Mechanically Pumped Fluid Loops for Spacecraft Thermal Control

Conceptualization:

Architecture, Characteristics & Technology

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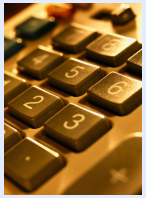
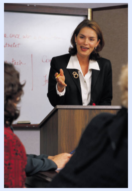
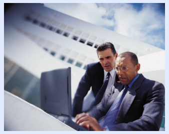
Outline of the Class

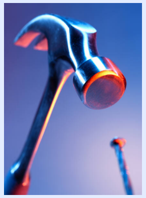
TFAWS 2012

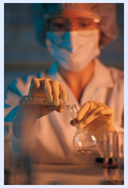
- Conceptualization


- Implementation





- Fabrication



- Observation

Outline

- Fundamental Requirements for Thermal Control of Robotic Spacecraft & Instruments
- Traditional Methods for Thermal Control of Spacecraft
- What is a Mechanically Pumped Fluid Loop?
- Why Use a Pumped Fluid Loop for Thermal Control?
- Fundamental Physics of Pumped Fluid Loops
- Basic Architecture
- History
- Working Fluids
- Key characteristics of Pumped Loop Components
- Leaks, Leaks, Leaks

Outline

(Continued)

- **Compatibility of Fluids and Wetted Materials**
- **Development Tests**
- **Past, Present & Future applications of Pumped Loops**
- **Case Study of MSL**
- **Key Factoids for MSL Pumped Loop**
- **Next Generation Loops**
- **Key Conclusions**
- **Summary**
- **Acknowledgements**

Fundamental Requirements for Thermal Control of Spacecraft

- **Primary Goal: Maintain temperatures of all components within their allowable limits with minimal complexity, maximum reliability and minimal use of resources like electrical power, mass, cost, etc.**

- **All components are thermally connected to space via the internals of the spacecraft**
- ***If one is trying to reject heat:***
  - **Pick up heat from heat sources and *eventually* reject it to space via radiation**
    - **Radiation to space is the only heat loss mechanism due to lack of an atmosphere**
- ***If one is trying to conserve heat:***
  - **Insulate the heat sources from the heat sink (use insulation)**
- ***If one is trying to supply heat:***
  - **Pick up heat from heat sources and *eventually* insert it to the component**

- **The *designing* and *controlling* of this *connection* to achieve temperature levels within each component that satisfy their allowable limits is one of the most important aspects of thermal control of spacecraft**

Fundamental Requirements for Thermal Control of Spacecraft

- **Typical Allowable Flight Temperatures**
  - **Electronics: -40/50C**
  - **Battery: -20/30C**
  - **Actuators: -55/25C (Operating)**
    -105/40C (non-operating)
  - **Propulsion Tanks: 15/30C**
  - **Propulsion lines: 15/50C**
  - **Thruster Valve: 20/110C (operate), 20/50C (non-operate)**

Traditional Methods for Thermal Control of Spacecraft

- **Typical thermal control methods rely on a** *passive connection* **between innards of the spacecraft and space**

- *Passive couplings* **could be conductive or radiative**
  - **Examples of** *conductive coupling***:**
    - **S/C metallic structure from electronics to radiator**
  - **Examples of** *radiative coupling***:**
    - **High emissivity thermal control paints, tapes**

- *Passive isolations* **could be conductive or radiative**
  - **Examples of** *conductive isolation***:**
    - **Non-metallic structure (fiberglass isolators) from electronics to radiator**
  - **Examples of** *radiative isolation***:**
    - **Low emissivity thermal control paints, tapes, Multi-Layer insulation (MLI)**

- **Louvers are radiative means to achieve variable emissivity passively**
  - **Lightweight & low profile**
  - **Very sensitive to solar exposure & contamination**
  - **Degrade emissivity and lead to larger radiator area/mass**

Traditional Methods for Thermal Control of Spacecraft

- **Conventional heat pipes are “semi-passive’ means to connect components to space**
  - **Use liquid-vapor phase change to transport heat**
  - **Superior to ordinary conductors**
  - **Can be used to conduct or isolate (Variable conductance heat pipe)**
  - **Very sensitive to gravity and tilt**
    - **Very hard to test in 1-g for complex 3-D geometries**

- **Loop heat pipes (LHPs) are significant improvements of conventional heat pipes**
  - **Much less sensitive to gravity degradation**
  - **Sensitive to start-up and shutdown logistics**
  - **Multiple evaporators/condensers need some additional proving**
  - **Hermetic systems (need to integrate spacecraft/instrument around them)**
  - **Delicately balanced performance (need to be tuned)**

- *Active* **means of achieving** *variable connections*
  - **Heat Switches**
    - **Heavy and low heat flow capacity**
- *Active* **means of** *supplying/removing* **heat for T/C**
  - **Heaters with Thermostats/PRTs**
  - **RHUs**
  - **Thermoelectric coolers**

History of Thermal Control of Mars Spacecraft

JPL

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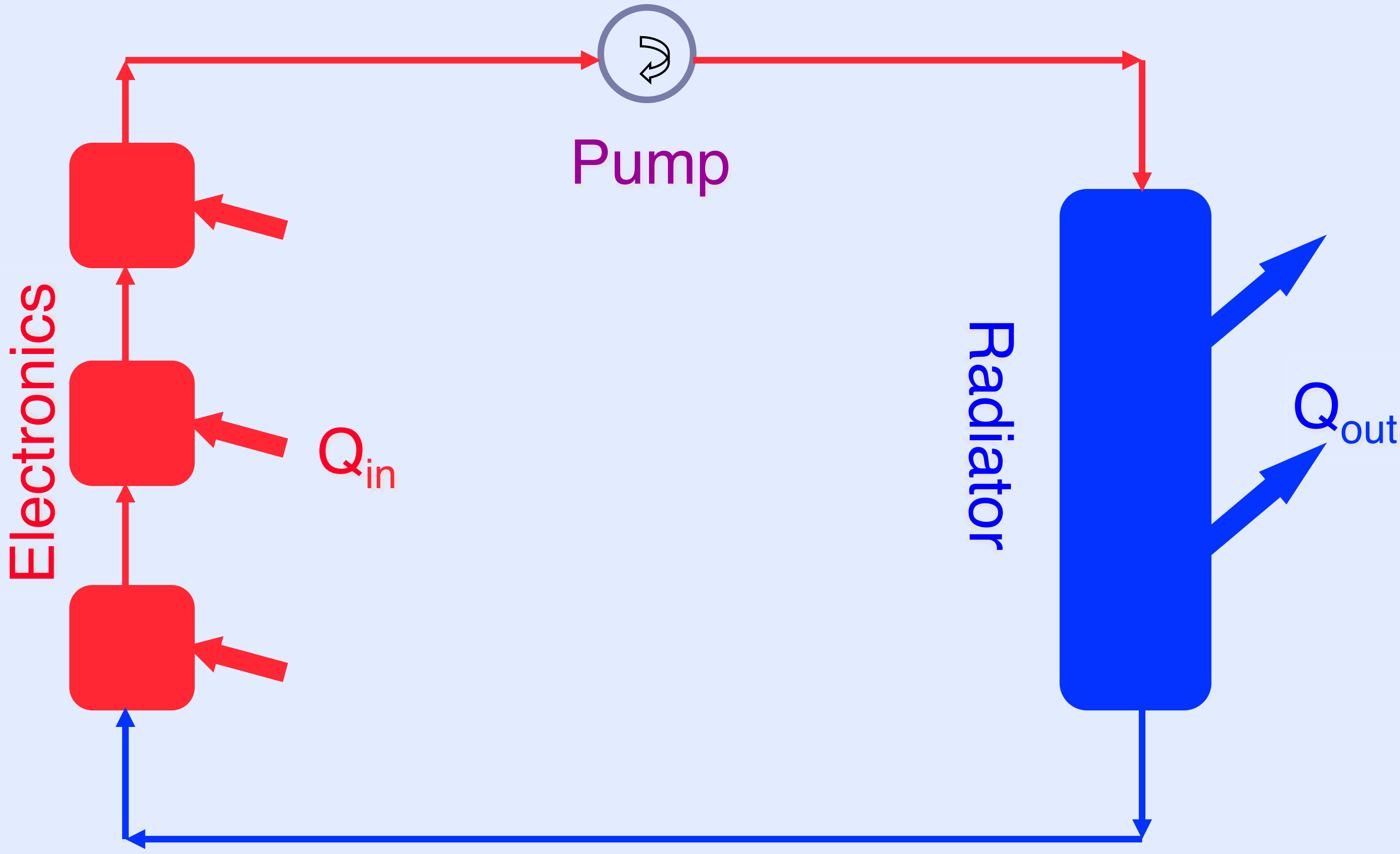
Mission	Launch	Cruise	EDL	Surface
Viking	Active	Passive	Passive	Passive
	Fairing Purge Cooling	Radiative	Thermal Capacitance	Heat Switch
Mars Pathfinder	Active	Active	Passive	Passive
	Fairing Purge Cooling w/MPFL-HRS	Cruise MPFL-HRS	Thermal Capacitance	Thermal Capacitance
Mars Polar Lander	Active	Passive	Passive	Passive
	Fairing Purge Cooling	Radiative	Thermal Capacitance	Thermal Capacitance
MER	Active	Active	Passive	Passive
	Fairing Purge Cooling w/MPFL-HRS	Cruise MPFL-HRS	Thermal Capacitance	Thermal Capacitance
MSL	Active	Active	Passive	Active
	Fairing Air-Conditioning w/MPFL-HRS	Cruise & Rover MPFL-HRSs	Thermal Capacitance	Rover MPFL-HRS

MPFL = Mechanically Pumped Fluid Loop
HRS = Heat Rejection System

What is a Pumped Fluid Loop?



How is a Pumped Fluid Loop Different from Traditional Means?

- **The key difference between traditional means of T/C and the use of mechanically pumped fluid loops lies in the** *connection* **between the** *thermally controlled components* **and the** *heat loss surface* **(radiator)**
- **The connection is** *convective* **instead of** *conductive* **or** *radiative*
- **Fluid flowing through tubes connected to the two sets of surfaces (source/sink) convectively picks up heat (source) and dissipates it (sink)**
- **A mechanical pump is the prime mover of the fluid**
- **This is the closest one comes to a true THERMAL BUS where we can BOTH pick-up and reject heat simultaneously and automatically at multiple locations**
- **Until now only** *single phase* **fluid flow using** *liquid* **has been tried for interplanetary spacecraft**
- **Future missions could used two phase flow for higher watt densities**
  - **Use liquid-vapor phase change within heat source**
  - **Condense vapor in heat sink**
  - **Use liquid (only) within pump to create pressure difference**

Why Use a Pumped Fluid Loop?

- Mechanically Pumped Fluid Loops (MPFL) are most useful for spacecraft thermal control when heat pickup/rejection capacity, control of this capacity, testability and/or mechanical integration are driving factors
- Advantages when compared with traditional spacecraft thermal control technologies:
  - Scalability of heat rejection capacity
  - Ability to accept and reject heat at multiple locations
  - Flexibility in locating heat dissipating equipment
  - Adaptability to late changes in spacecraft design
- Their use in robotic space missions has been limited earlier due to reliability concerns, but are increasingly being used recently (last 15 years) to solve complex thermal control problems
  - Mars Pathfinder (Cruise), 2x Mars Exploration Rovers (Cruise) and Mars Science Laboratory (Cruise + Rover) used Heat Rejection Systems based on pumped fluid loops

Pros of Pumped Fluid Loop

PROS:

- **Integration flexibility -** Easily adaptable to previously defined geometrical configuration
- **Predictablity -** Thermal and hydraulic analysis is very simple and predictable
- **Testability -** Ground testing is very easy and performance can be easily fine tuned
- **Robustness and Controllability -** Very tight temperature control (few deg. C) of remotely located components possible with widely varying power dissipation and thermal environment
- **Heat fluxes -** Can handle high local fluxes (e.g., electronic components; ~ 3 W/in length of 1/4" dia. fluid tubing)
- **Isothermality -** Small ΔT between source and sink (electronics and radiator)
- **Thermal switchability -** Valving, turning off pump or venting working fluid provides reversible/irreversible switching
- **Deployability -** Using flexible tubing (e.g., Teflon flex lines)
- **Resource usage -** Compact, light, cheap and low power usage
- **Versatility -** Can be used for a variety of diverse missions

Cons of Pumped Fluid Loop?

POSSIBLE CONS and Preventive Measures:

- ***Any of the following causes could lead to partial or complete failure of the thermal control system***
  - **Leaks - Leaks through mechanical joints or corrosion of tubing/ components**
    - Use well qualified fittings
      - Vibration/thermal
      - Accumulator sized to accommodate nominal leak rates
  - **Pump failure - Long term operation of pumps could degrade their performance or lead to their complete failure**
    - Use redundant pumps
  - **Clogged filter - Filters used to guard small passages in pumps against particles could clog**
    - Use well qualified and sized filters
    - Use check valves to automatically bypass filter in flight

Thermal ***Bus*** Architecture

(***Supply*** as well as ***Reject*** Heat)

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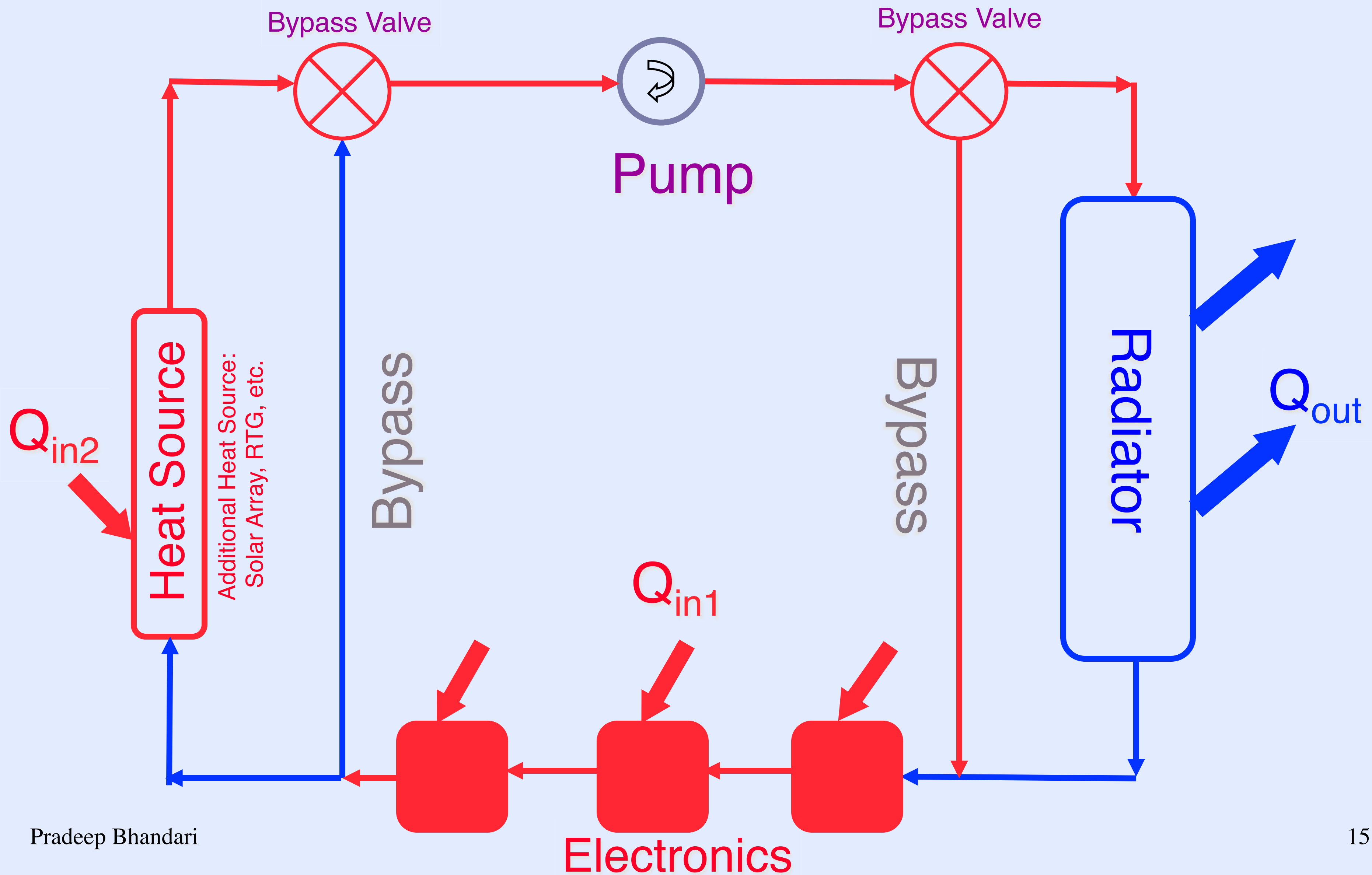
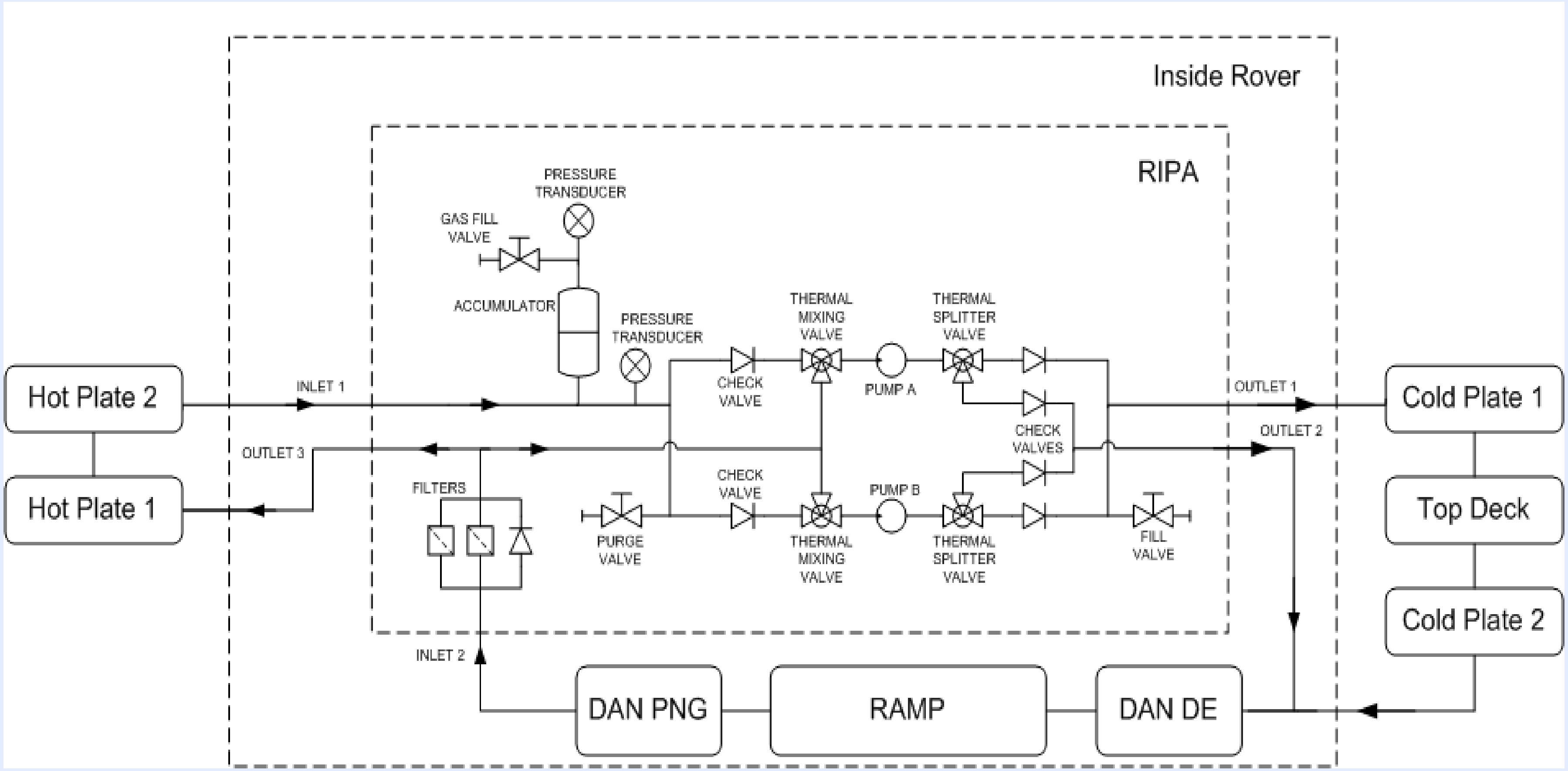


Basic Architecture of Integrated Pump Assembly



Fundamental Physics of a Pumped Fluid Loop

- **The Fundamental Physics is Really *Very* Simple!!**
  - *Barely need an undergraduate degree to design it!*
  - *Hardly need a sophisticated computer model*
    - *Hand calculator & EXCEL will suffice*
  - **Loop Pressure drop:** $\Delta P = \Sigma f(L/D)\rho V^2/2$
  - **Flow Heat transfer coefficient** $= (k/D)0.023Re^{0.8}Pr^{0.33}$
  - **Heat Pickup**
    - **Aluminum face-sheet (component interface)**
    - **Use simple fin efficiency to estimate delta-T from tube surface**
  - **Heat Rejection**
    - **Radiator**
    - $Q = mC_p\Delta T = AF\varepsilon\sigma(T^4 - T_s^4)$ **for fluid temp. drop (high rad. flow, hot cases)**
    - **Use Radiant fin equation for sizing thickness**

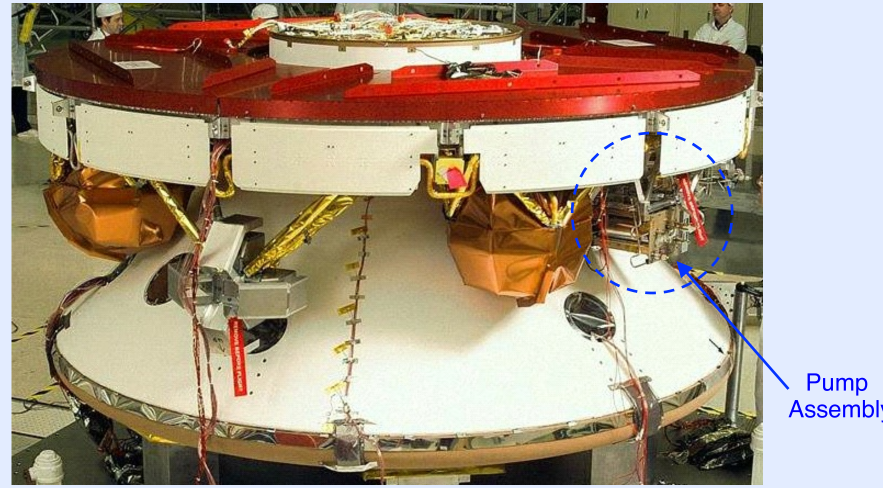
- **Most of the effort goes into engineering and qualifying the system to be reliable and robust**

History of Mechanically Pumped Fluid Loops @ JPL

- **Mars Pathfinder (JPL, 1996) was the 1st Interplanetary Spacecraft to use a mechanically pumped cooling loop for thermal control during cruise**
- **Mars Exploration Rover (JPL, 2004) used a similar design adapted to its configuration, also during cruise** *(2 missions)*
- **Mars Science Laboratory (JPL, 2011) employs *two* mechanically pumped fluid loops for thermal control**
  - **During cruise & launch to cool the Radioisotope Thermo-Electric Generator (RTG) which generates 2000 Watts of heat**
    - **Also for thermal control of several electronic components in the cruise & descent stages**
  - **For thermal control of the rover**
    - **For** *both* **heating and cooling**
    - **For** *both* **cruise and Mars surface operations**
    - **Harvests waste heat from the RTG for cold conditions**
    - **Uses radiators to maintain rovers temperatures during hot conditions**
  - **1st instance of using pumped fluid loop as a *Thermal Bus* to** *supply* **as well as** *pick-up* **heat from electronics**

Mechanically Pumped Fluid Loop for Robotic Missions

Mars Science Lab Spacecraft & Rover



Mars Pathfinder Spacecraft

Mars Exploration Rover Spacecraft

Pumped Fluid Loops in NASA (non-JPL) Missions

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Skylab
(methanol-water)

NSTS (Space Shuttle)
(water/CFC-21)

International Space Station
(water/ammonia)

Criteria for Selecting Working Fluids

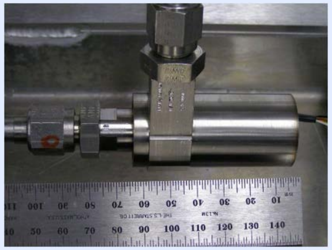
- **Temperature Limits:**
  - Low freezing point (~ < -100°C)
  - High critical temperature (> 150°C)
- **System Operational Pressure:**
  - Moderate to low vapor pressure at high temperature (< 200 psia)
- **Thermo-physical Properties:**
  - High specific heat → Lower required mass flow
  - High thermal conductivity → Smaller delta-T between fluid and component
  - Low viscosity → Lower pressure drop in loop (pump)
- **Material Properties:**
  - Chemical compatibility, degradation of fluid over time
- **Heritage:**
  - Space applications (NASA, Aerospace Industry), Terrestrial applications
- **Handling:**
  - Easy to handle in air conditioned environment, non-toxic, non-explosive, non-flammable

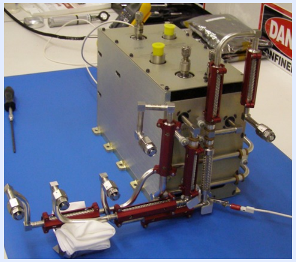
Working Fluid Comparison

Working Fluid	Liquid Temperature Limits (°C)	Freezing Point (°C)	Normal Boiling Point (°C)	Vapor Press. @ 200°C (psia)	Specific Heat (J/kg-C)	Thermal Conductivity (W/m-C)	Viscosity (Pa-s*10^4)	Heritage
CFC-11	-111 to 180	-111	24	~650	Low (883)	Low (0.09)	Low (4.4)	MPF, MER, MSL
Water	0 to 370	0	100	225	High (4180)	High (0.61)	Med (9)	NASA STS ISS
Therminol LT	-75 to 315	-75	181	24	Med (1800)	Low (0.125)	Med (9)	Chemical Processing Industry
Syltherm XLT	-100 to 260	-111	177	30	Med (1750)	Low (0.1)	High (14)	JPL Laboratory chillers
Galden HT-55	-110 to 170	-110	55	?	Low (970)	Low (0.065)	Med (7.4)	GSE Chillers for MSL

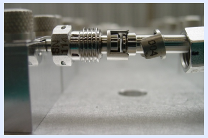
Typical Characteristics of Components in Pumped Loop

- **Pumps**
  - The prime mover of fluid
  - Typically centrifugal
  - Dedicated drive electronics
  - Journal bearings, all welded construction
  - Redundant set used for reliability

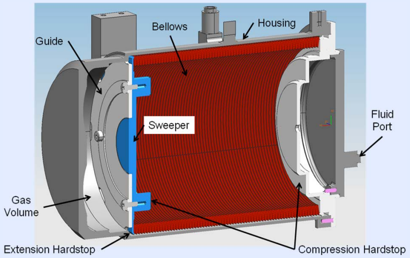




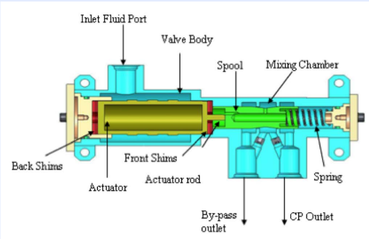
- **Filter**
  - Protects pump bearings from particles
  - Typically uses a check valve in parallel to bypass filter if it saturates in flight
- **Mechanical Joints**
  - **Prevention of leaks is of paramount importance!!!**
    - Entire system is hermetically sealed (welded) except for few mechanical joints (~20-50) for system integration
    - Light, ease of in situ integration, robust for repeated integration/de-integration, repeatable performance, integrity to survive launch



- **Accumulator**
  - Gas charged with bellows separating gas from fluid
  - Accommodate total max. system liquid volume changes during mission
  - Maintains pressure in system throughout mission to prevent
    - Local boiling at every location
    - Cavitation in pumps
    - Excessive pressures (<MEOP)

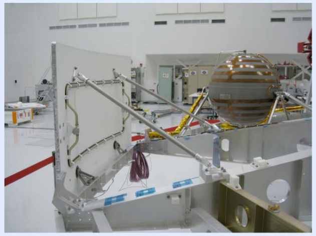


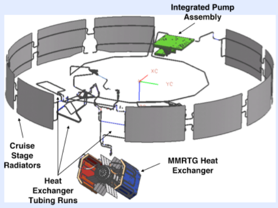
- **Thermal Control Valves**
  - Used to control direction of flow towards or away from radiator **(heat sink)**
  - Or to direct flow towards or away from hot plates **(heat source)**
  - **Passive** (wax or liquid actuated) – no power required
  - Pre-set control temperature
  - Change in operating temperatures automatically expands or contracts actuator
    - Which then opens or closes ports connected to tubing directed towards heat radiator or hotplate



Typical Characteristics of Components in Pumped Loop

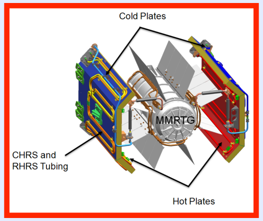
- **Check Valves**
  - Spring loaded (small cracking pressure)
  - Isolate redundant pump from flow path
  - Bypass particle filter, if it gets saturated

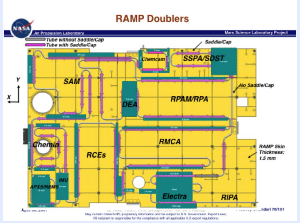




- **Radiator**
  - Rejects heat to space
  - Metallic (Alum) Plate: welded, glued or brazed to fluid tubing

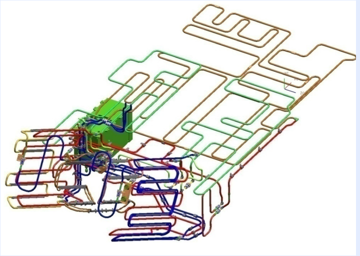
- **Hot Plate**
  - Pick up heat from heat source
  - Metallic (Alum)





- **Component Mounting/Interface Plate**
  - Thermally controlled component mounting interface
  - Loop tubing bonded/brazed to this plate

- **Tubing**
  - **Aluminum (for heat transfer)**
    - Used in heat transfer areas
      - Heat pickup and rejection
    - Lighter
  - **Stainless Steel (for transport of fluid)**
    - Non-heat transfer areas
    - Maximum compatibility with working fluids
    - Heavier



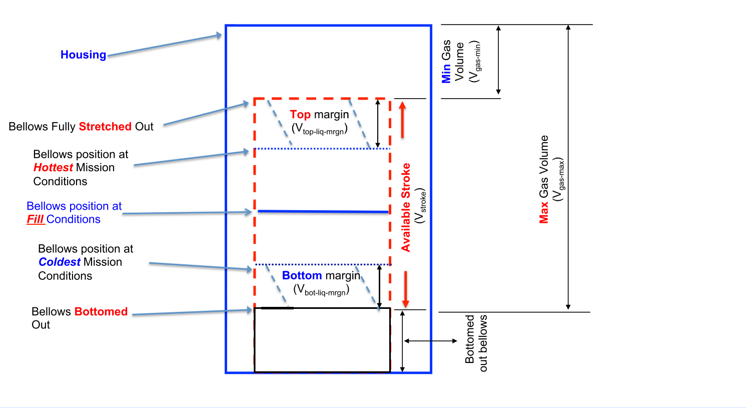
- **Pressure Transducers**
  - Monitor system pressure during test, launch, cruise and surface operations
  - Use to charge liquid and gas in system

Basic Process & Relationships to Design Accumulators
(Liquid Volume Sizing)

- **Change in density of liquid with temperature**
  - **$dV_l/dT = (d\rho_l/dT)_T$**
  - **Determines required *minimum* stroke of bellows**

- **Accounting for nominal leak through fittings, volume errors & margins**

- **Provides *total* required bellows**

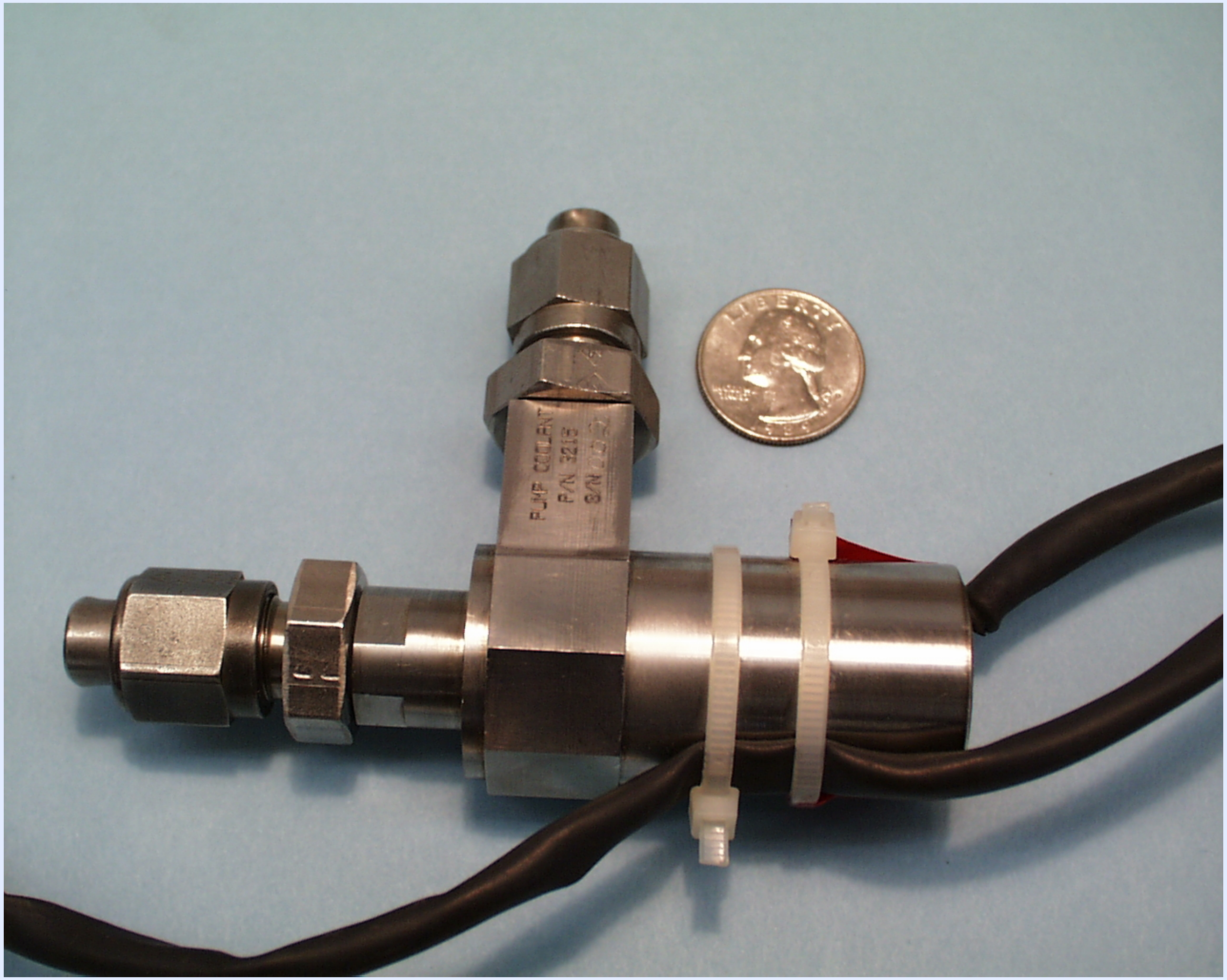


Key Factors Affecting Control of Operating Pressures During Mission

- **Boiling**
  - Liquid pressure > Saturation vapor pressure at local temperatures for all conditions
  - Single phase system
  - Based on Structural integrity of accumulator assembly

- **Pump Cavitation**
  - Local liquid pressure – Saturation Vapor Pressure > NPSH
    - NPSH = Net Positive Suction Head (~30 psi or 0.2 MPa for CFC-11)
  - Required for adequate pump performance
  - Avoid damage to impeller

Mars Pathfinder Centrifugal Pump



- Journal Bearings
- Hydro-dynamically Lubricated
- 12,000 rpm
- 250 g
- All Stainless Steel construction
- Permanent Magnet embedded in Rotor
- Hall Sensors and rotating magnetic field in Stator
- Pacific Design Technologies (PDT)Manufacturer

Leaks, Leaks and Leaks!

- Single most important part of the design of pumped fluid loop is the prevention of leaks!
  - Leaks of sizes larger than accumulator is sized for would be catastrophic
    - Could lead to mission failure
- System is of a welded construction as much as possible
- Mechanical joints used sparingly - only when integration requires them
  - Keep number of mechanical joints less than ~20-50
- Size Accumulator to accommodate nominal leak rates via joints
- Use highest quality - leak wise - mechanical joints
- Attractive Mechanical Joints
  - Swagelok VCR & Omnisafe (Swagelok like design with no torque on joint)
    - Most leak tight ($<10^{-8}$ scc/s He; used in MSL)
    - Heavier & needs welding to tube ends
    - Robust to repeated mates/de-mates
  - A-N (B-Nuts)
    - More leaky ($<10^{-4}$ scc/s He; used in Pathfinder/MER)
    - Lighter, does not need welding to tube ends (swaged)
    - Not robust to repeated mates/de-mates
  - Ring Seals (O-Rings on A-N)
    - Less leaky than A-N, but has soft O-rings (compatibility questions)
- Take mechanical joints out of load paths
  - Provide stress relief bends in tubing near joints
  - Brace joints by splines
- Qualify, Qualify, Qualify
  - Thermal and Vibrational
  - Leak tests

Compatibility of Fluids & Wetted Materials

- **Long term compatibility of materials in wetted path paramount**
- **Typically designed to last 1 to 3 years or more**
- **Extremely low moisture content in Freon-11 systems is very critical**
  - Typically < 10 ppm desirable
  - 100 ppm (saturation) leads to extensive corrosion
- **Stainless steels (e.g., 316 L) are very attractive**
  - Good compatibility with Freon-11
  - Automatic tubes welding applicable (robust welds)
  - Heavier and less conductive
- **Aluminum is also very attractive from thermal and mass standpoint**
  - Compatibility similar to SS
  - Hand welding required (not as robust as Automatic Tube Welding)
- **For water based fluid systems, ultra pure (DI) water very desirable**
  - Some anti-corrosion additives would inhibit corrosion
    - But would require trade-off with thermo-fluid properties
- **Motor/Pump material list to be carefully examined to ensure extreme compatibility with working fluid**

Development Tests

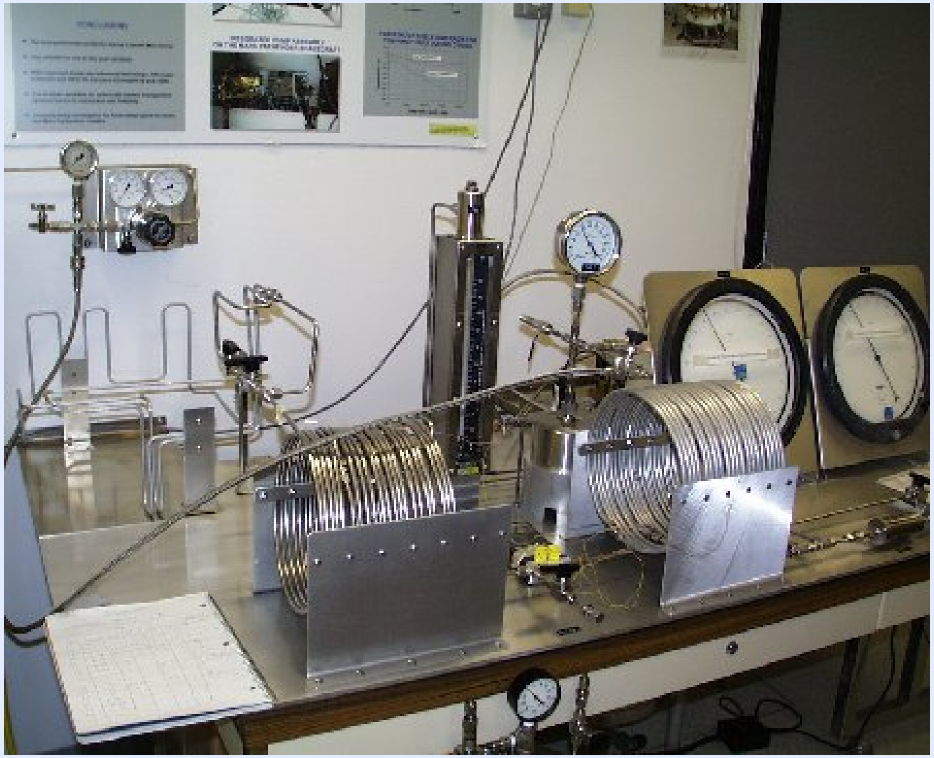
- **Thermal-Hydraulic**
  - Simulate Electronic Shelf & Radiator To Validate Thermal And Hydraulic Performance Models

- **Leaks:**
  - Simulate Thermal Cycling & Launch Flexing Of Fittings To Investigate Leak Potential -- Leak Rates Very Low (< 10^{-8} scc/s He)
  - Measure Leak Rate Of Freon Through Flex Lines -- Small Leak Rate
  - Accumulator Size Adequate To Accommodate Measured Leak Rates

- **Material Compatibility:**
  - Freon Moisture Tests
  - All Materials In Contact With Freon Underwent Long Term Compatibility Tests With Varying Levels Of Moisture (Al, SS, VITON, etc.)
  - Extremely Important To Minimize Moisture To Prevent Corrosion; Elaborate Safeguards Taken In Freon Storage & Loading Process

ΔP/Flow Design Verification for MER

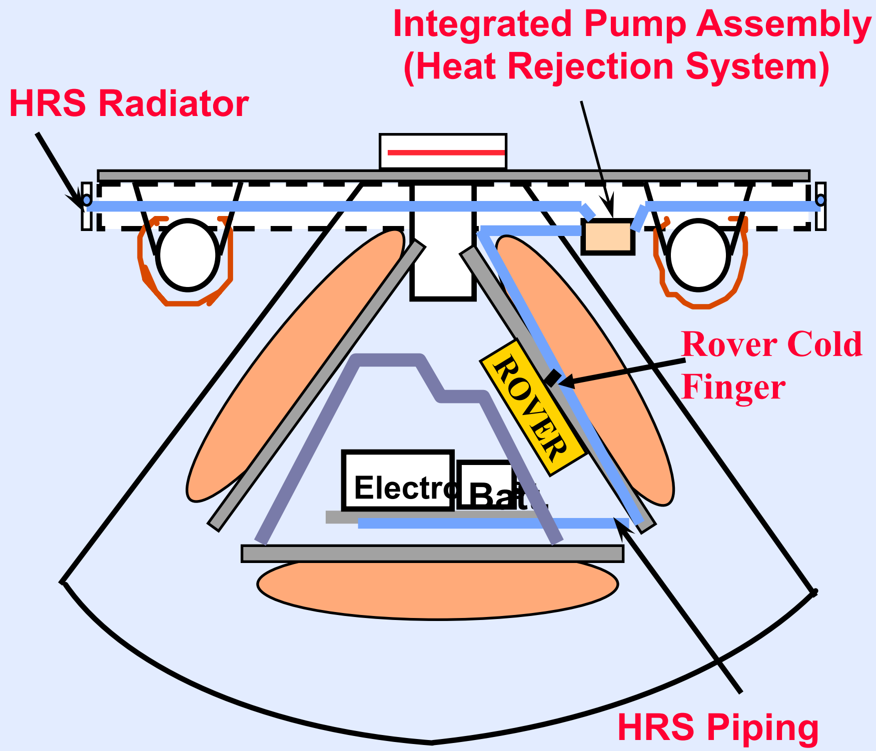
Hydrodynamic Test Setup at Integrated Pump Assembly Level



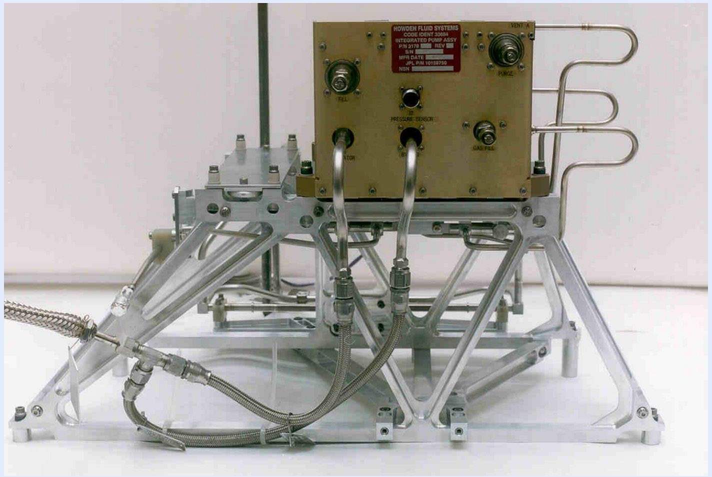
Front View of Test Stand

Side View of Test Stand

Mars Pathfinder (MPF) (*Past*)

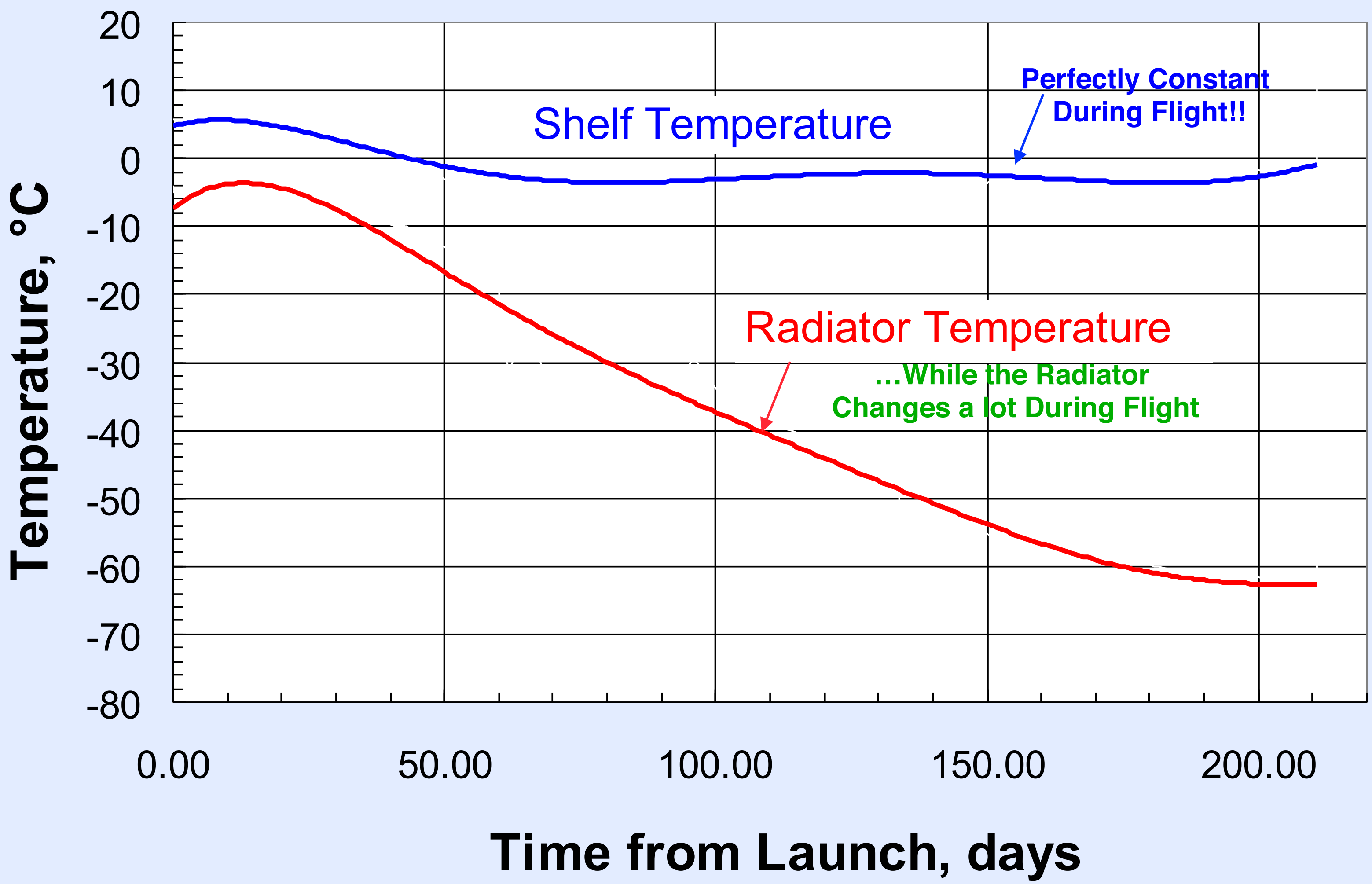


- Working Fluid: CFC-11
- Pressure rise: 4 psid
- Flow rate: 0.2 gpm
- Power: 10 Watts
- HRS mass: ~20 kg
- Heat rejected: 150 Watts

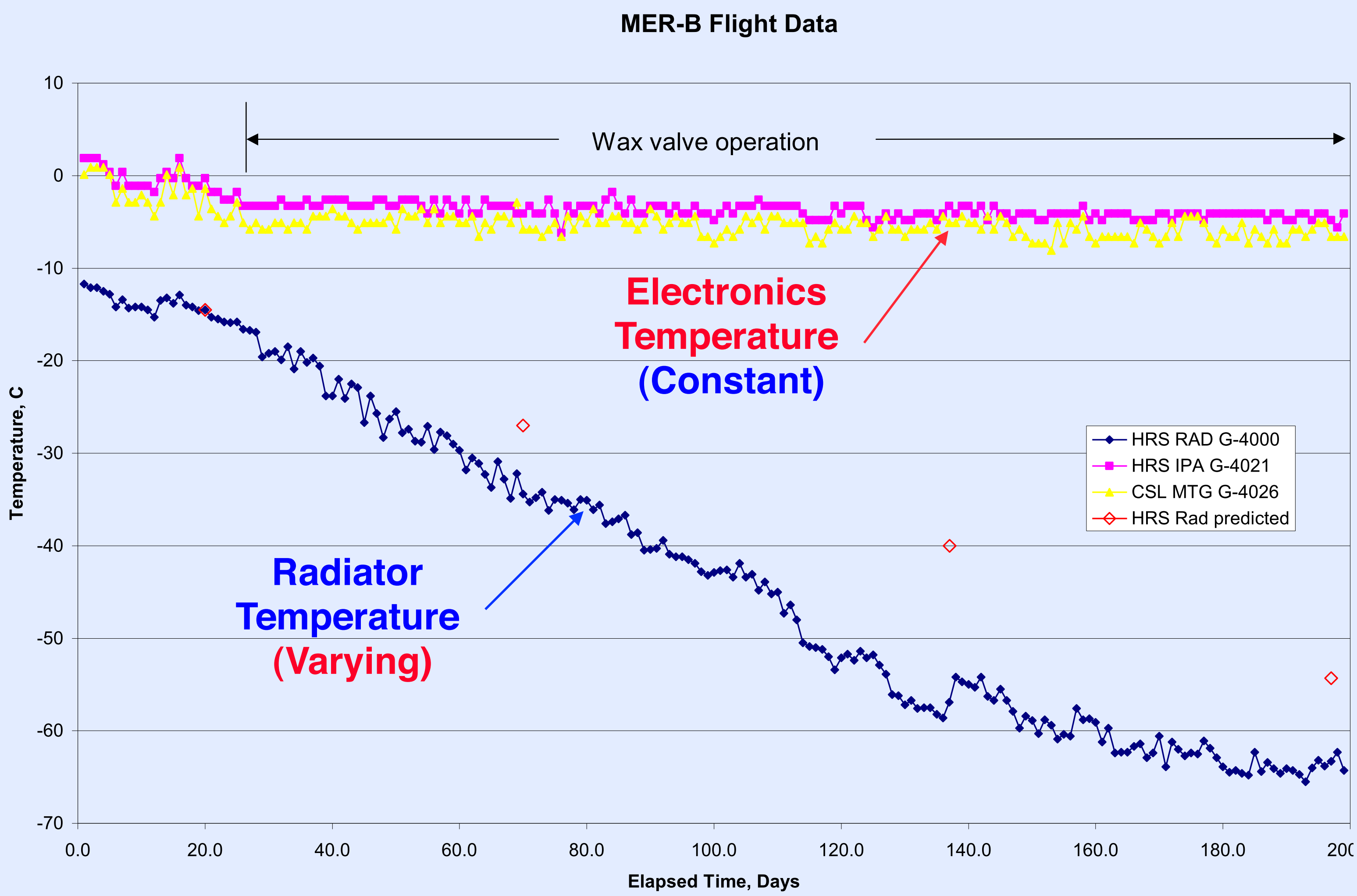


MPF HRS Pump Assembly

MPF Electronics Shelf Temperature During Flight

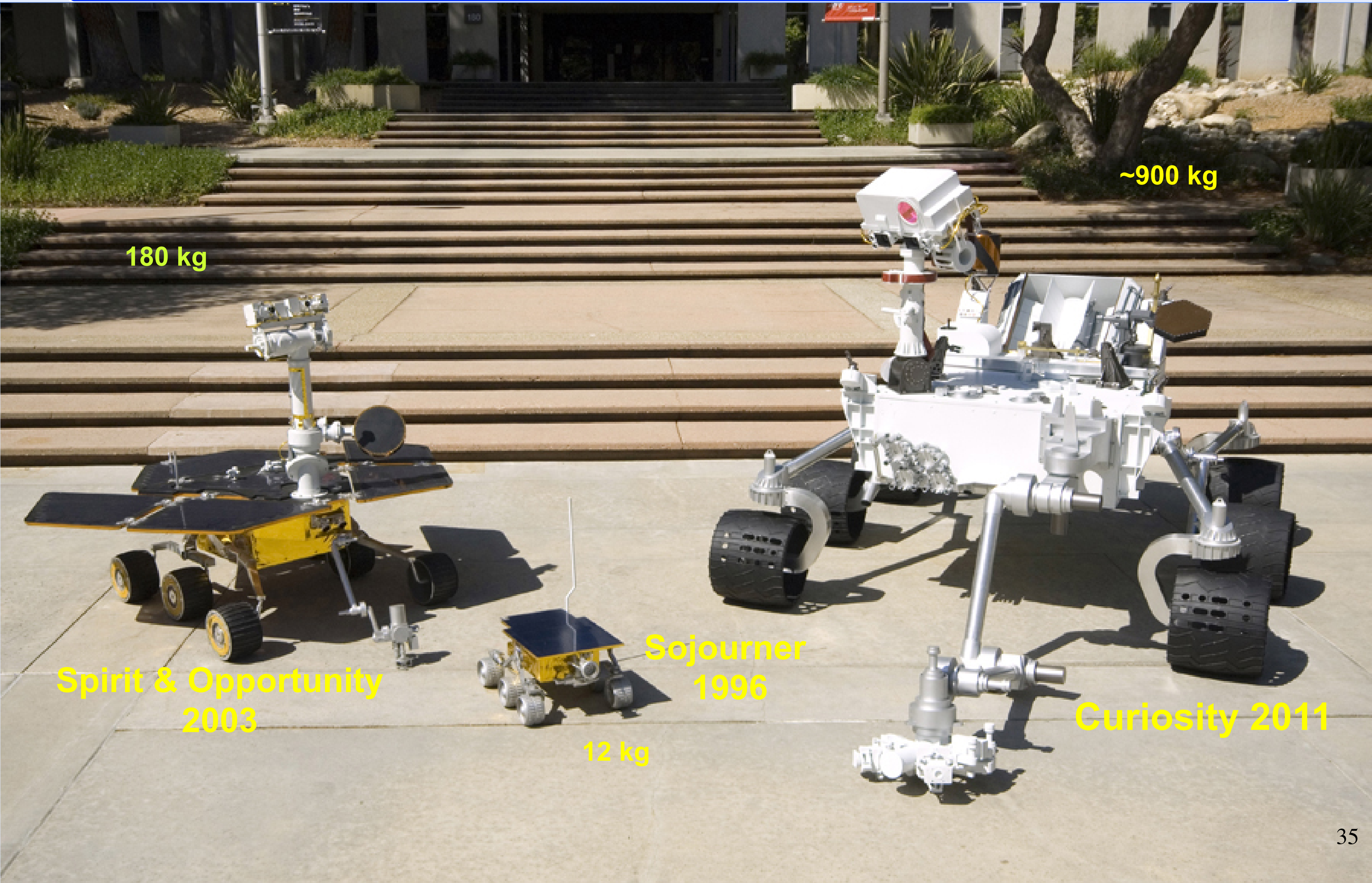


MER Electronics Temperatures During Flight



Rover Family Portrait

- All Employed HRS for Thermal Control!



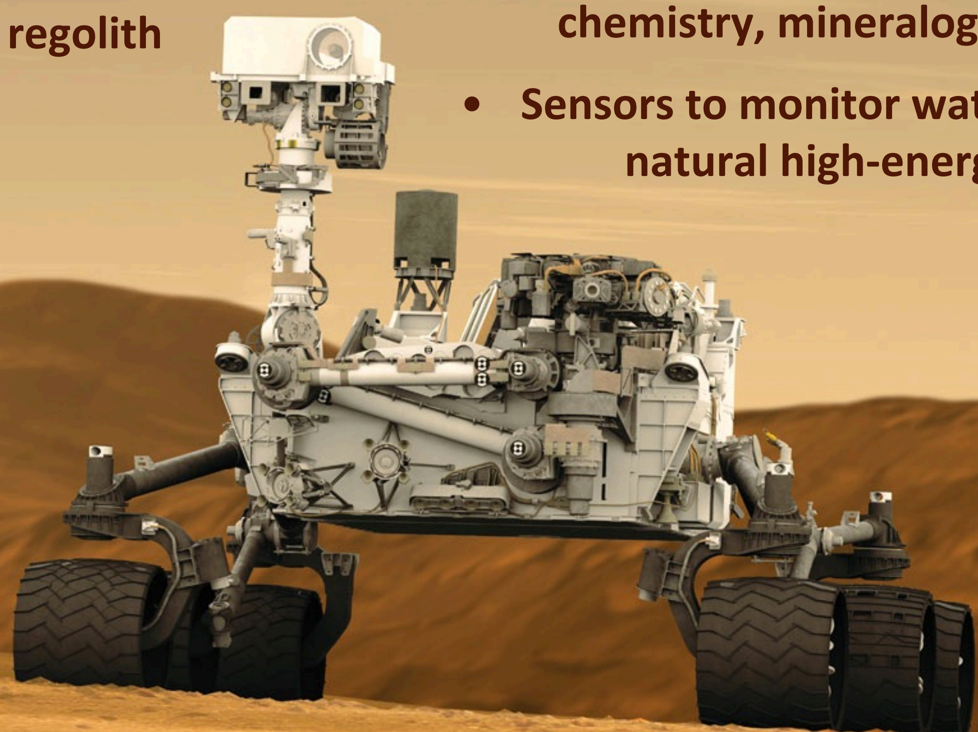
MSL: Curiosity's Capabilities

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

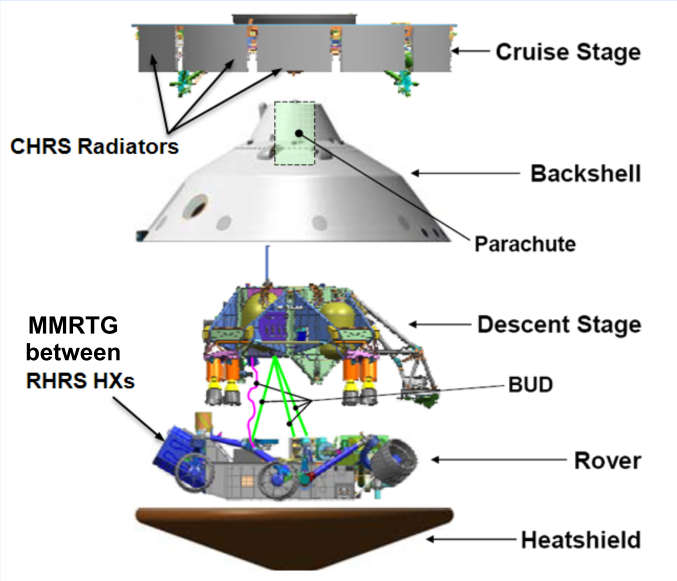
- Ability to acquire and process dozens of rock and soil samples
- Instruments that analyze samples for chemistry, mineralogy, and organics
- Sensors to monitor water, weather, and natural high-energy radiation

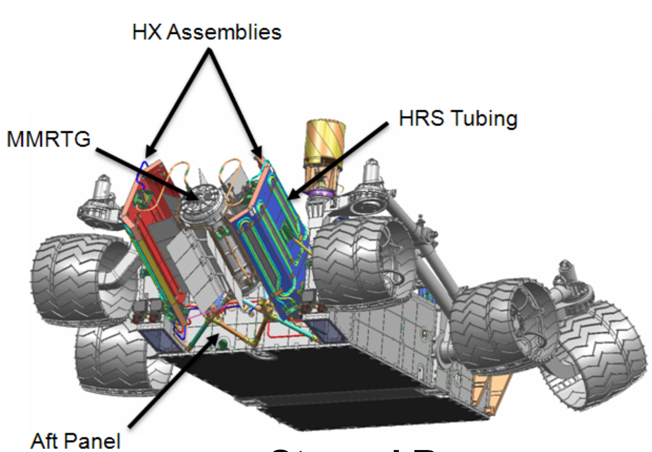


MARS SCIENCE LABORATORY

MSL S/C and Rover Configuration

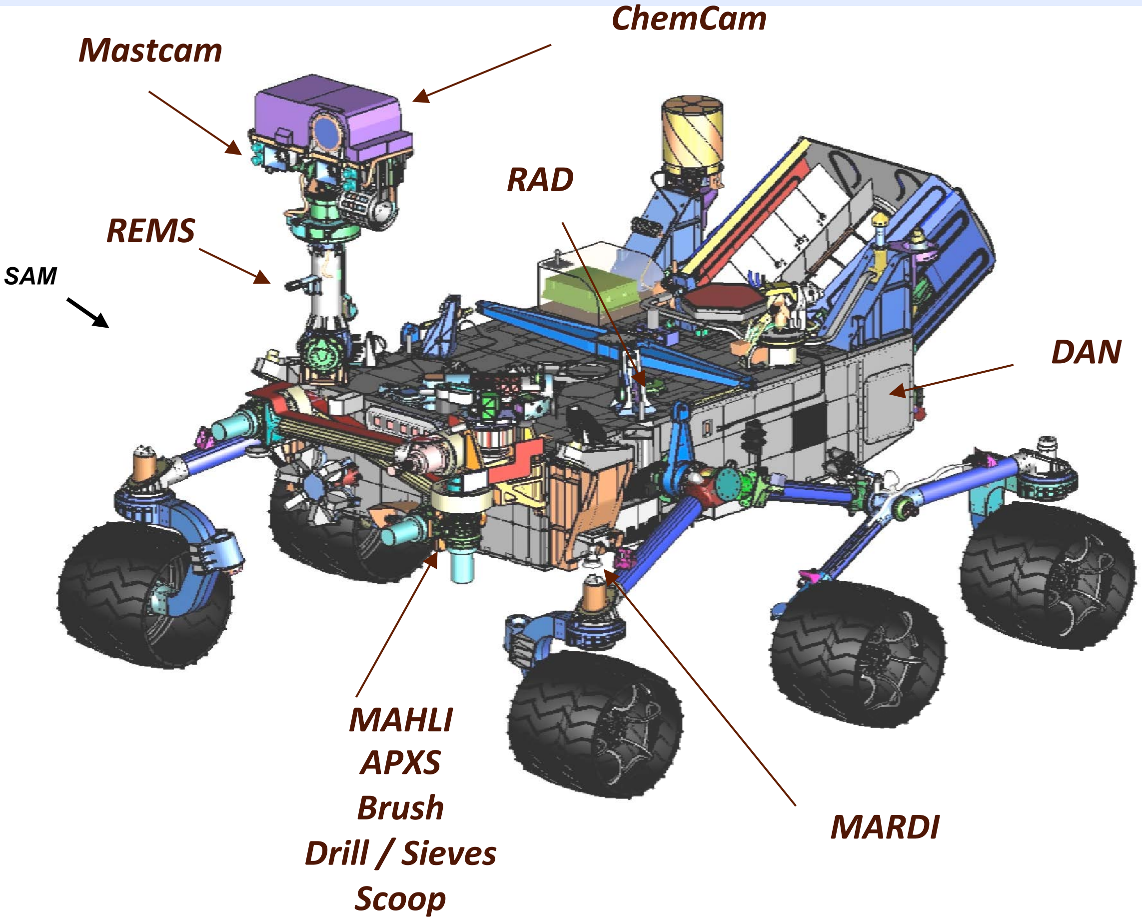
- Launched November 26, 2011, payload of 10 instruments
- Landed Phase Mission Duration: 1 Martian Year
- Required to fully operate on Mars between 30^o North and 30^o South latitudes *day or night*
- Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)
  - 110 W electrical, 2000 W thermal dissipation
- Martian surface temperatures range from -123^{o}C to 38^{o}C
- Rover Electronics and Instruments need to be maintained at -40^{o}C to 50^{o}C
- Thermal Management provided by 2 Mechanically Pumped Fluid Loops (Freon):
  - Cruise Loop (CHRS) & Rover Loop (RHRS)





Stowed Rover

MSL Rover on Mars



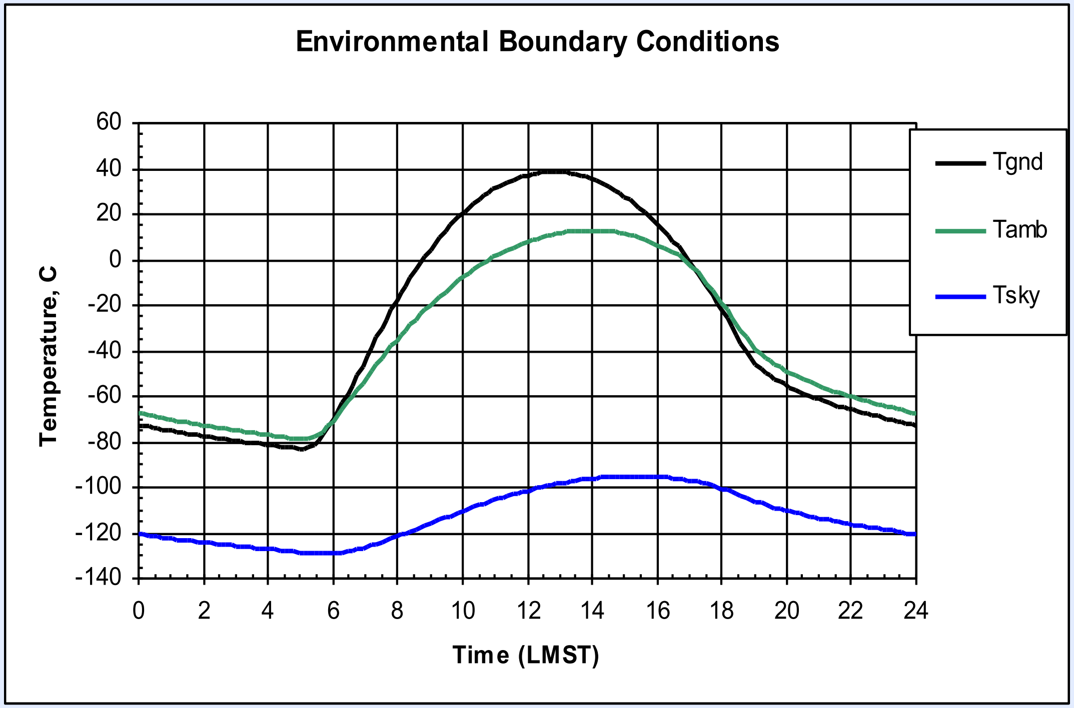
Rover Width:	2.8 m
Height of Deck:	1.1 m
Ground Clearance:	0.66 m
Height of Mast:	2.2 m

Thermal Control Challenges of MSL During Cruise

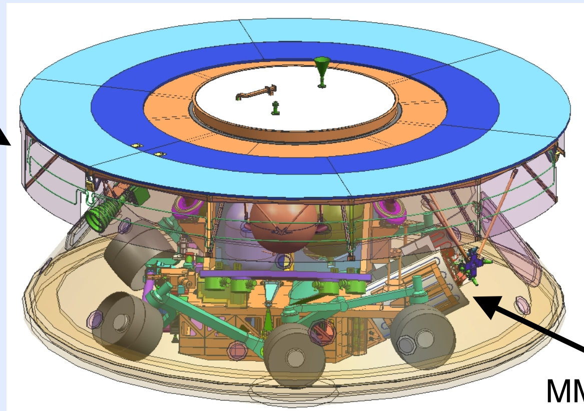
- **Demanding heat removal requirements**
  - Large MMRTG waste heat (~2000 W) management during launch/cruise
  - Around 200-300+ W of additional heat to be removed from various electronics within
- **Requirement to maintain MMRTG to be cold enough to avoid overheating of the adjacent sensitive instruments, electronics and propulsion system**
  - MMRTG max temp. <~120 C during entire cruise
- **Hence cannot passively dissipate this heat within closed aero-shell, otherwise it would be impossible to meet the temperature requirements**
- **Therefore the need for an active cooling system, like the mechanically pumped fluid loop HRS**
- **It would safely pick up the heat from the MMRTG/Electronics, direct it out of the aero-shell and dissipate it on the large Cruise stage HRS radiators**

Thermal Control Challenges of MSL Rover

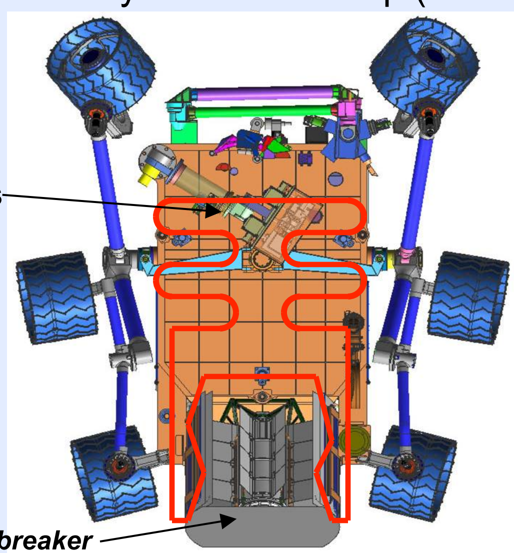
- **Demanding thermal control requirements**
  - Extreme diurnal environment (-129 C to 40 C, full sun to no sun) from winter to summer for the large landing site range of -30° → +30°
  - Large MMRTG waste heat (~2000 W) management during launch/cruise & Mars surface
  - Tight temperature requirements of electronics & 10 science instruments
  - Long life & Rover mobility challenges (configuration, dust, etc.)



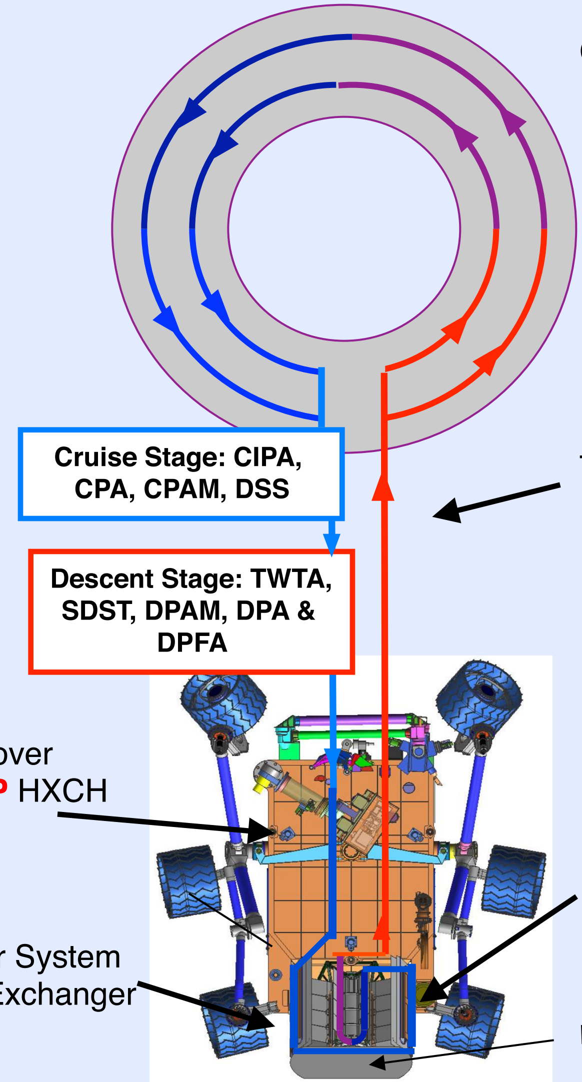
MSL Heat Rejection Systems



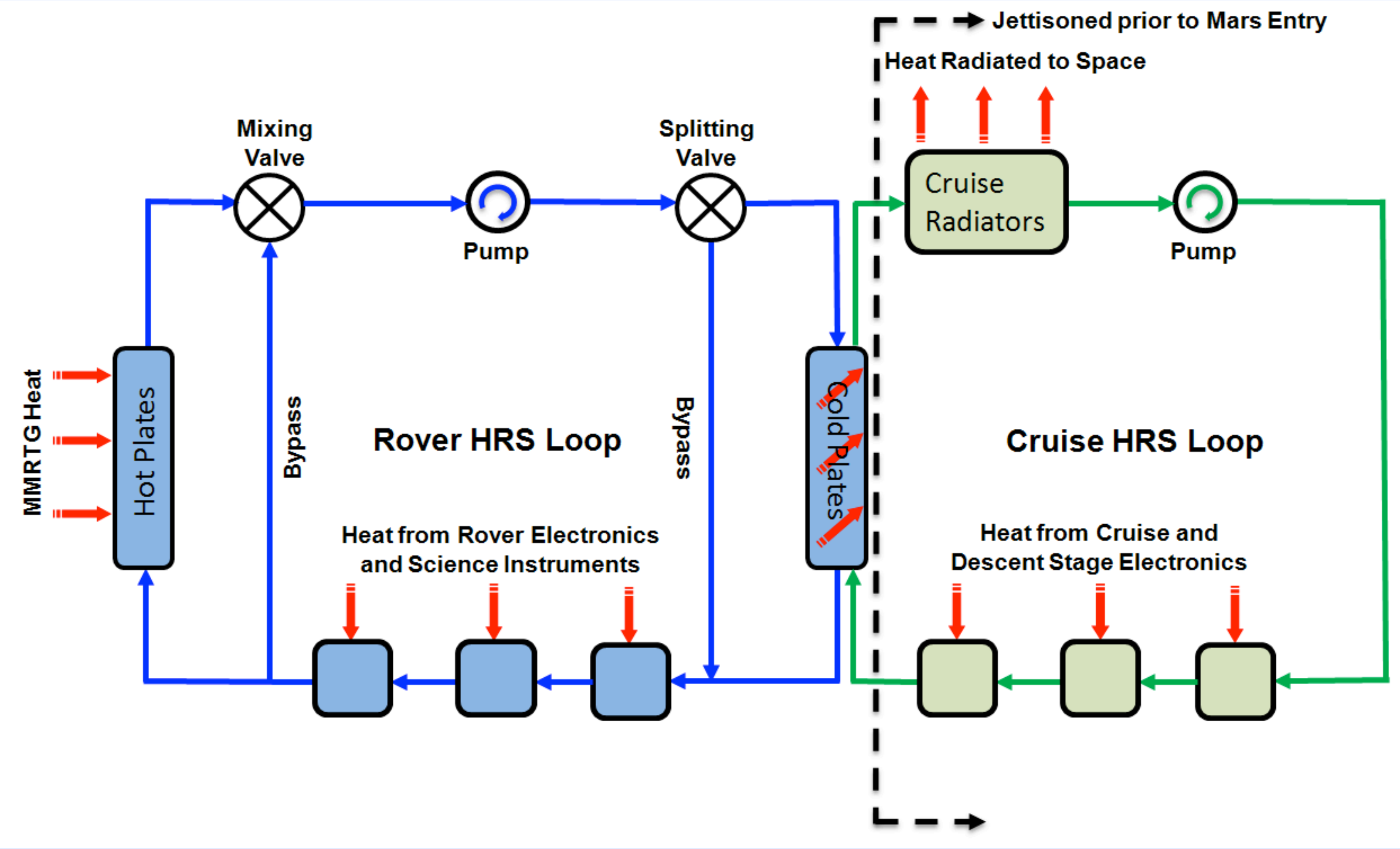
Rover System Fluid Loop (RHRS)



Cruise Pumped Fluid Loop (CHRS)



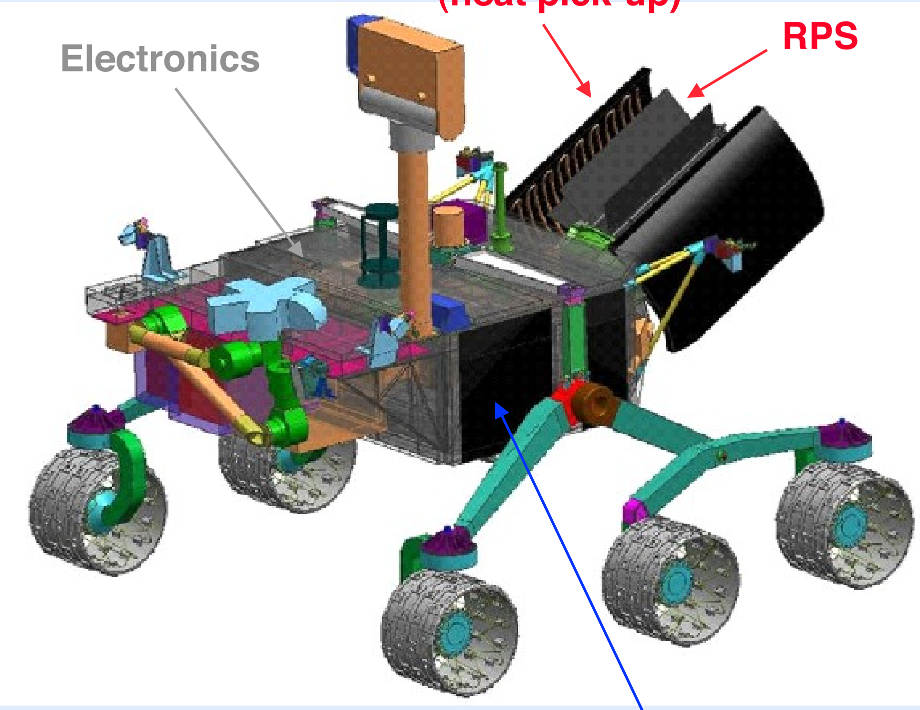
Basic Architecture of MSL HRS



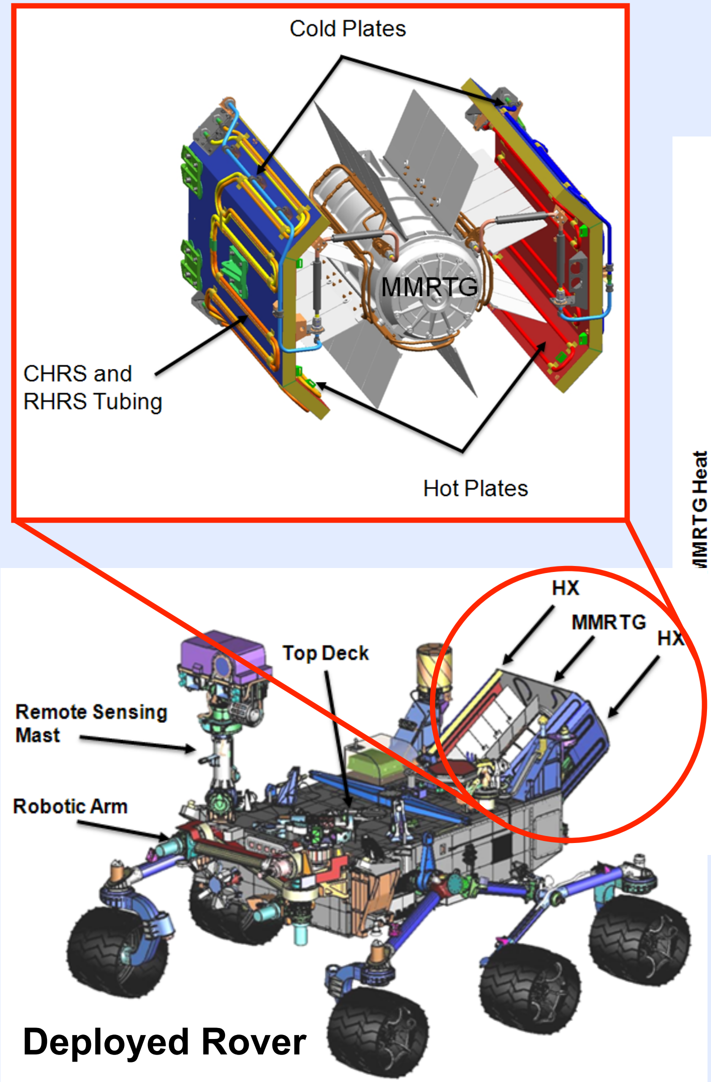
MPFL Rover *Thermal Bus* for MSL
(Surface)

- **For thermal control of the rover during *Surface* Operations**
  - **For *both* heating and cooling**
  - **Harvests up waste heat from the RTG for cold conditions**
  - **Uses radiators to maintain rovers temperatures during hot conditions**

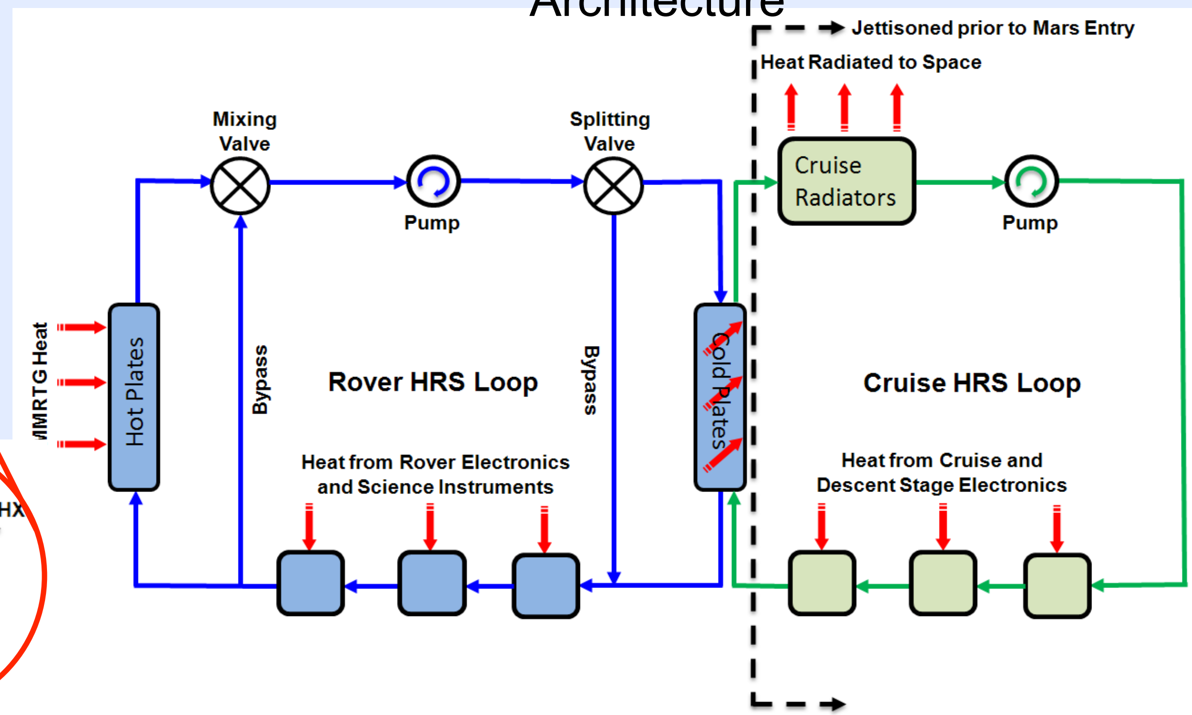
- **1st instance of using pumped fluid loop as a *Thermal Bus* to *supply* as well as *pick-up* heat from electronics**



Mechanically Pumped Fluid Loop Architecture

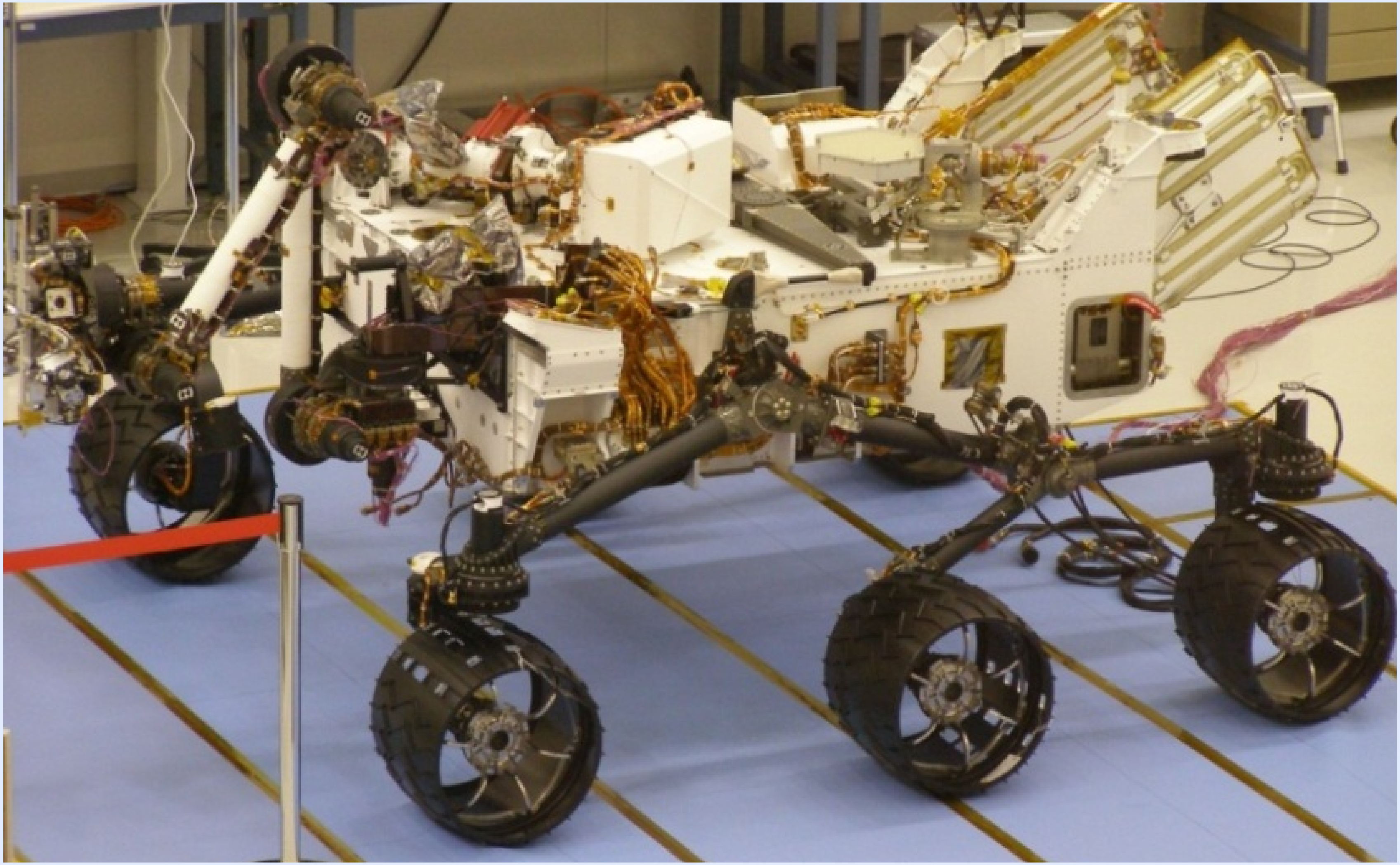


MSL Mechanical Pumped Fluid Loop Architecture



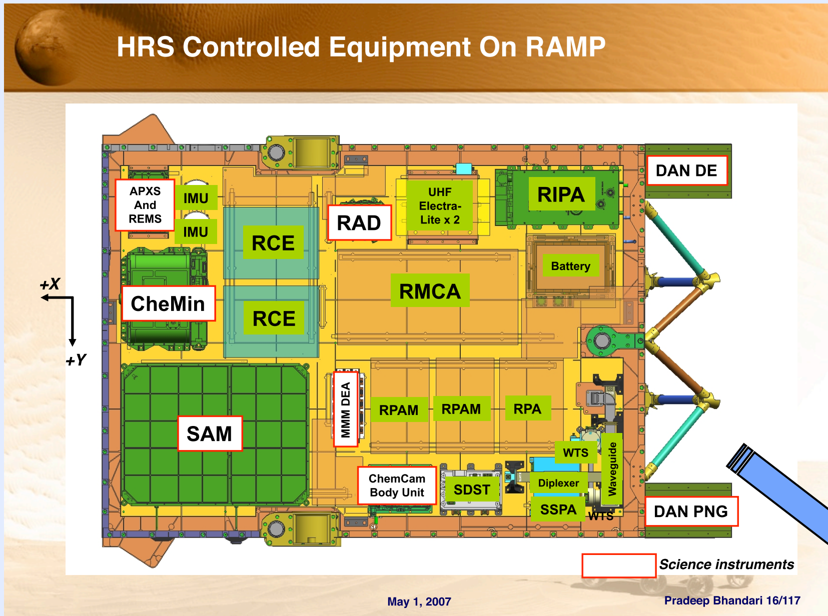
Simultaneously collect heat from MMRTG ***and*** reject waste heat to either the Cruise Loop or directly to Martian environment depending upon mission phase

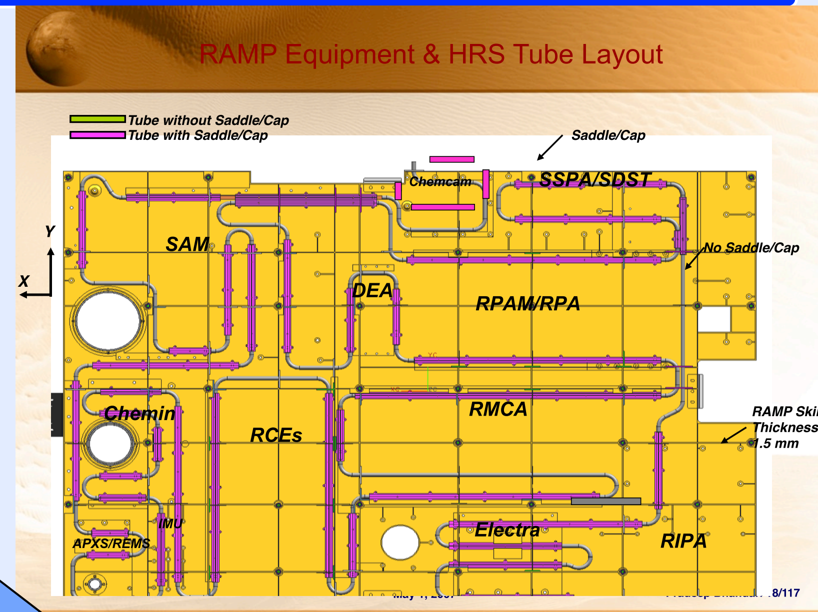
MSL Rover with HRS



RAMP Conceptualization to Delivery

TFAWS 2012

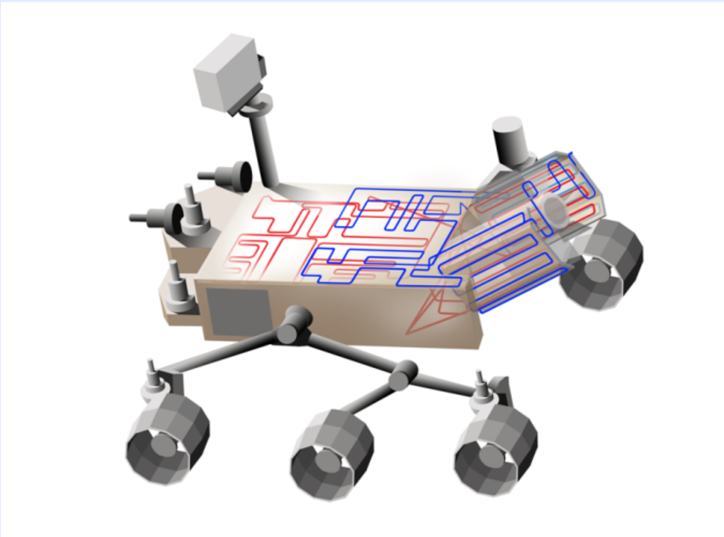


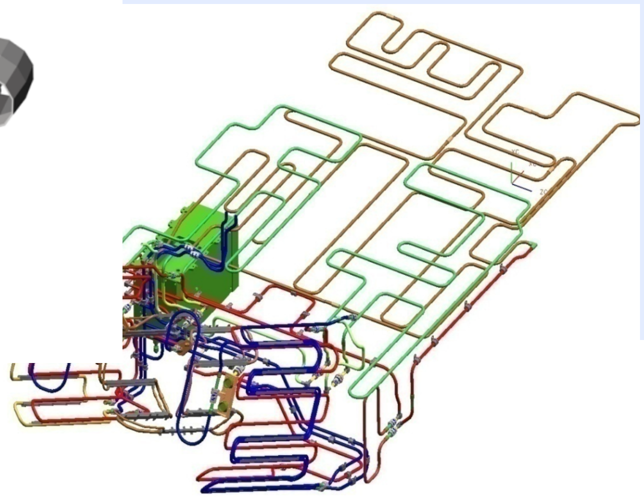


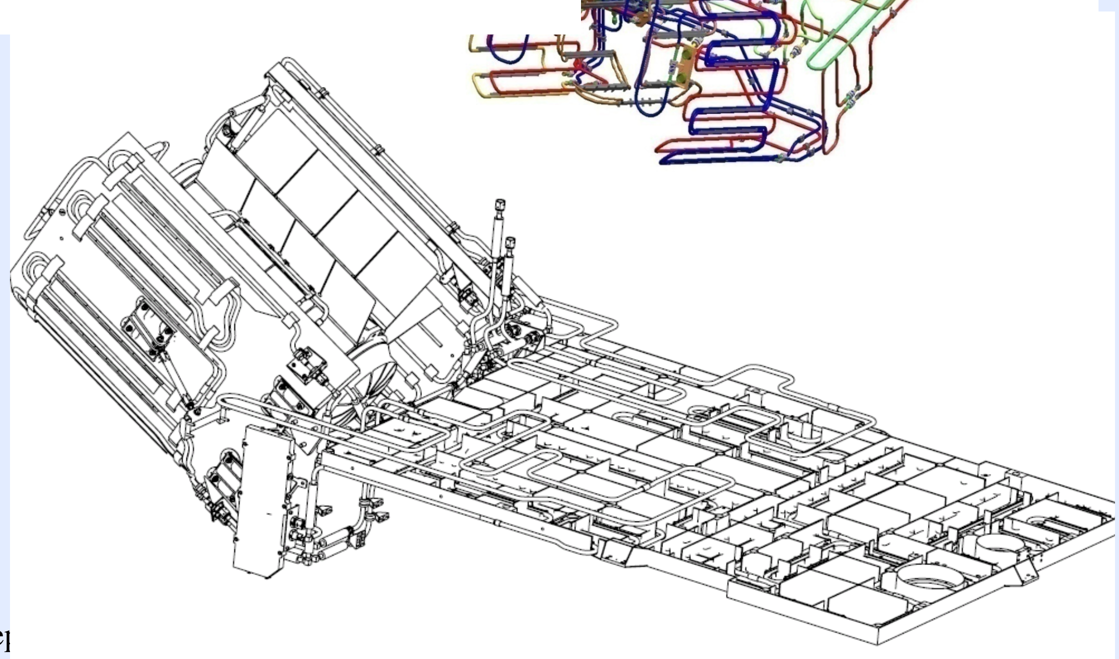
All smiles after lots of hard work!

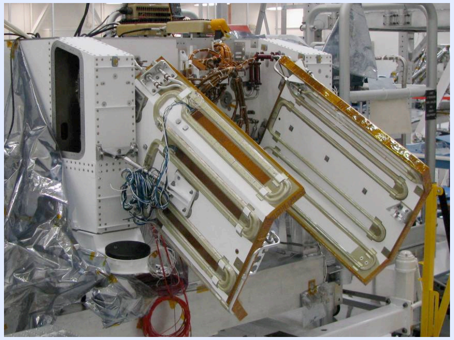
Pradeep Bhandari

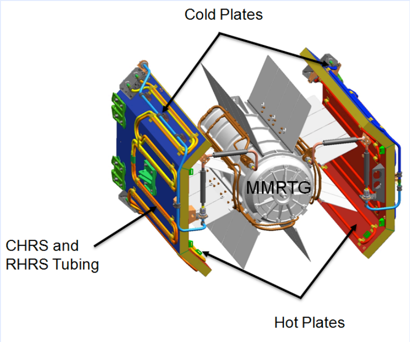
MSL RHRS Tubing Labyrinth!

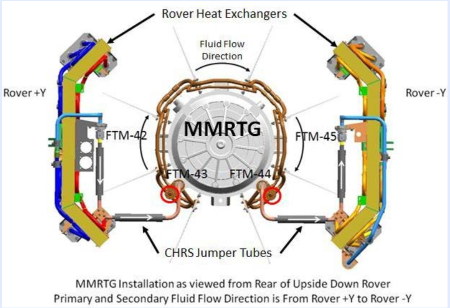




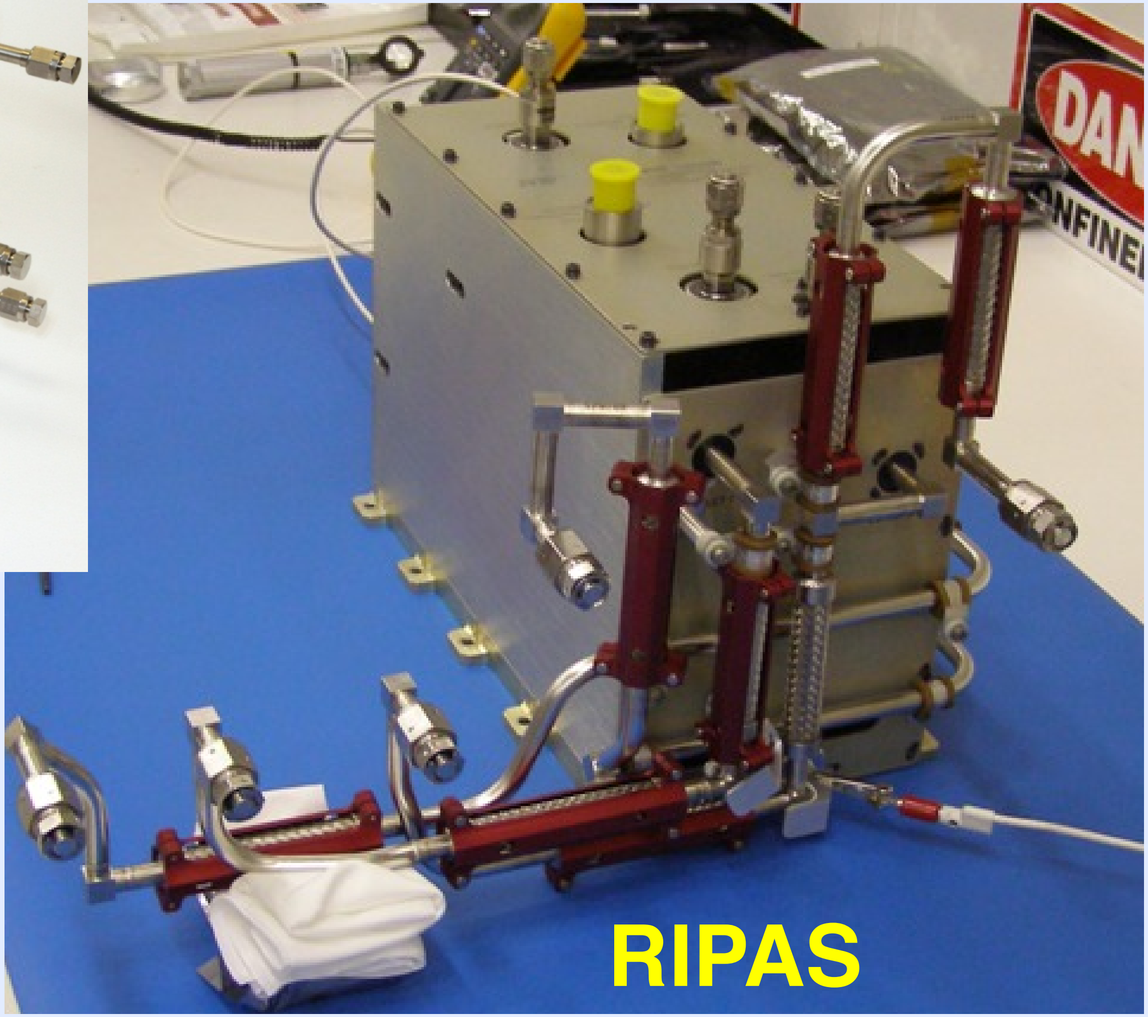




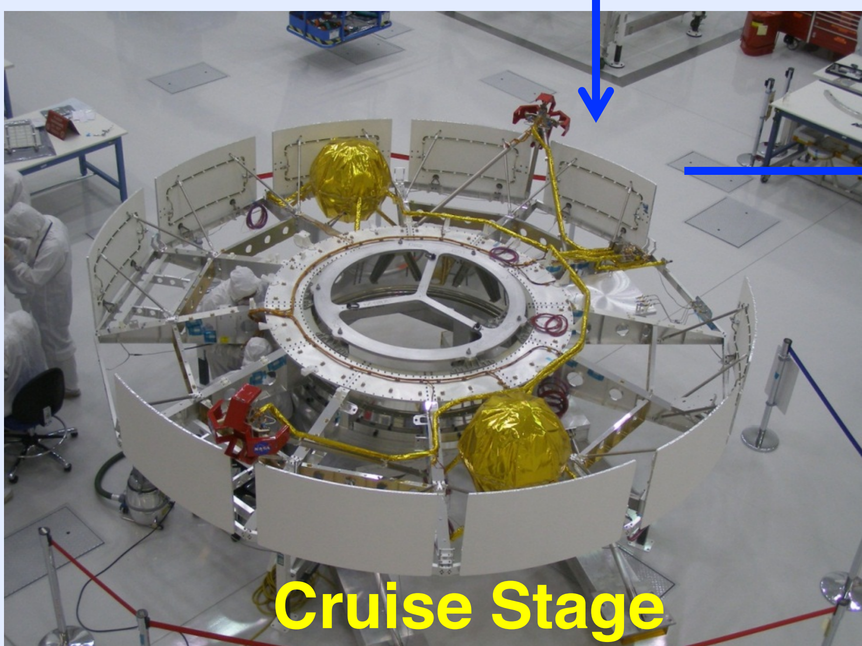




RIPA/RIPAS Design and Build



CIPAS & CHRS on S/C



Key HRS Factoids for MPF/MER/MSL

	Pathfinder/MER	Mars Science Lab	
Type of HRS	Cruise	Cruise	Rover
Working Fluid	CFC-11	CFC-11	CFC-11
Pressure Rise (psid)	4	10	8
Flow rate (lpm)	0.7	1.4	0.7
Power (W)	10	12	10
HRS Mass (kg)	~20	~90	~55
Total Heat Rejected (W)	150	~2000	~150

Pradeep Bhandari

HRS Operation during Launch/Cruise

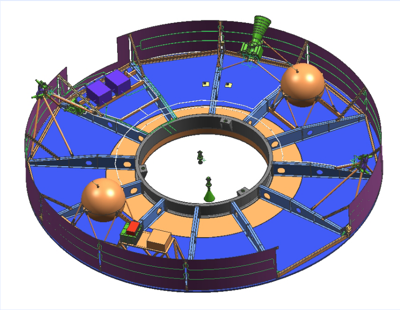
- All the pumps were turned on in both CHRS (2+1) and RHRS (2 pumps) before launch
- After a few hours into flight only one pump is operating in each loop
- The backup pumps in each loop were turned on for an hour every four weeks for maintenance check
- Both active loops are operating very smoothly and as expected

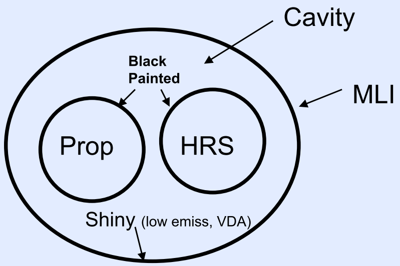
It takes A Village!

Propulsion System Thermal Control

- **HRS lines laid next to the prop lines**
  - **Could serve to provide very deterministic and constant thermal control of these lines**

- **It would also minimize or zero out the electrical power needed for these prop lines**
  - **By picking up waste heat from the electronics and supplying it to the prop lines**





Next Generation Loops *(continued)*

- **Full-Blown S/C Thermal Bus**
  - Clever use of bypass valves, active valves, employing loop as a thermal bus to "pick up" heat from unwanted locations (e.g., solar array) and insertion in locations needing heat for t/c (e.g., electronics)
  - → *Reduce total system heater power requirements for cold phases of missions*
  - → ***Could potentially take over the thermal control of the entire spacecraft and become a true "facility" which works "passively" in the background without needing any active control***

- **Pump Modulation**
  - Variable speed pump
  - Cycling pump
  - → *Smaller power usage of pumps*

- **Lighter Accumulators**
  - Accumulators usually the largest and heaviest component in the integrated pump assemblies
  - Composite materials could be used for construction
  - → *Reduce mass of accumulators*

- **Different Operating Fluids**
  - *Freezing point and vapor pressures; thermal conductivity, density, viscosity, compatibility*
  - → *More optimized to meet specific system requirements*

- **Two Phase Loops**
  - *Reduce mass/size of loops for large heat loads*
    - *Currently being envisioned by the Dutch Space Agency for a flight mission*

Key Conclusions

- **This architecture is the nearest we come to a "thermal bus" concept where the entire thermal control of the spacecraft could be regulated by a single system that works in the background**
  - **Thermal engineer's dream come true**

- **This architecture is very adaptable for almost any kind of mission or spacecraft design**

- **The architecting phase of the loops is less time consuming and expensive compared to conventional passive control systems because of the robust nature of the loops**

- **But… the implementation phase is where the rubber hits the road!**

- **The systems are typically redundant from many points of view, but large leaks are a single fault failure. So great attention has to be paid to measurement and prevention of leaks**

- **For future missions, alternative working fluids should be looked at carefully to account for many limitations of CFC-11**
  - **No longer produced (only recycled)**
  - **Extreme shortage of CFC-11 – may not even be available in the future**
  - **Alternative fluids like Galden HTxxx series may not have freezing potential ("pour point") & have reasonable normal boiling points**

Key Conclusions *(Continued)*

- **Inexpensive and quick "bench top" tests were invaluable in retiring technical risks early**
- **Development tests pay off very well**
  - **An early HRS characterization test is very desirable to iron out any concerns early**
- **Fluid compatibility testing in the early stages retires concerns before it is too late**
- **The design of the whole spacecraft continuously evolved over the design and implementation phase, and the robust and stable nature of the HRS architecture was invaluable in accommodating these changes**

Summary

- **Active heat rejection systems consisting of mechanically pumped single-phase liquid have been successfully demonstrated for the following 5 missions:**
  - **Mars Pathfinder (MPF), the two Mars Exploration Rovers & the two HRS for the Mars Science Laboratory**

- **The successful flight demonstration (5 out of 5) of these mechanically pumped cooling loops in these missions has shown that active cooling systems can be reliably used in deep space missions**

- **The Mars Science Laboratory (MSL) Mission (2009 launch) utilizes** *two* **mechanically pumped fluid loop systems and serves as a thermal bus to be the backbone of the thermal control system**
  - **One for cruise to cool the RTG, one for thermal control of the rover**
  - **The rover loop is a true thermal bus**
  - **To achieve thermal control of the rover, it simultaneously picks up heat from the RTG and rejects excess heat to radiator**

- **The next generation of loops would extend the state of the art to make them true thermal buses working as a facility in the background requiring no active control**

- **The flexibility provided by mechanically pumped fluid thermal control systems in the design, integration, test, and flight operation of spacecraft makes this thermal control system a very attractive and reliable system for future missions**

Acknowledgements

- **The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration**

List of Papers Published by the JPL Team on Mechanically Pumped Fluid Loops – Part I

JPL

TFAWS 2012

1. Birur, G., Bhandari, P., Gram, M., and Durkee, J., "Integrated Pump Assembly – An Active Thermal Control System for Mars Pathfinder Thermal Control," Paper No 961489, presented at the 26th International Conference on Environmental Sciences, Monterrey, California, July 1996.
2. Bhandari, P. and Birur, G., "Mechanically Pumped Cooling Loop for Spacecraft Thermal Control," Paper No 961488, presented at the 26th International Conference on Environmental Sciences, Monterrey, California, July 8-11, 1996.
3. Bhandari, P. and Birur, G., "Long Term Life Testing of a Mechanically Pumped Cooling Loop for Spacecraft Thermal Control" Paper No AIAA-97-2470, presented at the 32nd Thermo-physics Conference, Atlanta, Georgia, June 23-25, 1997.
4. Birur, G. and P. Bhandari, "Mars Pathfinder Active Thermal Control System: Ground and Flight Performance of a Mechanically Pumped Loop," Paper No AIAA-97-2469, 32nd Thermo-physics Conference, Atlanta, GA, June 23-25, 1997.
5. Birur G., and Bhandari, P, "Mars Pathfinder Active Thermal Control System – Successful Demonstration of a Mechanically Pumped Cooling Loop," Paper No 981684, presented at the 28th International Conference on Environmental Sciences, Danvers, MA, July 1998.
6. Lam, T., Birur, G., and Bhandari, P., "Pumped Fluid Loops," Satellite Thermal Control Handbook, (2nd Edition), The Aerospace Corporation, American Institute of aeronautics and Astronautics, November 2002.
7. Ganapathi, G., Birur, G., Tsuyuki, G., and Krylo, R., "Active Heat Rejection System on Mars Exploration Rover – Design Changes from Mars Pathfinder", Space Technology Applications International Forum 2003, Albuquerque, NM, Feb. 2-5, 2003.
8. Novak, K., Phillips, C., Birur, G., Sunada, E., and Pauken, M., "Development of a Thermal Control Architecture for the Mars Exploration Rovers," Space Technology Applications International Forum 2003, Albuquerque, NM, February 2003.
9. Izraelev, V., Bhandari, P., and Birur, G., "Novel Long-Life Mechanical Pump for Spacecraft Thermal Control," 14th Aerospace Spacecraft Thermal Control Workshop, The Aerospace Corporation, El Segundo, California, March 13-15, 2003.
10. Tsuyuki, G., Ganapathi, G., Bame, D., Patzold, J., Fisher, R., and Theriault, L., "The Hardware Challenges for the Mars Exploration Rover Heat Rejection System," AIP Conference Proceedings, Vol. 699(1), pp. 59-70. February 2004.
11. Ganapathi, G., Birur, G., Tsuyuki, G., and Krylo, R., "Mars Exploration Rover Heat Rejection System Performance – Comparison of Ground and Flight Data," Paper No 2004-01-2413, presented at the 34th International Conference on Environmental Sciences, Colorado Springs, Colorado, July 19-22, 2004
12. Paris, A., Bhandari, P., Birur, G.C., "High Temperature Mechanically Pumped Fluid Loop for Space Applications – Working Fluid Selection", SAE 2004-01-2415, 34th International Conference on Environmental Systems, July 2004.
13. Bhandari, P, "Mechanically Pumped Fluid Loops for Spacecraft Thermal Control, Past , Present and Future", 15th Annual Thermal & Fluid Analysis Workshop (TFAWS), 2004, Pasadena, CA

List of Papers Published by the JPL Team on Mechanically Pumped Fluid Loops – Part II

12. Bhandari, P., Birur, G., Pauken, M., Paris, A., Novak, K., Prina, M., Ramirez, B., and Bame, D., "Mars Science Laboratory Thermal Control Architecture," SAE 2005-01-2828, 35th International Conference on Environmental Systems, Rome, Italy, July 2005.

13. Bhandari, P, et al, "Mars Science Laboratory Rover Thermal Control Using a Mechanically Pumped Fluid Loop", Space Technology & Applications International Forum (STAIF-2006), March, 2006

14. Birur, G., Bhandari, P., Prina, M., Bame, D., Yavrouian, A., and Plett, G., "Mechanically Pumped Fluid Loop Technologies for Thermal Control of Future Mars Rovers," SAE 2006-01-2035, 36th International Conference on Environmental Systems, Norfolk, Virginia, July 2006.

15. Birur, G.C., Prina, M, Bhandari, P, et al, "Development of Passively Actuated Thermal Control Valves for Passive Thermal Control of Mechanically Pumped Single Phase Fluid Loops for Space Applications," 38th International Conference on Environmental Systems, San Francisco, California, June 29-July 2, 2008

16. Paris, A.D, et al, "Thermal Design of the Mars Science Laboratory Powered Descent Vehicle," 38th International Conference on Environmental Systems, San Francisco, California, June 29-July 2, 2008

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18. Mastropietro, A.J., Beatty, J., Kelly, F., Birur, G., Bhandari, P., Pauken, M., Illsley, P., Liu, Y., Bame, D., and Miller, J., "Design and Preliminary Thermal Performance of the Mars Science Laboratory Rover Heat Exchangers," Paper AIAA2010-6194, 40th International Conference on Environmental Systems, Barcelona, Spain, July 2010

19. Bhandari, P., Dudik, B., Birur, G, Karlmann, P., Bame, D., and Mastropietro, A.J., "Design of Accumulators and Liquid/Gas Charging of Single Phase Mechanically Pumped Fluid Loop Heat Rejection Systems," 42nd International Conference on Environmental Systems, San Diego, CA, July 2012

20. Birur, G., Bhandari, P., Bame, D., Karlmann, P., Mastropietro, A.J., Liu, Y.M., Miller, J., Pauken, M., and Lyra, J. "From Concept to Flight: An Active Fluid Loop Based Thermal Control System for Mars Science Laboratory Rover," 42nd International Conference on Environmental Systems, San Diego, CA, July 2012

21. Mastropietro, A. J., Bame, D., Birur, G, Bhandari, P., Miller, J., Cucullu, G., and Lyra, J "Launch Pad Closeout Operations for the Mars Science Laboratory's Heat Rejection System", 42nd International Conference on Environmental Systems, San Diego, CA, July 2012

22. Paris, A., Kelly, F., Kempenaar, J., and Novak, K., "In-Flight Performance of the Mars Science Laboratory Spacecraft Cruise Phase Thermal Control Systems," 42nd International Conference on Environmental Systems, San Diego, CA, July 2012

23. Novak, K., Kempenaar, J., Liu, Y., Bhandari, P., and Dudik, B., "Mars Science Laboratory Rover System Thermal Test," 42nd International Conference on Environmental Systems, San Diego, CA, July 2012

Overall Class Conclusions

- Active heat rejection systems consisting of mechanically pumped single-phase liquid have been successfully demonstrated for the following 5 missions:
  - Mars Pathfinder (MPF), the two Mars Exploration Rovers (MER) & the two HRS for the Mars Science Laboratory (MSL)
- The successful flight demonstration (5 out of 5) of these mechanically pumped cooling loops in these missions has shown that active cooling systems can be reliably used in deep space missions
- When compared to passive systems, these loops are relatively easier to architecture & design for simple to very complex configurations, environments and requirements
- Their robust and self regulating nature makes them ideally suited to serve as a thermal bus, which works without control, automatically in the background, with no need for any external inputs
- The analytical and predictive resources required for these thermal systems is significantly smaller than for passive system

Overall Class Conclusions

- The main challenge associated with these systems lies in their successful implementation because of their emphasis on "hardware" as opposed to "software"
- While there is lot to be learned from the extensive experience developed by the JPL thermal engineers in successfully designing and implementing these systems, they can then be easily adapted for widely different configurations
- The primary focus in their successful implementation is directed to attention to making them leak-proof, establishing the compatibility of all materials in the wetted path with the working fluids, and the adequate & optimized use of redundancy in key elements like pumps
- The next generation of loops would extend the state of the art to make them true thermal buses working as a facility in the background requiring no active control
- The flexibility provided by mechanically pumped fluid thermal control systems in the design, integration, test, and flight operation of spacecraft makes them very attractive and reliable systems for many future space missions