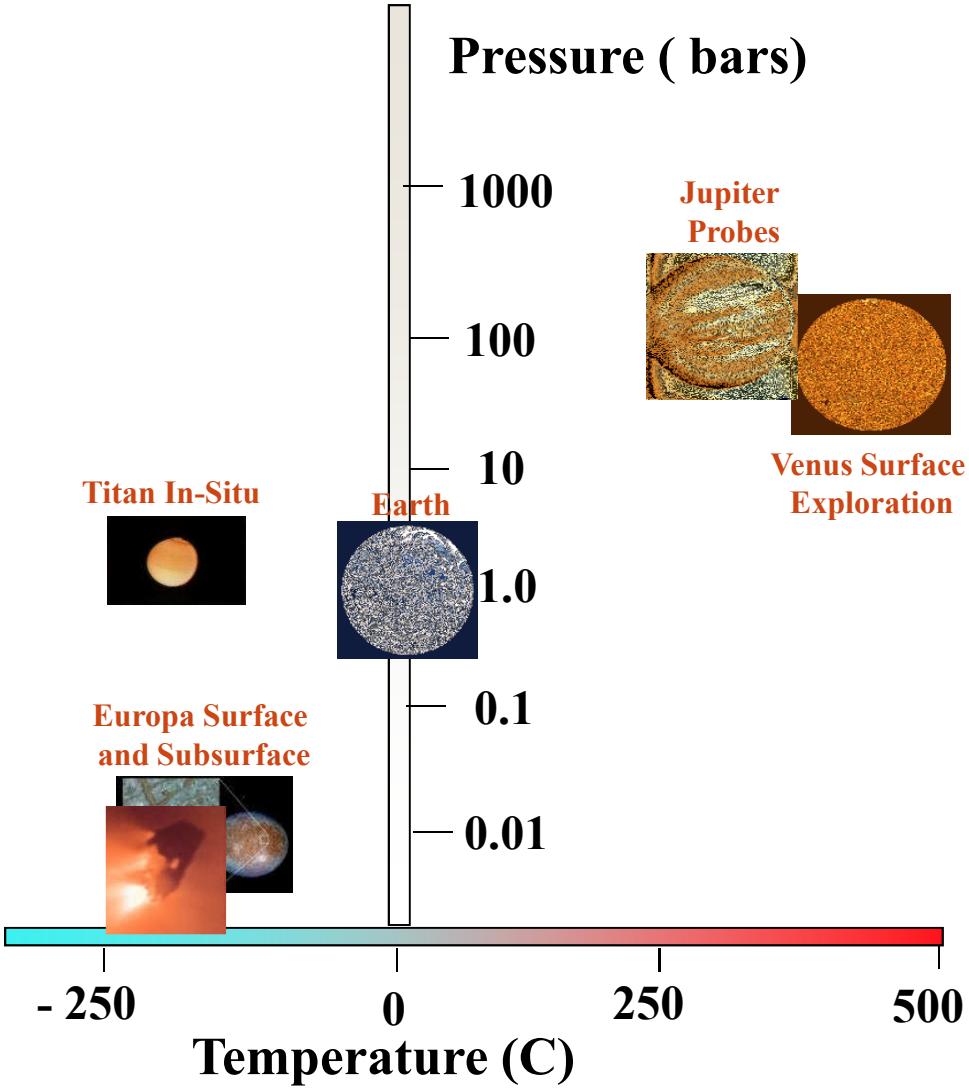
NASA's Mars Exploration



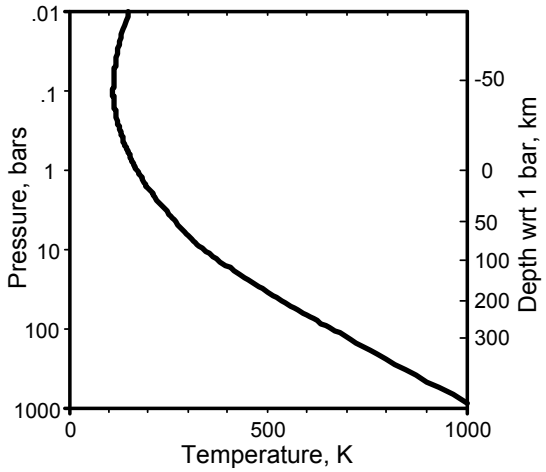
Advanced Thermal Technologies Roadmap

- Thermal Control Challenges of JPL/NASA Robotic Space Science Missions
- Future NASA Space Science Instruments and Missions
- JPL Thermal Control Technology Roadmap
  - Mission Specific Focused Technologies
  - Advanced Thermal & Cryogenic Technologies
- Summary

Planetary Extreme Environment



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



Jupiter Pressure Plot

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Spacecraft Thermal Control Challenges

- **Thermal and physical environments of the target space**
  - **Temperatures, pressures, radiation, particles, dust etc**
    - Extreme temperatures – Lunar, Mars, Titan, Venus
    - Extreme Pressures - Venus, Jupiter
    - Dust – Lunar surface, Mars surface etc
- **Temperature requirements of instruments & equipment**
  - **Temperature limits, Temperature stability, Temperature gradients**
    - Battery (-20 to 40 C), prop tanks (10 to 40 C), sensors (<-80 C)
    - Optical benches & reflectors (<.1 C/m), less than 100 m K/min
- **Large heat loads and high heat fluxes**
  - **MMRTG (2000 Watts), fluxes of 20 to 50 W/cm2**
- **Spacecraft Configuration**
  - **Orbiter, lander, rover, deployable/inflatable structures**

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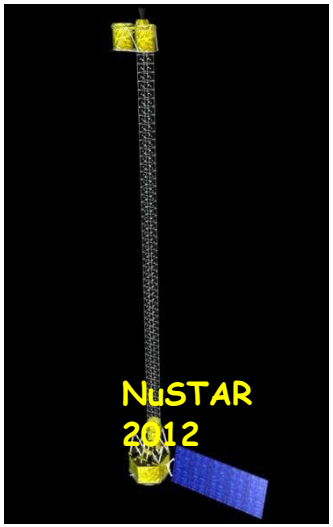
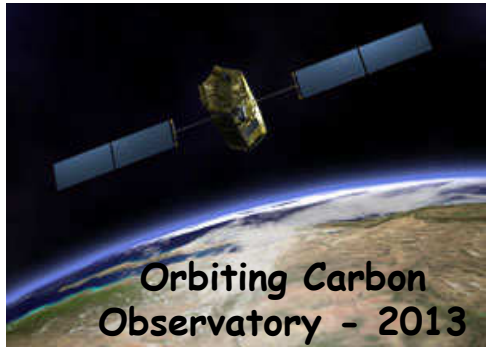
Active Spacecraft Across the Solar System (and beyond)

2012 Launches & Future Missions





Future Missions Proposed

2016 and later ???

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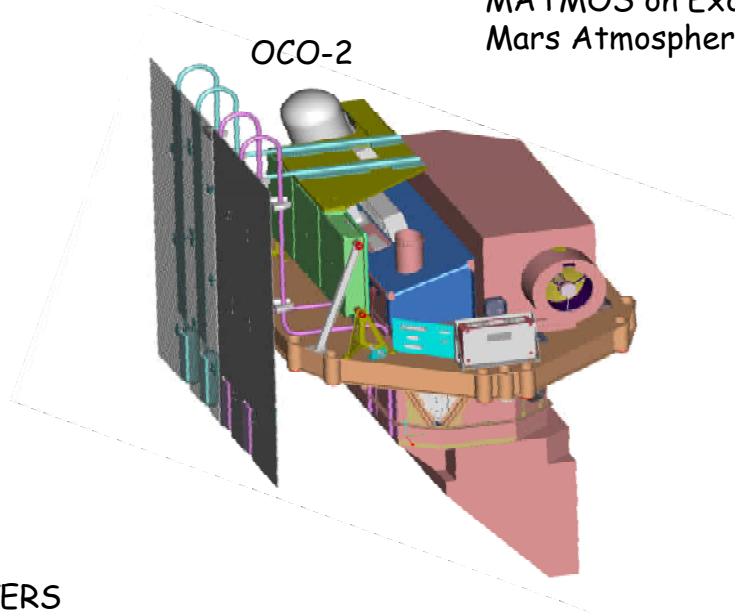
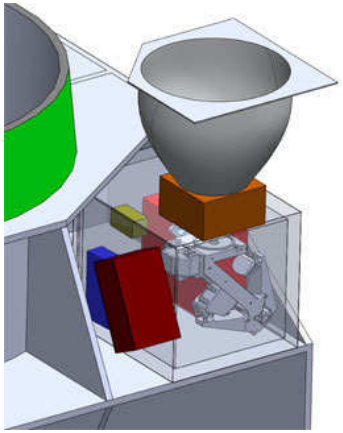
Future Instruments under Development

MIRI on JWST

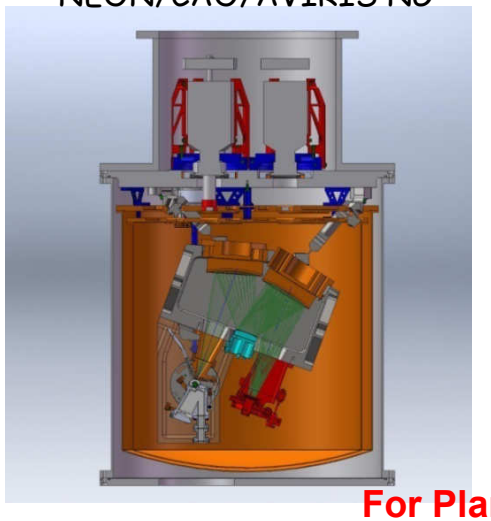
OCO-2



MATMOS on ExoMars/Trace Gas Orbiter
Mars Atmospheric Trace Occultation Spectrometer



AIRBORNE SPECTROMETERS
NEON/CAO/AVIRIS NG



EMCS on ExoMars/Trace
Gas Orbiter
ExoMars Climate Sounder

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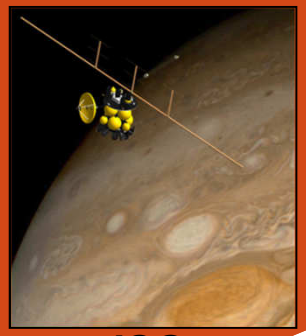
Conceptual Design of Potential Sequence of Flagship Missions

Water, organics, and prebiotic chemistry… the evolution of habitable environments

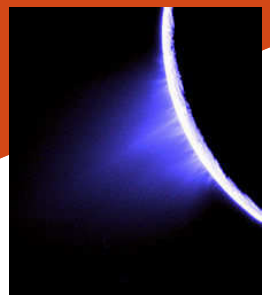
Europa



JSO

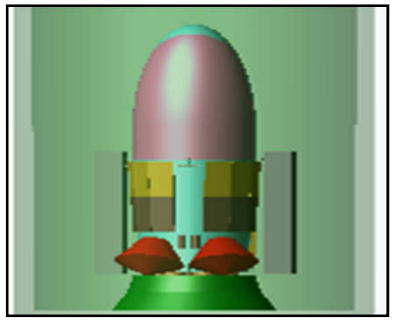
MSR

Titan

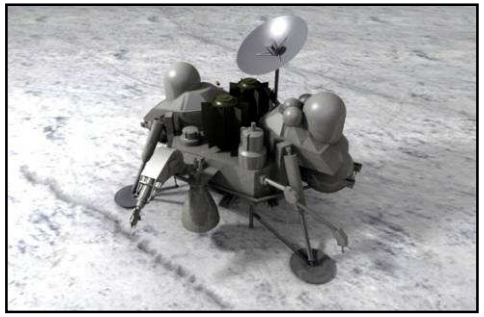


Enceladus

Venus Explorer



Neptune/Triton Orbiter/Probes



Europa Astrobiology Laboratory

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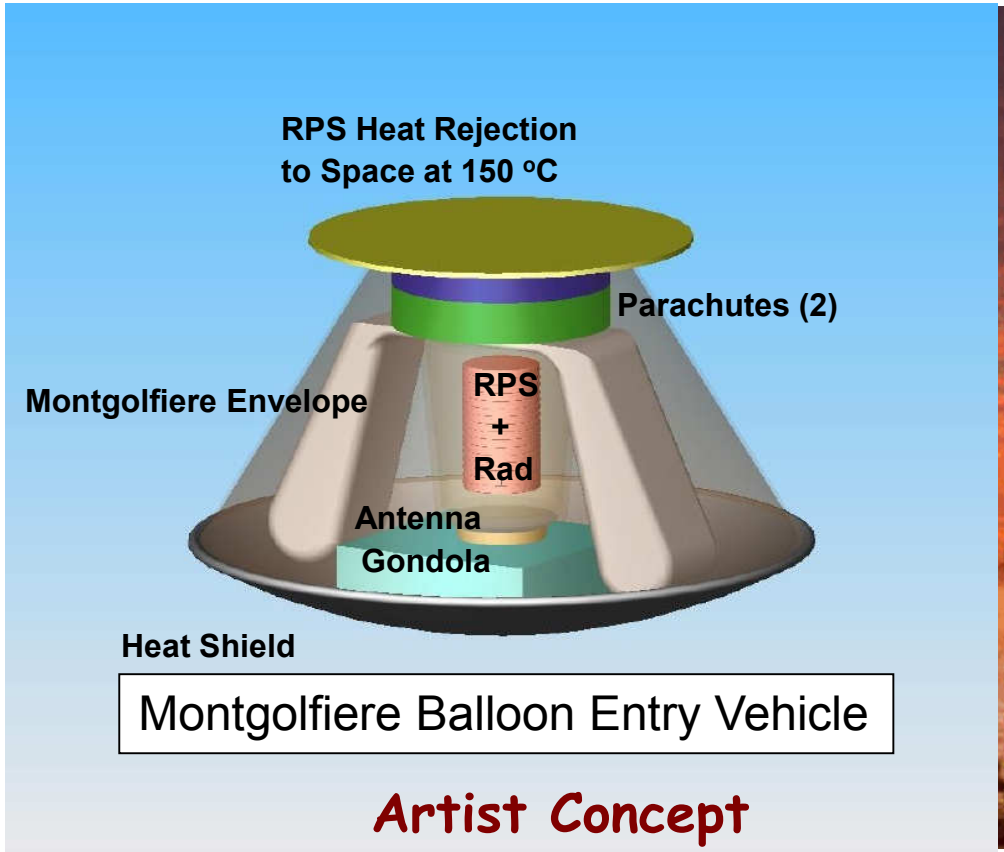
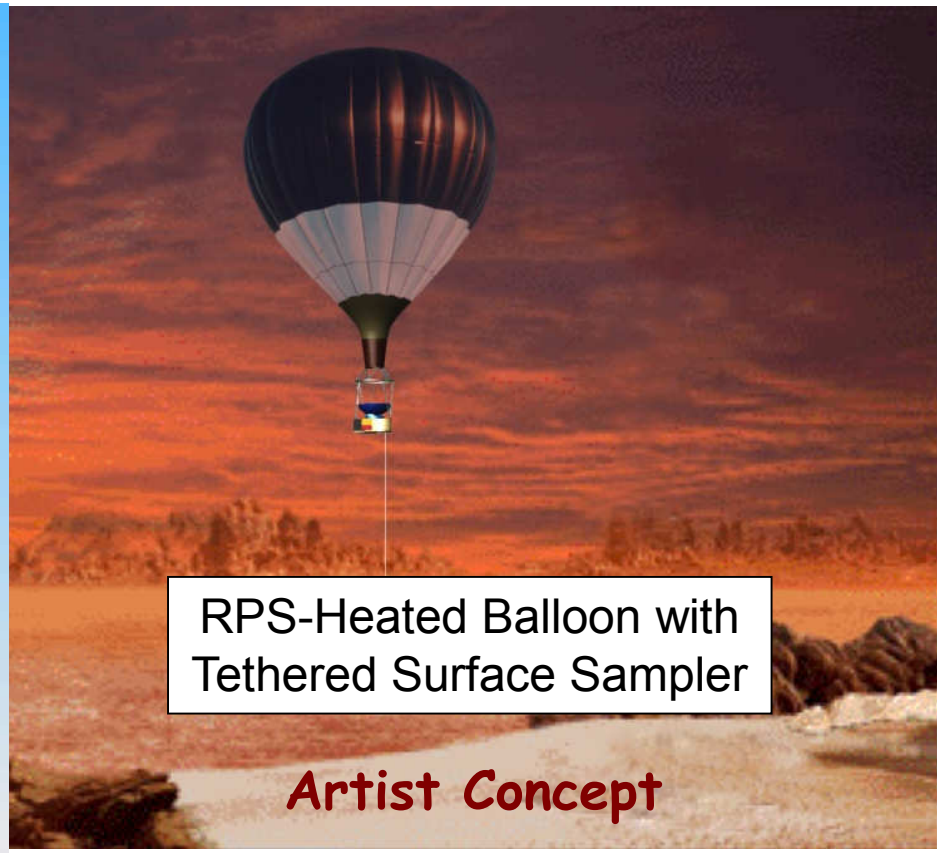
Conceptual Design of Potential Future Titan Planetary Explorer





A packed balloon heated by RPS waste heat would be packaged in an entry vehicle, filled with cold ambient nitrogen gas, and could be controlled to float at any altitude between the Titan surface and about 10-km altitude.

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NASA Human Exploration Program – Beyond Earth Missions

Artist Concept

Thermal Control Challenges

- Thermal control of human-rated and robotic missions near-Earth missions
- Challenging thermal environment and thermal control requirements (dust, extreme cold/hot environment, etc)
- Thermal management of large thermal loads (both equipment and human); Passive and active thermal control technologies for heat collection, rejection, and transport

Thermal Technologies Investigated

- Lightweight Radiator
- Evaporative Heat Sinks
- Contaminant insensitive sublimator
- TCS fluids for pumped loops
- PCM phase change thermal storage

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Mission Focused Technologies

- Earth – Passive and active cooling technologies, thermal-powered autonomous underwater vehicles (AUVs)
- Mars – Mechanically Pumped Fluid Loop
- Venus – Pressure vessel, Thermal storage, High temp insulation
- Jupiter – High pressure/high temperature technologies
- Titan – Low temperature thermal control technologies and RPS-heated baloons
- Moon – Variable Heat Rejection Radiators
- Europa – Low temp. & radiation resistant thermal control
- Comets – Low temperature technologies

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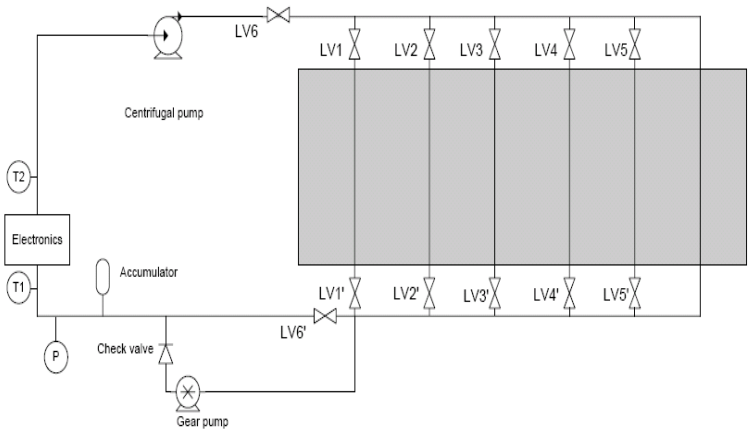
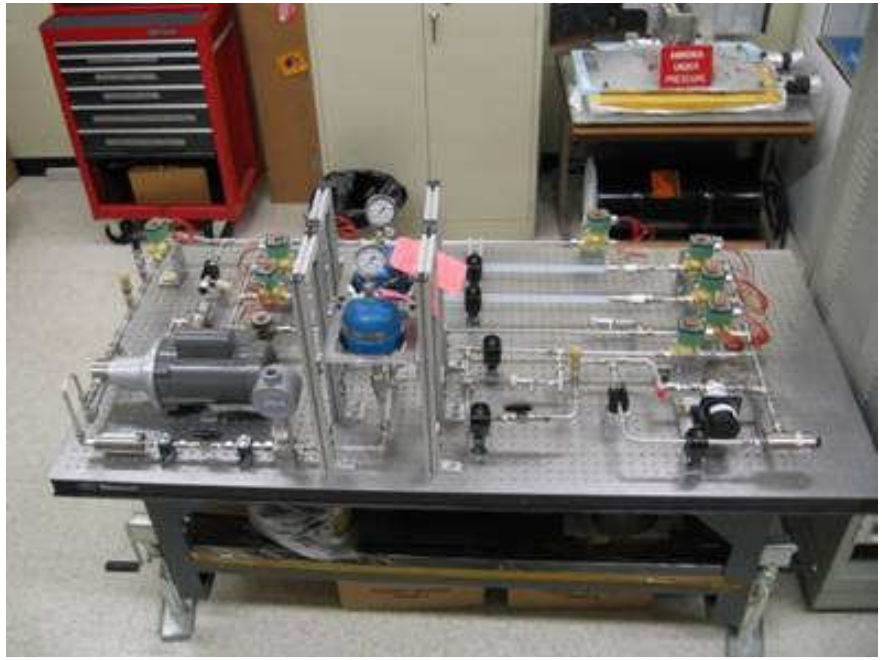
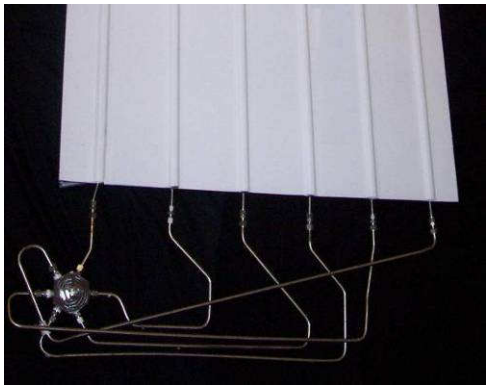
Thermal Control Technologies for Exploration



Variable Heat Rejection Radiator (Digital Radiator)

Digital Radiator Test Set up (JPL)





Stagnation Radiator (Apollo Mission)

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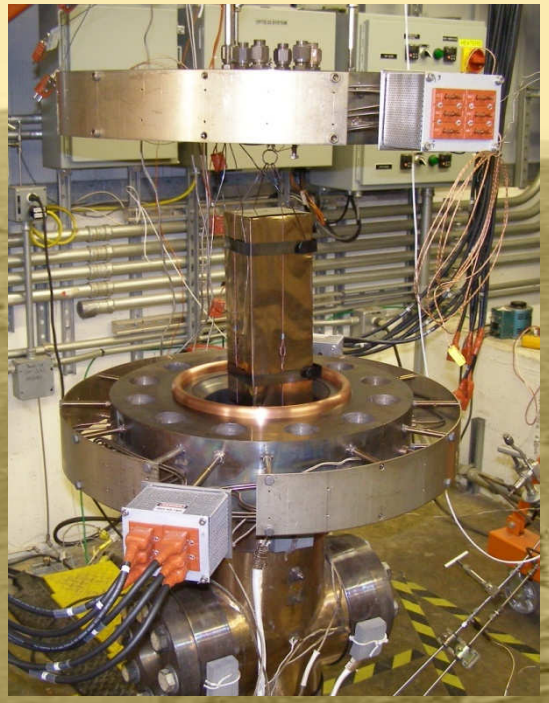
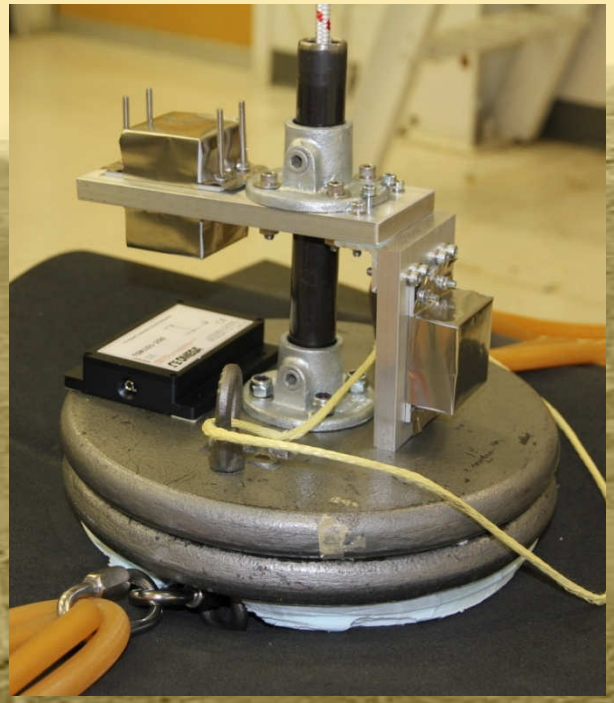
Thermal Technologies for Future Venus Lander

- Develop a thermal control system enabling a Venus Lander Mission to survive for ~ 4 hours on surface at 92 bars and ~470°C
  - Survive 2 times longer than previous missions with passive thermal control
  - Determine thermal and mechanical properties of external insulation materials
  - Quantify lifetime performance of thermal energy storage materials.



Insulation Testing in Venus Chamber



Acceleration Testing of Insulation

Life Testing of Energy Storage Materials

Don P. Mitchell

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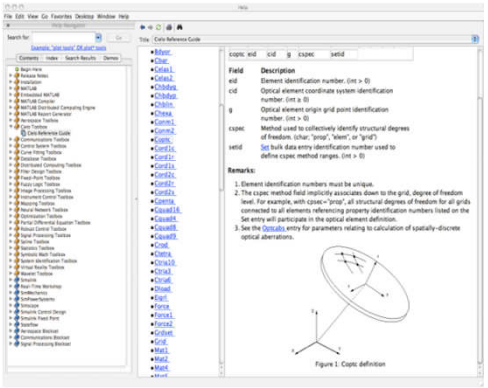
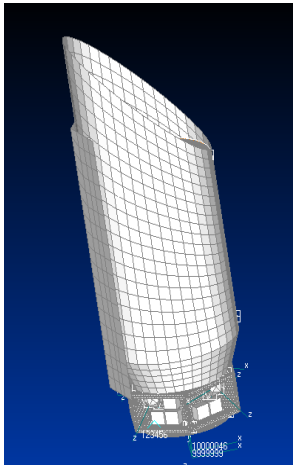
Integrated Thermal-Structural Modeling with Cielo

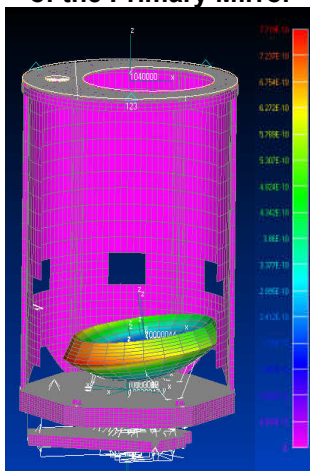
- Cielo is a general-purpose finite element-based code for advanced thermal, structural and optical aberration analysis.
  - Replaces traditional "STOP" (Structural, Thermal, Optical) analysis with a truly integrated system-level capability
  - Highly configurable to project needs
  - Motivated by extreme challenges in precision deployable structure analysis and design.
- Cielo consists of a MATLAB-hosted client and a parallel compute server.
- Performance limited only by parallel hardware availability.



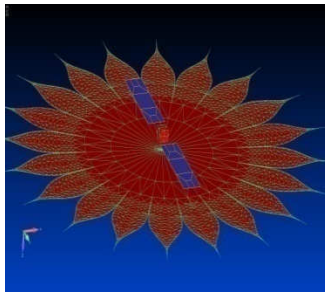
Coronagraph Common Model



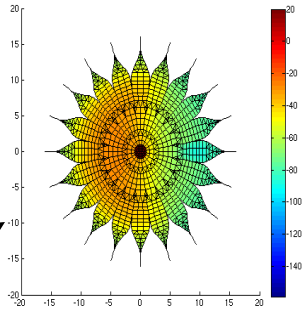
Thermal Deformation of the Primary Mirror



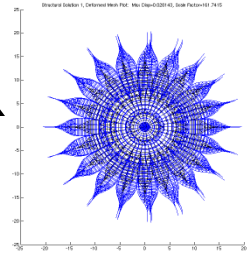
Occulter Common Model



Temperature Distribution



Thermal Deformation



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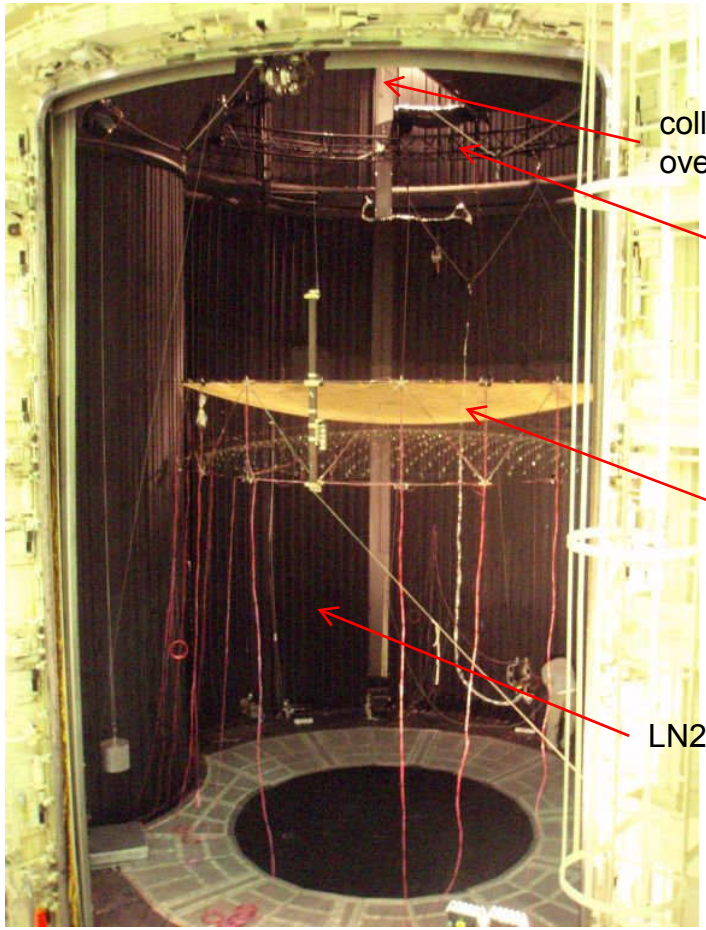
Integrated Thermo-Elastic Characterization Testing at JPL

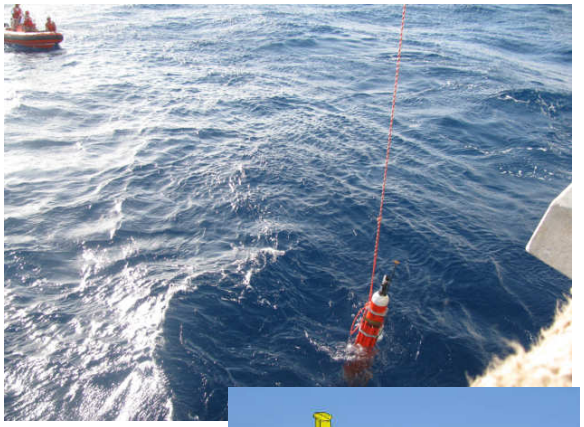
- Test article: 5m aperture NGAS AstroMesh reflector
- Thermal disturbance: 1.25 Suns on half the reflector
- Deformation measurement technique:
  - Photogrammetry camera system mounted on a cart/track system
- Achieved a resolution of ~30 microns over the 5m reflector aperture

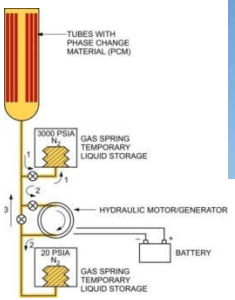


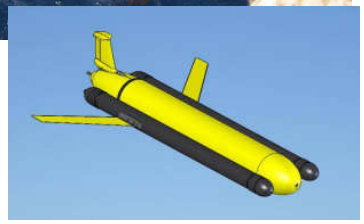
Active Optics Efforts at JPL

- Thermal technologies for affordable Space telescope costs
  - Distortions can be fixed in space
  - Set points can be changed in space
  - Indirect heaters to stabilize the temperatures
  - Control mirror shape

SOLO-TREC Thermal Powered AUV







Next Generation Thermal Powered AUV

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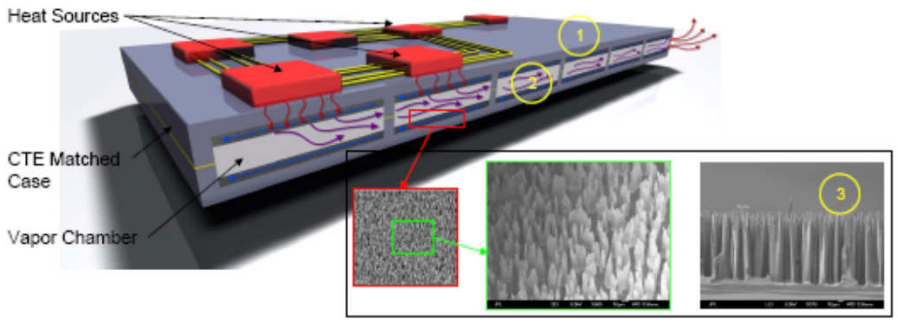
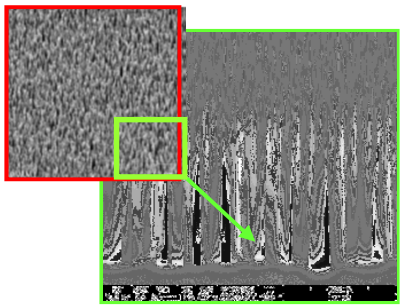
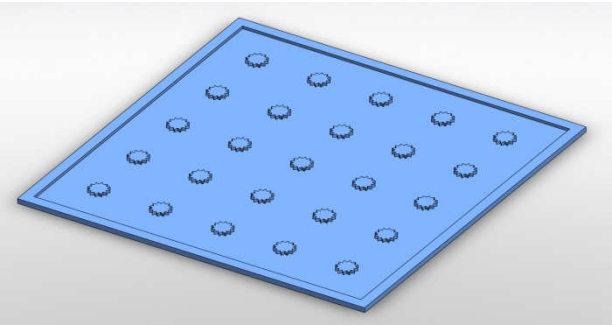
Silicon Heat Pipe Array for Cooling of Microelectronics





Nanotip wick structure



Internal Rib Structure

- Design features of JPL silicon heat pipe array
  1) Case is constructed of high thermal conductivity silicon and is rib reinforced for wicking across sides and structural integrity. CTE matched to electronic component case.
  2) Vapor chamber ~400 microns high. Total heat pipe thickness = 1.4mm
  3) Nano-textured wick is etched from the silicon case is densely packed to enable large capillary forces. Effective pore radius ~ 30 microns.

- Marginal performance to date possibly due to insufficient vapor chamber height
  - Max operating temperature: 125 deg C
  - Max heat load: > 20W
  - Max heat flux: > 2.5W/cm2
  - Effective thermal conductivity of assembly: 300 W/m-K

Principal Investigator: **Dr. Karl Yee**
Co-Investigator: **Eric Sunada**
Co-Investigator: **Dr. Gani Ganapathi**

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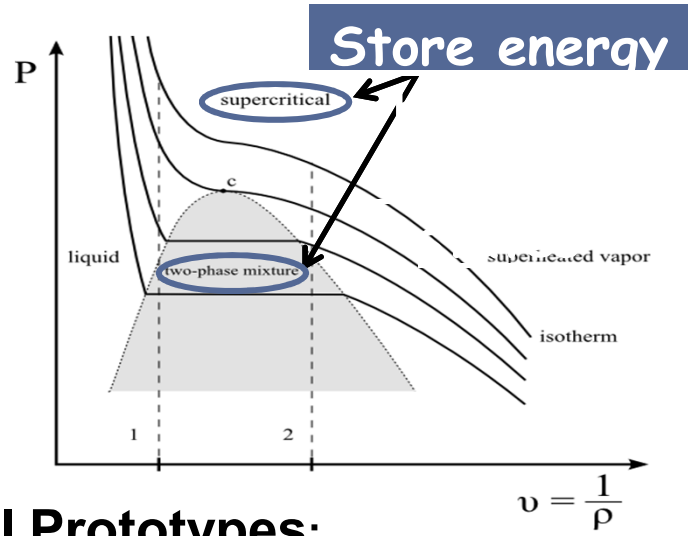
Thermal Storage with Supercritical Fluids

Supercritical operation permits:

1) taking advantage of latent and sensible heat, both in the two-phase regime as well as in supercritical regime

2) reducing the required volume by taking advantage of the high compressibility

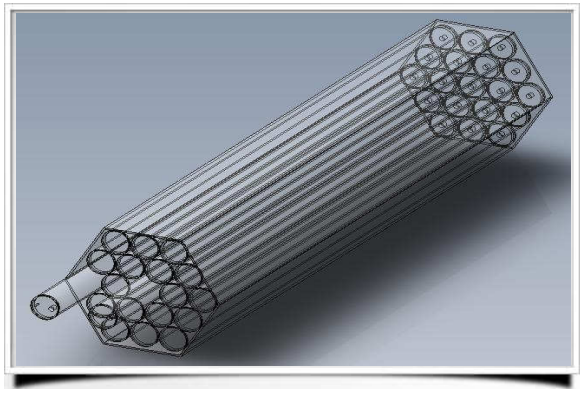


Supercritical Prototypes:

5 kWh & 10kWh laboratory testing facility (500 °C)

Advantages:

- Internal heat exchanger
- No separate pumping needed
- Modular design
- Multiple vendors



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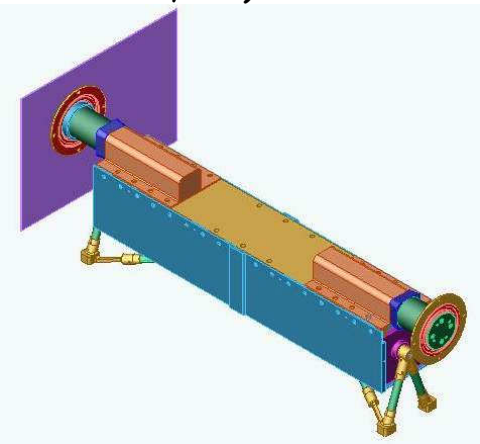
Heat Switch for Space & Mars Surface Applications

MER Wax Actuated Heat Switch (Starsys, Boulder, CO)



Description

- Wax actuated heat switch for Mars with target performance of 0.4 W/C, switch ratio of 30 in 8 torr CO_2, weighing less than 120 gms. Currently functioning well on the two MER rovers

Cryogenic Heat Switches

MIRI 6K heat switch

Gas-Gap Heat Switch

Description

The MIRI 6K heat switch measured "on" performance was 250mW/K. The measured heat switch "off" conductance was 0.5mW/K.

A high temperature version (~300-400K) of the gas-gap switch is operating flawlessly in space on the Planck sorption cooler.

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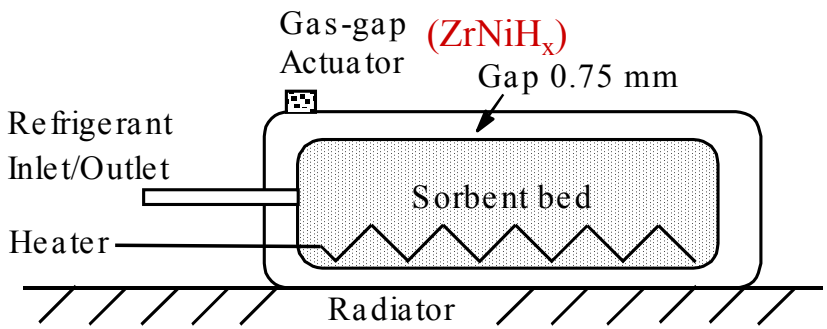
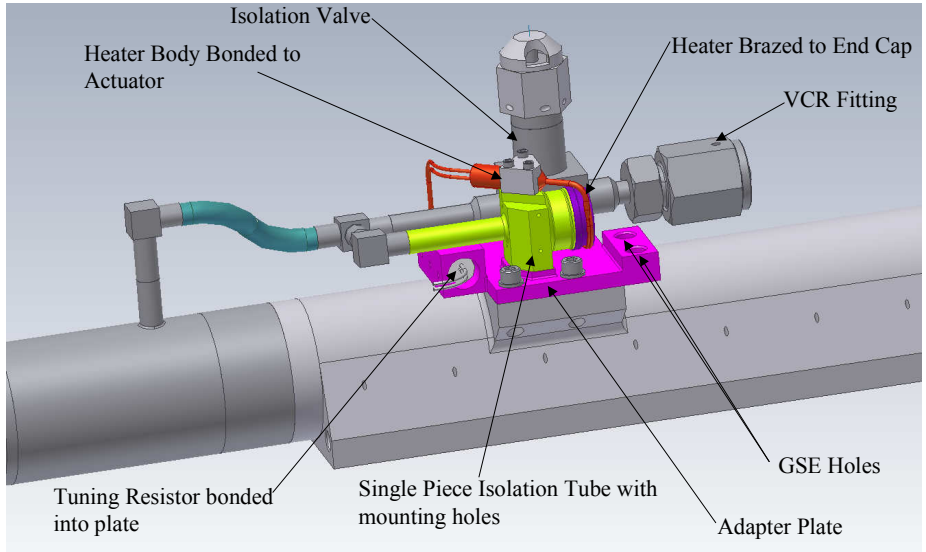
Planck ZrNiHx Gas Gap Heat Switch

Hydride Gas Gap Actuator (GGA) developed for Planck Sorption Cooler

- Large ON/OFF conductance switching ratios (>200)
- Long life (~5+ years)
- Closed Cycle operation (i.e., does not require separate gas bottle to supply vented gas with an open-cycle switch)
- Low power requirements (< 10 W per switch)
- High TRL level (based on Planck flight coolers and development tests)
- Low mass/volume
- Simple operation (turn ON or OFF by throwing an electrical switch)
- No moving parts
- No hysteresis
- Simplicity of implementation





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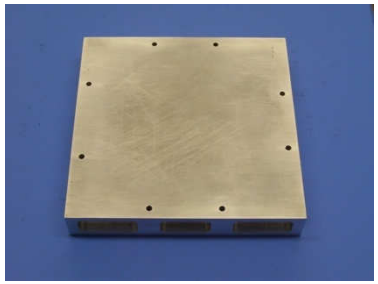
PCM Thermal Storage Technology

Dodecane PCM Thermal Storage Unit

Hexadecane PCM Thermal Storage



RUBITHERM RT 35
Melt. Temp., 35 C
Ht. of Fusion, 157kJ/kg

Description

- Phase Change Material (PCM) used for increasing the equipment thermal capacity for thermal control during transient situations (batteries on rover, Venus lander etc)
  - Dodecane (Melting point of - 10.5 C)
  - Hexadecane (Melting point of 18 C)
  - RUBITHERM RT 35
  - Lithium Nitrate
  - Barium Hydroxide

Participants & Facilities

- ESLI has built Dodecane and Hexadecane PCM thermal storage units for Mars Technology program
- XC Associates has built thermal storage unit for Venus Lander Technology

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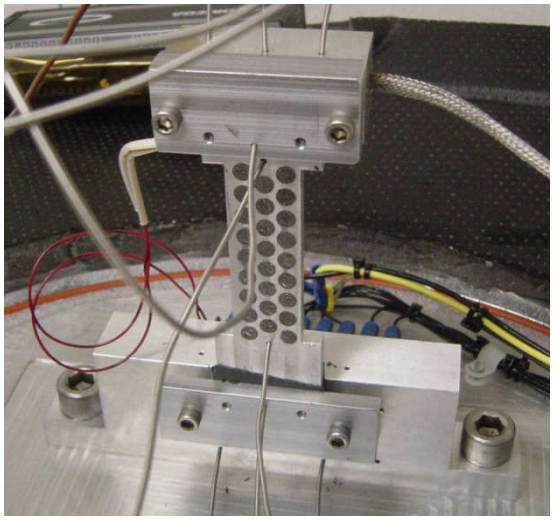
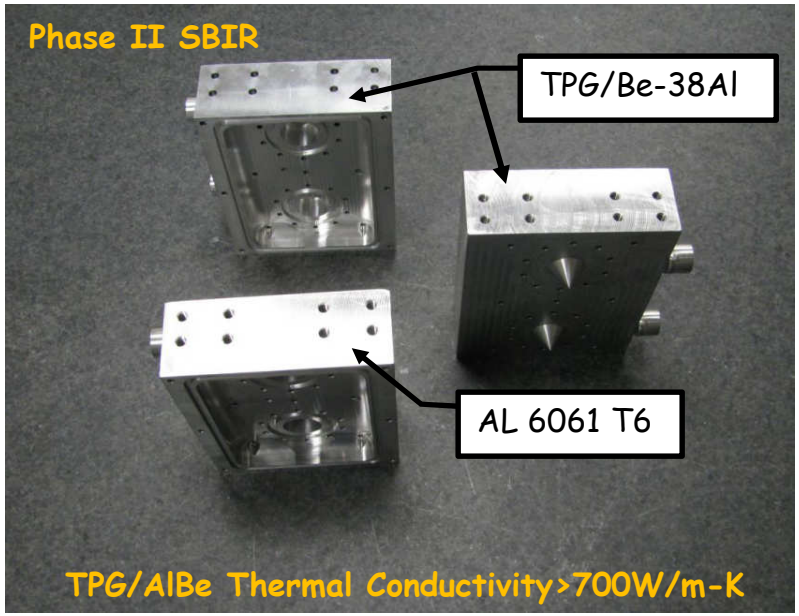
Thermal Pyrolytic Graphite Enhanced Components



Peregrine has successfully embeded Thermal Pyrolytic Graphite (TPG) into aluminum-beryllium. Results show a thermal conductivity in excess of 700W/m-K, four times higher than aluminum while being almost 20% lower in mass. This enabling technology provides a powerful solution in meeting power, performance, volume and mass constraints on Cryocoolers. This technology can significantly reduce the mass of a cryocooler system and input power for the same cooling load.



Cryocooler Component for TPG/AlBe prototyping

Material System	Thermal Conductivity (W/m °K)	Density gm/cc	Specific Thermal Conductivity
Aluminum 6061T6	170	2.70	63
AL-Be 162H	210	2.10	100
Copper, OFHC	391	8.94	44
Beryllium	216	1.85	117
TPG in Al-Be	**721**	**2.20**	**328**

Robert Hardesty, Peregrine Falcon Corp., Pleasanton, CA
COTR: Dr. Jose Rodriguez

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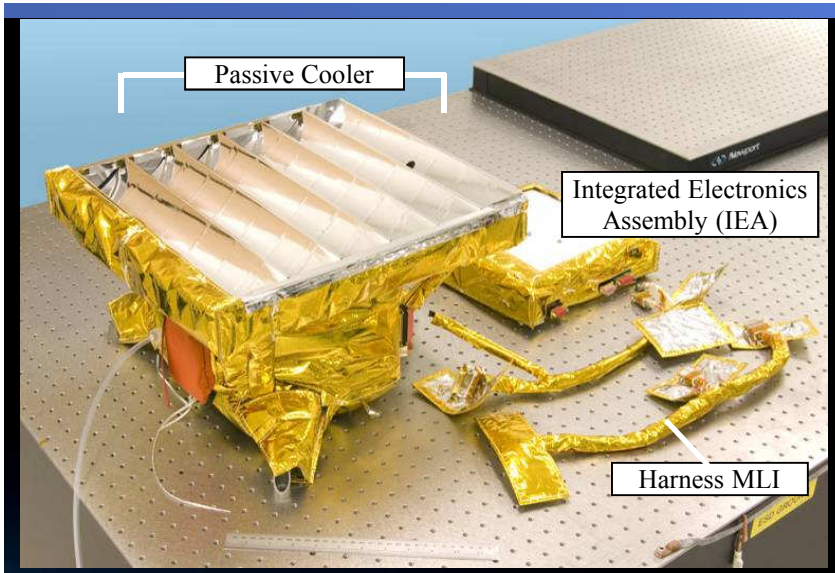
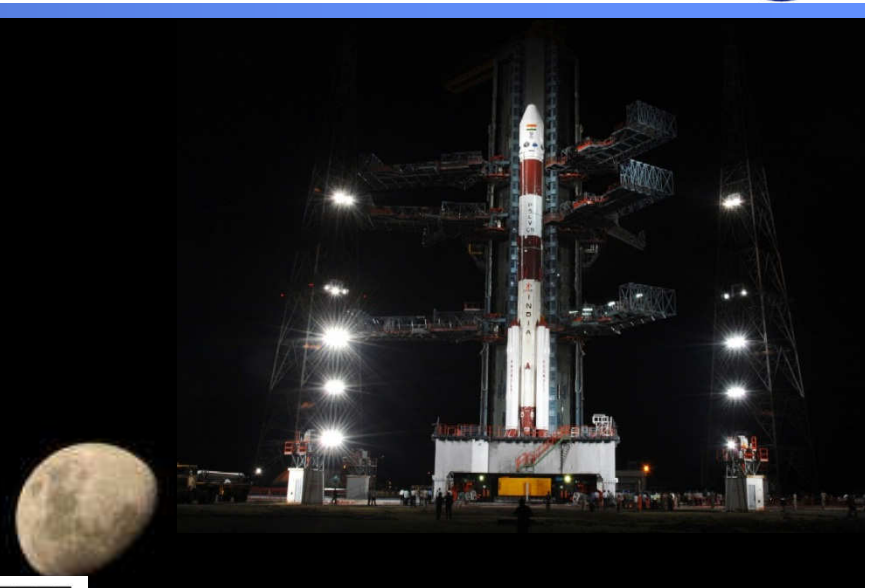
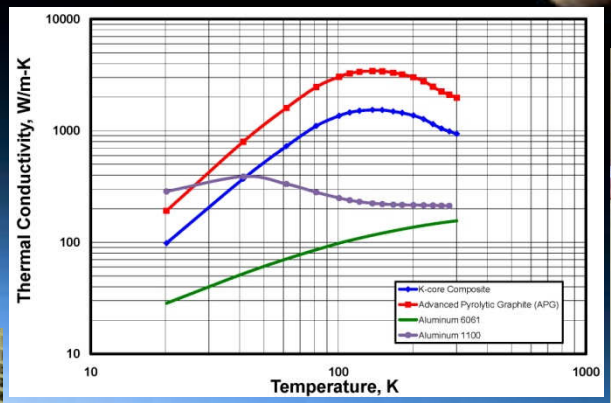
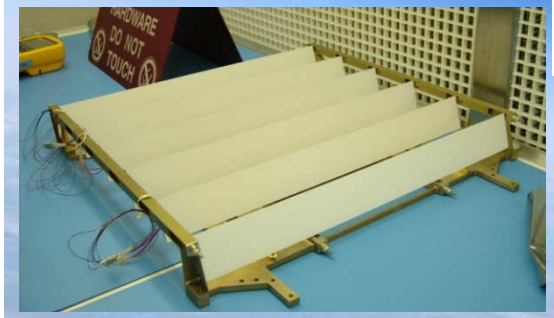
Moon Mineralogy Mapper (M3) Passive Cooler









M^3 Instrument
(Dr. Jose Rodriguez)

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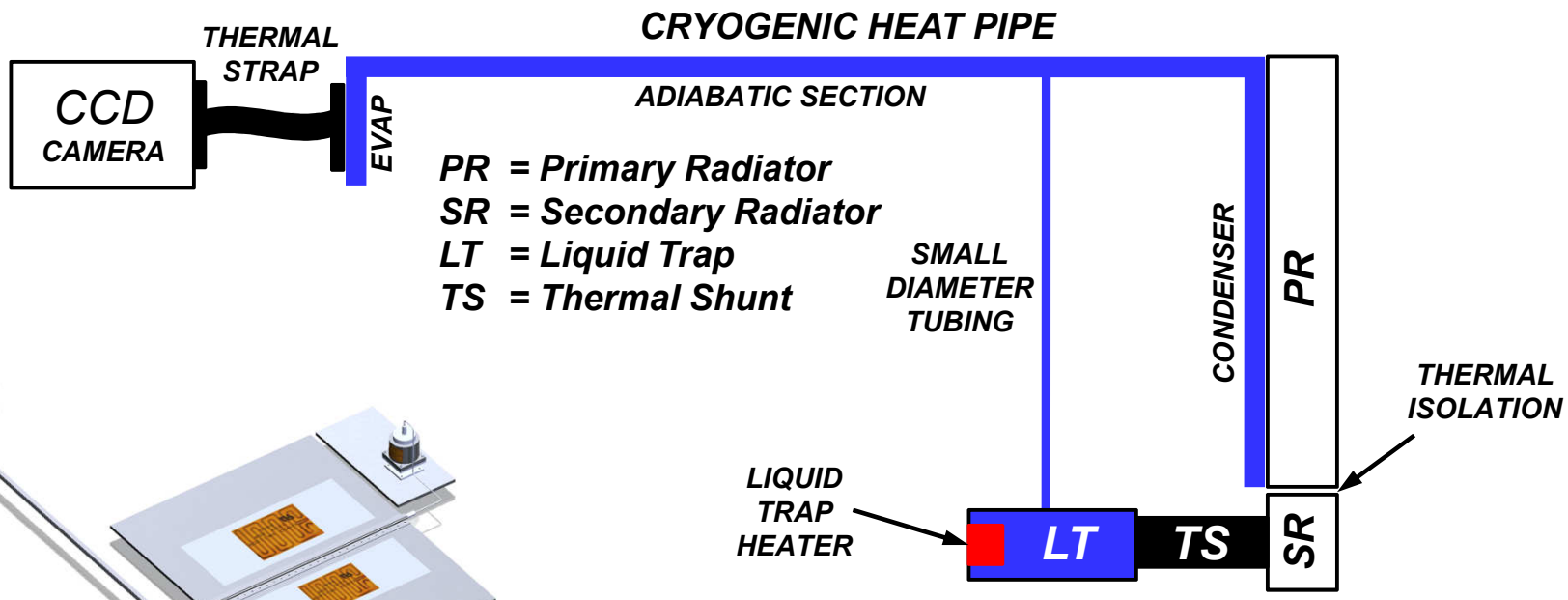
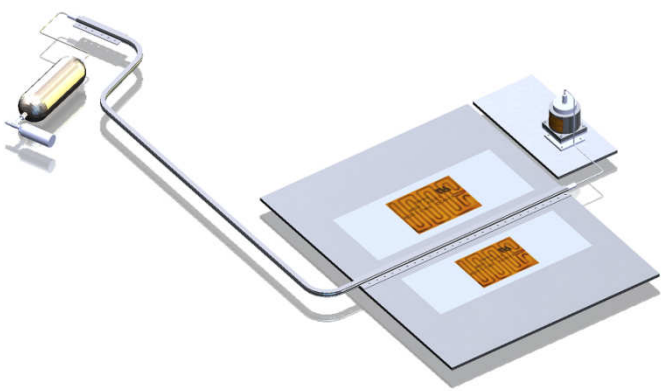
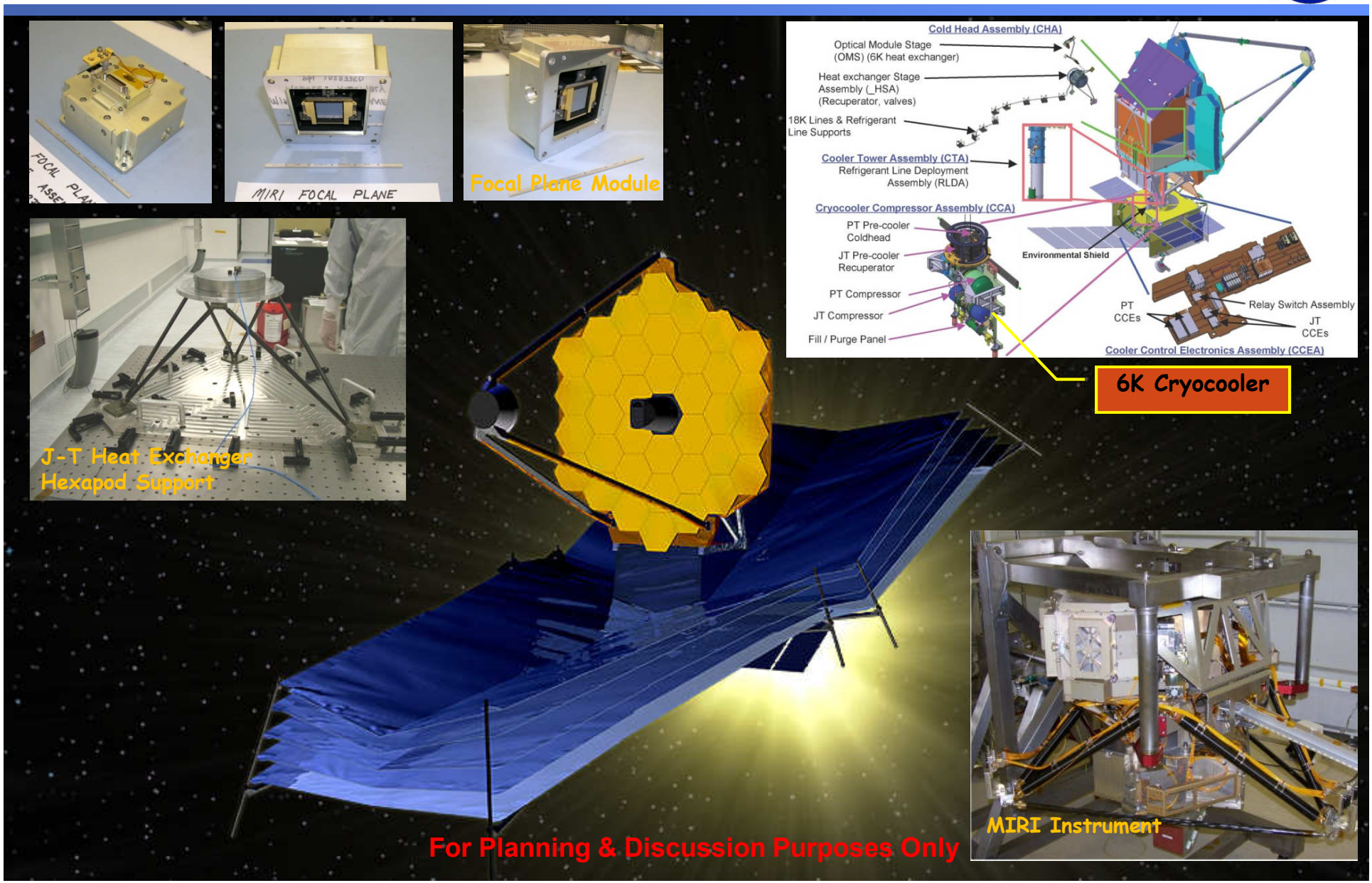
Cryogenic Heat Pipe with Thermal Switching

- ***Solution:*** *Cryogenic heat pipe with thermal switching capability provided by a secondary radiator thermally isolated from the primary radiator, a thermally shunted liquid trap, and small liquid trap heater.*
  - *During **normal operation**, the small liquid trap heater keeps the liquid trap warm enough so that it is filled with vapor only thus the heat pipe is ON.*
  - *During **decontamination**, the liquid trap heater is turned off and all the working fluid migrates to the liquid trap turning the heat pipe OFF.*

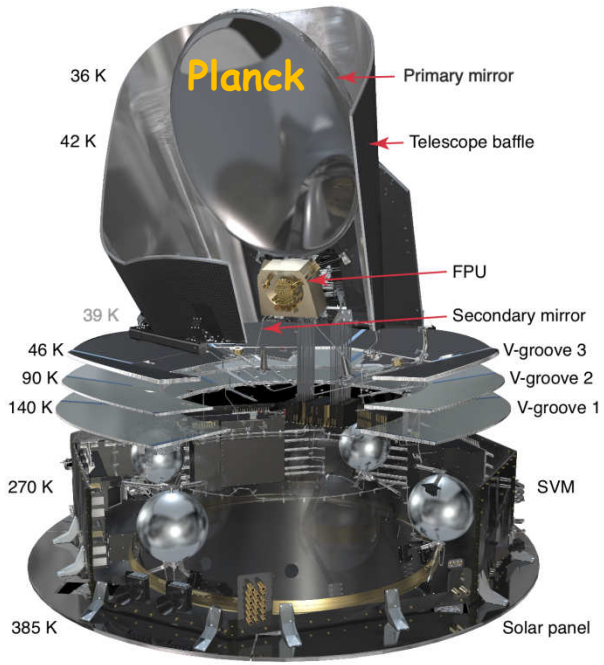




MIRI Instrument on JWST

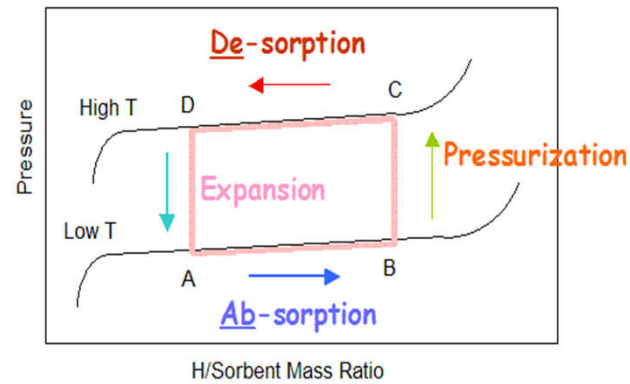


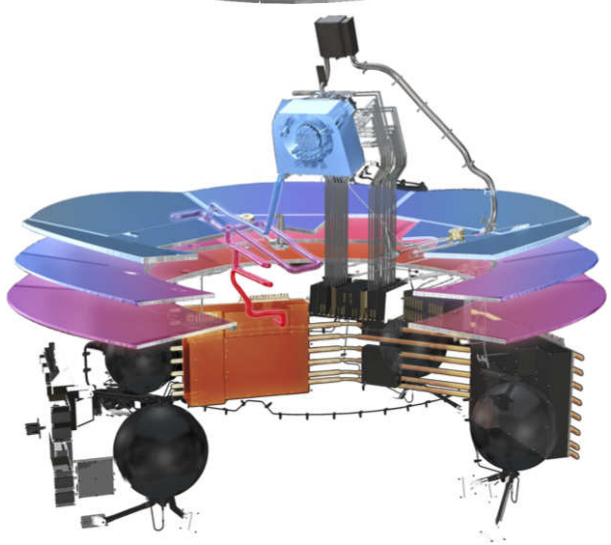
Planck Sorption Cooler (PSC)



- Developed by JPL, PSC uses a closed-cycle Joule-Thomson (J-T) refrigeration cycle to produce liquid H_2 at <19 K
- Compression is done thermally by heating and cooling the metal hydride, no mechanical moving parts apart from check valves
- Light weight gas storage for fuel cell power systems is one possible further application
- Active research ongoing for DOE hydrogen storage for automobile fuel cells, can be applied for space-based applications

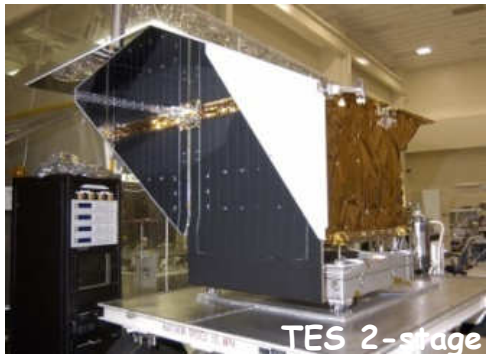
Using metal hydrides to provide 1 Watt of vibration free cooling at 20K

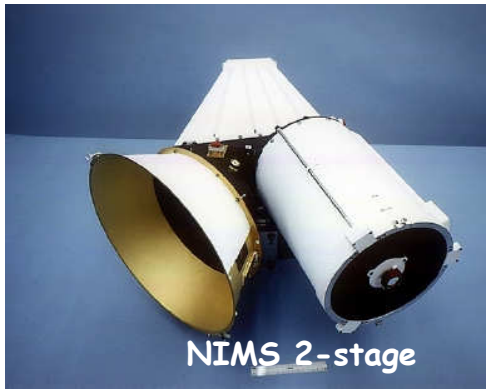


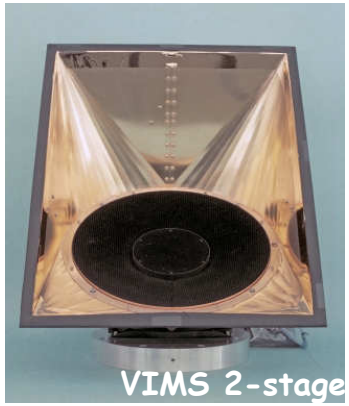


Sorption cooler system. The system is fully redundant. The orange box houses one of the compressor assemblies, mounted on one of the warm radiator panels, which faces cold space. Heat pipes run horizontally connecting the radiators on three sides of the service vehicle octagon. The second compressor assembly is the black box on the right. A tube-in-tube heat exchanger carries the high and low pressure hydrogen gas from the compressor assembly to the focal plane assembly, with heat-exchanging attachments to each of the three V-grooves. The colors indicate temperature, from warm (red, orange) to cold (blue).

Multi-Stage Passive Coolers







Performance:
The performance of passive coolers is optimized for the specific application. Operating temperatures and heat loads as well as orbit constraints are key drivers for the design. Cryogenic multi-staging is used to optimized the designs and produce higher heat lifts at the upper stages. The M3 three-stage design without a Moon shade makes use of parabolic infrared reflectors to guard against the high Moon infrared heat loads at 100km orbit altitude. M3's passive cooler on-orbit performance proved successful and this technology has been baselined for several future JPL instruments.

Description:
Multi-stage passive coolers are ideal for cooling instrument optical benches and detectors to near 120K in LEO orbits. These coolers require Earth shades to guard against Earth infrared heat loads. Deployable Earth shades are typically required due to launch volume envelope constraints. Two-stage cooler designs were developed to cool the AIRS and TES optical benches to near 150K and 170K, respectively. A three-stage passive cooler to cool the focal plane to 150K and optical bench to 170K was recently developed for JPL's M3 instrument in a low altitude Lunar orbit.

Applications: Provides multi-stage cooling to spacescience instruments

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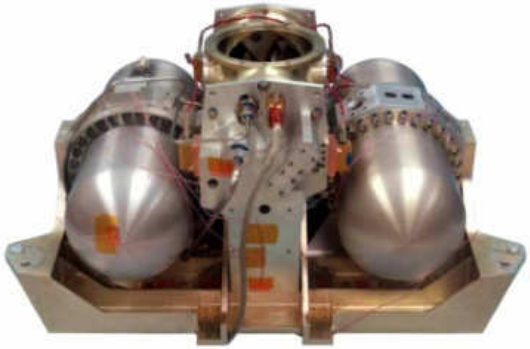
Long-life Mechanical Coolers



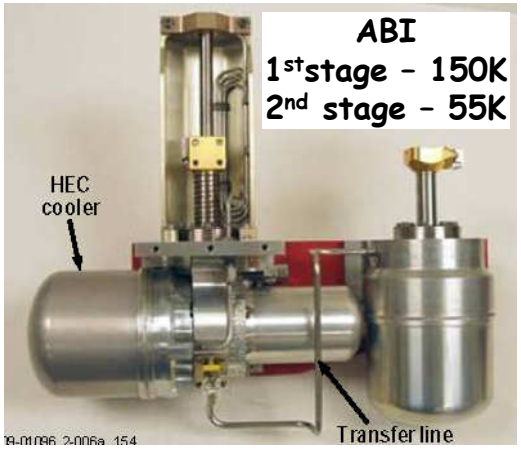
AIRS – 55K

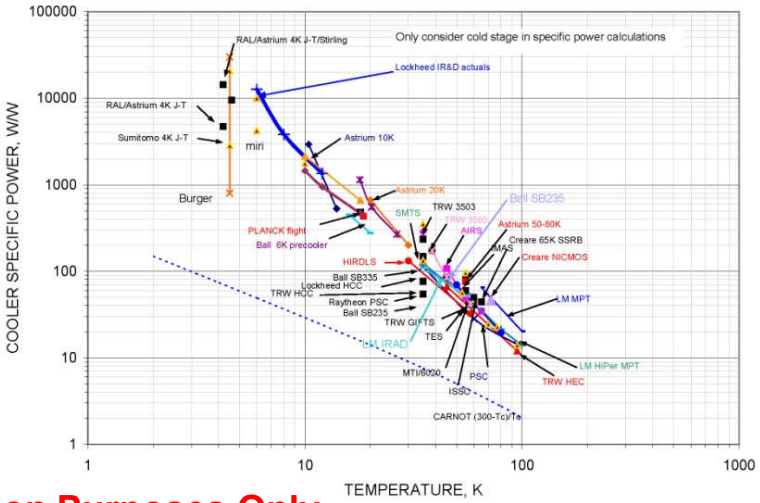
TES – 65K
OCO1 – 110K

Performance:
The AIRS class Oxford style cryocooler with flexure bearing technology have been used extensively and characterized at JPL. Thermal performance characterization testing as well as exported vibration testing including EMI/EMC testing is performed on all flight coolers. An extensive performance database exists at JPL. The AIRS coolers provide cooling to a focal plane at 55K and have been operating in space without degradation for over 8 years. The TES coolers cool the focal planes to 65K and have been operating in space without degradation for over 6 years. This class of cooler technology has proven successful and is baselined for JPL's next generation of spacescience instruments.

Description:
Long-life single-stage mechanical pulse tube cryocoolers have been developed and used on cryogenic spacescience instruments requiring cooling down to 55K. Pulse tube coolers have a long successful history of operation in space. Pulse tube coolers were first selected at JPL in the early 90's for development and were first flown on the AIRS instrument in 2002. Pulse tube cooler technology continues development and significant gains in efficiency and reductions in mass and volume have been achieved. Most recent designs show 2.5X mass reductions and specific power improvements in the order of 20-30% over the AIRS type cooler.

Applications: Provides single and multi-stage cooling to spacescience instruments





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Recent Long-life Space Cryocooler Flight Operating Experience as of June 2011

Cooler / Mission	Hours/Unit	Comments
Air Liquide Turbo Brayton (ISS MELFI 190K)	43,000	Turn on 7/06, Ongoing, No degradation
Ball Aerospace Stirling (60K HIRDLS)	60,000	Turn on 8/04, 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)	99,000	Turn on 3/00, Ongoing, No degradation
JPL Sorption (PLANCK 18K JT (Prime & Bkup))	7,300	Bkup on 8/10, Ongoing; Prm failed at 10,200 h
Mitsubishi Stirling (ASTER 77K SWIR system)	95,000	Turn on 3/00, Ongoing, Load off at 71,000 h
NGAS (TRW) Coolers		
CX (150K Mini PT (2 units))	119,000	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)	99,000	Turn on 3/00, Ongoing, No degradation
Hyperion (110K Mini PT)	91,000	Turn on 12/00, Ongoing, No degradation
SABER (75K Mini PT)	87,000	Turn on 1/02, Ongoing, No degradation
AIRS (55K 10cc PT (2 units))	79,000	Turn on 6/02, Ongoing, No degradation
TES (60K 10cc PT (2 units))	60,000	Turn on 8/04, Ongoing, No degradation
JAMI (65K HEC PT (2 units))	52,000	Turn on 4/05, Ongoing, No degradation
GOSAT/IBUKI (60K HEC PT)	20,700	Turn on 2/09, Ongoing, No degradation
STSS (Mini PT (4 units))	10,200	Turn on 4/10, Ongoing, No degradation
Oxford/BAe/MMS/Astrium Stirling		
ISAMS (80 K Oxford)	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))	94,000	Turn on 3/00, one disp. failed at 10,300 h
ODIN (50-80K Astrium (1 unit))	90,000	Turn on 3/01, Ongoing, No degradation
AATSR on ERS-1 (50-80K Astrium (2 units))	81,300	Turn on 4/02, Ongoing, No degradation
MIPAS (50-80K Astrium (2 units))	81,300	Turn on 4/02, Ongoing, No degradation
INTEGRAL (50-80K Astrium (4 units))	76,200	Turn on 11/02, Ongoing, No degradation
Helios 2A (50-80K Astrium (2 units))	56,500	Turn on 1/05, Ongoing, No degradation
Helios 2B (50-80K Astrium (2 units))	12,000	Turn on 2/10, Ongoing, No degradation
Raytheon ISSC Stirling (STSS (2 units))	10,200	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
Planck (4K JT)	17,800	Turn on 6/09, Ongoing, No degradation
Sumitomo Stirling Coolers		
Suzaku (100K 1-stg)	52,000	Turn on 7/05, Ongoing, No degradation
Akari (20K 2-stg (2 units))	35,000	Turn on 2/06, 2nd Degraded, 1st failed at 13,000 h
Kaguya GRS (70K 1-stg)	14,600	10/07- 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 (75K RHESSI)	82,000	Turn on 2/02, Ongoing, No degradation

Creare NICMOS

NGAS (TRW) Mini PT

NGAS (TRW) AIRS PT

Astrium (BAe) 50-80K

RALATSR

Sunpower

1yr = 8760hrs

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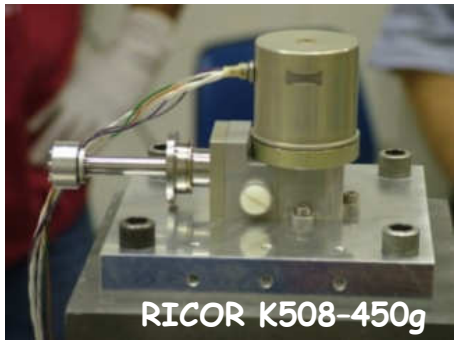
Limited-life Mechanical Coolers



Performance:
Performance characterization mapping of these coolers shows acceptable performance comparable to the long-life fully flight qualified machines. To increase the life expectancy of these machines, the compressors are operated at near room temperature and with reduced heat loads in the 50% range of maximum capacity. The low cost of these machines allows the implementation of redundant coolers, when practical, to increase the instrument operational lifetimes. The small Ricor cooler has been extensively characterized at JPL and is fully flight qualified.

Description:
The need for single-stage coolers for flight instruments with lifetimes in the order of a few months to a few years has increased and has resulted in the flight qualification of low cost tactical coolers for these applications. They offer acceptable thermodynamic performance at the expense of limited lifetimes due to mechanical wear. Rotary and linear drive designs are available with commercial electronics. Cooler exported vibration and EMI/EMC may be important issues which require special attention.

Applications: Provides single-stage cooling to instruments. Sunpower Cooler on NGIS, CAO and NEON imaging Spectrometers, Thales Cooler on ARTEMIS, RICOR Cooler on MSL CheMin and MRO CRISM.

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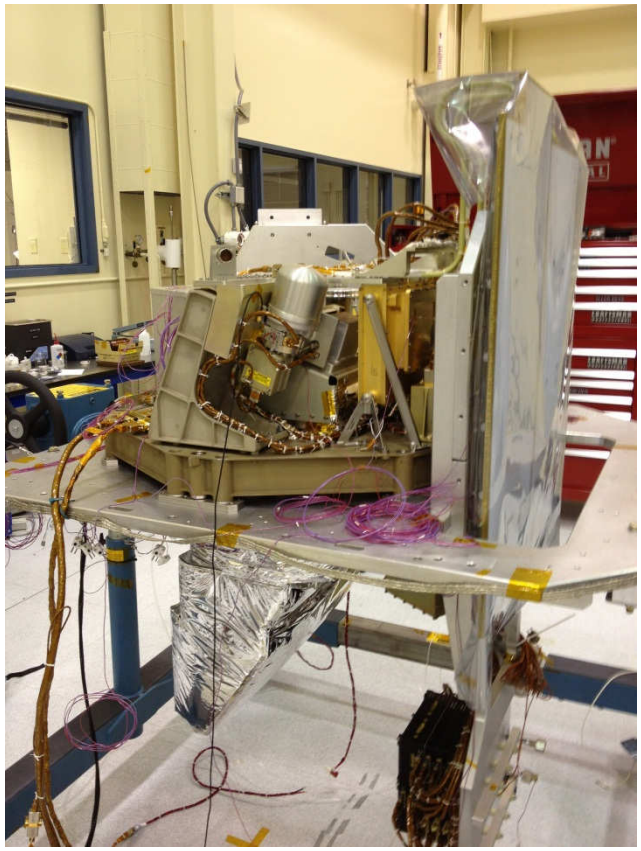
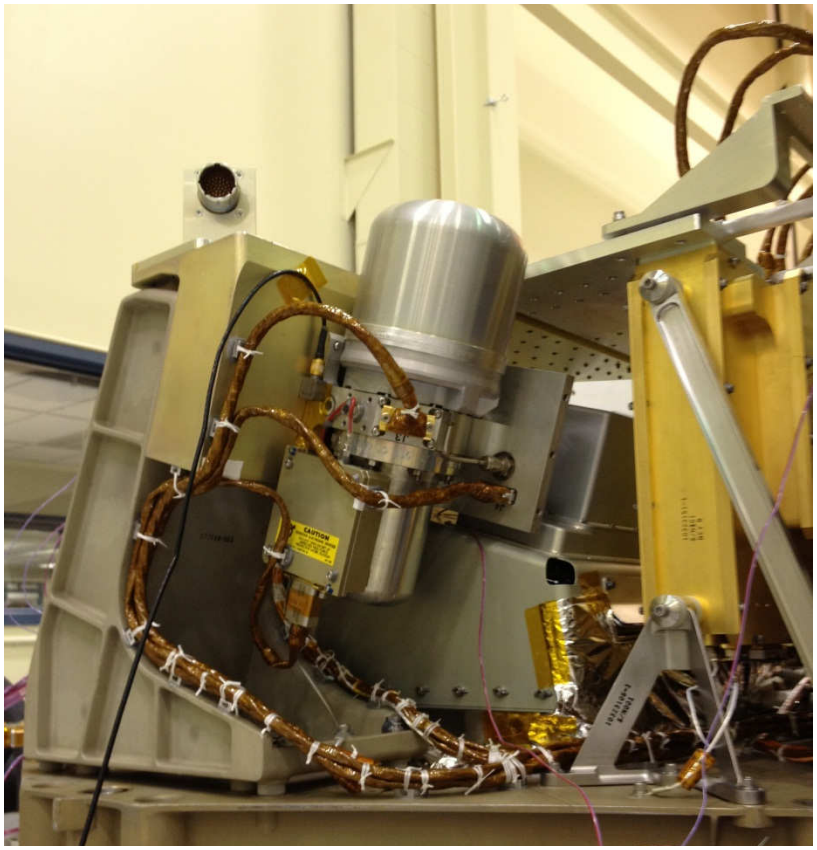
OCO-2 Mechanical Cooler (HEC)





Orbiting Carbon Observatory-2 (OCO-2): The 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).
A 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.

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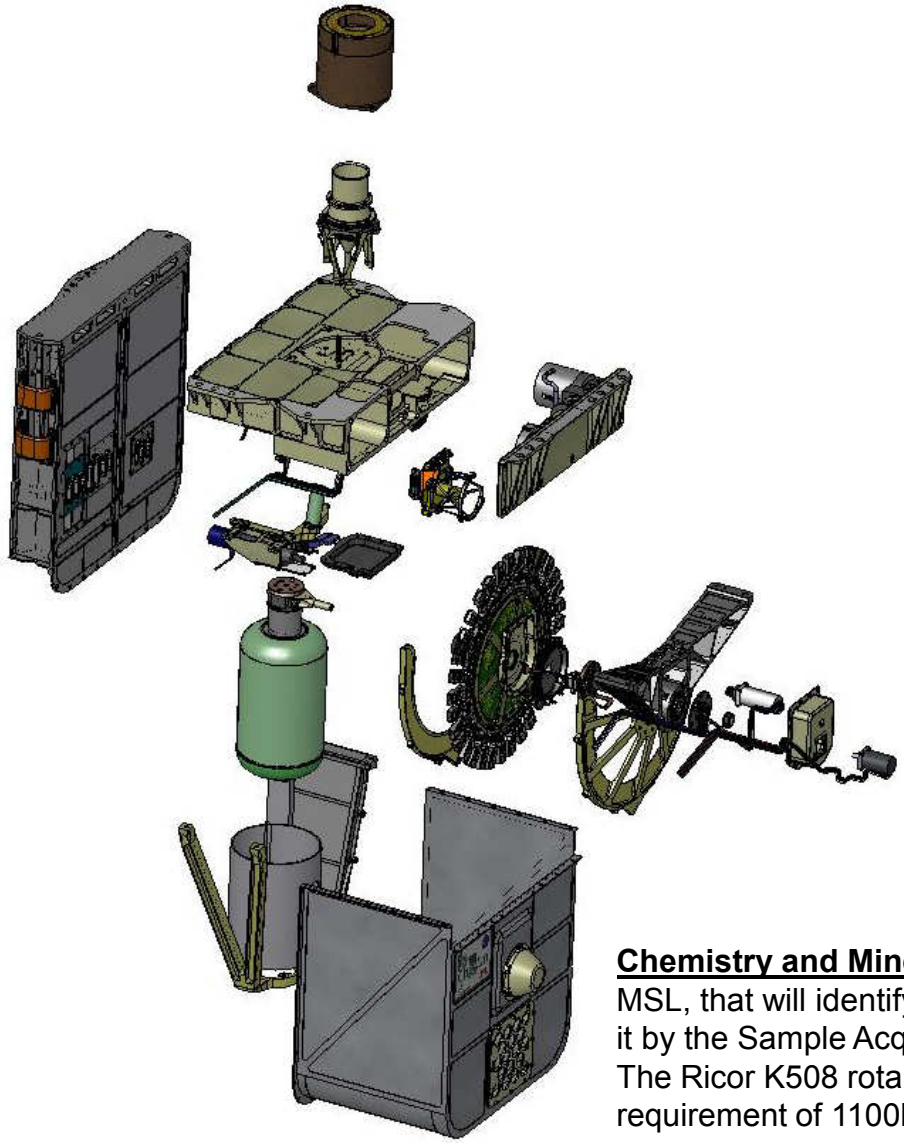
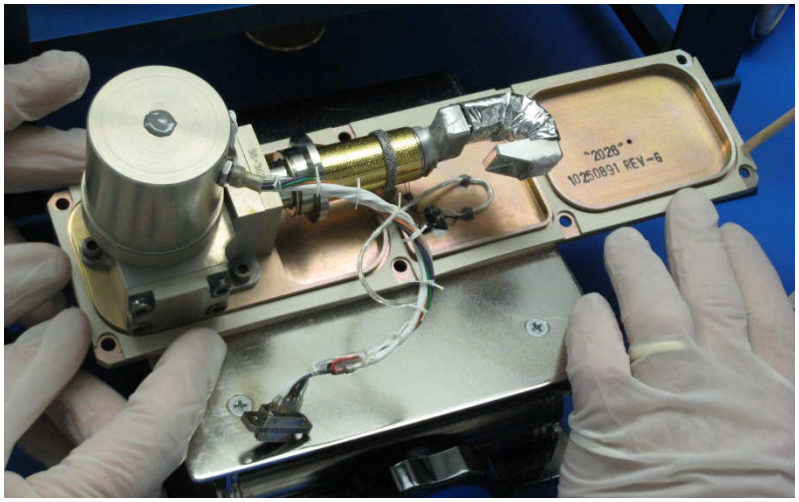
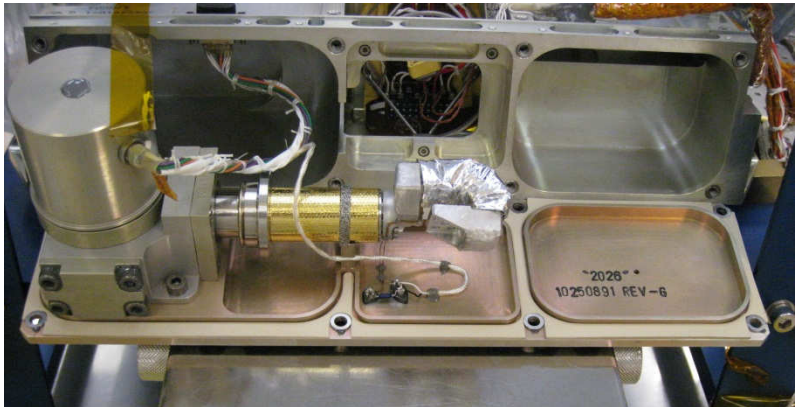
CheMin Mechanical Cooler (Ricor K508)







Chemistry and Mineralogy (CheMin): CheMin is a mineralogy instrument, onboard MSL, that will identify and quantify the minerals present in rocks and soil delivered to it by the Sample Acquisition, Sample Processing and Handling (SA/SPaH) system. The Ricor K508 rotary cooler provides cooling to CCD at 200K with a lifetime requirement of 1100hrs for surface operations.

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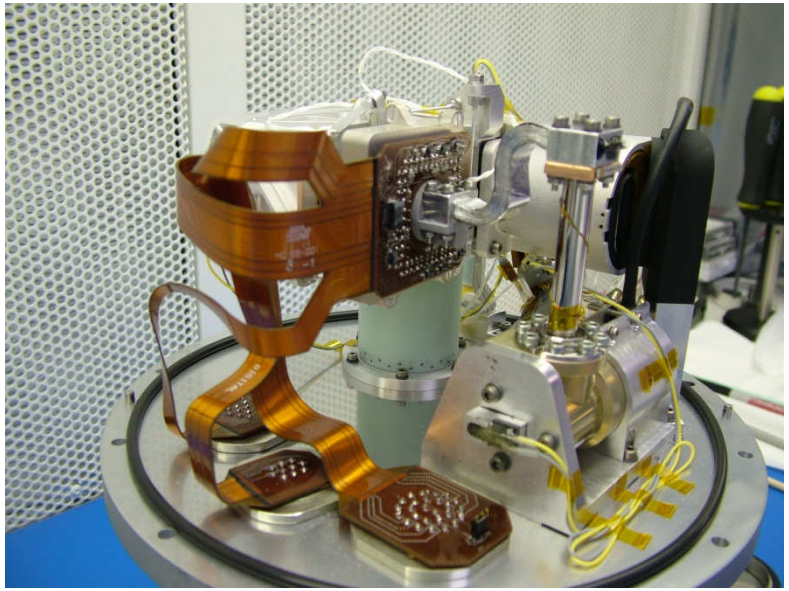
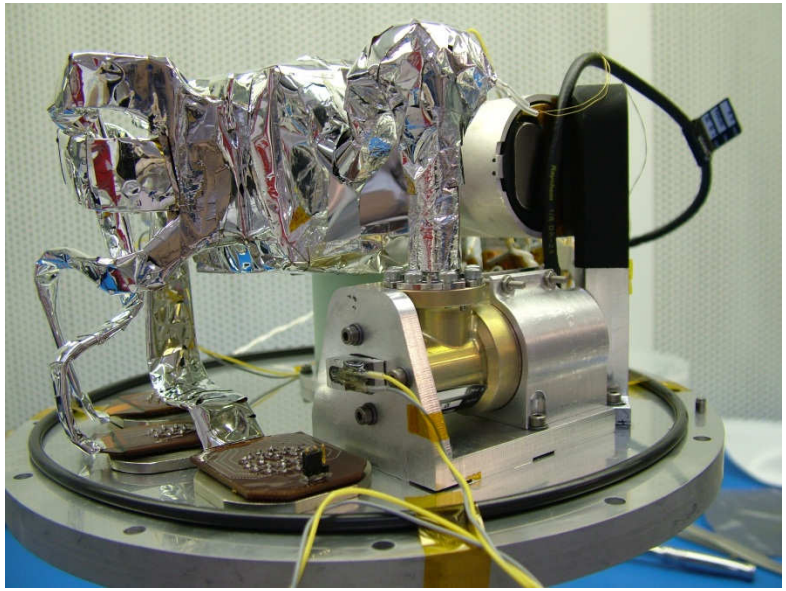
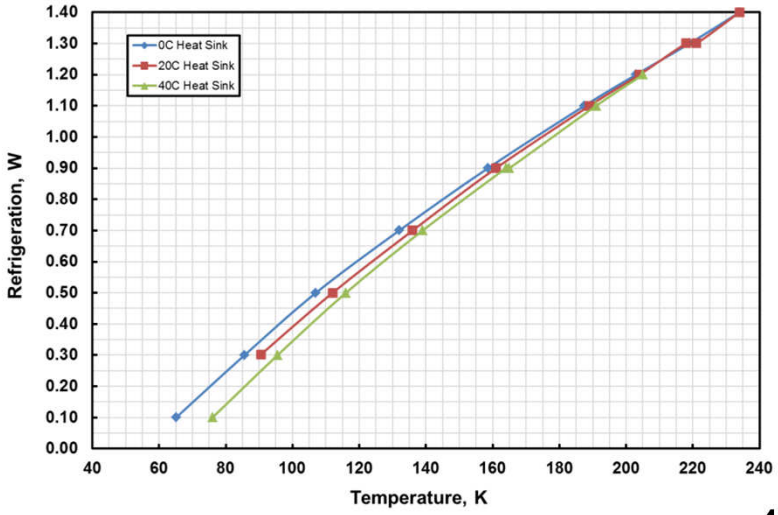
UCIS Mechanical Cooler (Ricor K562)





Ultra-Compact Imaging Spectrometer (UCIS):
State of the Art in imaging spectrometers with less than 6W input power and less than 3kg. Smallest rotary cooler available from Ricor offers high efficiency with acceptable life (MTTF is 5,000hrs). The Ricor K562 cooler is used to cool the focal plane to ~180K with lifetime requirement of ~6months.



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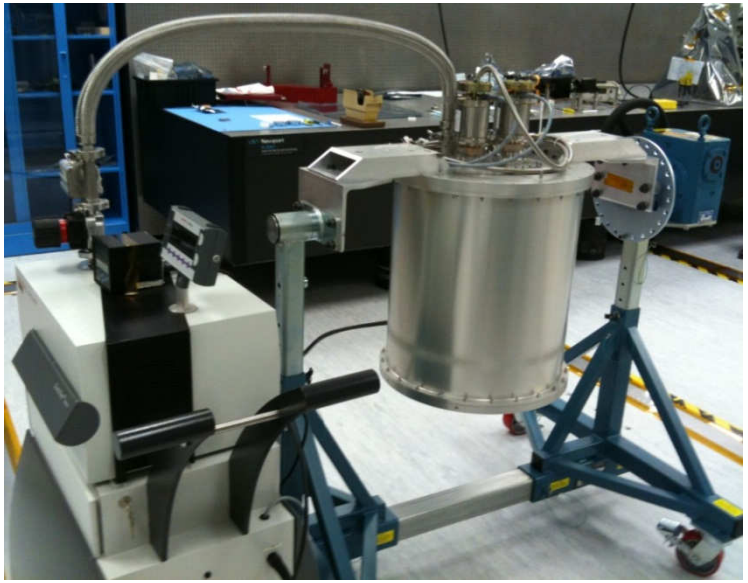
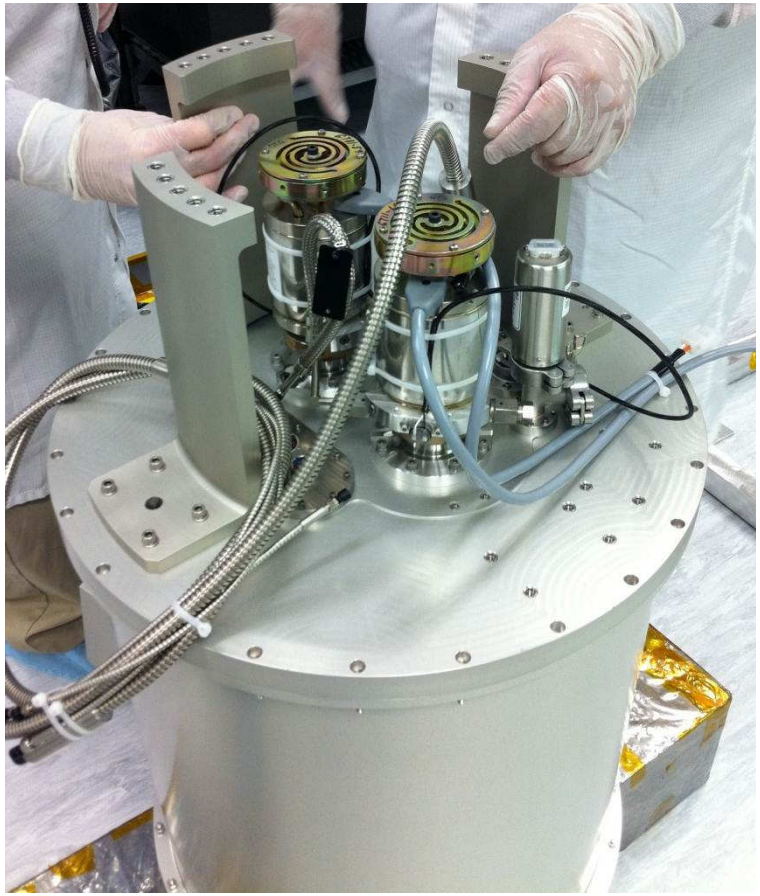
MSS Mechanical Cooler (Sunpower CryoTel)





SUNPOWER
CryoTel GT-3.1Kg

MaRSplus Sensor System (MSS):
Airborne imaging spectrometer with active cooling for focal plane and spectrometer. Each instrument makes use of two Sunpower CryoTEL GT tactical cryocoolers liquid cooled with recirculating chiller. The focal plane is cooled to 145K and spectrometer to 130K.

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Summary

- NASA's new emphasis on Human Exploration program for missions beyond LEO requires development of innovative & revolutionary technologies

- Thermal control requirements of future NASA science instruments and missions are very challenging and require advanced thermal control technologies

- Limited resources requires organizations to cooperate & collaborate; government, industry, universities all need work together for the successful development of these technologies

JPL Advanced Thermal Technology Team

Dave Bame	MER & MSL Pumped Fluid Loops
Dan Berisford	Pumped Fluid Loops
Pradeep Bhandari	Pumped Fluid Loops Design
Gaj Birur	Advanced Thermal Control Technologies
Gani Ganapathi	Single & 2-Phase Fluid Loops; Lunar Missions
Jack Jones	Titan Balloon Thermal Control
Dean Johnson	Long-life and limited-life Cryocoolers
Jennifer Miller	Lunar Mission Fluid Loops
Keith Novak	MER Loop Heat Pipe and Heat Switch
Tony Paris	High Temp. Fluid Loops; Micro-cooling tech.
Mike Pauken	LHP; Venus/Titan Thermal Technologies
Dave Pearson	Planck Cooler, Gas Gap Heat Switch
Chuck Phillips	Integrated Thermal Meodeling
Jose I Rodriguez	Cryocoolers, MIRI Heat Switch, TES LHP's, M3 Passive Cooler
Eric Sunada	Lunar Fluid Loops; MER Heat Switch

Sunset on Mars – Spirit Rover
May 19, 2005

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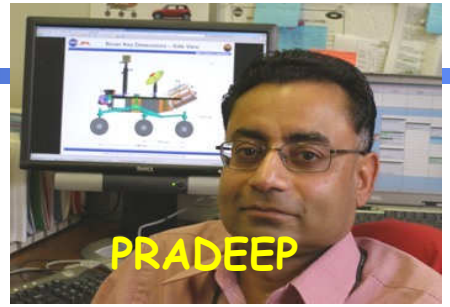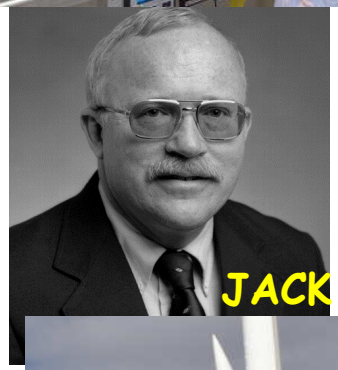
JPL Advanced Thermal Technology Team