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Performance of The Mechanically Pumped Fluid Loop Rover Heat Rejection System - Used for Thermal Control of The Mars Science Laboratory Curiosity Rover - on The Surface of Mars

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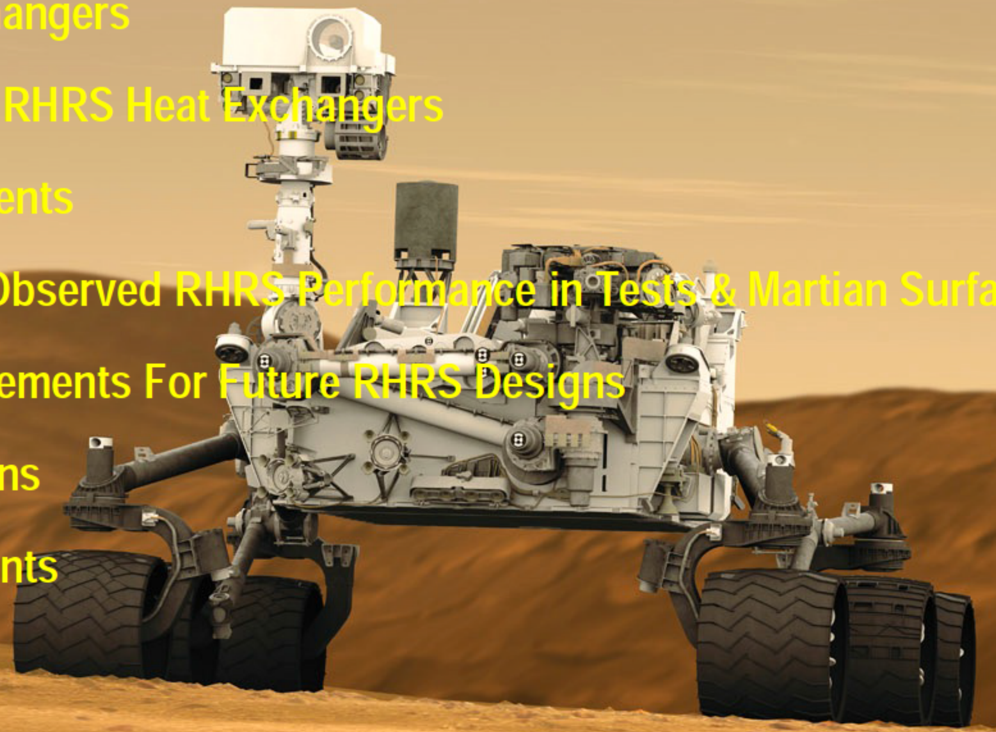
Jet Propulsion Laboratory
California Institute of Technology

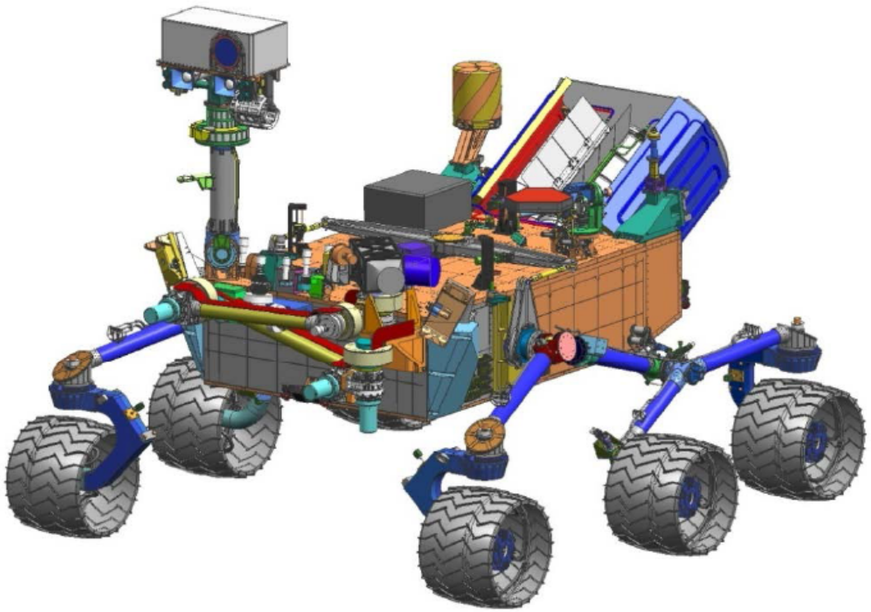
Agenda

- MSL Project Overview
  - Spacecraft & Rover Configuration
  - Overall Thermal Architecture
- Rover Heat Rejection System (RHRS) Overview
- RHRS Heat Exchangers
- Windbreaker for RHRS Heat Exchangers
- RHRS Requirements
- Predictions vs. Observed RHRS Performance in Tests & Martian Surface
- Possible Improvements For Future RHRS Designs
- Major Conclusions
- Acknowledgements



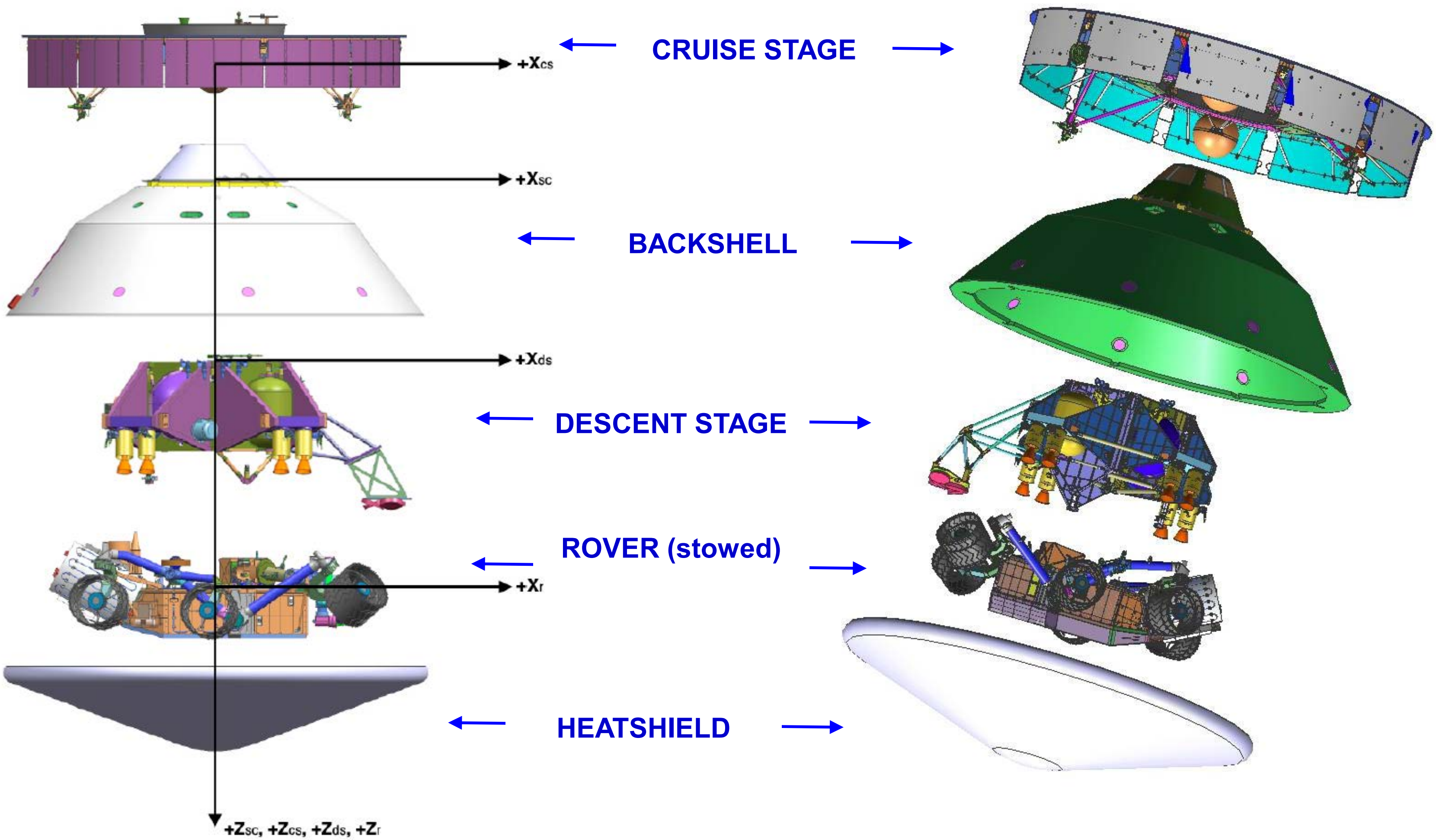
MSL Project Overview

Salient Features
- Mobile Science Laboratory
- One Mars Year surface operational lifetime (669 sols/687 days)
- Landing Capability over wide range of latitudes (± 30°)
- Controlled Propulsive Landing
- Precision Landing via Guided Entry
- Mass = 950 kg
- Launch: Nov 25, 2011; Landed: Aug 5, 2012

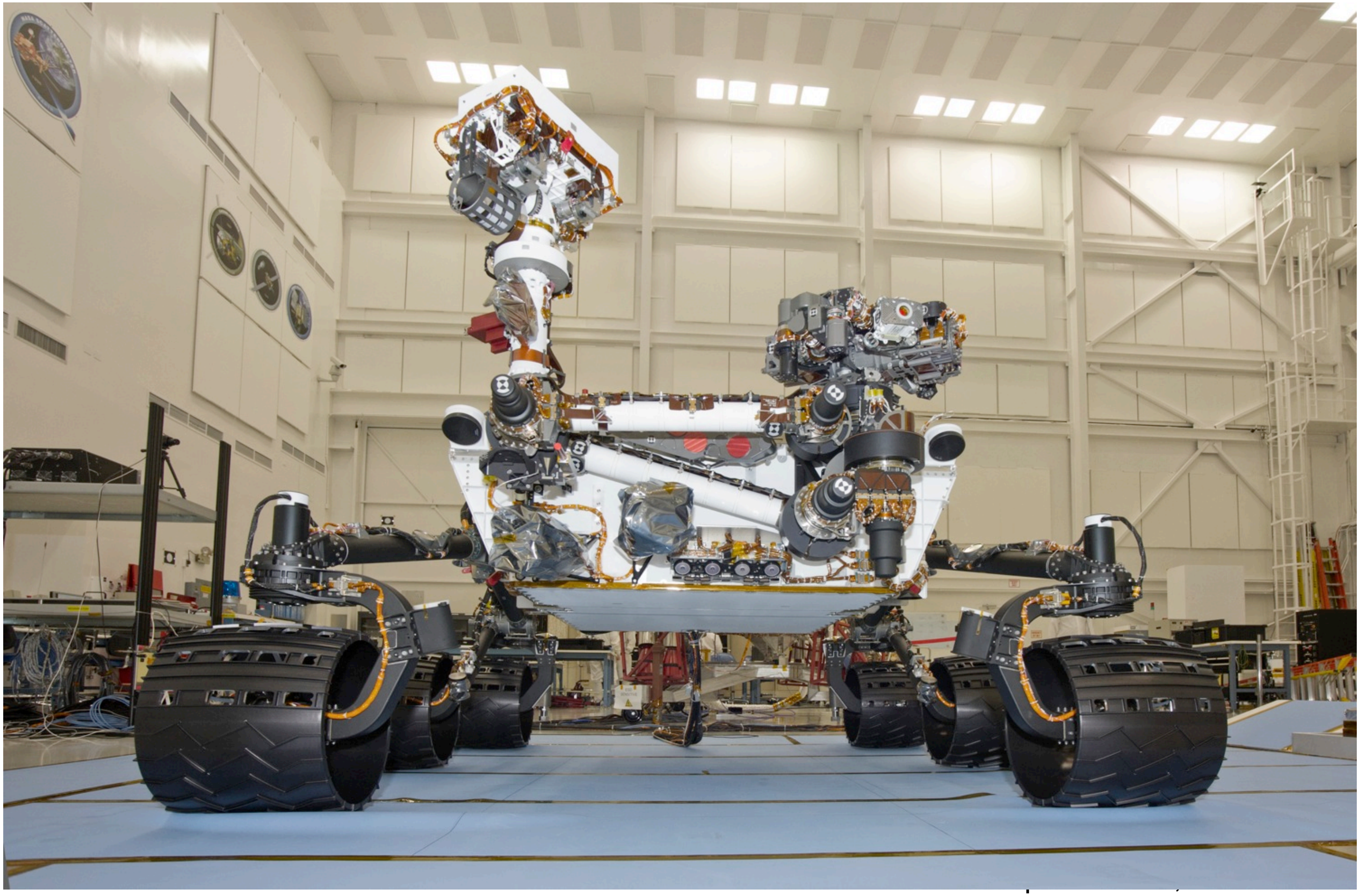


Science
- Mission science focuses on Mars habitability
- Next generation analytical laboratory science investigations (SAM & Chemin)
- Remote sensing/contact investigations (MastCam,ChemCam, MAHLI & APXS)
- Suite of Environmental Monitoring Instruments (DAN, REMS, MARDI & RAD)

MSL Spacecraft

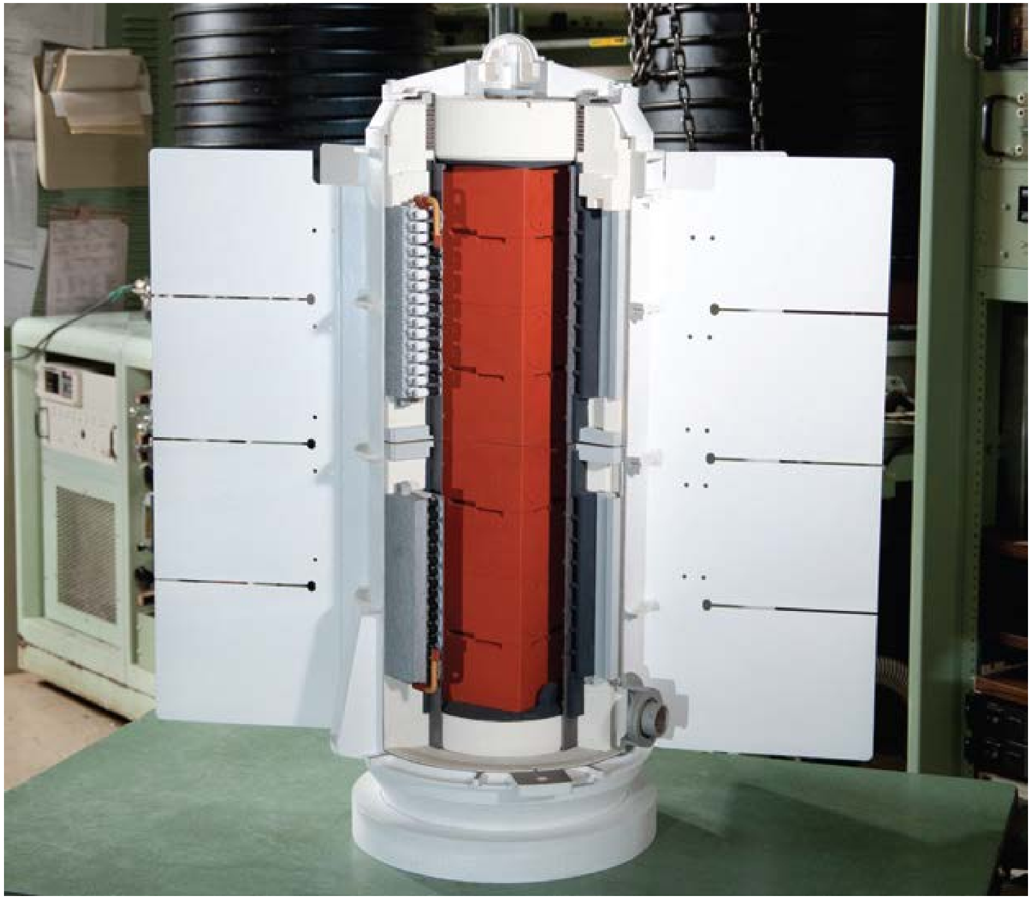


Curiosity 2011: *Terminator* on steroids…



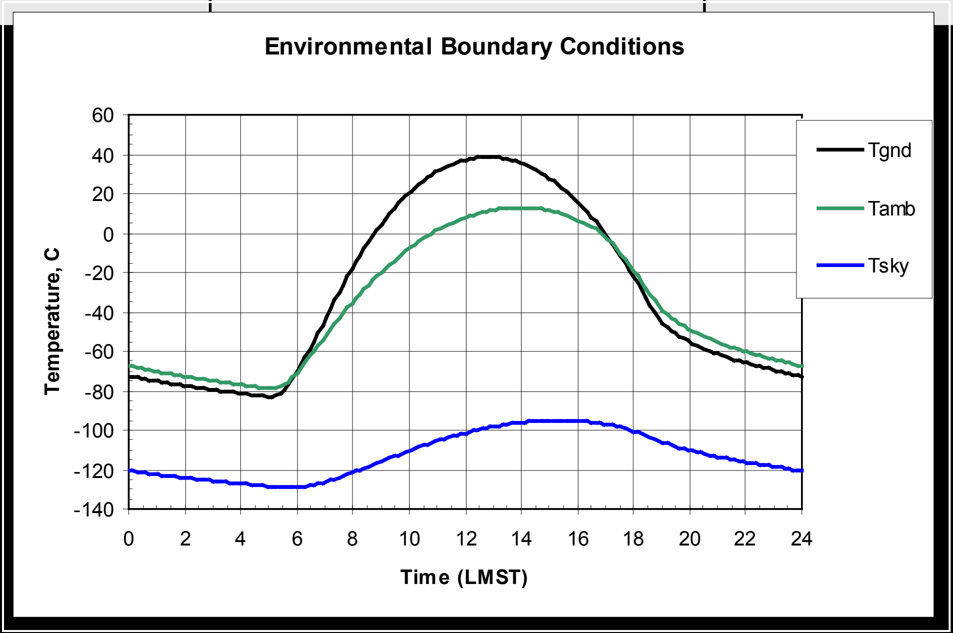
Multi-Mission RTG
-Radioisotope Thermoelectric Generator

- The **MMRTG** provides:
  - **~110 watts of electrical power**
  - 2000 watts of dissipated heat
- Life well in excess of mission requirements
- Utilized on several deep space exploration missions.



Let's Do Some Thermal Engineering!

	Coldest	Hottest
Earth	-89 C Antarctica	57 C Death Valley, CA
Mars	-140 C	20 C
Spacecraft in Space	-160 C (Shade)	120 C (Sun Side)
Space	-273 C	na



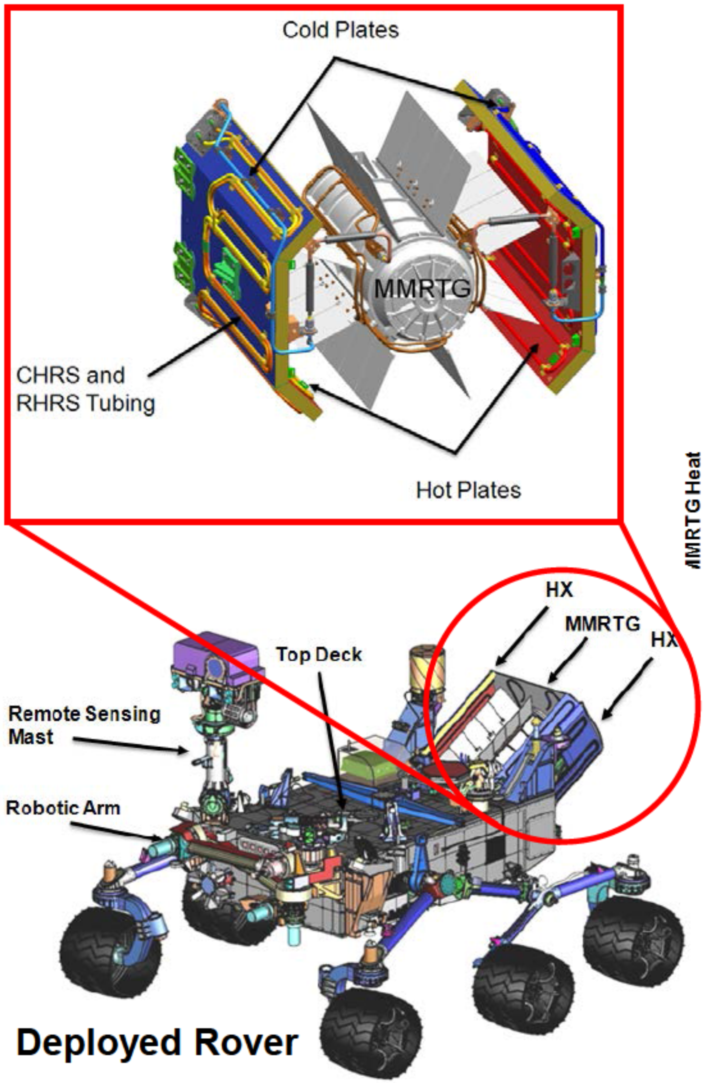
Thermal Control Challenges of MSL Rover

- 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
- Cannot passively dissipate this heat within closed aero-shell, otherwise it would be impossible to meet the temperature requirements
- Therefore a Mechanically Pumped Fluid Loops (MPFL) Heat Rejection System (HRS) was chosen to overcome these challenges
- 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

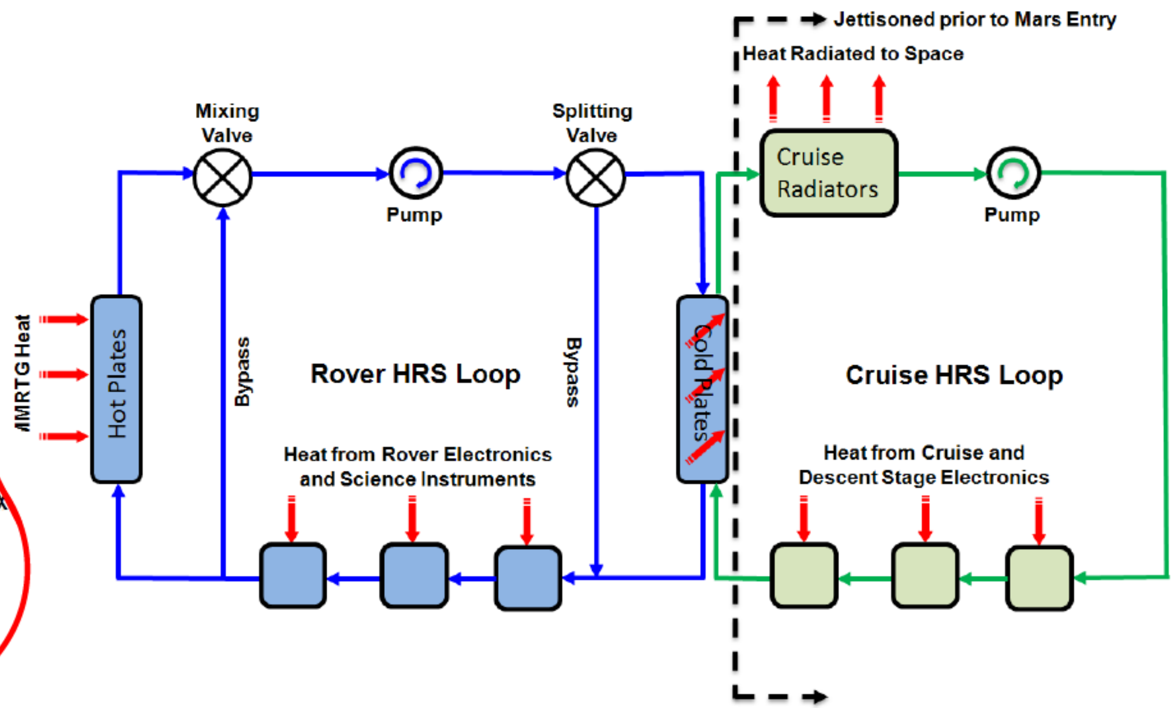
Why Use a Pumped Fluid Loop?

- Advantages of MPFL-HRS 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
- Have increasingly been used recently (last 15 years) at JPL to solve complex thermal control problems
  - Mars Pathfinder (Cruise)
  - 2x Mars Exploration Rovers (Cruise)
  - Mars Science Laboratory (Cruise + Rover)

Mechanically Pumped Fluid Loop Heat Rejection System (HRS)

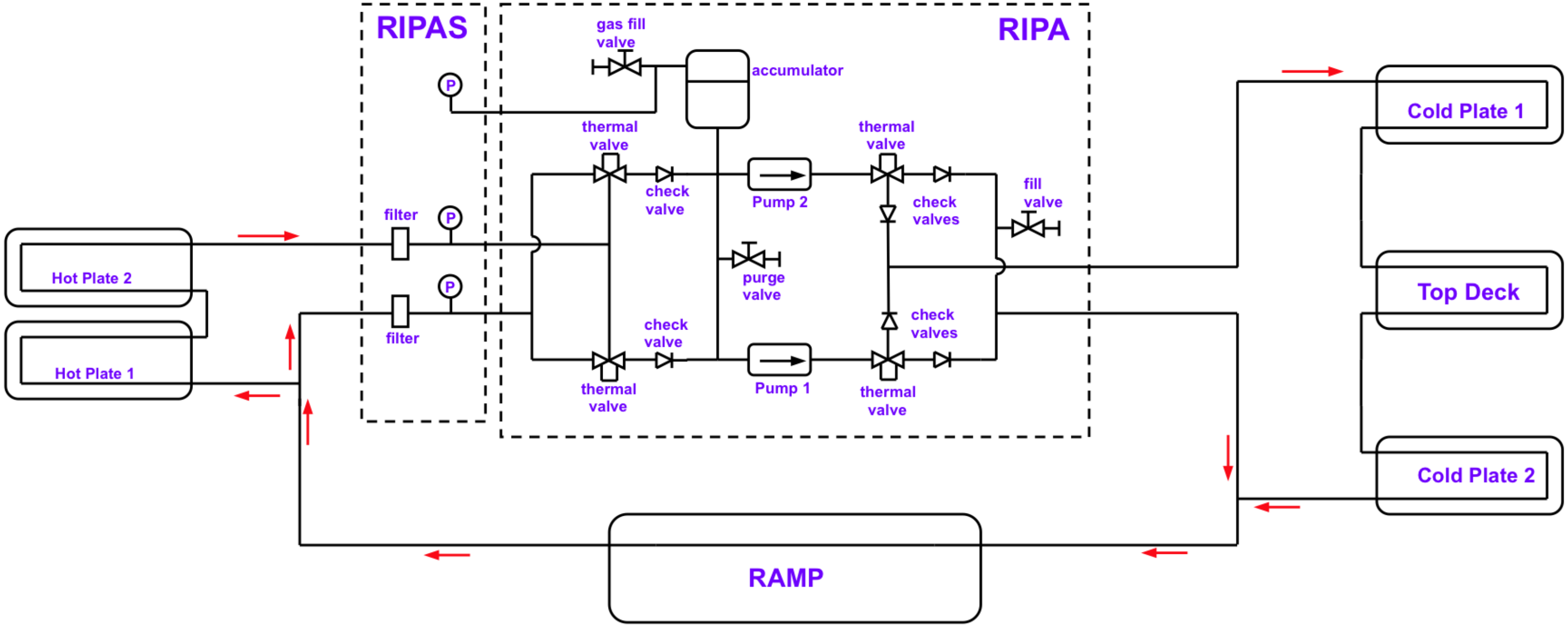


MSL Mechanical Pumped Fluid Loop Architecture

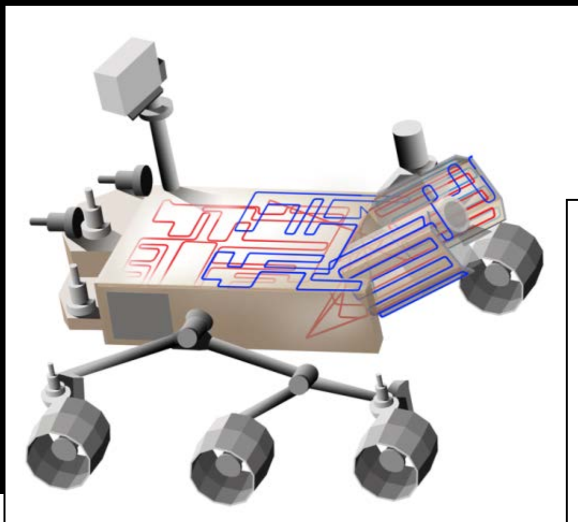


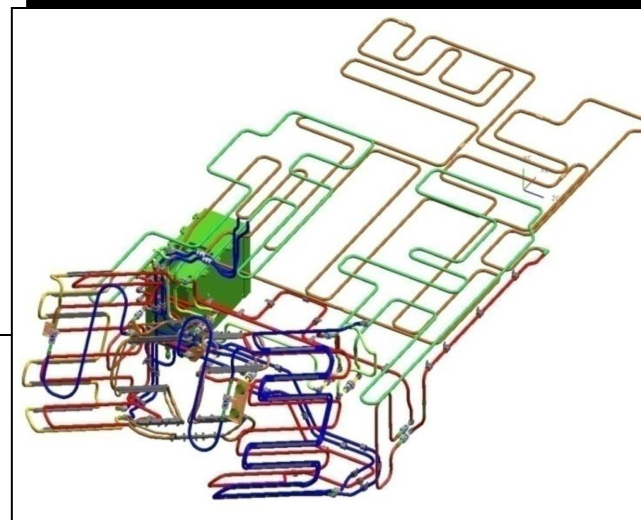
Simultaneously collect heat from MMRTG ***and*** reject waste heat to either the Cruise Loop or directly to Martian environment depending upon mission phase

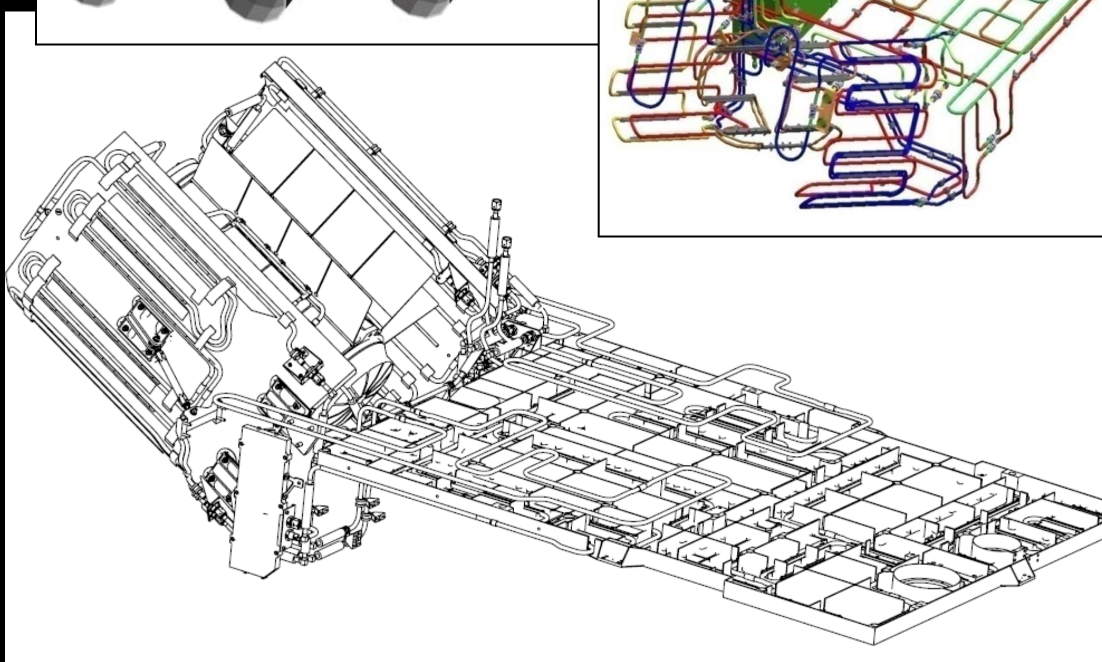
Rover Heat Rejection System Internal Schematic

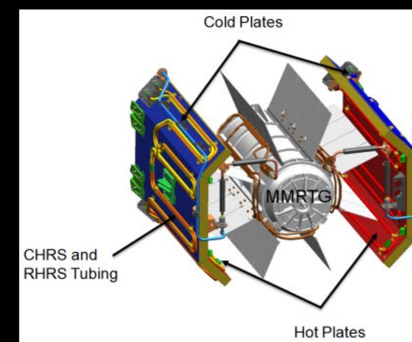


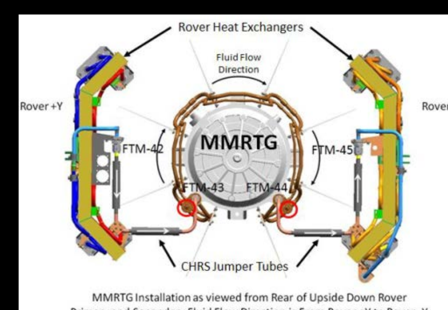
MSL RHRS Tubing Labyrinth!



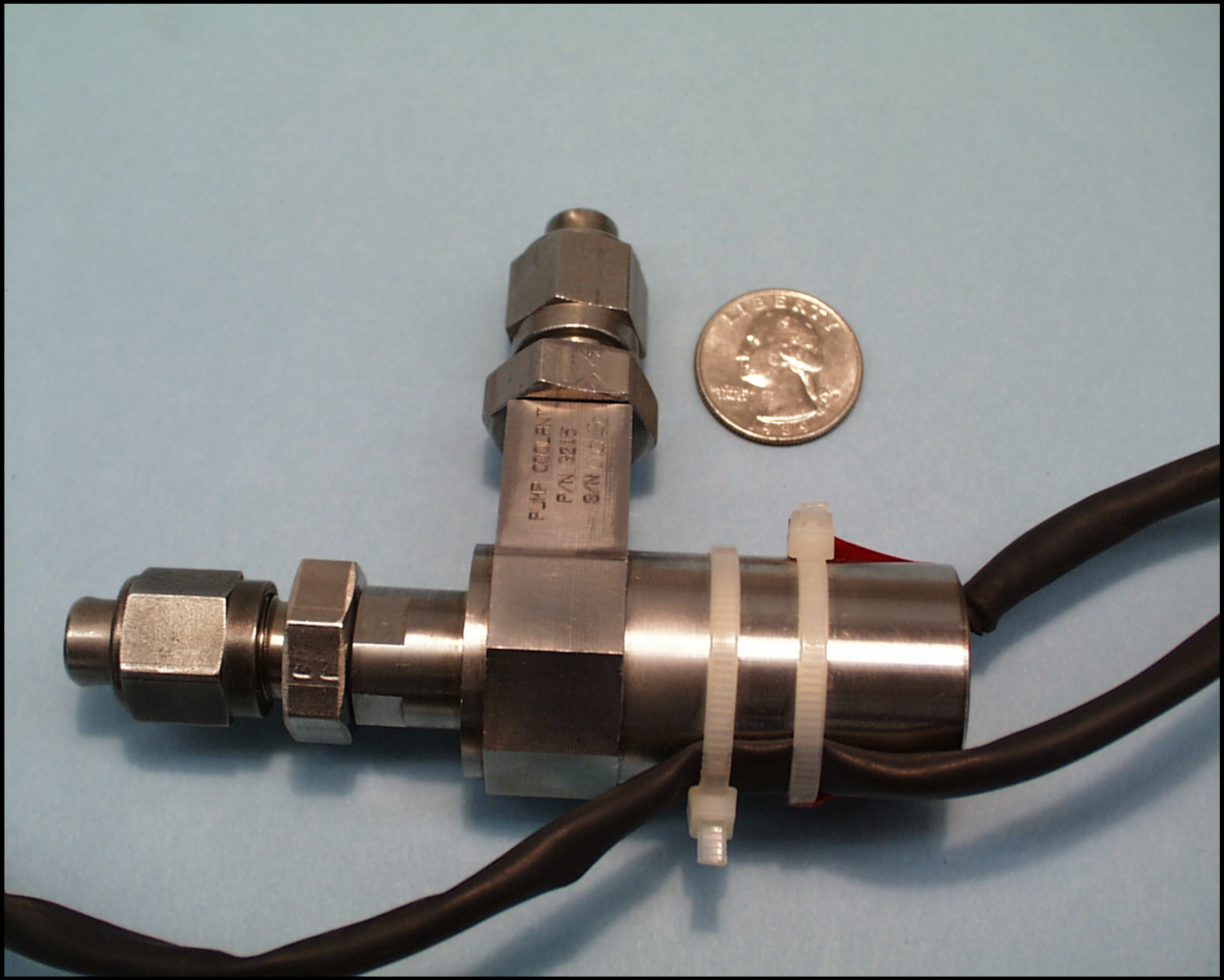






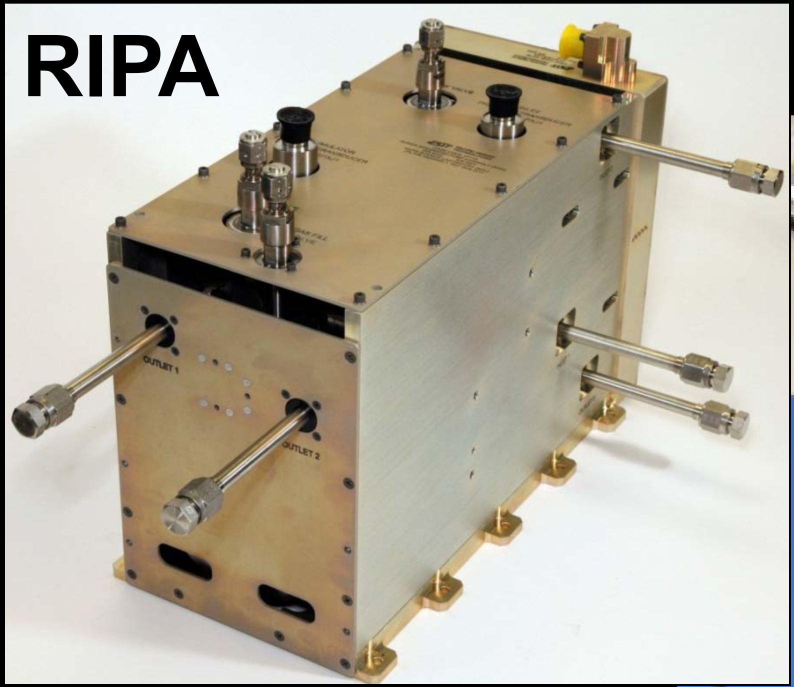


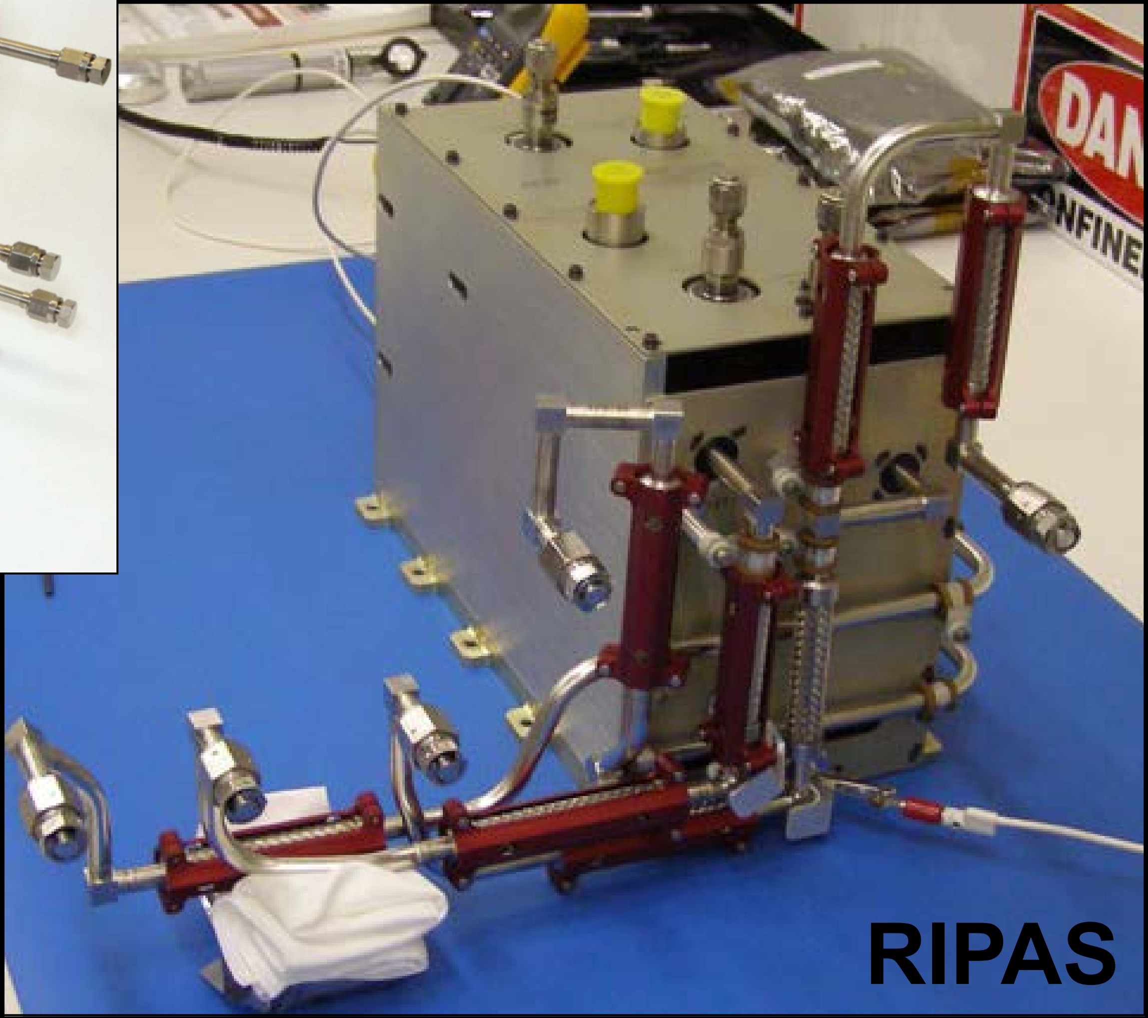
Mars Pathfinder Centrifugal Pump



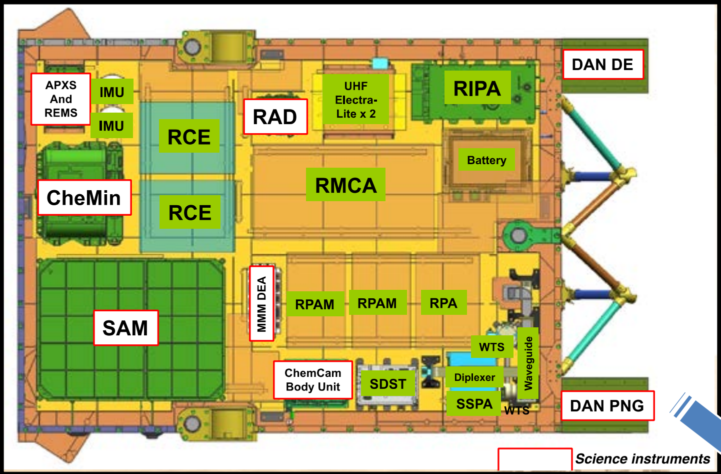
- Journal Bearings
- Hydro-Dynamically Lubricated
- 12,000 rpm
- 250 g
- All Stainless Steel Construction
- Permanent Magnet Embedded in Rotor
- Hall Sensors and Rotating Magnetic Field in Stator
- Pacific Design Technologies (PDT) Manufacturer

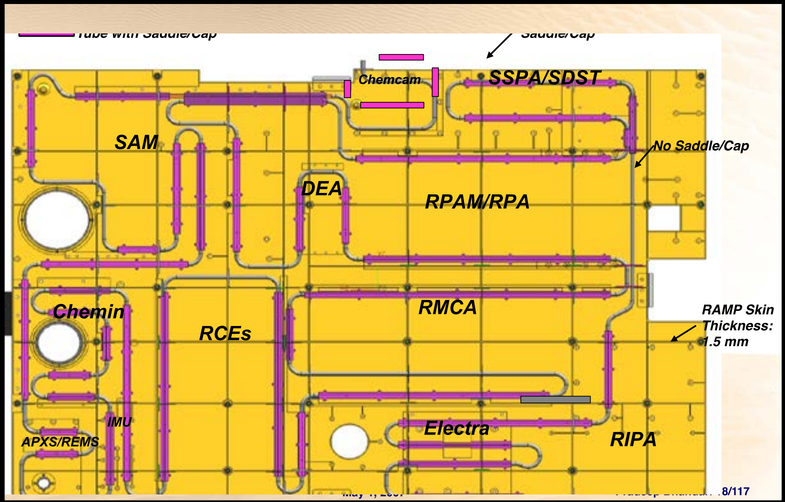
RIPA/RIPAS Design and Build





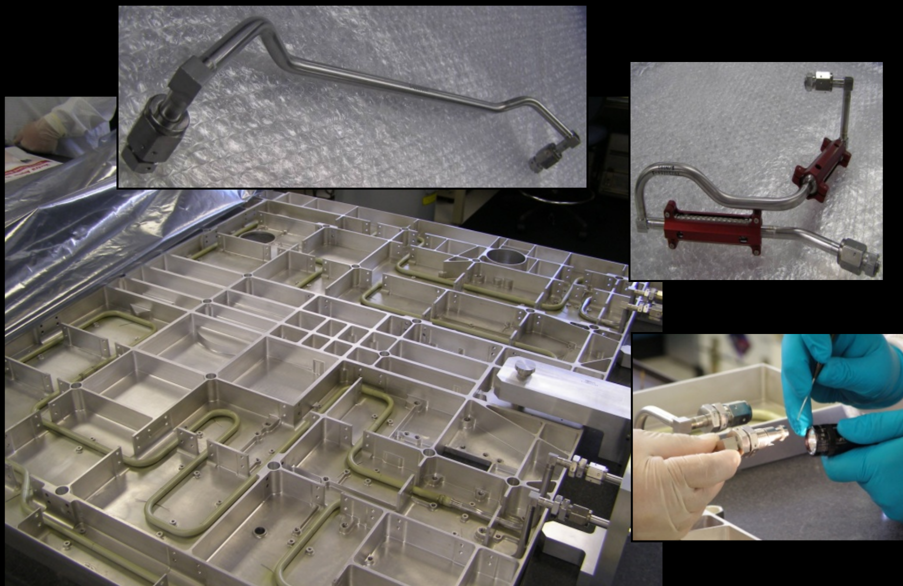
Rover Avionics Mounting Plate (RAMP) - Conceptualization to Delivery



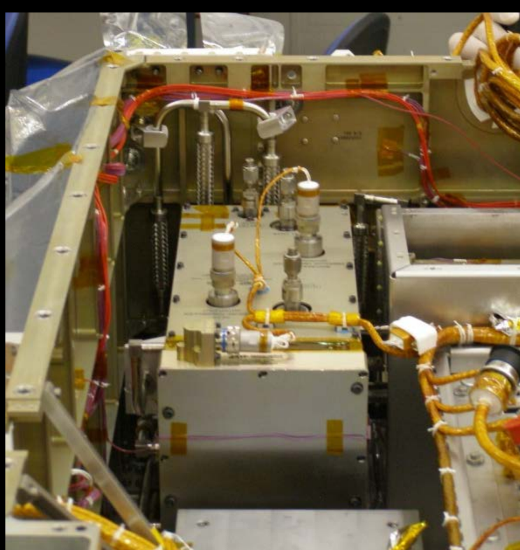
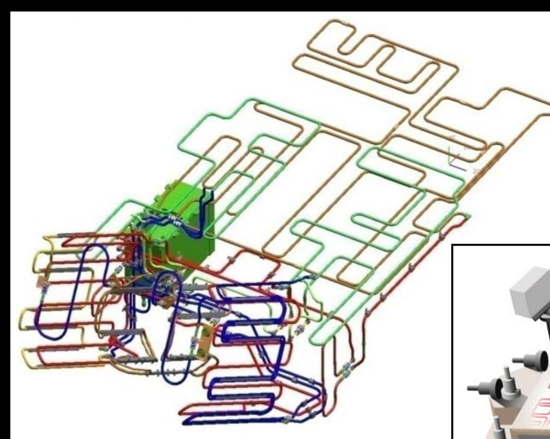
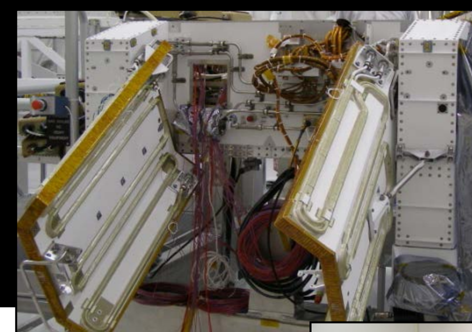
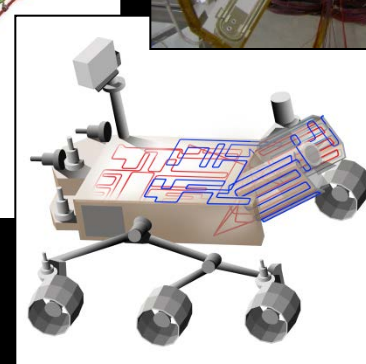


All smiles after lots of hard work!

HRS in the Curiosity Rover

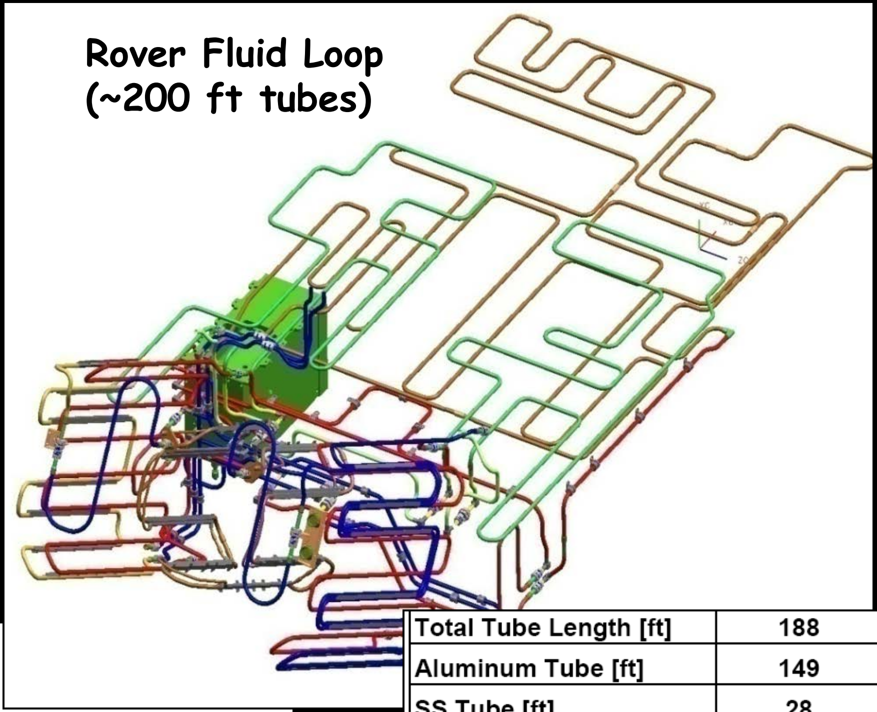


- Over 21 major assemblies
- 2 complex Integrated Pump Assemblies
- 425 ft (130 m) of tubes (over 100 flight tube assemblies)
- ~ 2-gallons (~4 2-L Coke Bottles) of CFC-11
- 10 radiator panels assembled
- Over 100 aluminum flight welds, over 340 SS orbital welds (not counting IPA welds)
- About 60 mechanical joints
- Over 10 major tooling fixtures

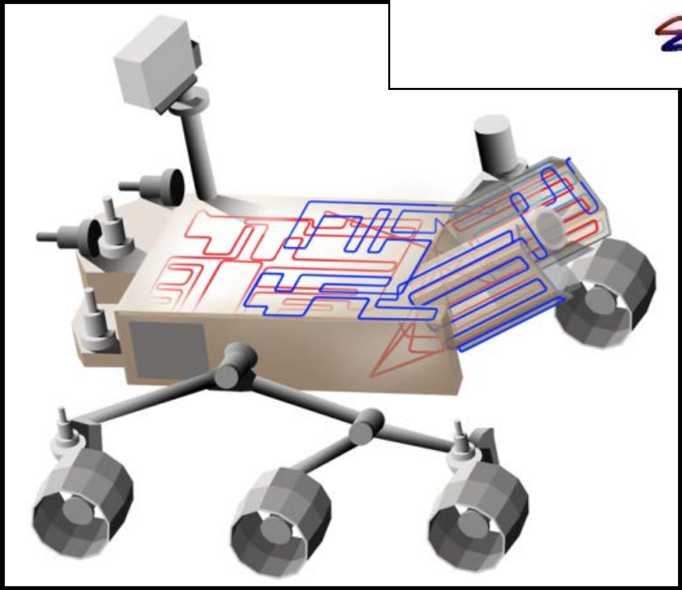





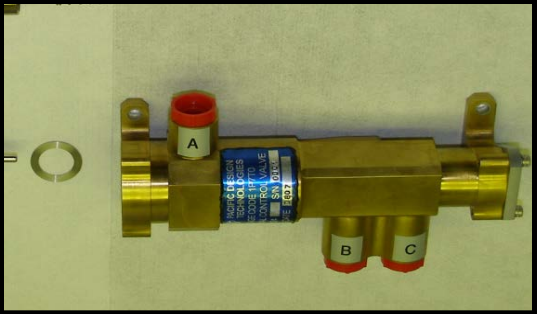

MSL Focused Technology Development

- **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

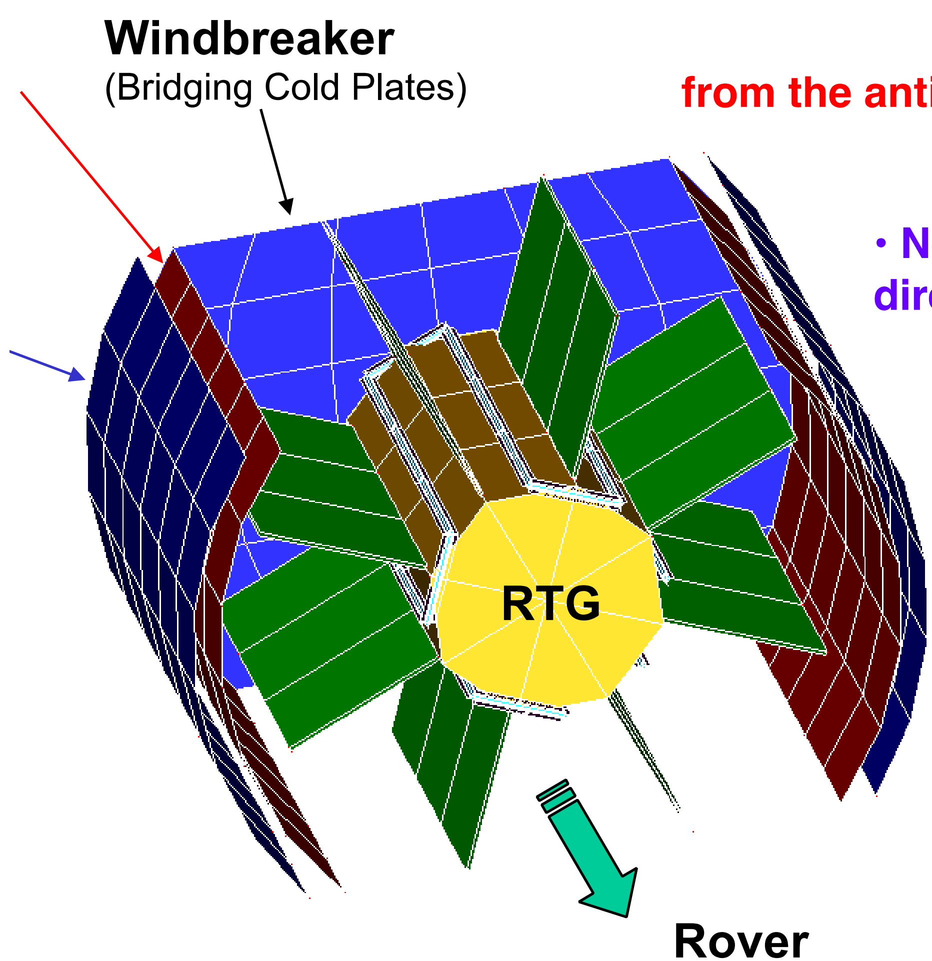


Total Tube Length [ft]	188
Aluminum Tube [ft]	149
SS Tube [ft]	28
Flex Line [ft]	11
Flex Bellows	30
Bi-Metal Joints	18
Aluminum Unions	12
Micro Elbows	47
Ominsafe Glands	42
Other SS Components	0
SS Orbital Welds	155
Aluminum Hand Welds	42
SS-AL Inertial Welds	18
Mechanical Fittings	21





HRS Heat Exchanger Windbreaker



• Need to ind at least in direction perpendicular to RTG axis

Rover HRS Requirements

- Recovers ~150 W of waste heat from MMRTG during Mars surface operations
- CFC-11 (working fluid): -100 to +100 C range
- Pumps & Valves: -40 to +100 C range
- Pump flow rate = 0.75 lpm
- Operating pressure < 200 psia
- Passive mixing/splitter types of thermal control valves (liquid based actuator)
- Pump input power = 10 W
- Three years operational life time

Component

Instruments*

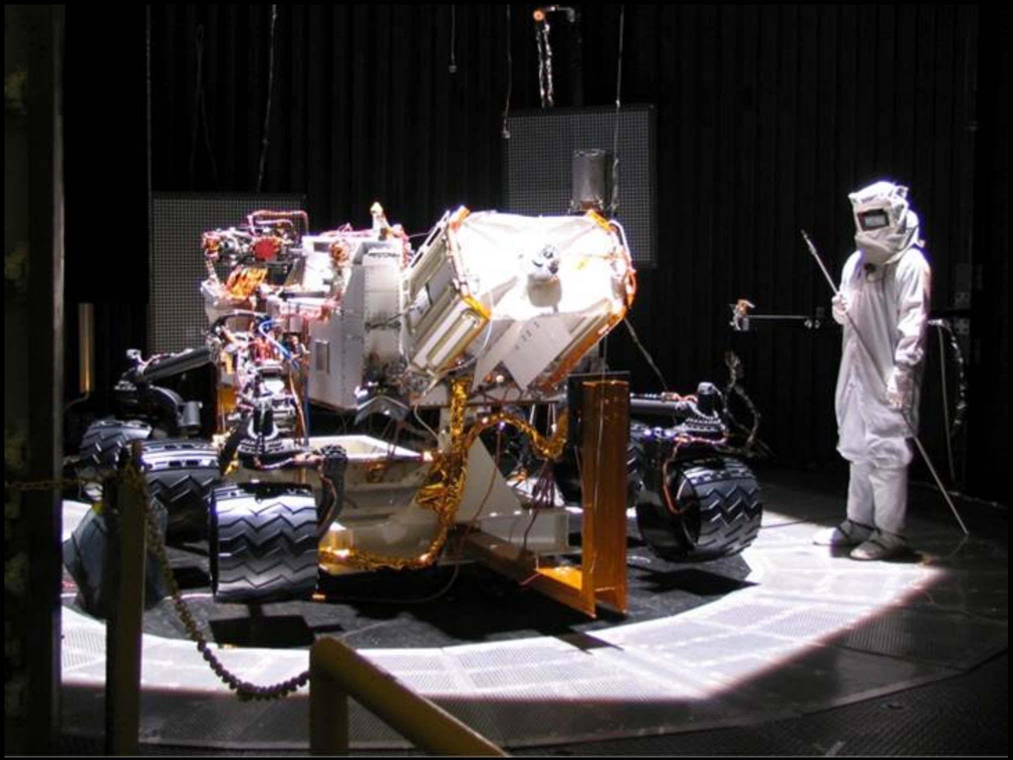
Overall Performance of RHRS on Mars

- The RHRS has performed exceptionally well on Mars – its been on the Martian surface for ~1 year
- It has experienced spring and summer on Mars, now in fall season
- No problems whatsoever on its operation and the thermal control of all components served by RHRS – all temperatures are within their allowable limits (-40/+50^{o}C)
- No fluid leaks have been observed – all operating pressures are as expected in their nominal range
- All the components employed by the RHRS have worked flawlessly without any hiccups whatsoever
    - Pumps, accumulator, thermal control valves, filters, heat exchangers, pressure transducers, check valves, RAMP, etc.
- The RAMP is very isothermal (about 2^{o}C gradient) in spite of large differences in heat loads from components controlled by RHRS, thus behaving like a true thermal bus
- The omnipresent CO2 gas-gaps employed in the thermal design of the rover have performed exceptionally well and should serve as pathfinders for future use of this type of insulation in Mars missions

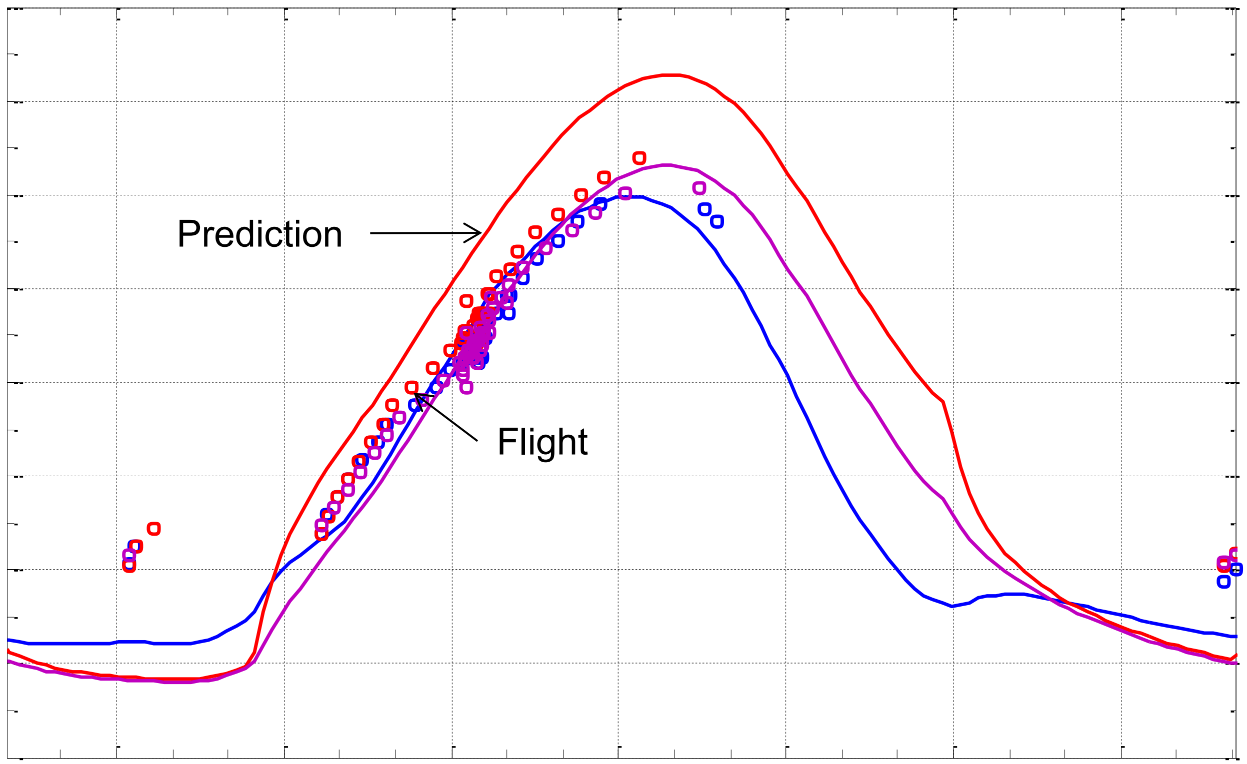
Seven Days of Terror – *Does our Design Work??*

System Thermal Vac Test
(Cruise Phase)

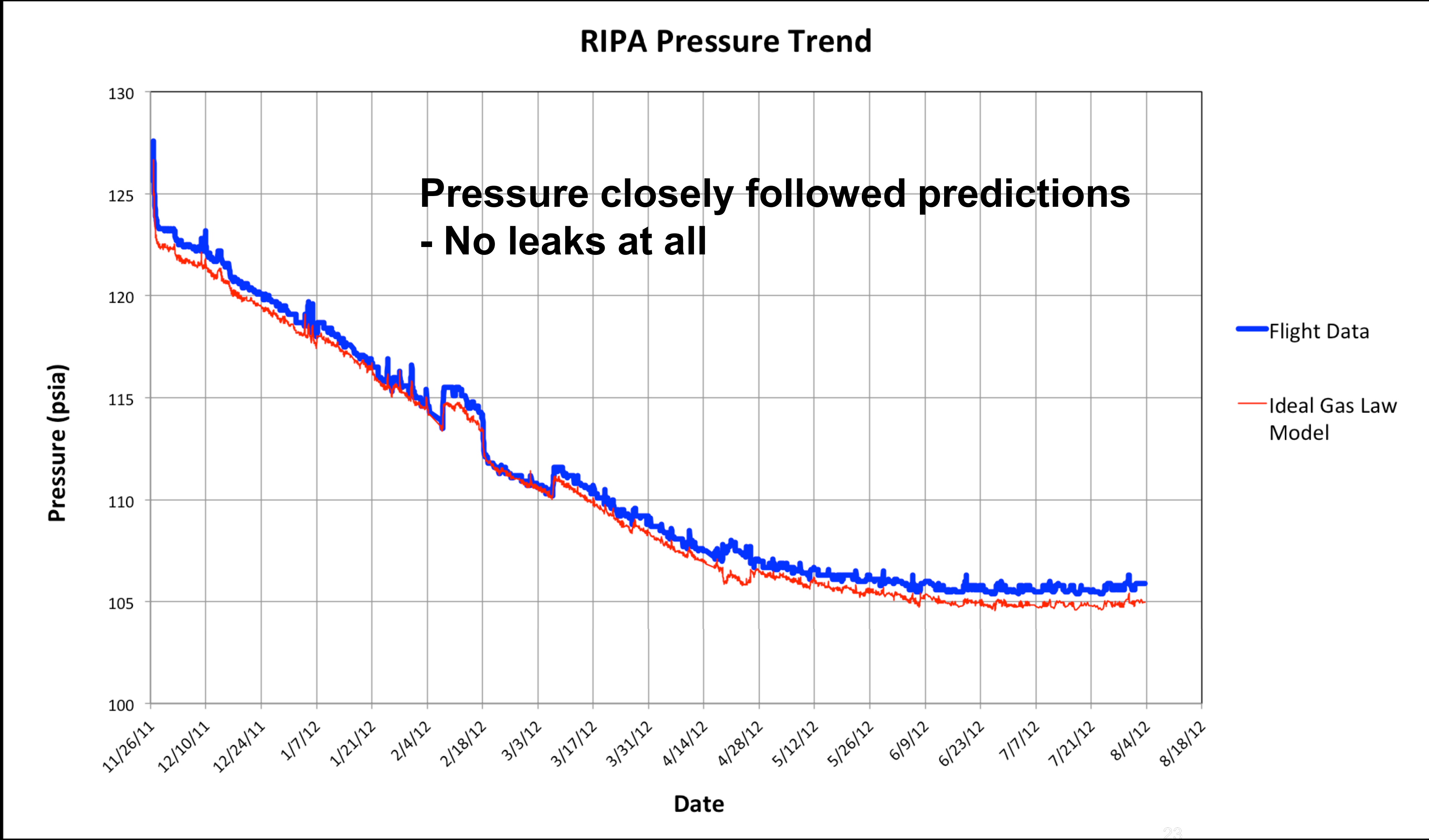
System Thermal Test
(Surface Phase)



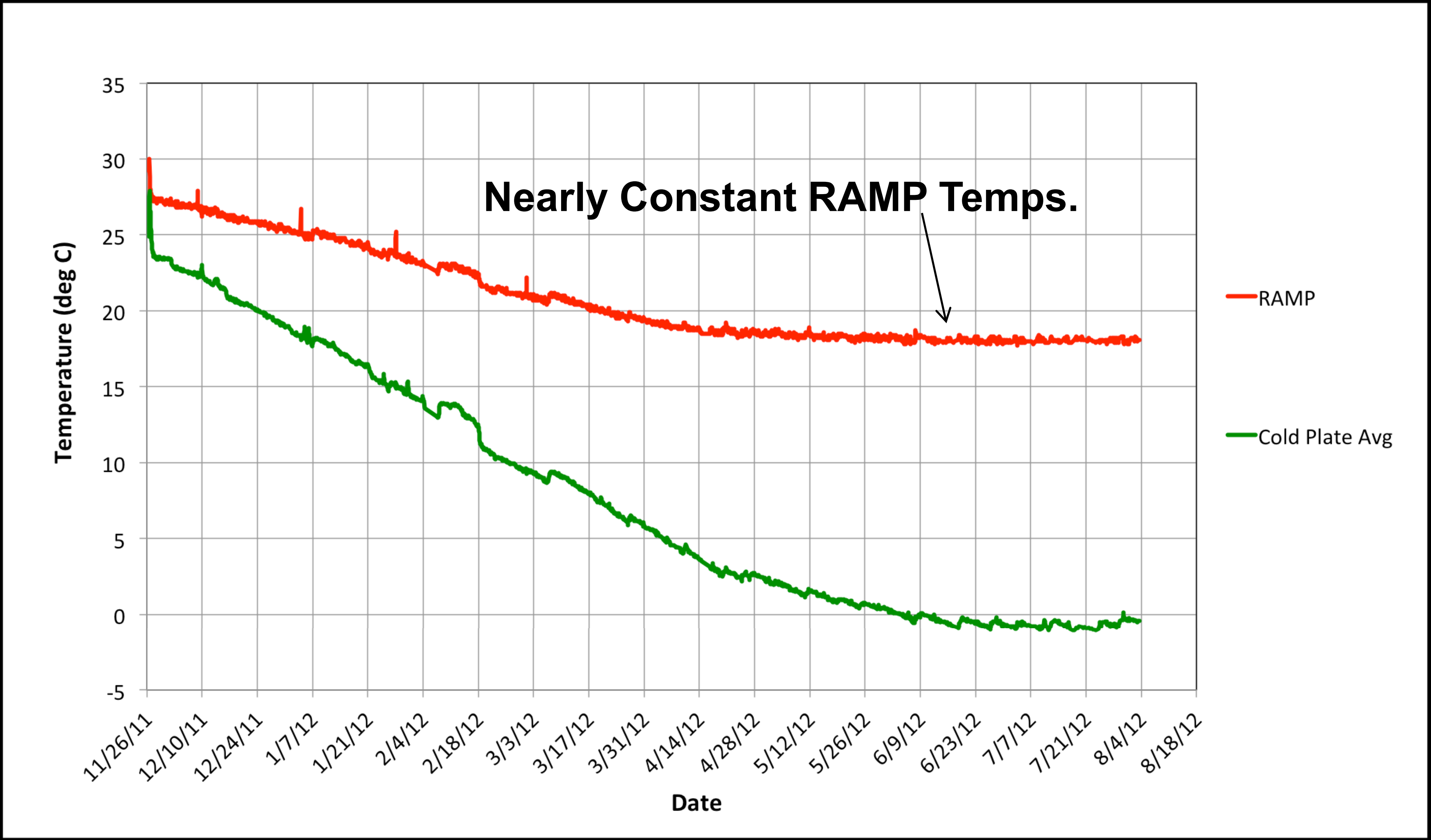
Rover HRS Predictions vs. Flight (RHRS Controlled Components)



Rover HRS Pressure During Cruise

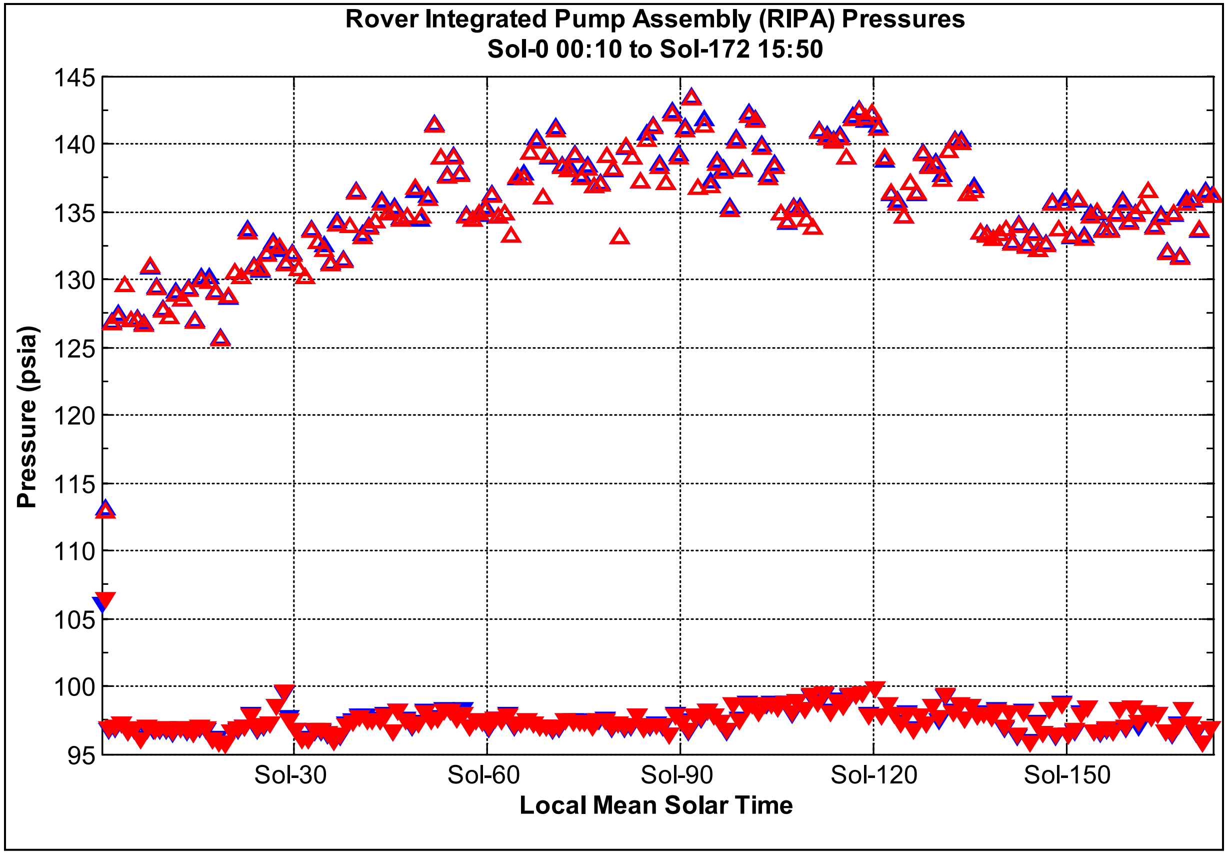


Rover HRS Controlled Temperatures During Cruise



RHRS Pressures During Flight

- Pressure shows diurnal changes recorded during surface operations (with no evidence of leaks)



Rover HRS Predictions vs. Flight

	Worst Case Cold, °C		On Mars, Gale Crater (Spring)		Allowable Min/Max Limit	Worst Case Hot, °C		On Mars, Gale Crater (Summer)	
Location	Pre-Test Prediction	Test Value	Flight Predict	Flight Value		Pre-Test Prediction	Test Value	Flight Predict	Flight Value
RHRS Fluid (RAMP In/Out)	-19/-30	-19/-21	21/26	27/24	-40/50	16/14	19/21	28/32	30/26
RAMP Mounted Components	-21/-28	-17/-24	31	31	-40/50	15/23	21/23	36	31
MMRTG (Fin root)	114	128	185	190	-40/50	170	171	186	192
RHRS Pressure (psia)		67	122	130	55/180		153	133	133

Possible Improvements for Future RHRS Designs

- Even though it is quite evident that the RHRS has performed exceptionally well in flight, there are still possible ways to improve it further for future missions.

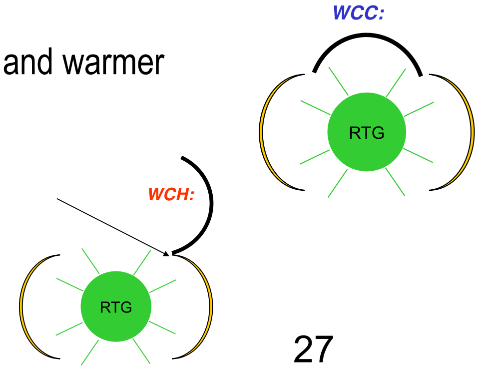
- The thermal design could be biased lower in desired temperatures by using lower thermal control valve control set points
  - Larger margin in hot conditions
  - Feasible because heat loss from rover turned out to be lower than originally predicted
  - There is roughly a 10°C margin at the low end that could be utilized to create this bias

- Cool MMRTG in hot conditions by increasing its view to Martian environment
  - Smaller hot plates
  - MMRTG fin root average temperatures were 5 to 10°C higher than predicted
  - Without significant reduction in cold case temperatures

- An actuator-operated flap for controlling view of MMRTG depending on the season or RAMP/MMRTG temperatures
  - Could be utilized to provide a more robust RHRS design
  - Closed flap in winter: MMRTG would have a more restricted view of the environment and warmer
  - Open flap in summer: Would bring configuration back to same as current one

- Qualification of alternative working fluids (instead of CFC-11)
  - CFC-11 no longer produced but only available in a recycled form

- Lighter weight and lower power pump assemblies would benefit future missions



Major Conclusions

- These are the 4th & 5th heat rejection systems that successfully utilized mechanically pumped fluid loops for thermal control of interplanetary missions
  - All JPL missions to Mars ☺!
- Its flawless performance in all phases of flight allowed it to tightly and robustly control the temperatures of all sensitive components within their allowable limits
- It was the first such system to harness waste heat (~150 W) from an MMRTG for the rover's thermal control
  - Allowing for all electrical power produced by the MMRTG to be used for mission operations
    - Except for 10 W required for operating the pump
- Overcoming the extreme thermal and mechanical environments encountered by this mission during the various mission phases was a major challenge and an enormous achievement!
- Employment of these systems in the Curiosity rover has paved the way for their use in the thermal control of future interplanetary missions in their current or extrapolated forms

Let’s Have The Drum Roll Now!

- The MSL Curiosity Mission has been an amazingly successful & thrilling journey for all of us!!

- The Pumped Fluid Loop HRS architecture is the nearest we have 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 without intervention*
  - Thermal engineer’s dream come true

- MSL’s challenging thermal requirements during its all phases were very successfully met with the Pumped Fluid Loop Heat Rejection System

- Several advanced pumped fluid loop thermal technologies were developed in order to ensure a robust thermal control system

- MSL’s thermal architecture will pave way for its usage on future NASA missions, Commercial satellites, and military missions

MSL HRS Team

(December 13, 2007)

It takes a village…

A Picture is Worth A Million Words…

Acknowledgements

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- **The authors wish to acknowledge the many engineers and scientists collaboratively working on the Mars Science Laboratory project, of which the thermal subsystem is a part of the greater whole.**