National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL Advanced Thermal Control Technology Roadmap - 2008

Gaj Birur
Jet Propulsion Laboratory
California Institute of Technology, Pasadena, California

150 acres &
5000 employees
60 Thermal Engineers
20 Thermal technologists

March 11-13, 2008
2008 Spacecraft Thermal Control Workshop
The Aerospace Corporation, El Segundo, California

JPL Advanced Thermal Technology Team

Dave Bame	MER & MSL 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
Brad Kinter	MSL Fluid Loop Technologies
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
Jose Rodriguez	TES Loop Heat Pipe, M3 Radiator
Eric Sunada	Lunar Fluid Loops; MER Heat Switch
Glenn Tsuyuki	MER Pumped Loop; CO2 Insul.; CEV HRS

Sunset on Mars – Spirit Rover
May 19, 2005

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Government sponsorship acknowledged.

JPL Advanced Thermal Technology Team

OUTLINE

- JPL/NASA Robotic Space Science Missions
- JPL Thermal Control Technology Roadmap
  - 1960's Missions
  - 1990's and later
- Specific Technologies Under Development
- Conclusions

Seventeen active spacecraft across the solar system (and beyond)

Spitzer

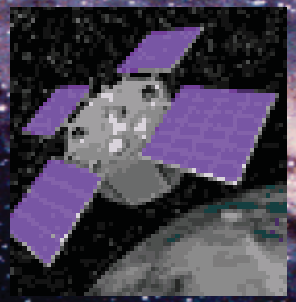
Ulysses

Mars Odyssey

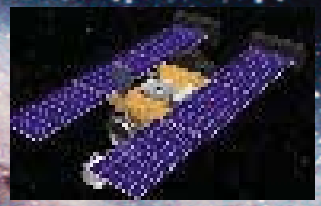
Cassini

GRACE

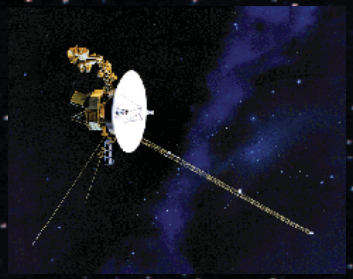
GALEX


ACRIMSAT

Mars Global Surveyor


Stardust

Jason


Voyagers I & II

MRO

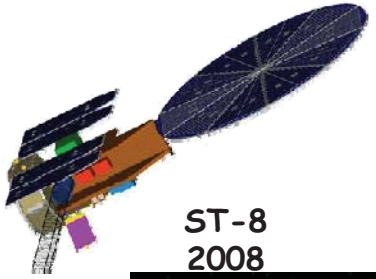
Deep Impact

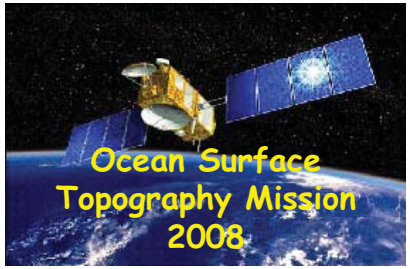
QuikScat

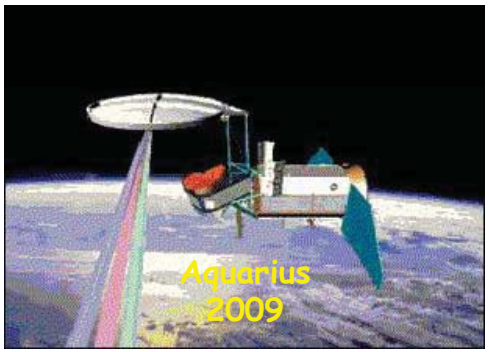
Spirit & Oppportunity

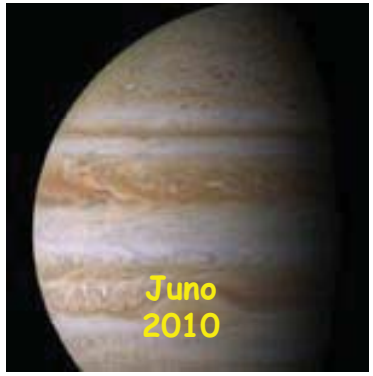
Plus ASTER, MISR, AIRS, MLS and TES instruments monitoring Earth.

Future Missions under Development







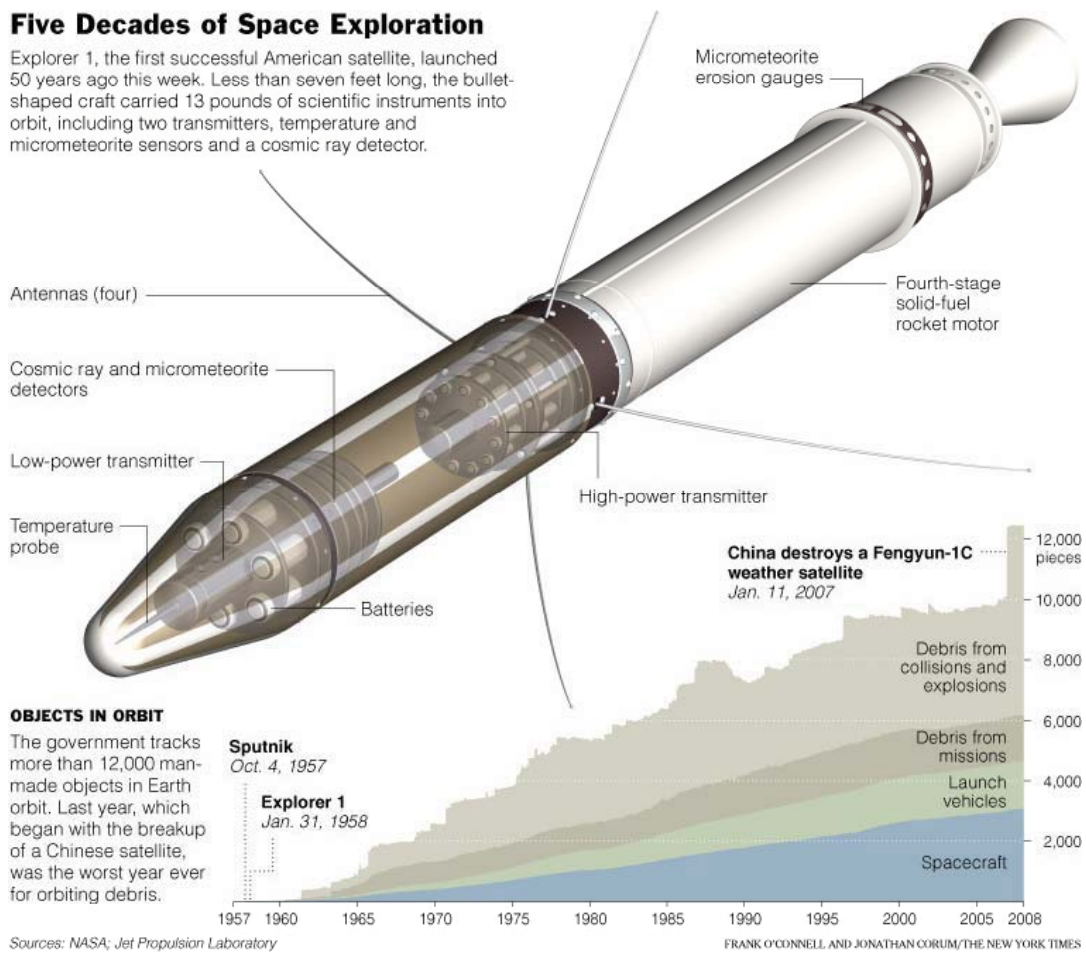


Spacecraft Thermal Control Challenges – Past Missions

- **Explorer Spacecraft (1958)**
  - Earth orbiting mission
- **Mariner Missions (Interplanetary, 1960's)**
  - Flyby Missions (Venus, Jupiter, Titan)
  - Orbiter missions (Venus, Mars, Jupiter, Saturn)
- **Deep Space Missions (1970's & 80's)**
  - Voyager, Viking, Galileo, Cassini

Explorer I – First U.S. Satellite

- Launched in January 31, 1958
- 90 days to design/build/launch
- Caltech/JPL agree join NASA
- Minimal thermal control hdwr.

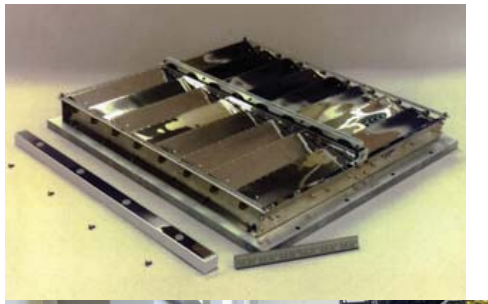


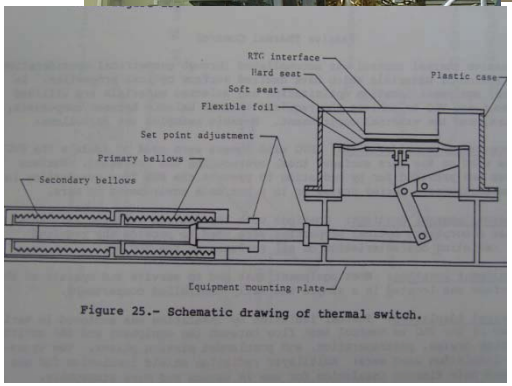
Thermal Control Technologies – Before 90's

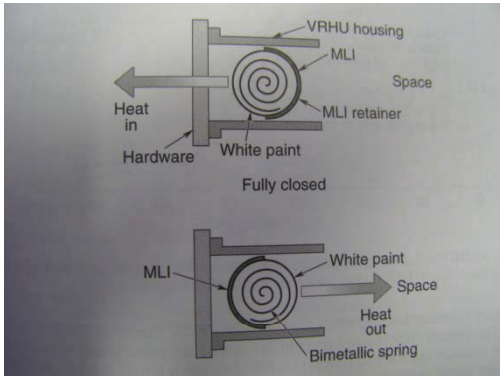
- Multilayer insulation blankets
- Heaters
- Radiators
- Thermostats & temperature sensors
- Mechanical louvers for Mariner interplanetary missions - 1962
- Heat switch for Viking – 1975
- Heat pipes
- RTG waste heat recovery – Cassini
- Variable RHU

Thermal Control Hardware: Pre-90's

- Mechanical louvers
- Mechanical heat switch
- Heat pipes
- VRHU



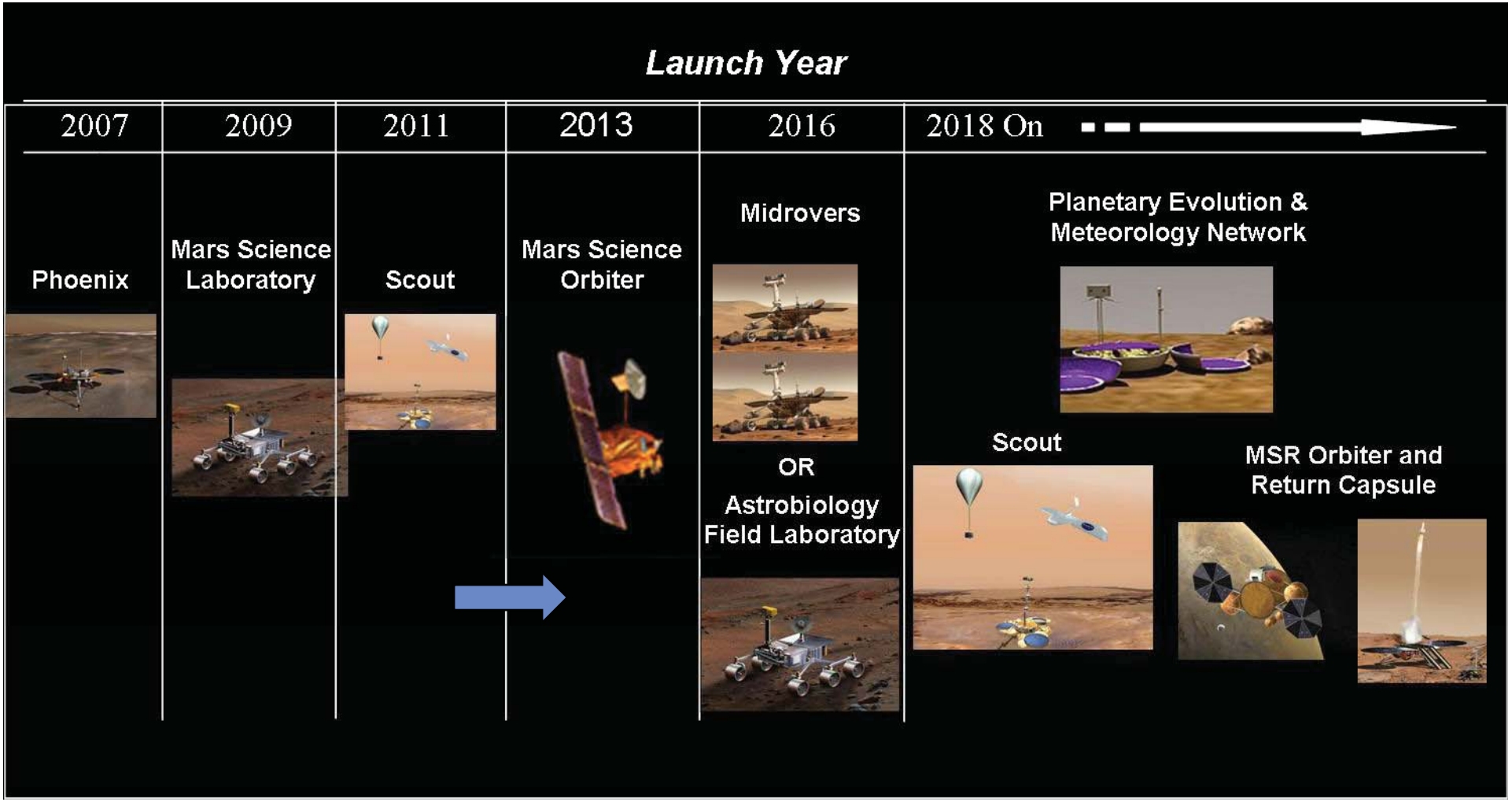




Thermal Control Challenges for Future Space Missions-1990's & 2000's

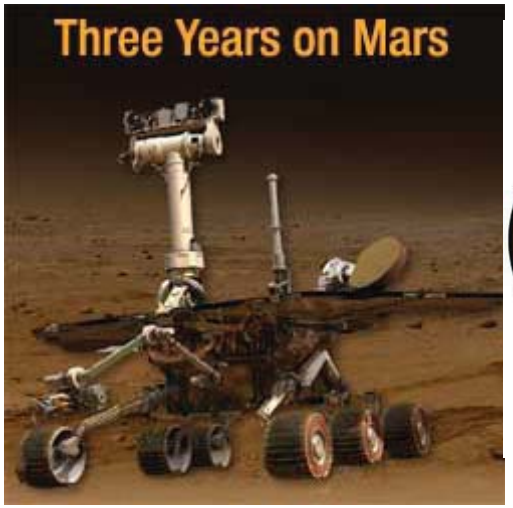
- **Mars and Lunar Surface Missions**
  - Extreme diurnal thermal environment (-129 C to 40 C for Mars and -180 to +120 C for Lunar surface)
  - Thermal management of Radioisotope Power Sources (RPS)
  - Rover mobility challenges to thermal control (configuration, dust etc)
  - Lunar Outpost and Lander Thermal Control (large scale)
- **Deep Space Science Missions** (surface Missions to other Planets)
  - Extreme environment: -180 C to 460 C & up to 100 bar (Venus, Jupiter, Titan)
  - Venus Surface Sample Mission, Jupiter Multiprobe, Titan surface mission
- **Other Space Missions -**
  - Extreme temperature stability requirement for telescopes (Space Interferometer Missions) and science instruments
  - Inflatable/deployable spacecraft requiring flexible thermal hardware
  - High heat flux removal from electronics and science instruments

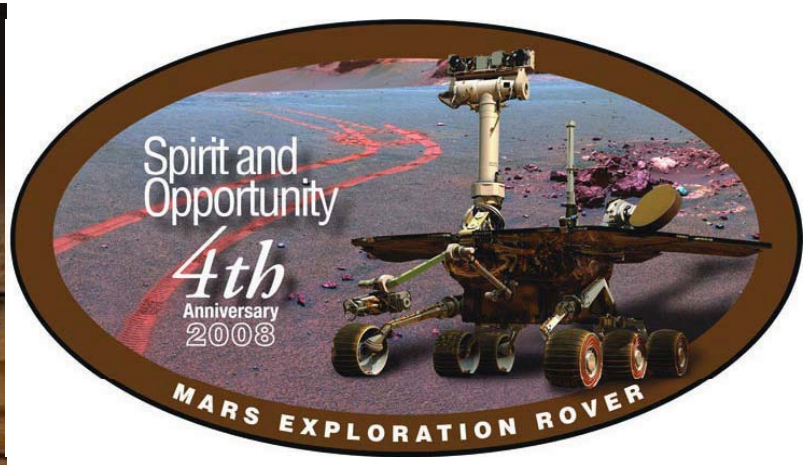
Proposed Mars Exploration Plan
(2007)



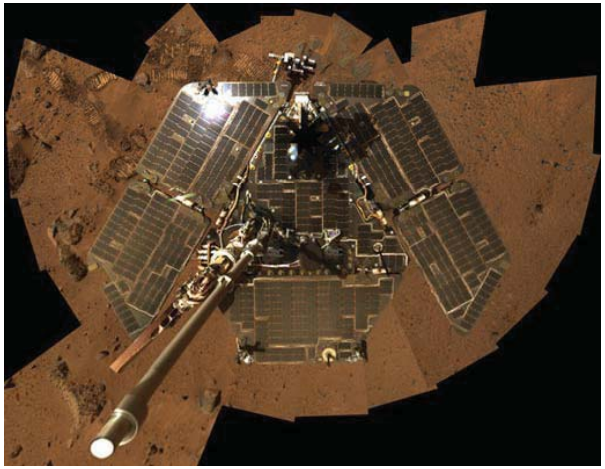
- Scout Mission moved from 2011 to 2013
- Landed part of MSR will be launched before 2020

Mars Exploration Rovers (2003)

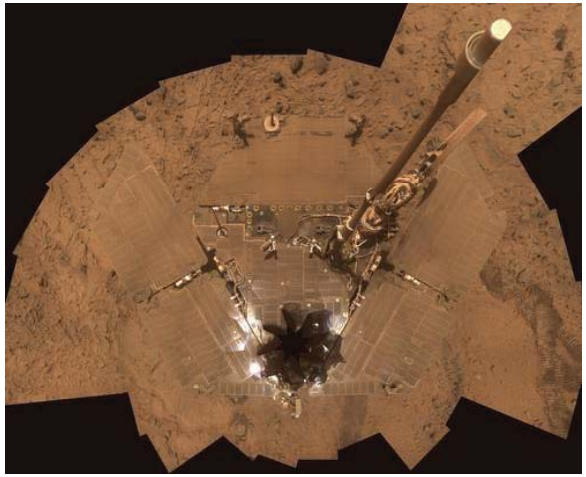




Spirit Rover 4th Anniversary
(January 4, 2008)



Spirit Rover self portrait
(Two Earth years later)

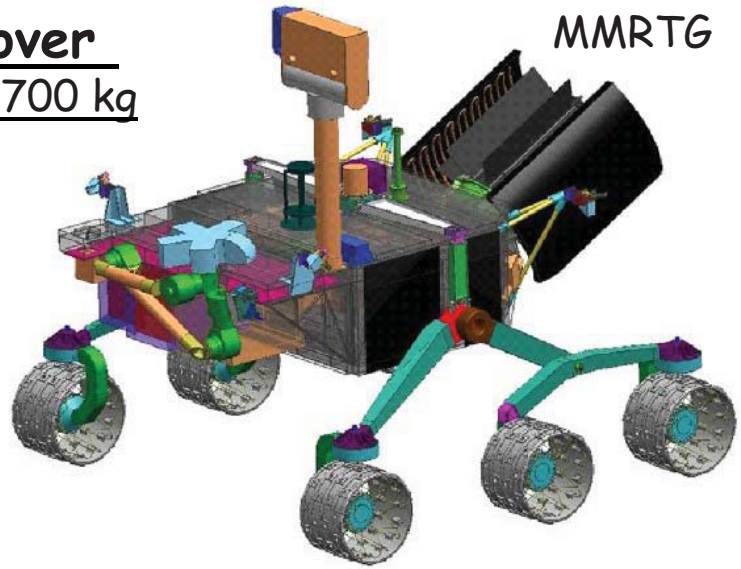


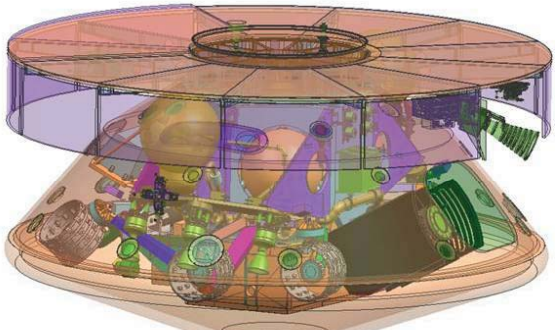
Spirit Rover self portrait
(December 10, 2007)

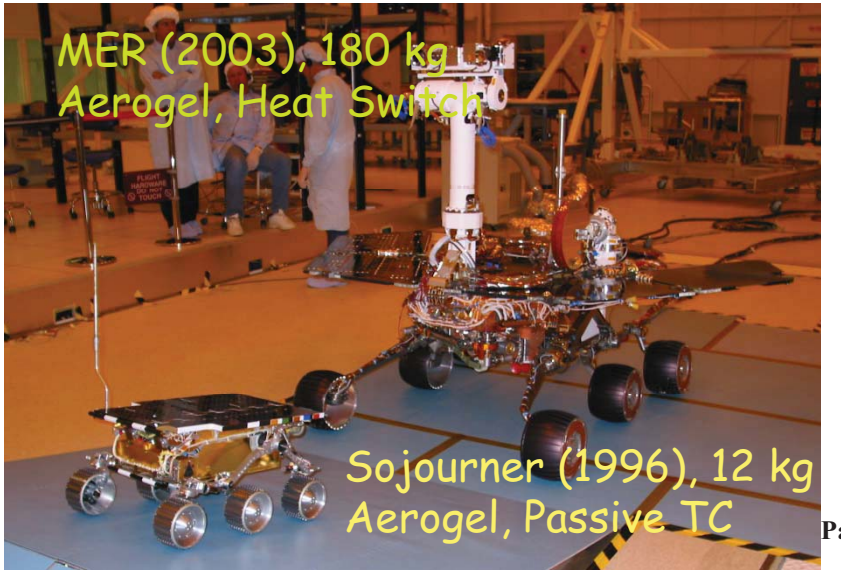
Sunset on Mars - Spirit

Mars Rovers – Past, Present, and Future

MSL Rover
(2009), ~700 kg







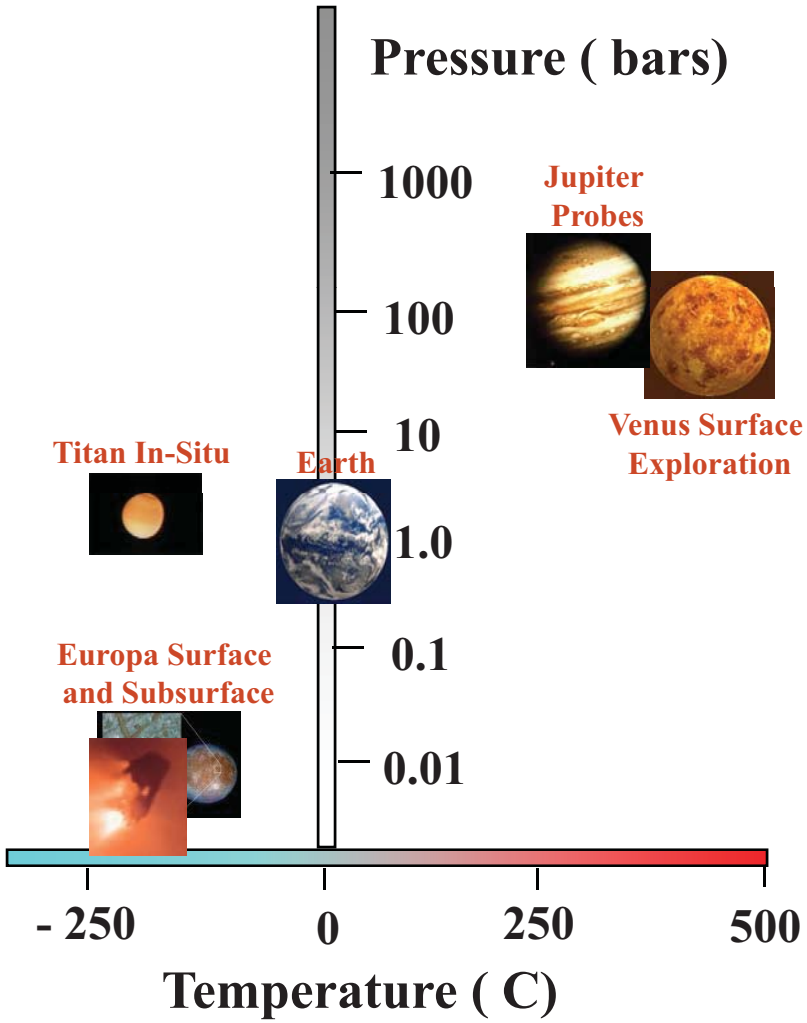
Thermal Challenges:

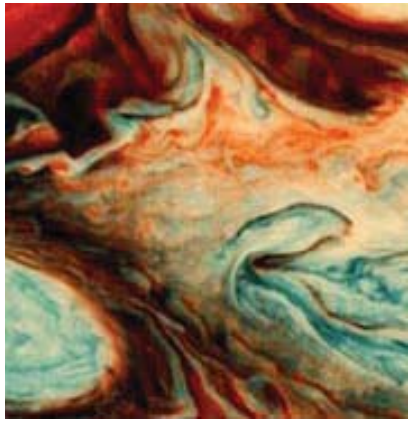
- Large thermal loads, ~2 kWt
- Long life on Mars, 2 Earth years
- MMRTG thermal management during launch, cruise, EDL, & Martian surface
- High heat flux and tight temperature requirements of science instruments and engineering equipment

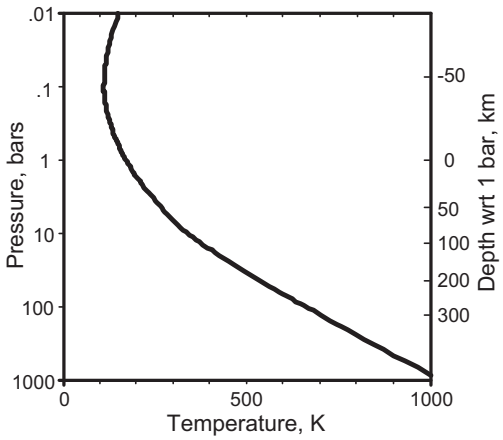
Thermal Architecture

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

Planetary Extreme Environment





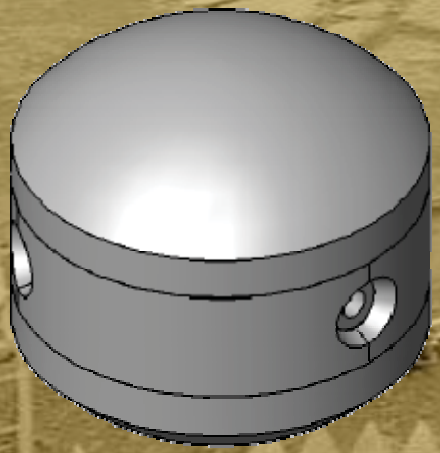


Jupiter Pressure Plot

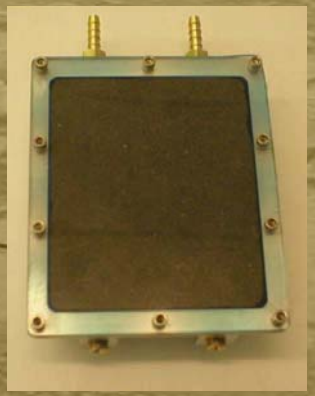
Venus Lander Thermal & Structural Technologies

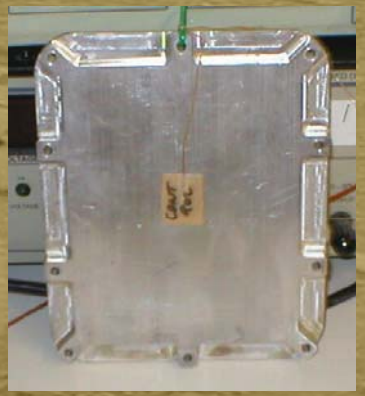
- Develop a pressure vessel and thermal control system enabling a Venus Lander Mission to survive for ~ 10 hours on surface at 100 bars and ~500°C
  - Survive 5 times longer than previous missions with passive thermal control
  - Reduce pressure vessel mass by 50% compared to previous missions with beryllium
- Thermal technologies needed are:
  - High temperature porous silica Insulation
  - Lithium Nitrate Phase Change Material thermal storage
  - Active thermal control (flow cooling) for long-term survival

Sphere Components



Insulated Sphere

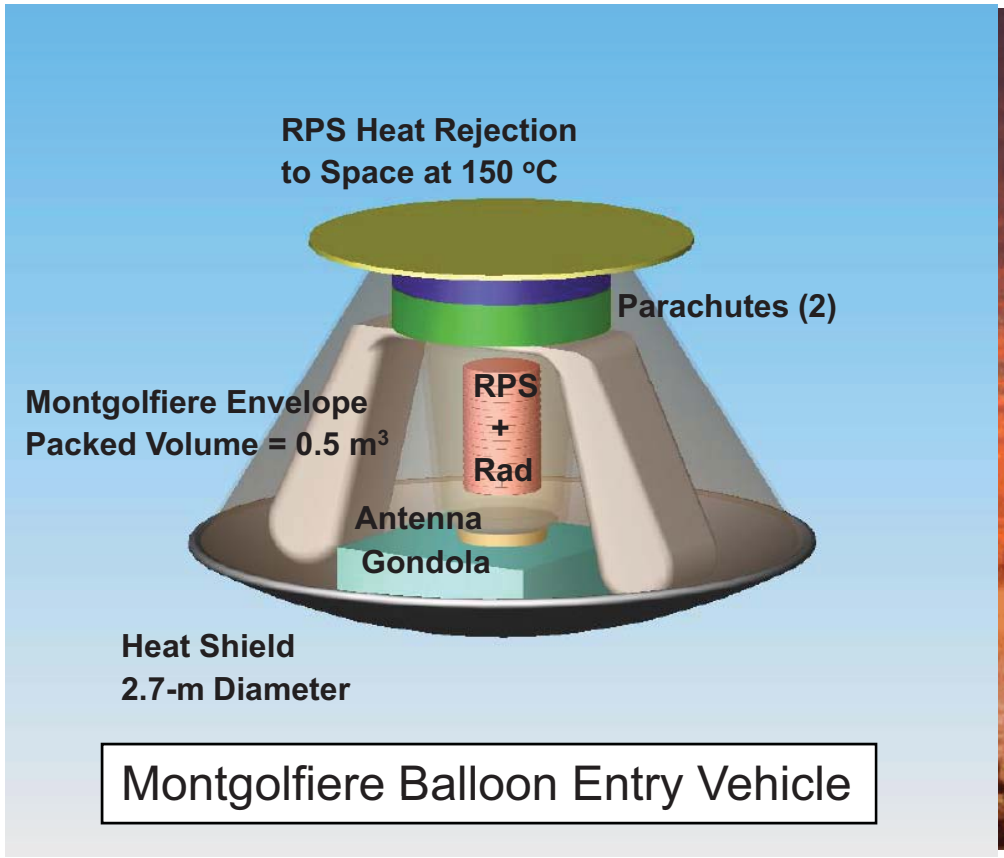




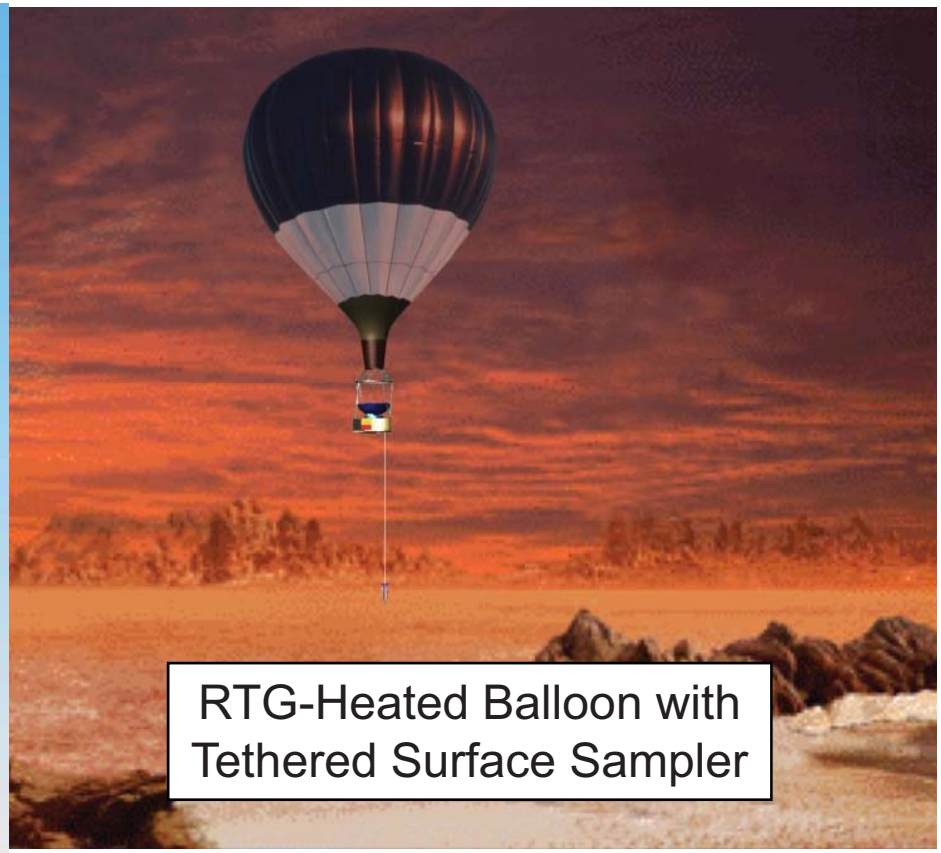
Thermal Storage Modules

Don P. Mitchell

Titan Planetary Explorer



Montgolfiere Balloon Entry Vehicle

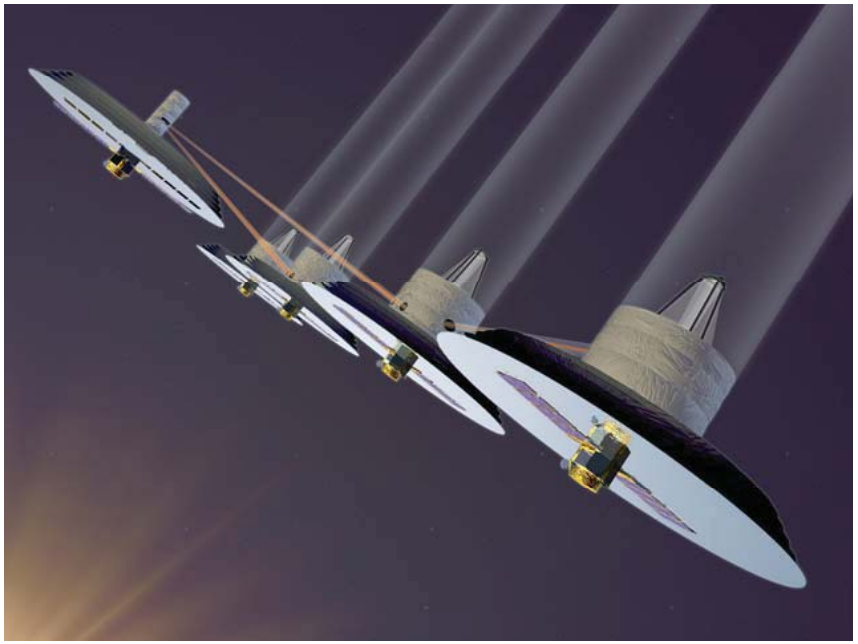


RTG-Heated Balloon with Tethered Surface Sampler

A packed balloon heated by RTG waste heat would be packaged in an entry vehicle, fill with cold (93 K) ambient nitrogen gas, and be controlled to float at any altitude between the Titan surface and about 10-km altitude. The balloon would have a tethered harpoon that would be dropped to the surface to gather water ice samples, and then retrieved and analyzed by science instruments in the gondola.

Space Interferometer Missions

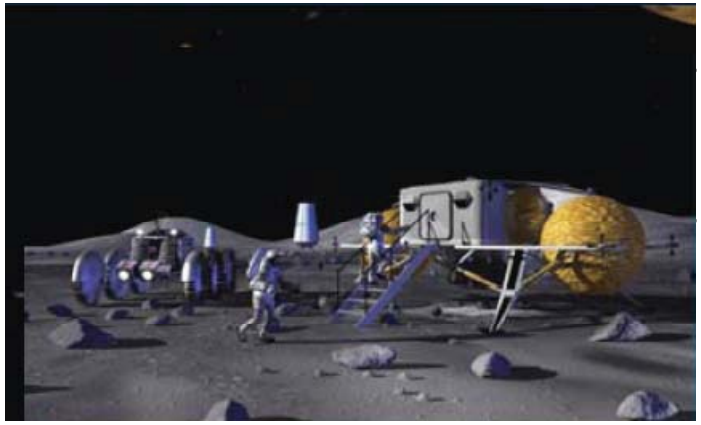
- Space Interferometer Missions and future space telescope missions need picometer accuracy and 100 micro-Kelvin/min stability



Infrared Interferometer based on formation flying telescopes

Space Interferometer Mission based on single large aperture

NASA Exploration Program – the Moon, Mars & Beyond



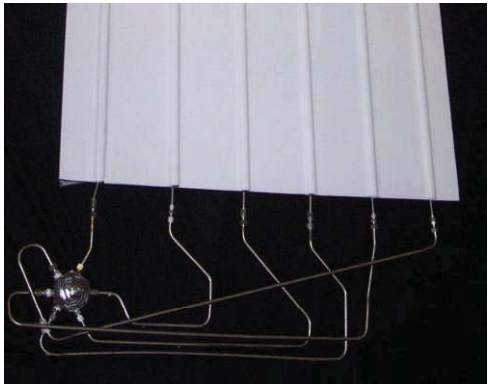
Thermal Control Challenges

- Thermal control of the Crew Exploration Vehicle (CM and SM)
- Thermal control of the Lunar Outpost, Lander, and robotic vehicles
- Challenging lunar thermal environment (large 14-day diurnal temperature swings, dust, extreme cold/hot environment)

Thermal management of large thermal loads (both equipment and human)

Passive and active thermal control technologies needed for heat collection, rejection, and transport

Thermal Control Technologies for Exploration

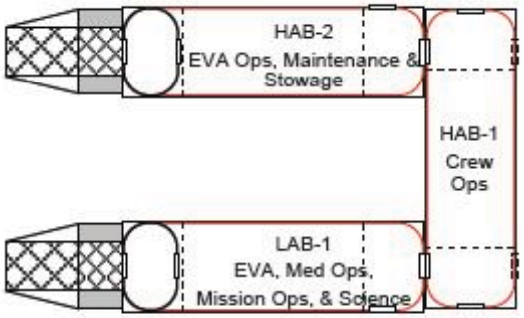


Stagnation Radiator for CEV

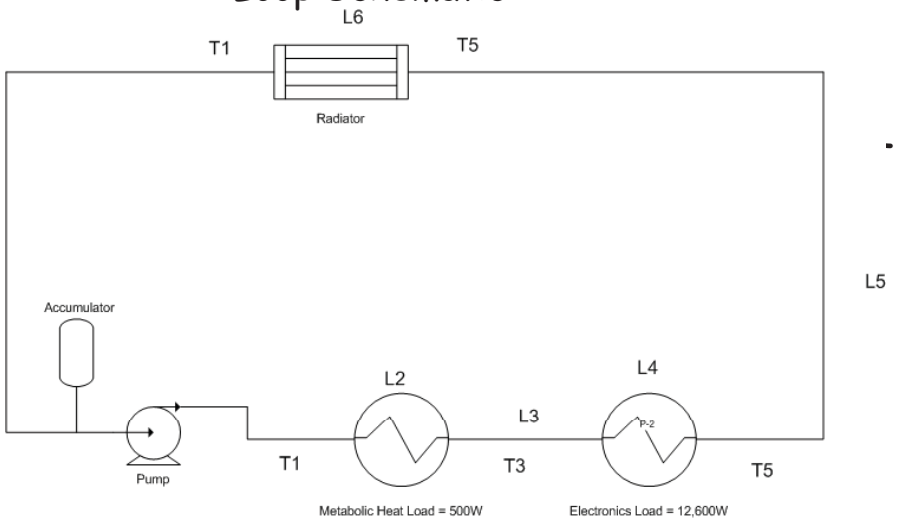
- **Thermal Control System Development for Exploration**
  (PM: Ryan Stephan, NASA/JSC,
  Co-I's: NASA/GRC, JPL, GSFC)
  - Lightweight Radiator
  - Multi-environment Evaporative Heat Sinks
  - Contaminant insensitive sublimator
  - TCS fluid for pumped loop
  - PCM phase change thermal storage

Two-Phase vs Single Phase Loop for Lunar Missions

LAT II Architecture



Loop Schematic



- **Trade Study for Exploration Missions**
  - Objective is to determine if two-phase loop trades favorably against single phase for lunar habitat, landers, and rover
    - LAT II architecture chosen
    - Ammonia fluid selected
    - Heat load of 12.6kW for habitat (+500W for metabolic load)
  - Model includes rigorous thermodynamics from NIST database (REFPROP)
  - Trades are being performed for flow rate, power levels and line lengths

L5

JPL Thermal Control Technology Roadmap

ACTIVE TECHNOLOGIES	
Long life pumps	Mars Rovers, Deep Space, Earth Orbiting, Comm. Sats.
High-temp. fluid loops	Mars Missions, Deep Space Missions
Active high heat flux and Micro-cooling Sys	Deep Space Missions, Microspacecraft, Earth Orbiting
Active Loop Architecture	Mars Missions, Lunar Misisons, CEV Thermal Control
PASSIVE TECHNOLOGIES	
Heat Pipes (LHP/VCHP)	Mars rovers, Microspacecraft, Deep Space Missions, ST-8
PCM Thermal Storage	Mars, Extreme Env. Missions (Venus)
Heat Switches	Deep Space, Mars rovers, Earth Orbiting Missions
Variable Emitt. Devices	Deep Space, Earth Orbiting, Microspacecraft Missions
High Cond. Materials	Lunar/Mars, Deep Space, Earth Orbiting Missions, SIM

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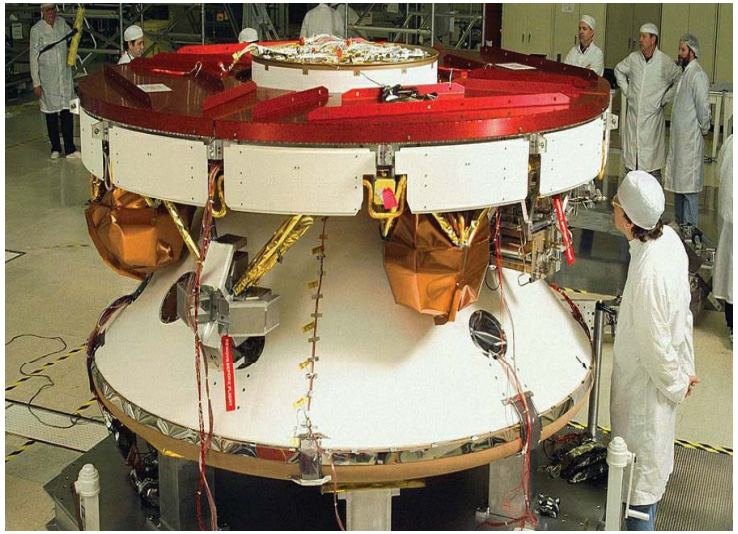
Mechanically Pumped Fluid Loops (MPFL)



Mars Pathfinder MPFL HRS (1996)

MER Integrated Pump Assembly (2003)

Description

- Mechanically pumped fluid (single-phase) loop was used on Mars Pathfinder (1996) and MER (2003) for thermal control
- A pump assembly of 7 kg uses CFC-11 to remove ~160 W from spacecraft electronics to an external radiator
- A high temperature (~100 C) MPFL is being developed for MSL rover (2009); has a heat rejection capacity ~2 KW_t)

Participants & Facilities

- JPL is investigating this technology for future Mars and deep space missions
- Engineering pump units, thermal control valves (Pacific Design Technology, Goleta, CA) are under life test at JPL

MPFL Component Development for MSL

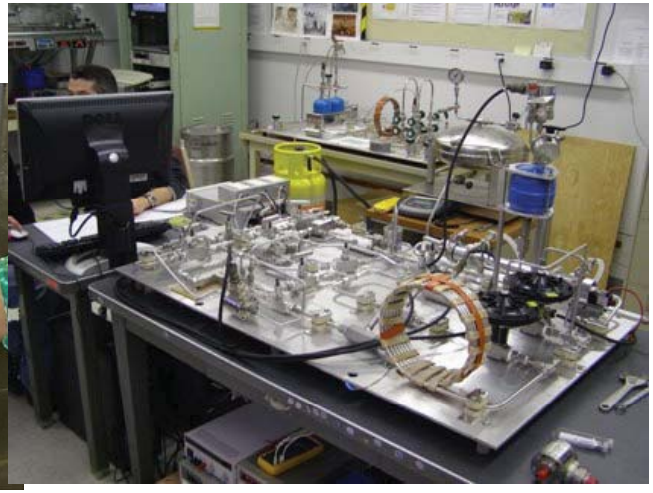
- **Pump Life Testing:**
  - MER pump >41,000 hrs (~20 C), CFC-11
  - MSL pump >21,000 hrs (15/55 C), CFC-11
  - MSL pump >2,900 hrs (120 C), water
  - MSL Pump >3000 hrs (90 C) CFC-11

- **Long-term chemical tests:**
  - CFC-11 with various material at ~100 C

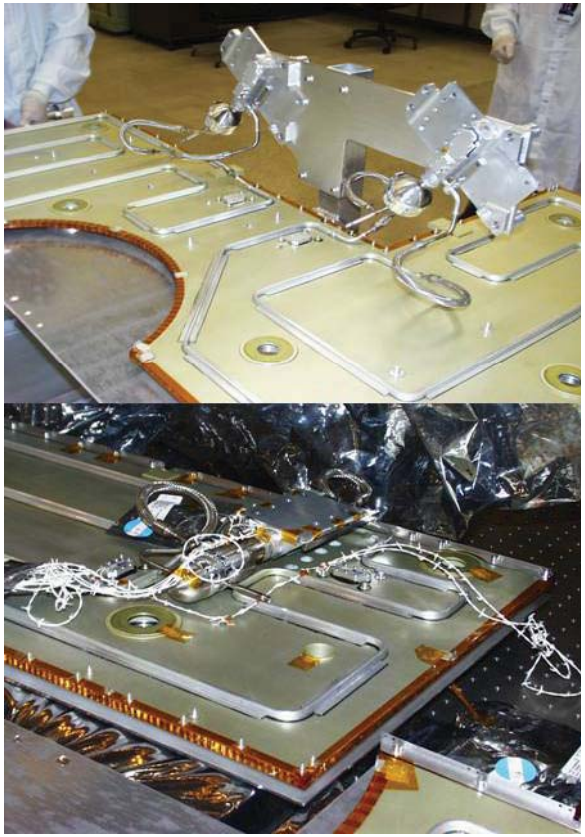
- **Thermal valves:**
  - Passive splitting type by-pass
  - Passive mixing-type by-pass

- **Mechanical Fittings:**
  - Omnisafe VCR-style joints
  - Inertial weld

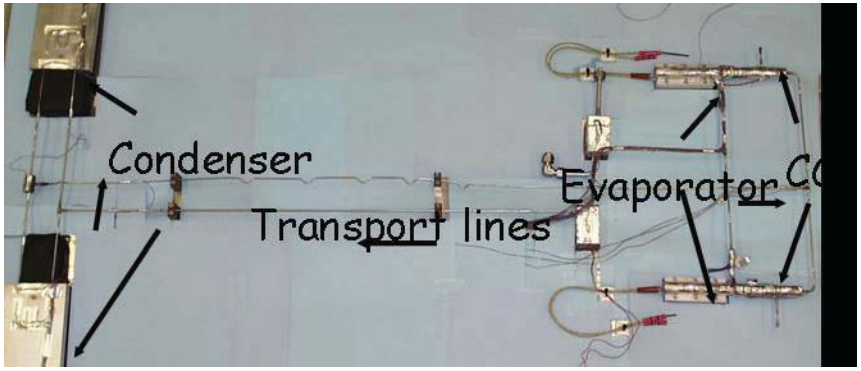
- **Working fluids:**
  - CFC-11,
  - Galden HT 70



Loop Heat Pipe Development

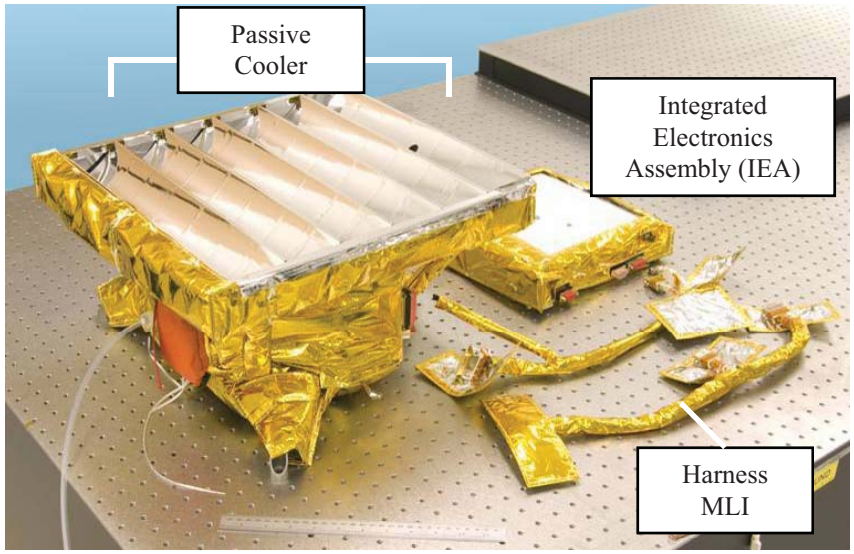


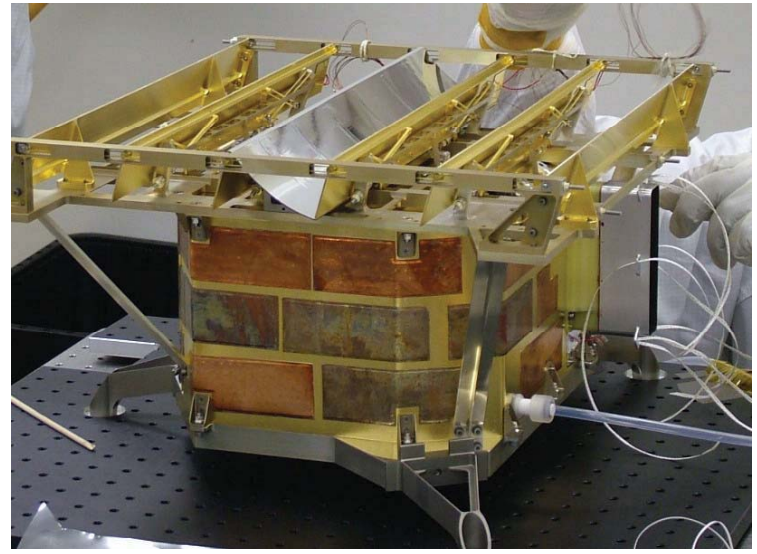
- EOS-TES is using five Propylene LHPs in the 75 to 150 W range in its thermal design (Dr. Jose Rodriguez, NASA/JPL)

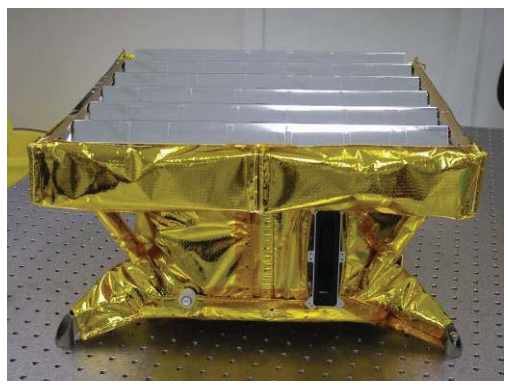


- Small loop heat pipe investigated and qualified for Mars Exploration Rover mission (MER, 2003)
- ST-8 investigating dual-evaporator LHP space experiment (Dr. Jentung Ku, NASA/GSFC)

M3 PASSIVE COOLER



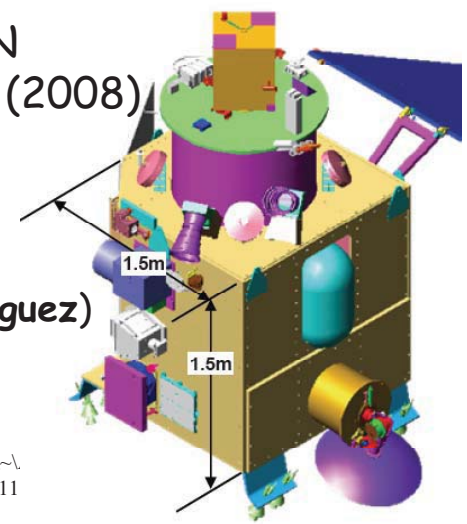




k-core composite
Radiators

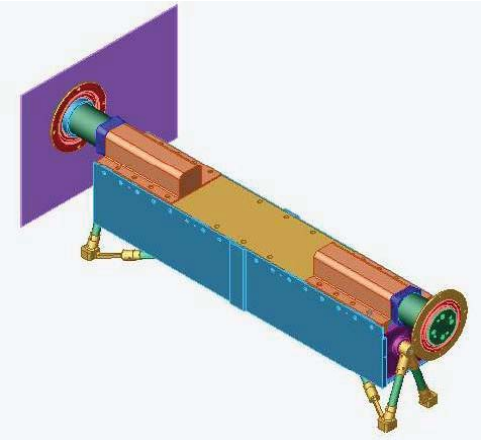
CHANDRAYAN
Lunar Orbiter (2008)

M^3 Instrument
(Dr. Jose Rodriguez)



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

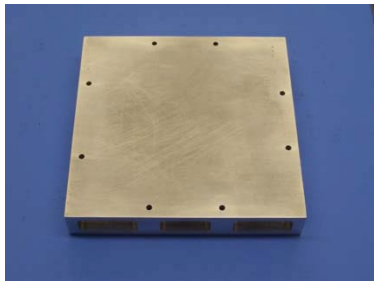
Participants & Facilities

- Wax actuated heat switch for MER was built by Starsys of Boulder, CO
- Four heat switches have been operating satisfactorily for over 1500 cycles/each on Mars on two rovers

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 (Melring point of 18 C)
  - RUBITHERM RT 35
  - Lithium Nitrate
  - Barium Hydroxide

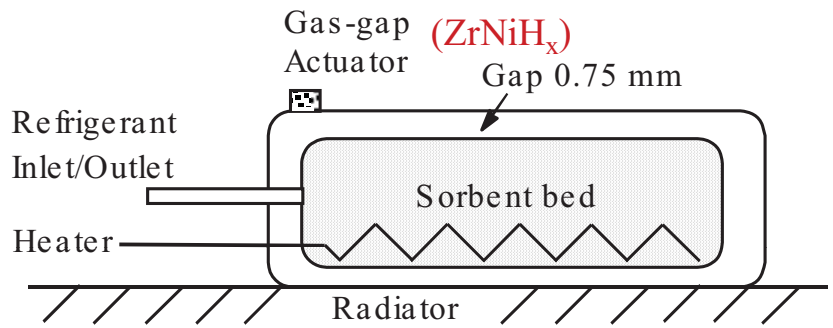
Participants & Facilities

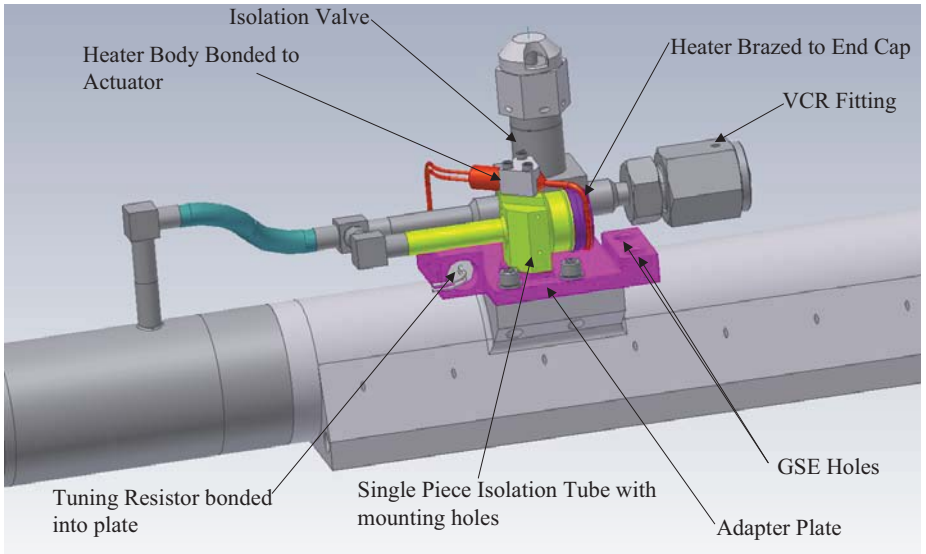
- ESLI has built Dodecane and Hexadecane PCM thermal storage units for Mars Technology program
- XC Associates has built thermal storage unit for Venus Lander Technology

$ZrNiH_x$ Gas Gap Heat Switch

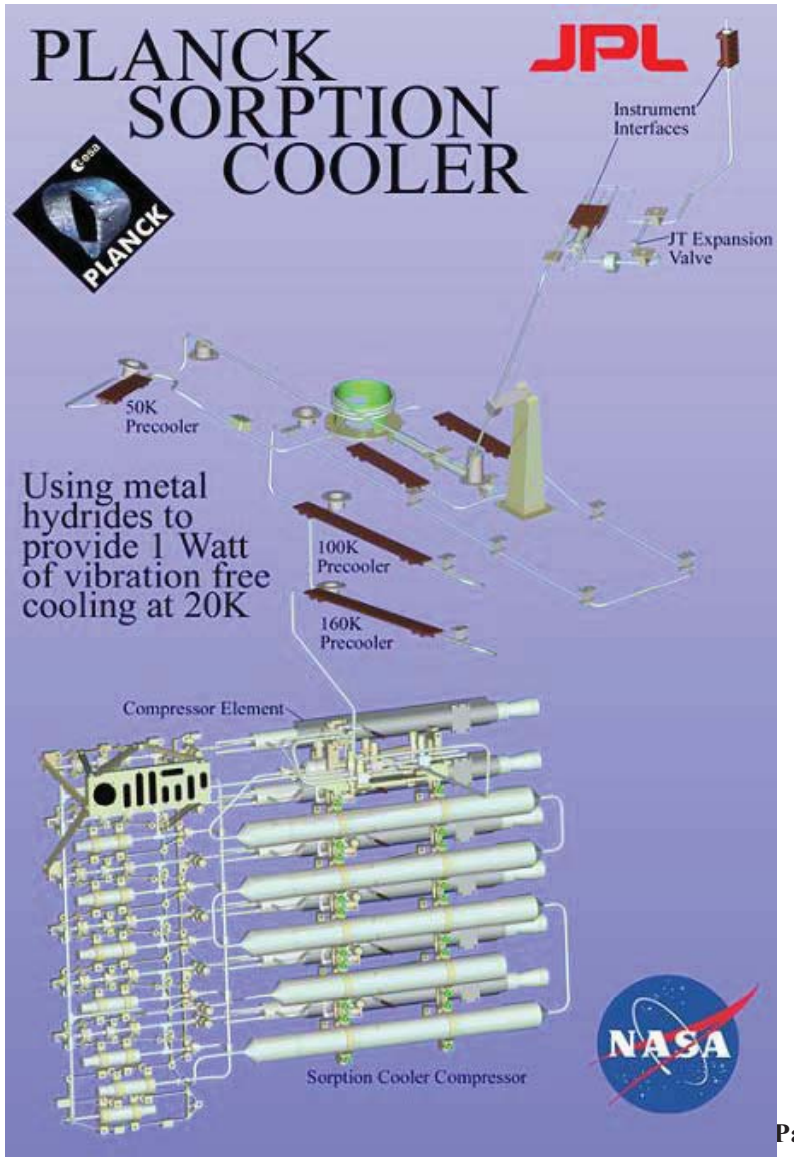
Hydride Gas Gap Actuator (GGA) developed for Planck Sorption Cooler

- 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

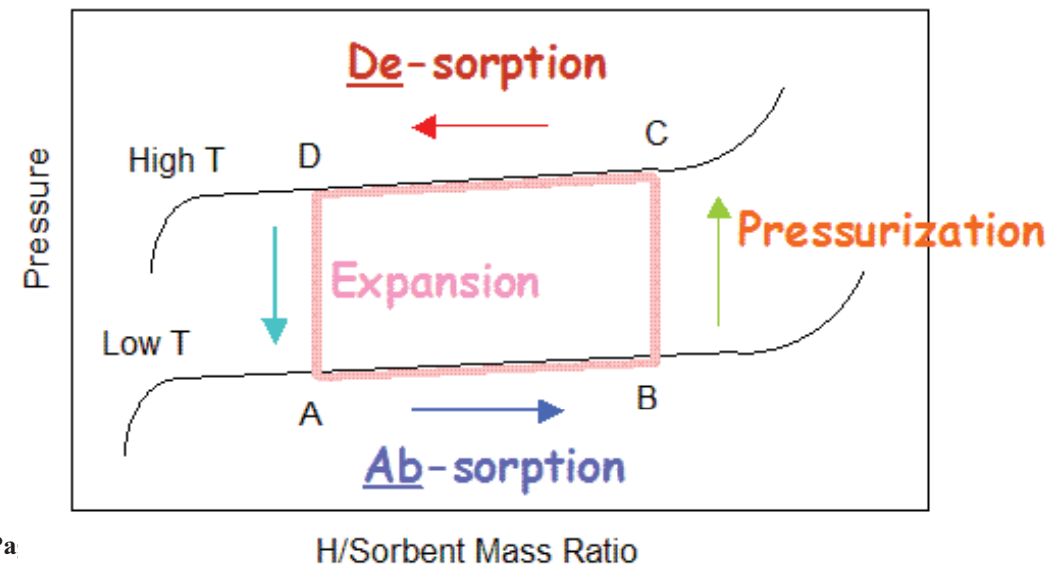




The Planck Sorption Cooler (PSC)



- 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



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Thermal Control SBIR Tasks at JPL

Phase 1

- S1.07-9924 A Thermal Switch for Space Applications (Atlas Scientific): Makes use of carbon-nanotube brush-like contacts (nanovelcro technology) to create a highly conductive thermal contact with low applied force. Cotr: Dr. Jose Rodriguez

- S1.07-8635 Thermal Pyrolytic Graphite Enhanced Components (The Peregrine Falcon Corporation), The objective of this proposal is to incorporate Thermal Pyrolytic Graphite (TPG) in aluminum-beryllium structures to enhance thermal conduction in critical areas for coolers and therefore improve cryocooler system performance without increasing the overall mass.

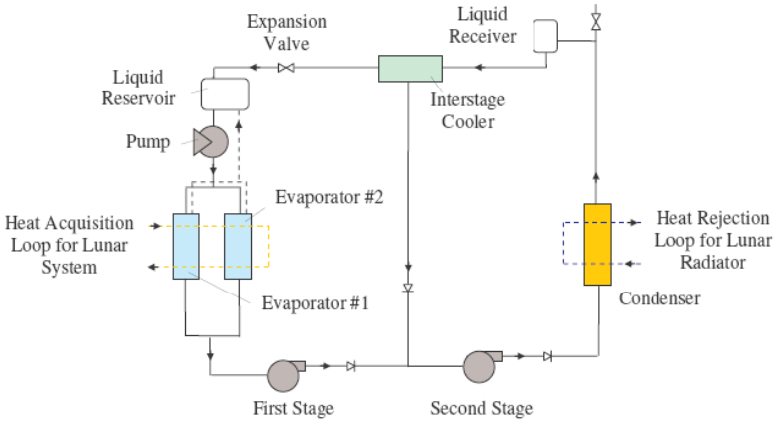
Phase II

- X11.01-8432 - Vapor Compressor Driven Hybrid Two-Phase Loop; Advanced Cooling Technologies, Inc.; COTR: Eric Sunada
- Advanced pumps for two-phase loops, Protonex Inc., Broomfield, COTR: Eric Sunada
- Lightweight and energy efficient heat pump, Rini Technologies, COTR: Eric Sunada

Vapor Compression – Hybrid Two Phase Loop

*NASA SBIR Phase II with **Advanced Cooling Technologies***

- Vapor Compression – Hybrid Two Phase Loop
  - Vapor compression heat pump
  - 2-Φ loop with an advanced evaporator capable of passive, gravity-insensitive phase separation ensuring 100% quality at the compressor inlet
  - Multi-evaporator system capable of handling high heat flux loads
  - > 60 °C temperature lift
  - > 3 kW/loop
- Participants and Facilities
  - PI: Jon Zuo, Advanced Cooling Technologies, Inc., Lancaster, PA. Jon.Zuo@1-act.com
  - NASA COTR: Eric Sunada



- Schedule and Milestones
  - 14-Feb-08: Kickoff Meeting
  - Jan-2009: Model development and subsequent optimization of component/system design complete
  - Jan-2009: High performance compressor design effort.
  - Jan-2010: Full-scale development unit built and tested
- Applications
  - Planetary missions with high effective sink temperatures
  - Lunar surface missions at the equator
  - Missions needing to minimize radiator mass and volume at the expense of compressor power

Advanced Pumps for Two Phase Cooling Loops

(SBIR Phase II)

- Integrated Motor/Pump Development for 2-φ Loops
  - Pump and motor integrated into a single compact package
  - < 12 cm^3 and <75g
  - Roller-vane (positive displacement) pump appears to be tolerant of 2-phase flow
  - Tested in a 2-φ loop using R-134a to lift up to 600W; pump input power < 10W

- **Participants and Facilities**
  - PI: Jerry Martin, Protonex, Inc., Broomfield, CO. Jerry.Martin@protonex.com
  - NASA COTR: **Eric Sunada**

- **Schedule and Milestones**
  - Dec-2008: Contract completed
  - Delivered two prototype pumps
  - Life testing is on-going. Currently > 2500 hrs.

- **Applications**
  - Spacecraft pumped fluid loops where pump may "occasionally" be subjected to two phase flow
  - Terrestrial cooling of electronics, rack mount computers
  - Smaller scale, low cost pump designs may find use in integrated cooling systems for portable electronics

Lightweight and Energy Efficient Heat Pump
(SBIR Phase I)

- Heat pump development for mid-range loads
  - Development of novel compressor for < 1kW load
  - Gravity insensitive, long life
  - Demonstrate in breadboard level heat pump with a goal of COP > 3.

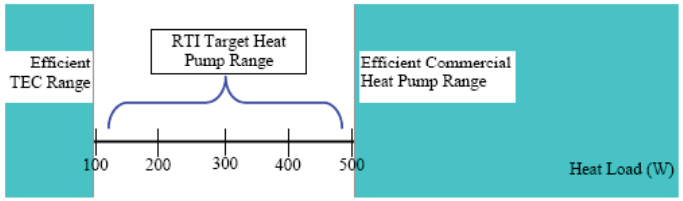


Figure 1. RTI target heat pump range for efficient operation.

- **Participants and Facilities**
  - PI: Daniel Rini, Rini Technologies Inc., Oviedo, FL; dan@rinitech.com
  - NASA COTR: **Eric Sunada**

- **Schedule and Milestones**
  - Task 1: Thermodynamic analyses
  - Task 2: Motor Selection
  - Task 3: Compressor performance testing
  - Task 4: Evaporator & cond. design & testing

- **Applications**
  - Planetary missions with high effective sink temperatures
  - Robotic missions needing to minimize radiator mass and volume at the expense of compressor power
- **Commercialization**
  - Electronics cooling
  - Personal and/or Microclimate cooling
  - Cool storage of medical or bio-samples

Conclusions

- Many of the future NASA science missions have stringent thermal control requirements that can only be met by advanced thermal control technologies

- A vigorous strategic advanced thermal technology development is key to the success of these missions

- Identifying key thermal technologies for future space missions and teaming between the industry, NASA, and Air Force Research Labs etc are key to advanced thermal technology development