Thermal Control of MSL Rover 'Curiosity' using an Active Fluid Loop

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Government sponsorship acknowledged

MSL Rover HRS Team

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Pradeep Bhandari	HRS Designer & MSL Thermal System Engineer
Dave Bame	HRS GSE Cog Engineer and HRS Lab Manager
Paul Karlmann	RIPAS/CIPAS Cognizant Engineer
AJ Mastropietro	HRS Fabrication and KSC HRS/GSE Engineer
Yuanming Liu	HRS Fabrication Cognizant Engineer
Jen Miller	HRS Fabrication and KSC HRS Engineer
Mike Pauken	HRS Fabrication Engineer
Jackie Lyra	MSL Thermal Product Delivery Manager

Sunset on Mars – Spirit Rover
May 19, 2005

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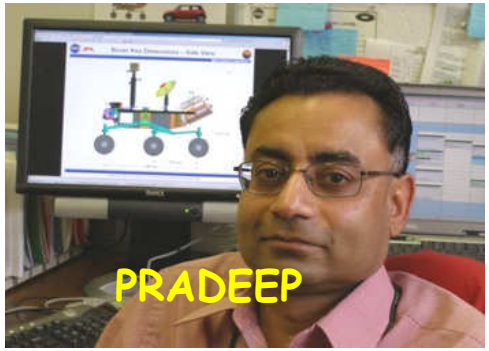
MSL Rover Heat Rejection System Team



OUTLINE

- MSL Rover Curiosity
- Thermal Challenges on Surface
- MSL Thermal Control with MPFL
  - (Mechanically Pumped Fluid Loop)
- Active Fluid Loop Technologies
- Changes during Design Phase
- HRS Fabrication and Integration
- MSL Thermal tests
- Lessons Learned

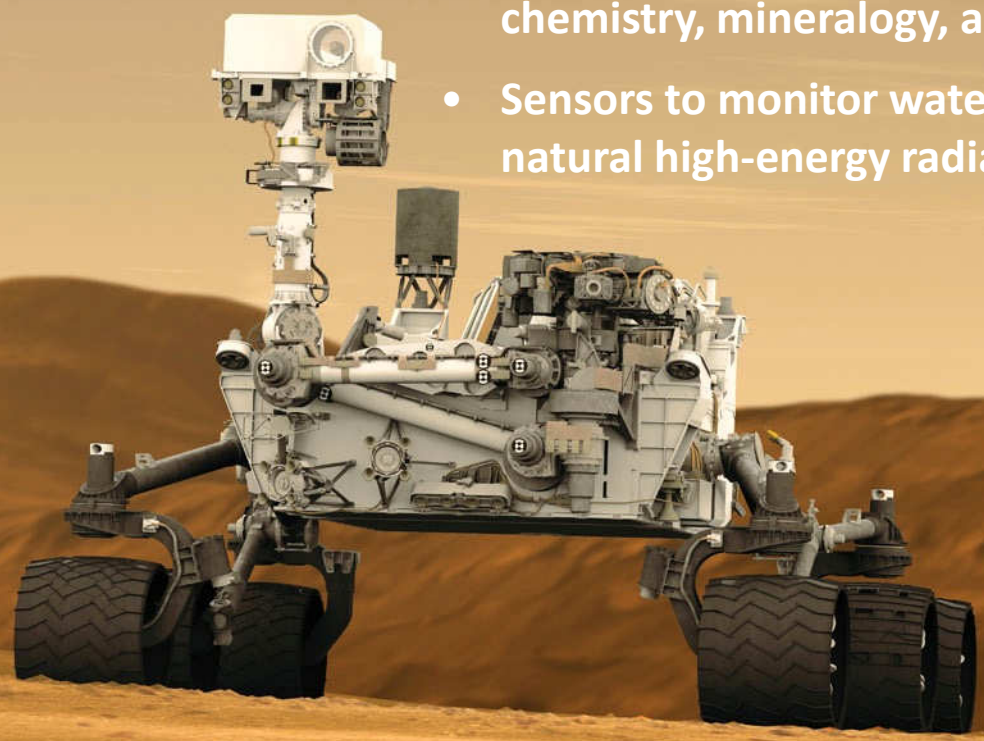
Curiosity's Capabilities

A Robotic Field Geologist

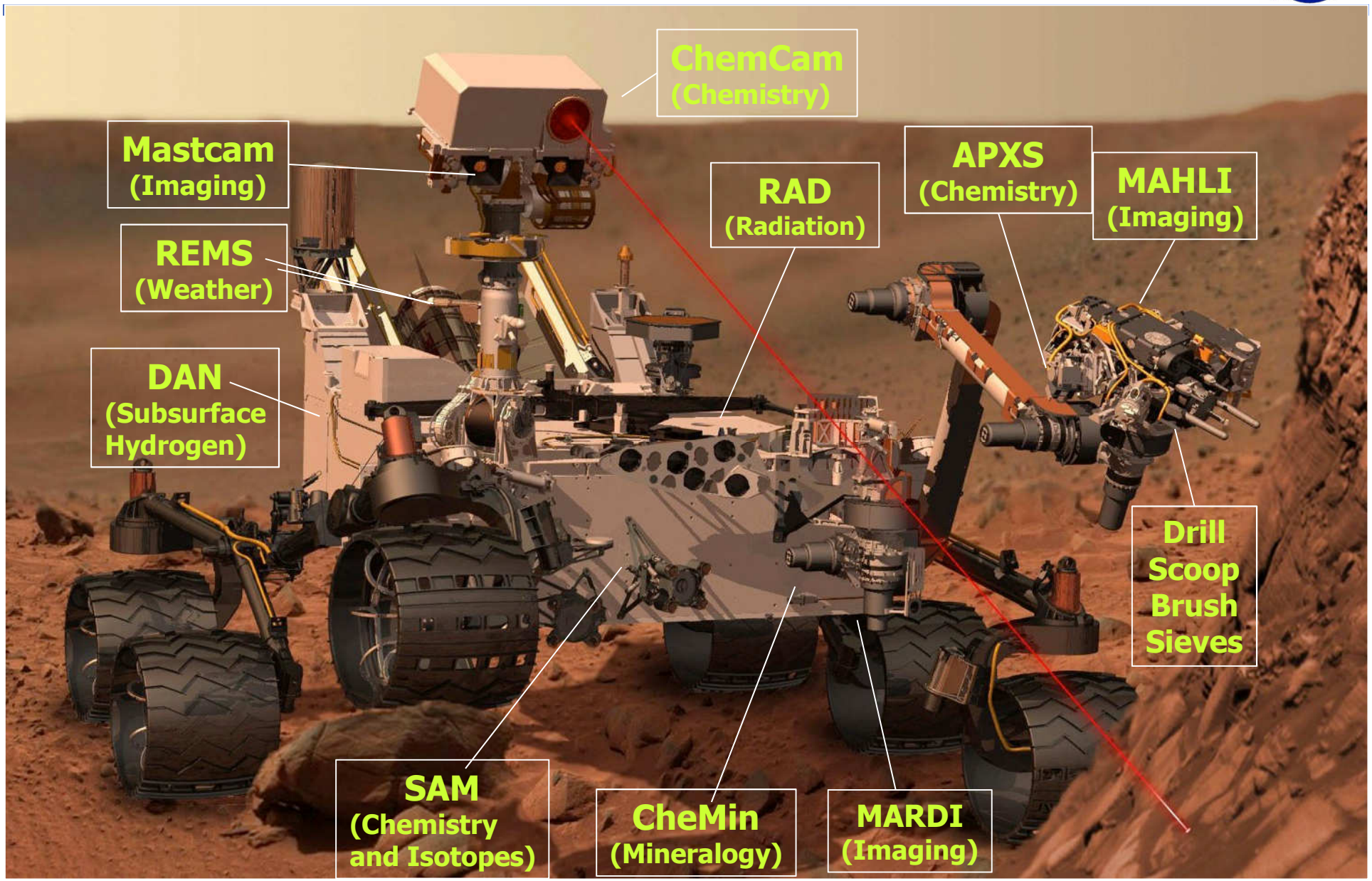
- Long life, ability to traverse many miles over rocky terrain
- Landscape and hand-lens imaging
- Ability to survey composition of bedrock and regolith

A Mobile Geochemical and Environmental Laboratory

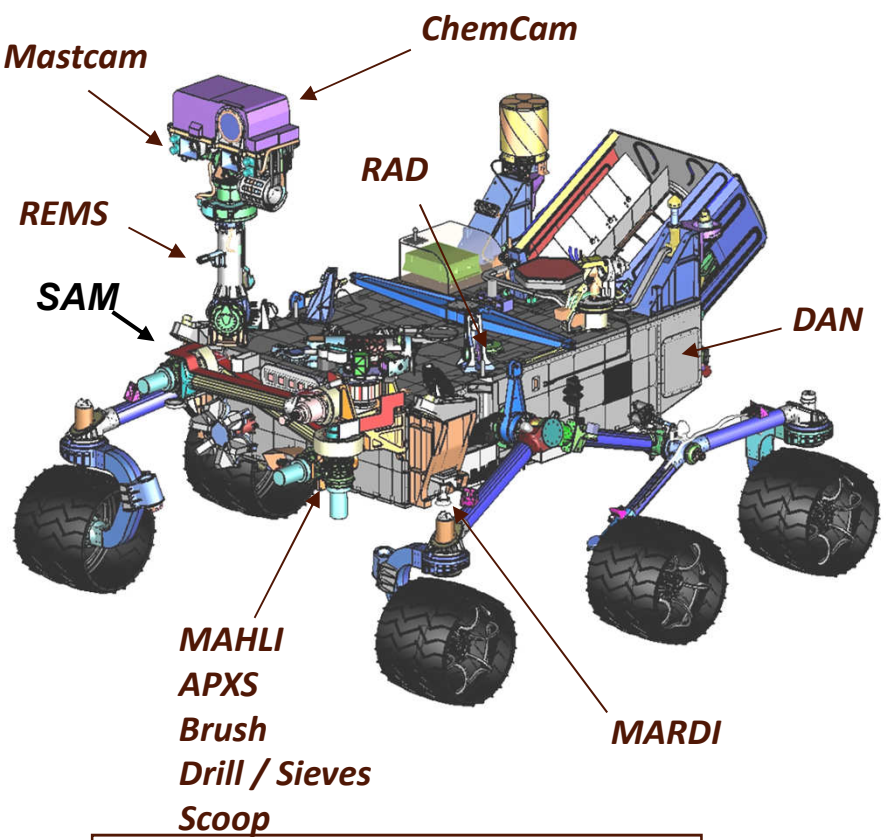
- Ability to acquire and process dozens of rock and soil samples
- Instruments that analyze samples for chemistry, mineralogy, and organics
- Sensors to monitor water, weather, and natural high-energy radiation



Ten Instruments



MSL Science Payload



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

REMOTE SENSING

Mastcam (MSSS) - Color and telephoto imaging, video, atmospheric opacity

ChemCam (LANL/CNES) – Chemical composition; remote micro-imaging

CONTACT INSTRUMENTS (ARM)

MAHLI (MSSS) – Hand-lens color imaging

APXS (Canada) - Chemical composition

ANALYTICAL LABORATORY (ROVER BODY)

SAM (GSFC/CNES) - Chemical and isotopic composition, including organics

CheMin (ARC) - Mineralogy

ENVIRONMENTAL CHARACTERIZATION

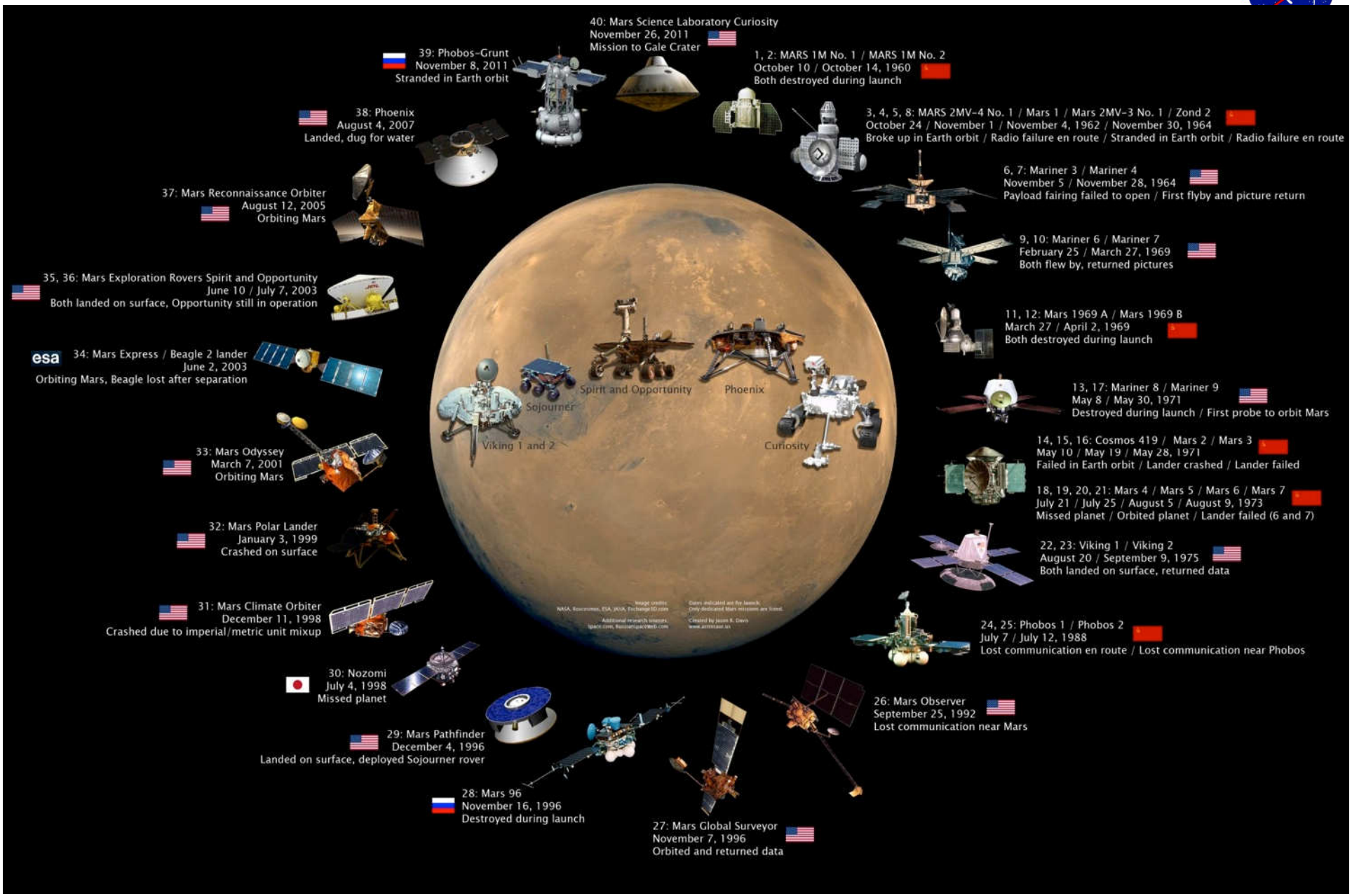
MARDI (M. Malin, MSSS) - Descent imaging

REMS (Spain) - Meteorology / UV

RAD (SwRI) - High-energy radiation

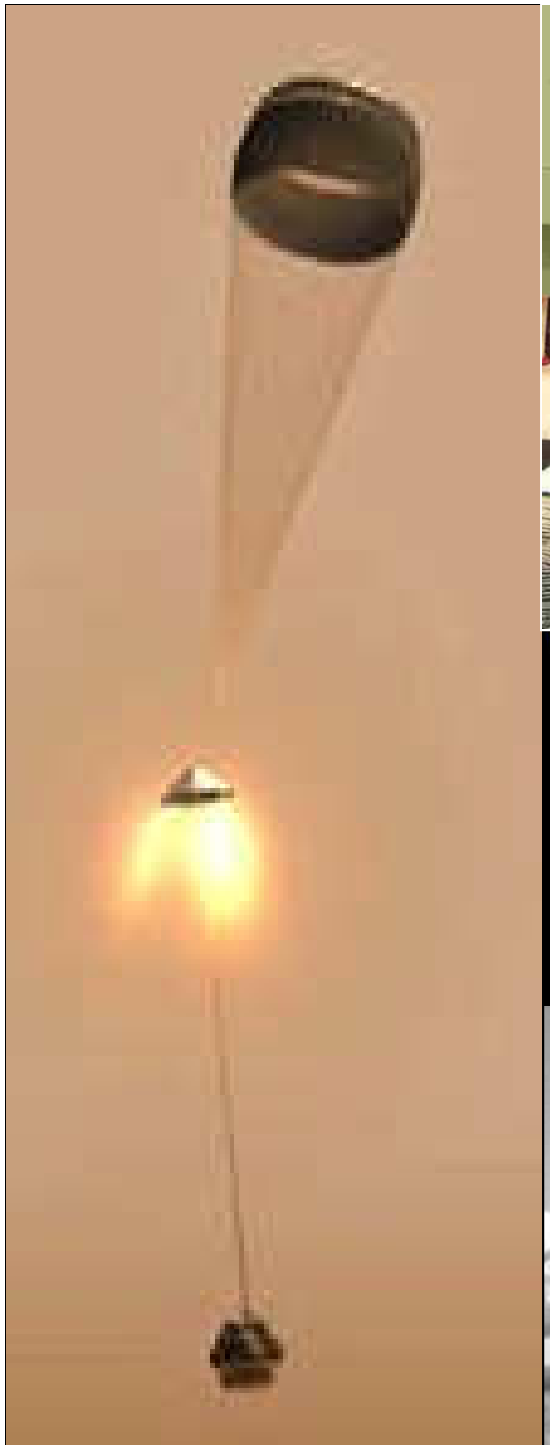
DAN (Russia) - Subsurface hydrogen

Mars Exploration Family Portrait

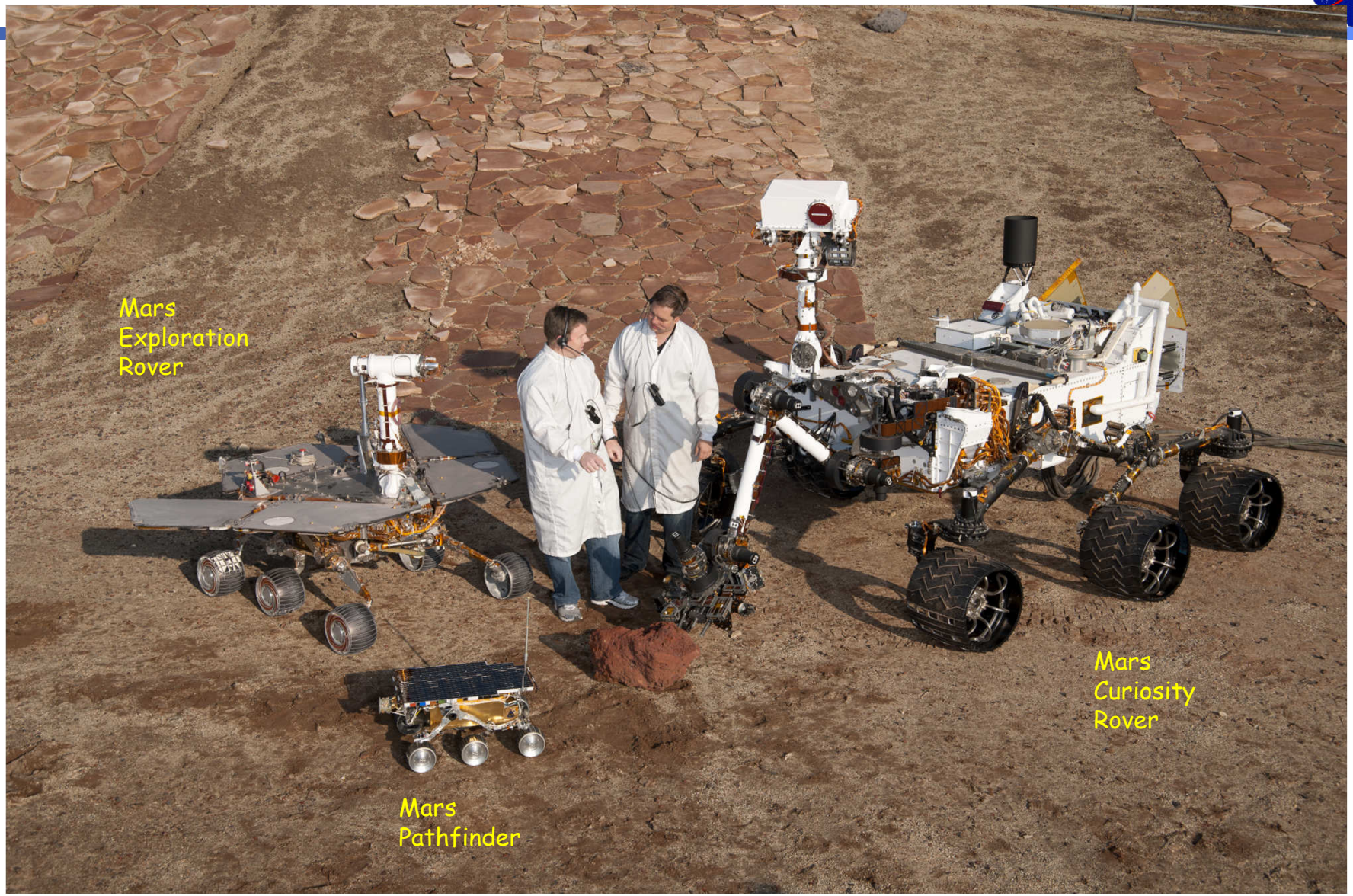


MARS IS HARD!
EARTH
HALF-TIME SCORE:
MARS
24
16

Mars Pathfinder and Sojourner (1997)

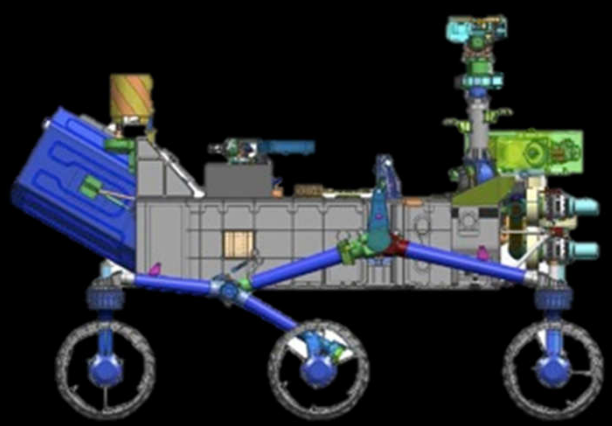


All in the Family…



Curiosity: Vitals

Height:	2.2 m	2.2 m Kobe Bryant	1.4 m
Mass:	899 Kg	6 Shaqs	1221 Kg
Speed:	0.14 Km/hr 4 cm/sec	47 cm/sec Tortoise	200 Km/hr
Wheel Diameter:	0.5 m	Shaq's Shoe Size	0.4 m



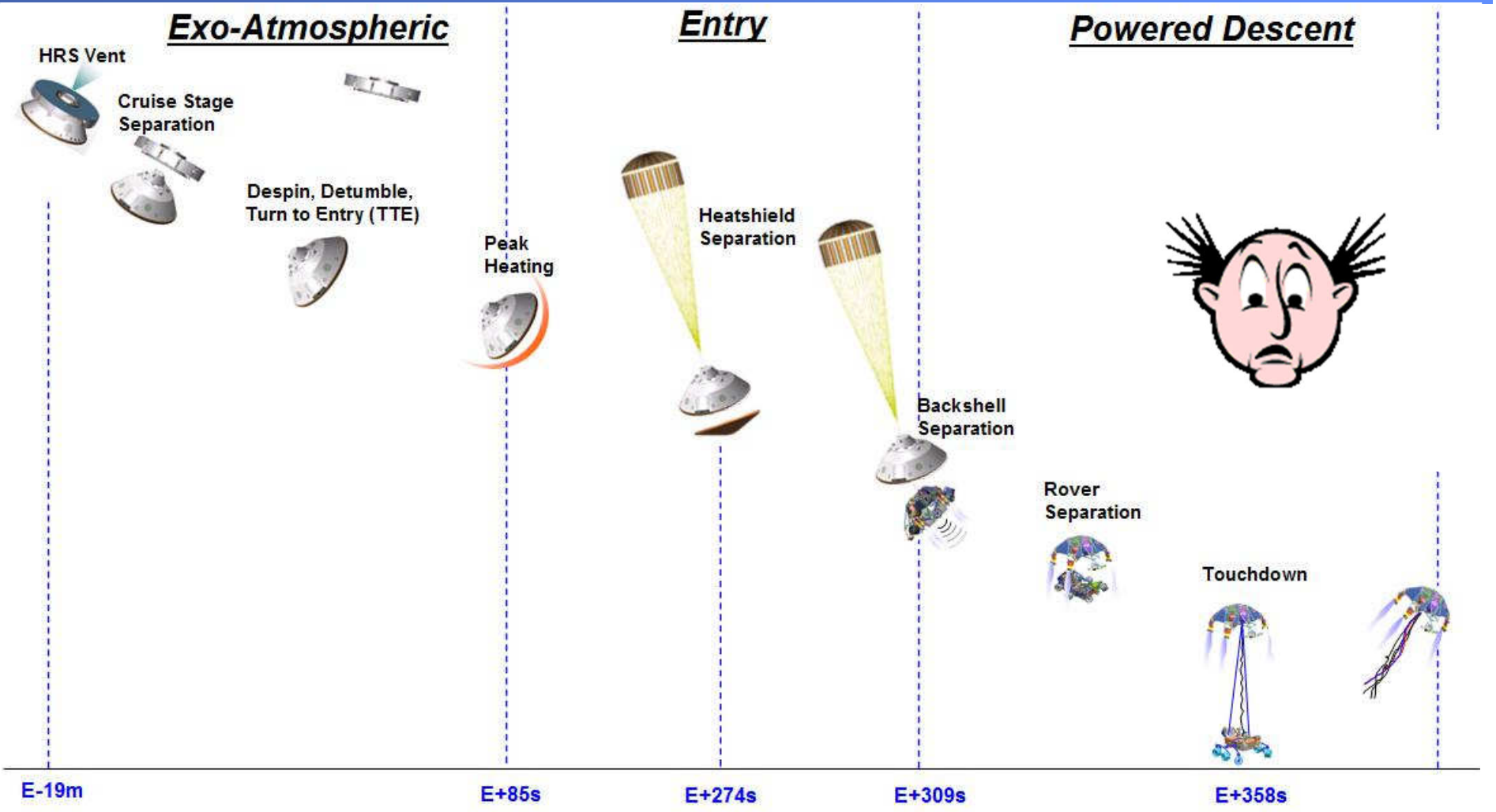
JPL Curiosity

Curiosity 2010: *First Driving Test*

MSL Rover EDL & MMRTG

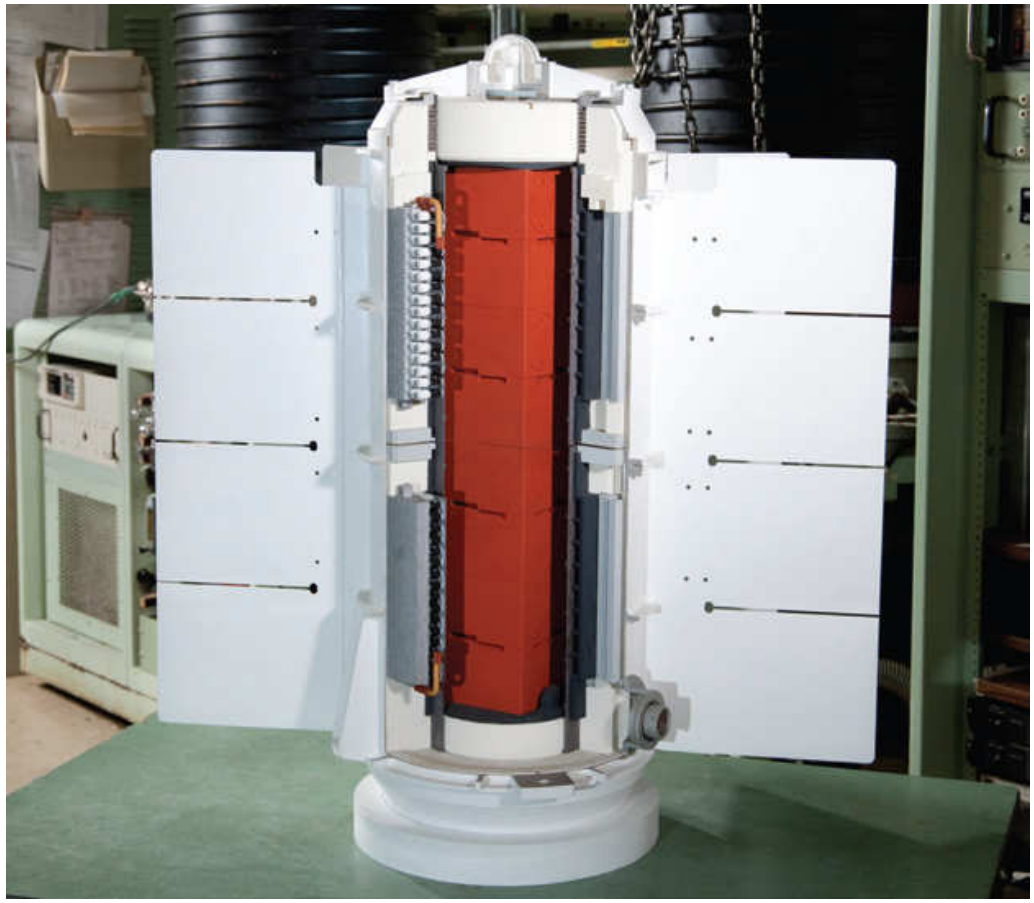
- Video -

The *SEVEN* Minutes of Terror!!



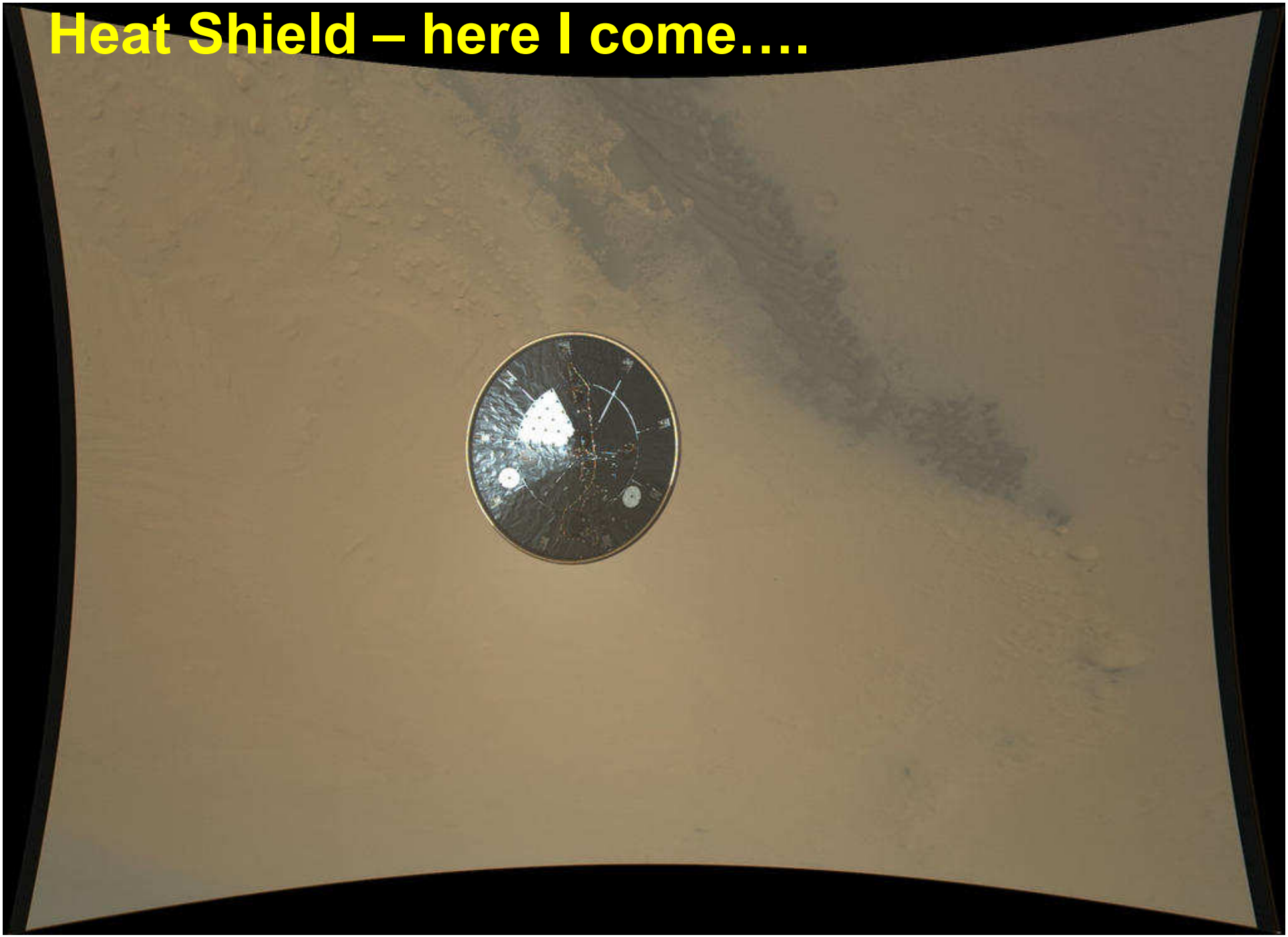
Multi-Mission RTG
-Radioisotope Thermoelectric Generator

- 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.



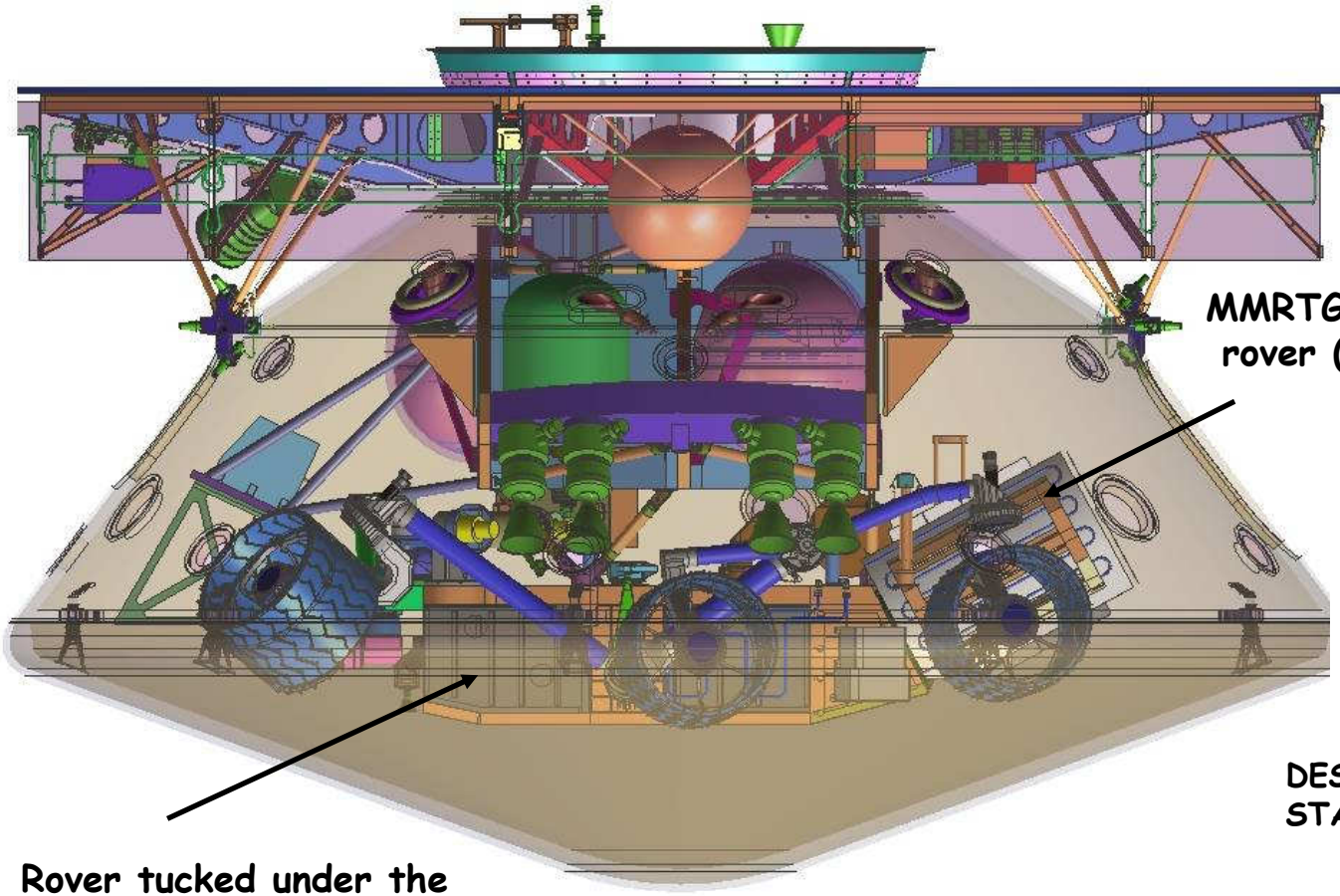
Gale Crater and Mount Sharp

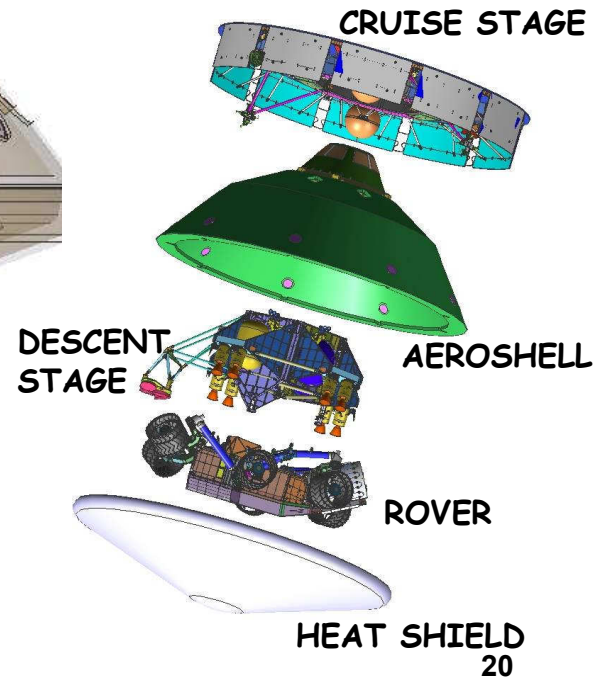
Heat Shield – here I come….



Photos taken by Mars Reconnaissance Orbiter

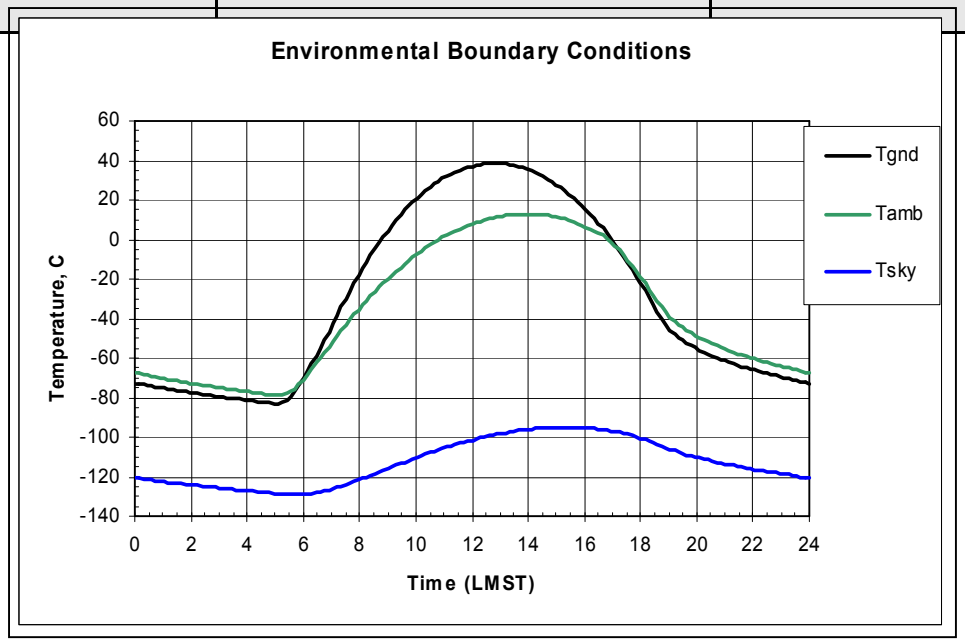
MSL Spacecraft in Cruise Phase





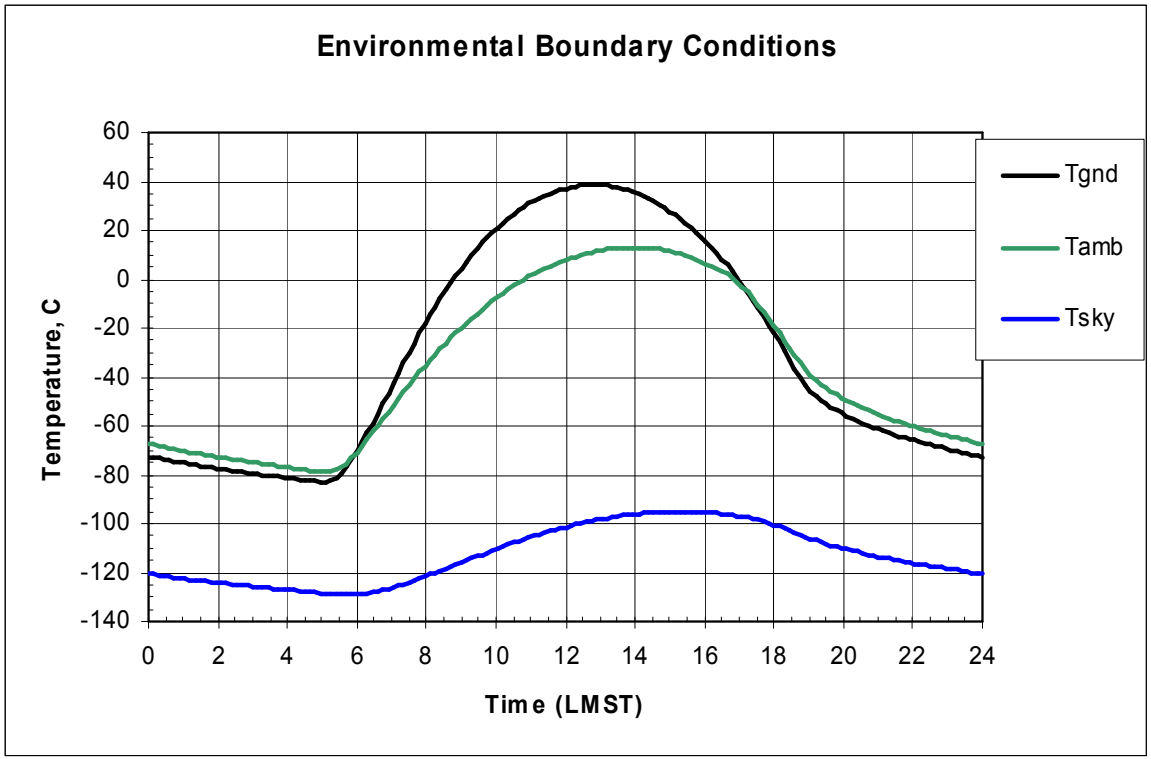
Let's Do Some Thermal Engineering!

	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

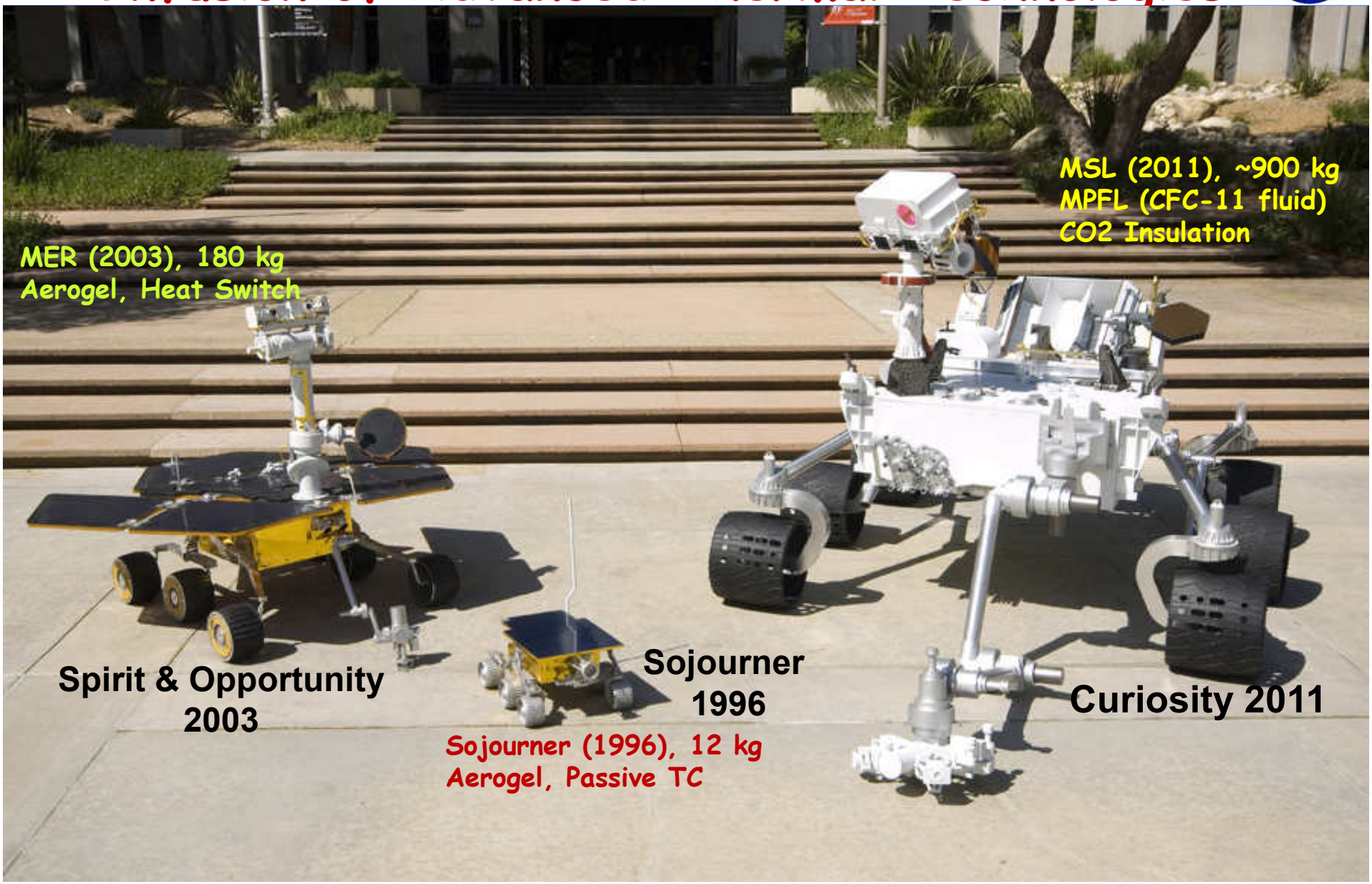


Thermal Control Challenges of MSL Rover

- **Demanding thermal control requirements**
  - Extreme diurnal environment (-123 C to 40 C, full sun to no sun)
  - Large RPS waste heat (~2000 W) during launch/cruise, & surface operations
  - Tight temperature requirements of Science Instruments
  - Long life & Rover mobility challenges (configuration, dust etc)



Rover Family Portrait –
Infusion of Advanced Thermal Technologies

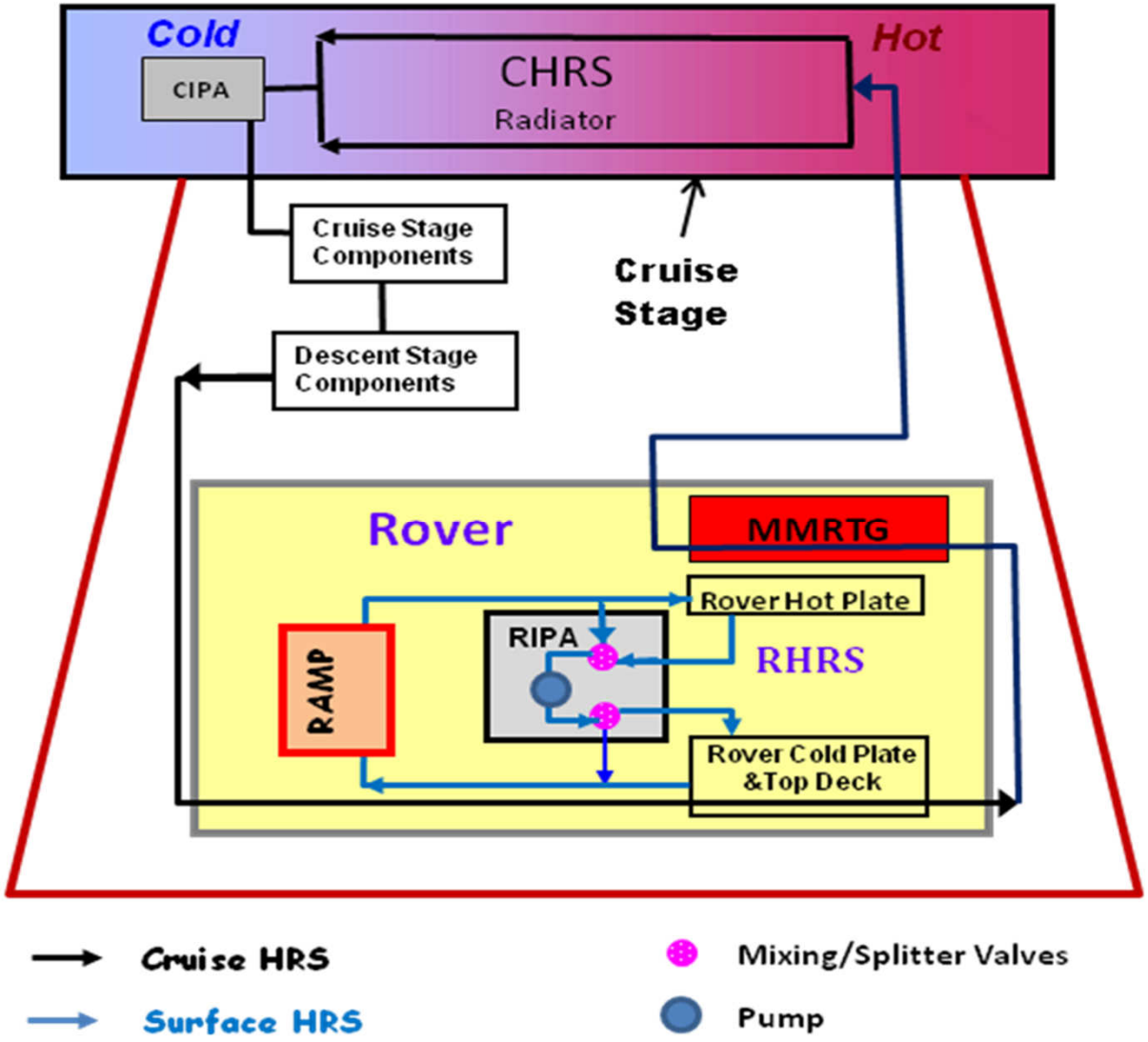


Why Use a Pumped Fluid Loop?

- 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

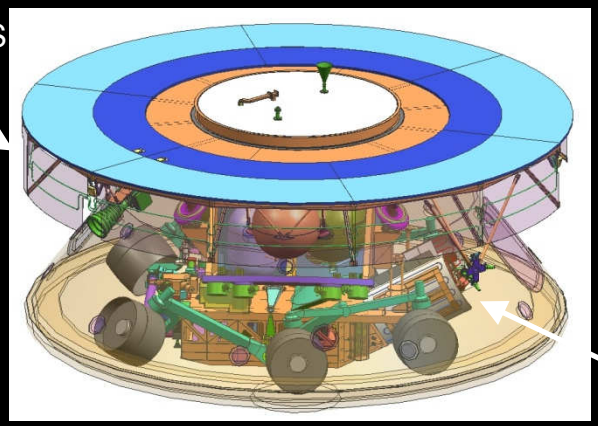
- Have increasingly been used recently (last 15 years) at JPL to solve complex thermal control problems
  - Mars Pathfinder (Cruise)
  - 2x Mars Exploration Rovers (Cruise)
  - Mars Science Laboratory (Cruise + Rover)

MSL Thermal Control with MPFL



MSL Heat Rejection Systems

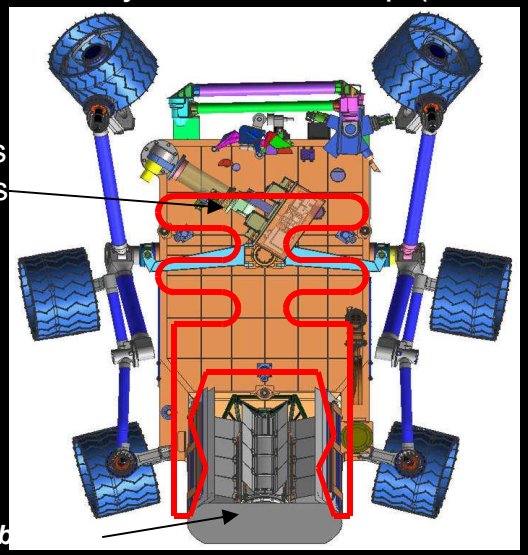
Cruise HRS Radiators



MMRTG

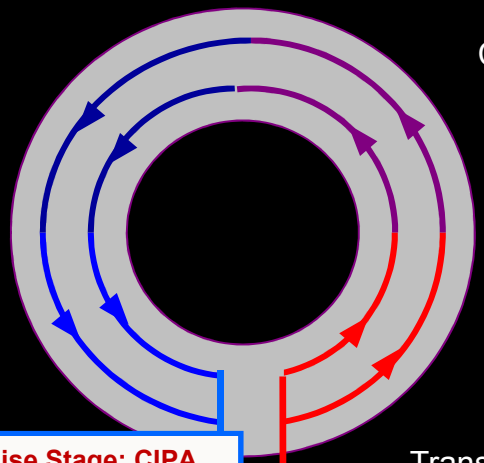
Rover System Fluid Loop (RHRS)

Loop controls ***both*** Avionics and Payload zones



Windb

Cruise Pumped Fluid Loop (CHRS)



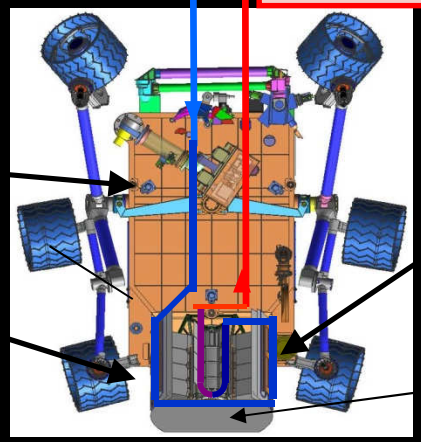
Cruise Radiator (split flow)

Cruise Stage: CIPA, CPA, CPAM, DSS

Transfer Lines

Descent Stage: TWTA, SDST, DPAM, DPA & DPFA

Rover **RAMP** HXCH

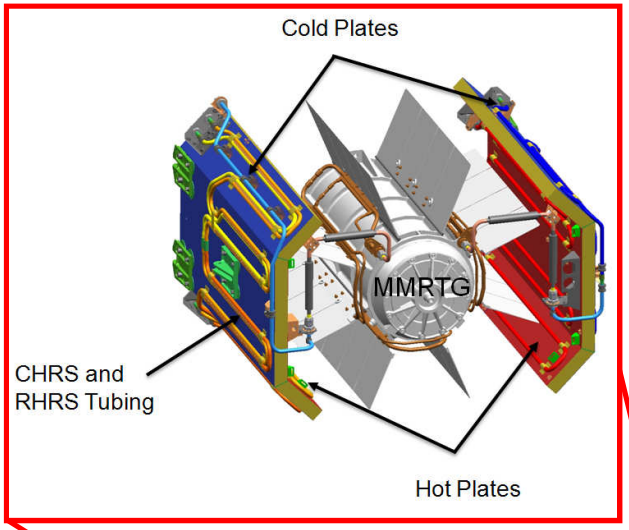


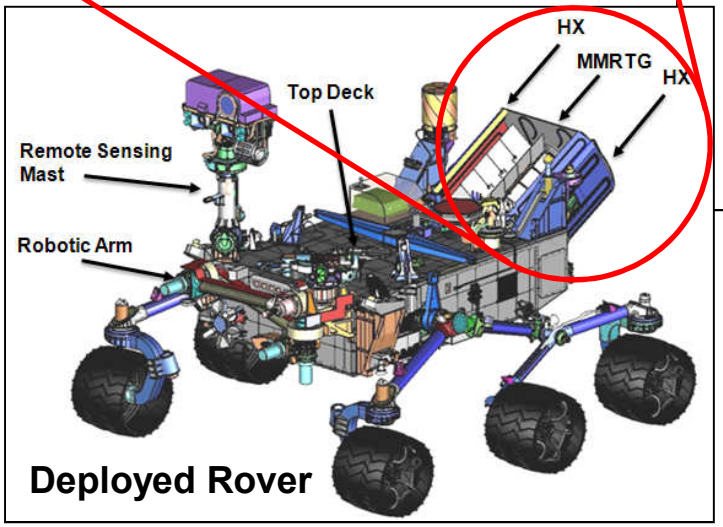
MMRTG Heat Exch

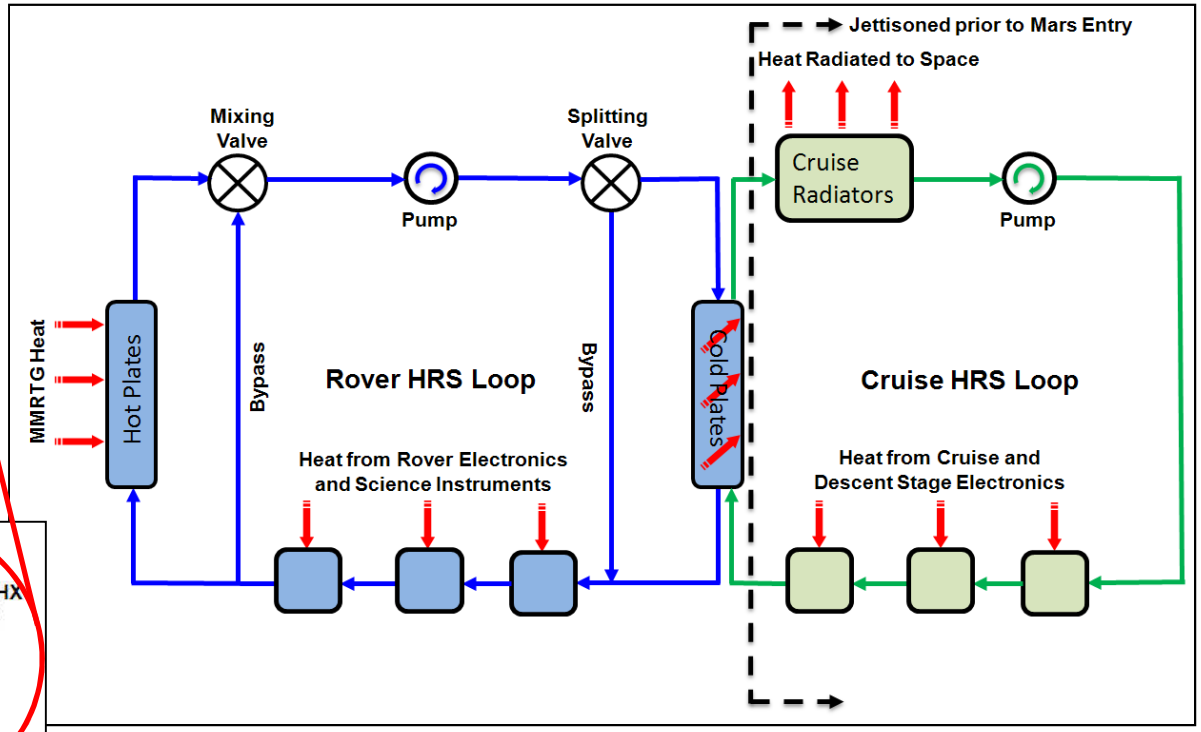
Rover System Heat Exchanger

Windbreaker

Mechanically Pumped Fluid Loop Architecture

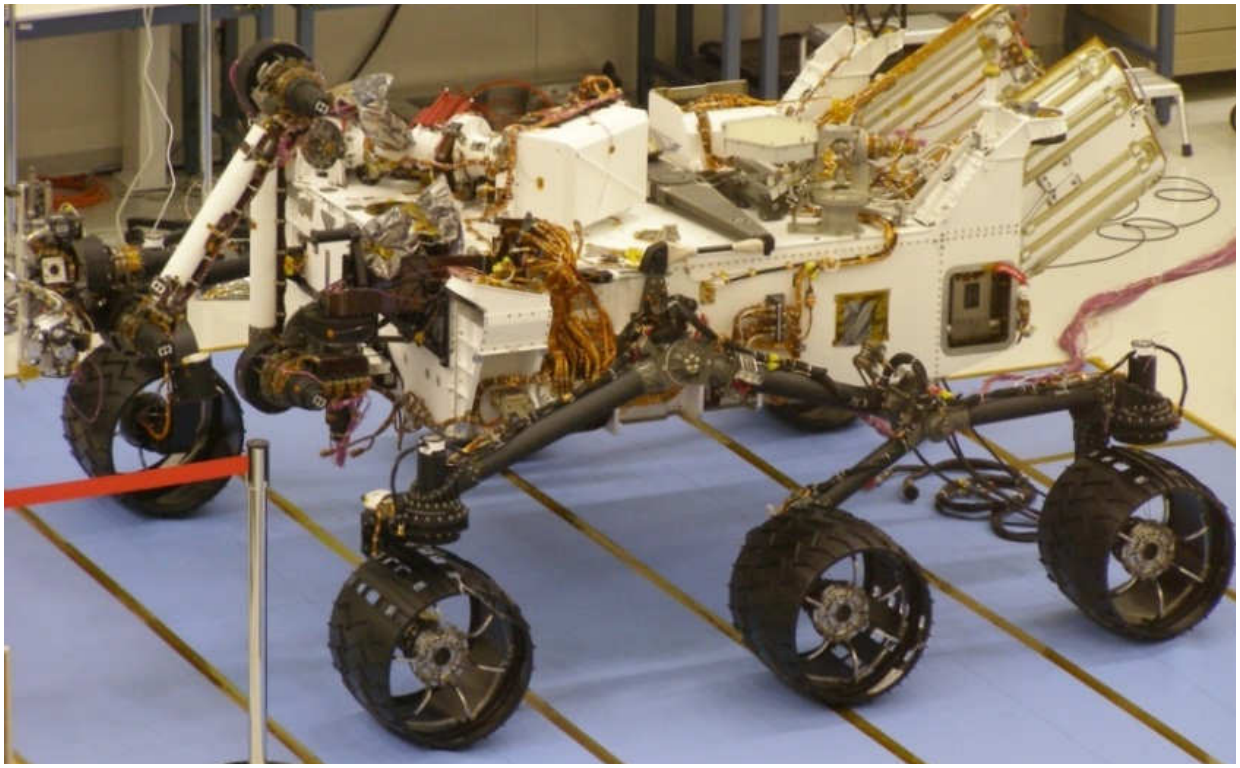


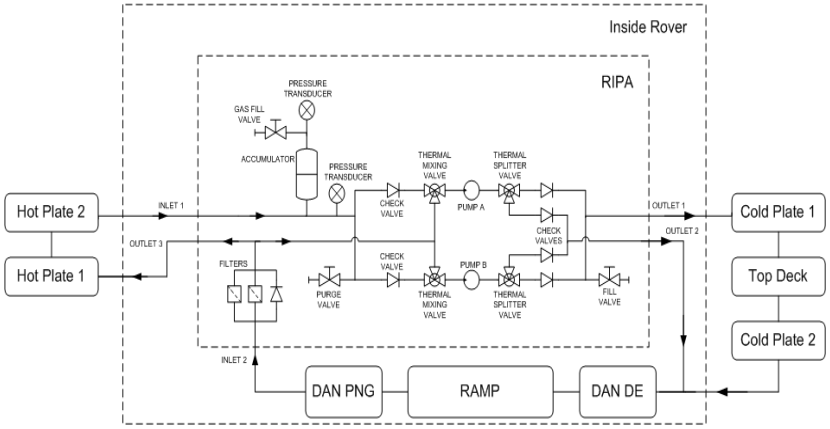




Simultaneously collect heat from MMRTG ***and*** reject waste heat to either the Cruise Loop or directly to Martian environment depending upon mission phase

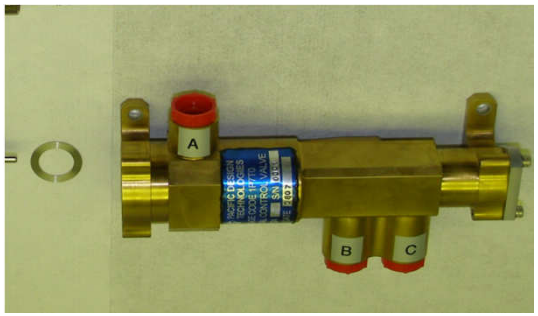
HRS Design Activities - RHRS

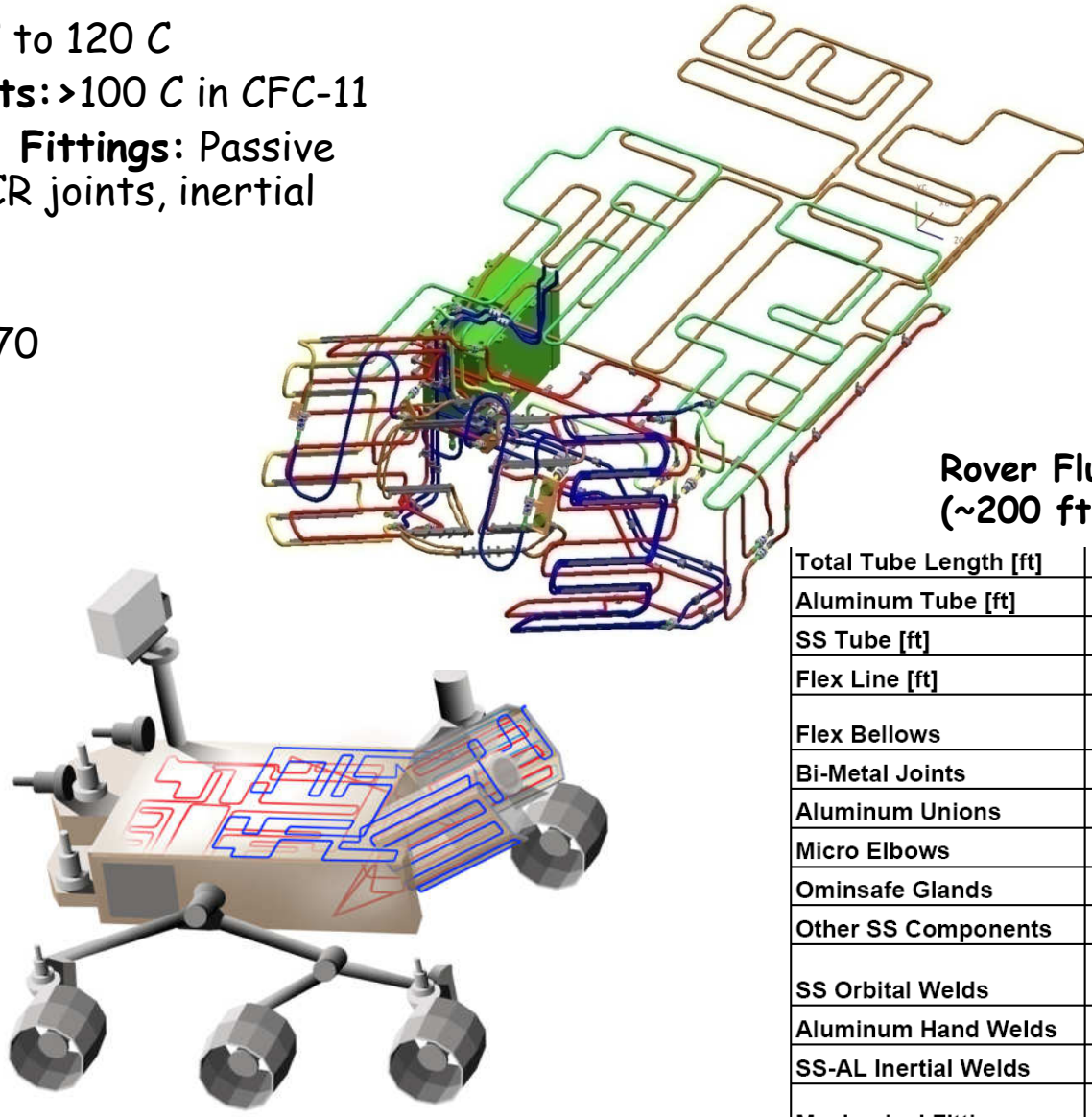




MSL Focused Technology Development

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



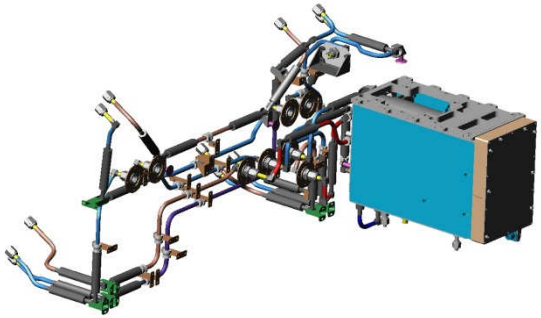


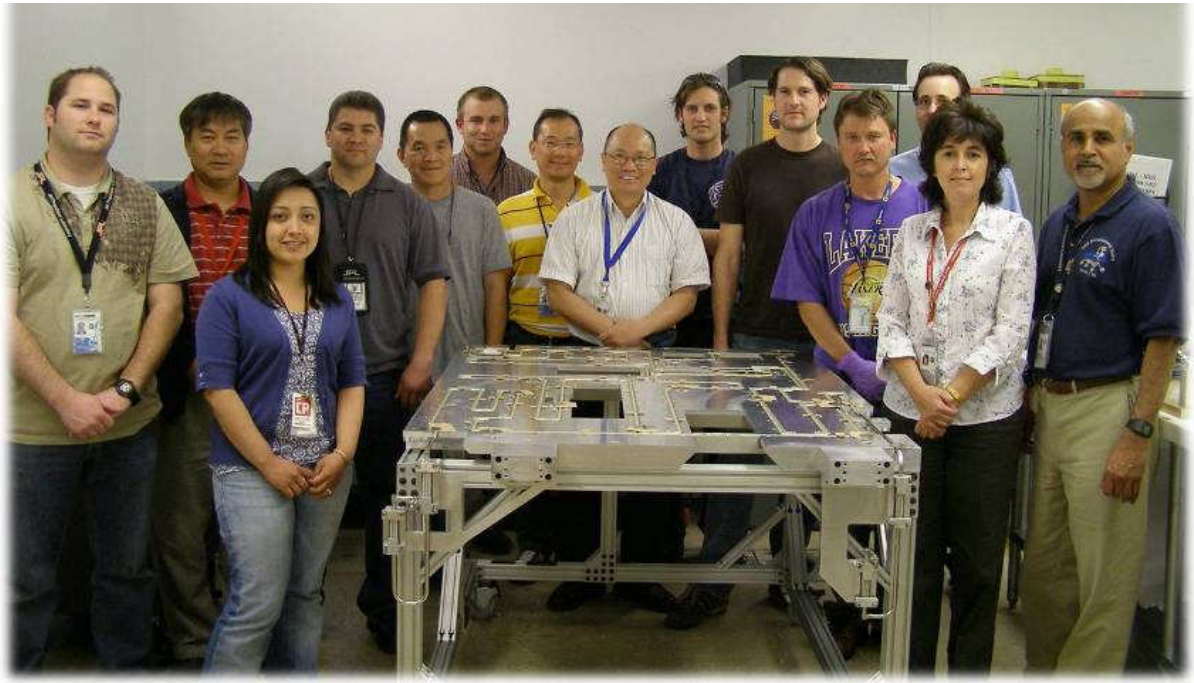
Rover Fluid Loop (~200 ft tubes)

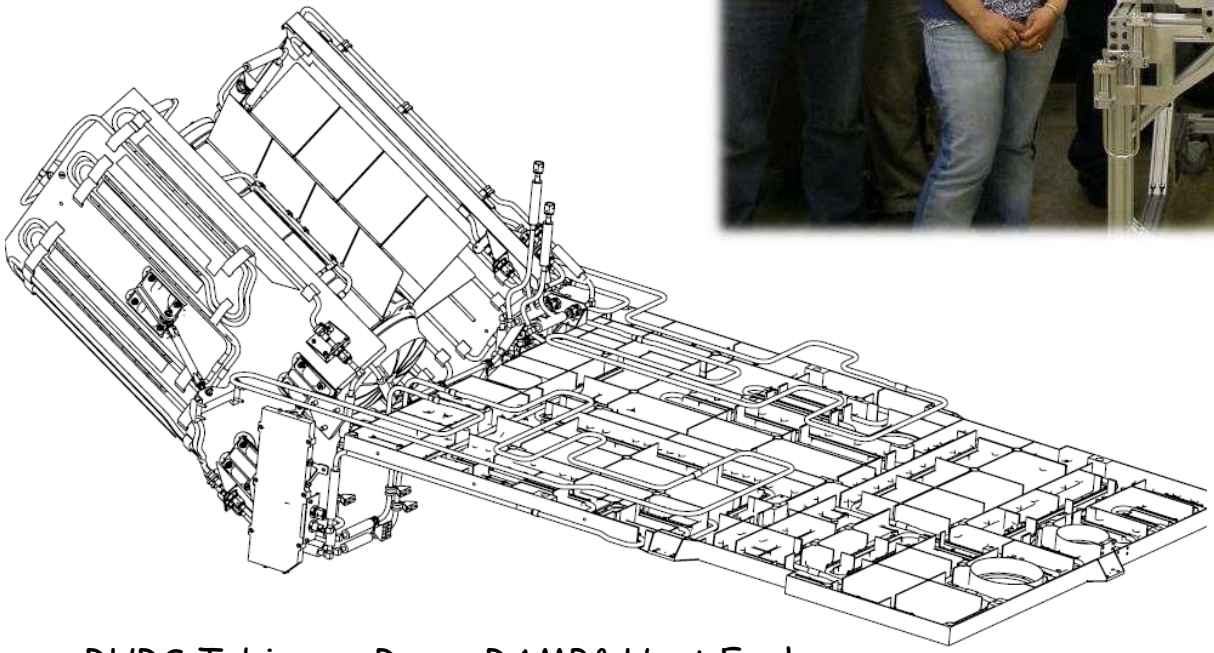
Total Tube Length [ft]	188
Aluminum Tube [ft]	149
SS Tube [ft]	28
Flex Line [ft]	11
Flex Bellows	30
Bi-Metal Joints	18
Aluminum Unions	12
Micro Elbows	47
Ominsafe Glands	42
Other SS Components	0
SS Orbital Welds	155
Aluminum Hand Welds	42
SS-AL Inertial Welds	18
Mechanical Fittings	21

MSL Rover RAMP Fabrication

RIPAS w/Rover Aft



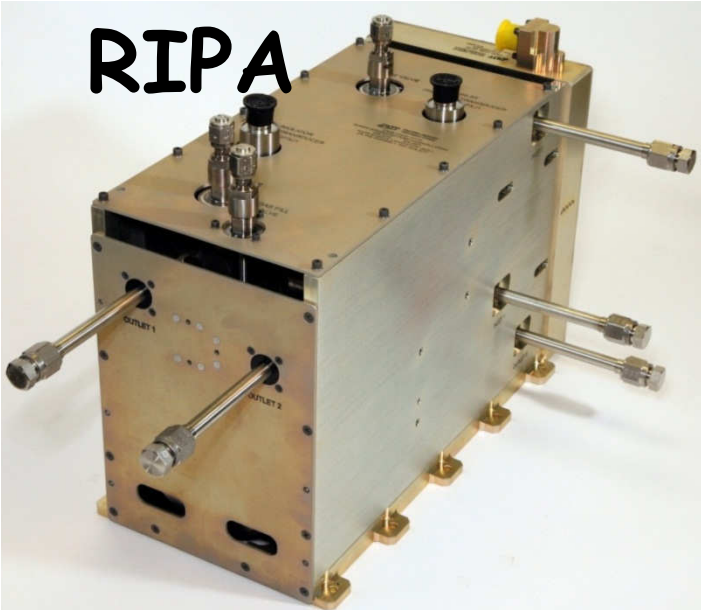


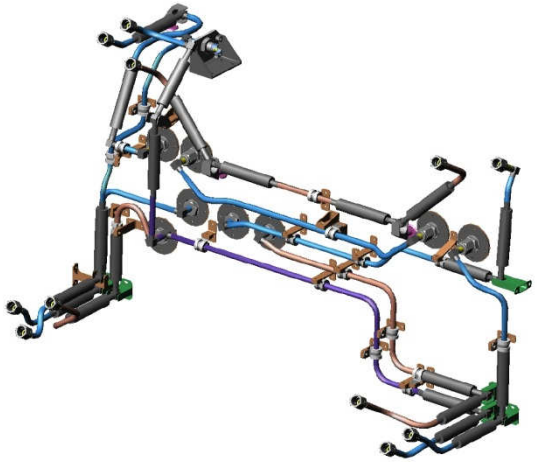


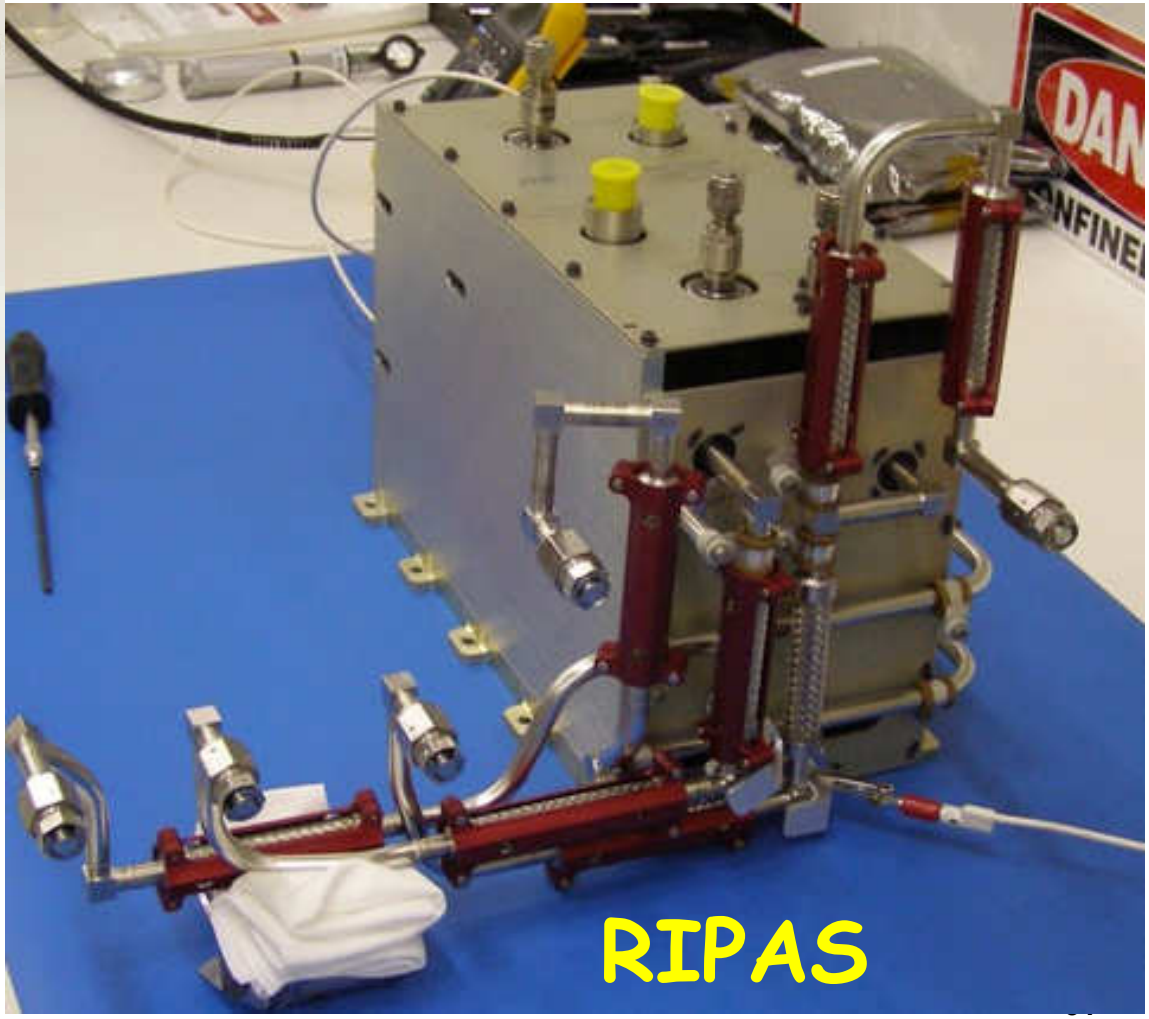
RHRS Tubing on Rover RAMP& Heat Exchanger

Rover Aft w/RHRS Tubing

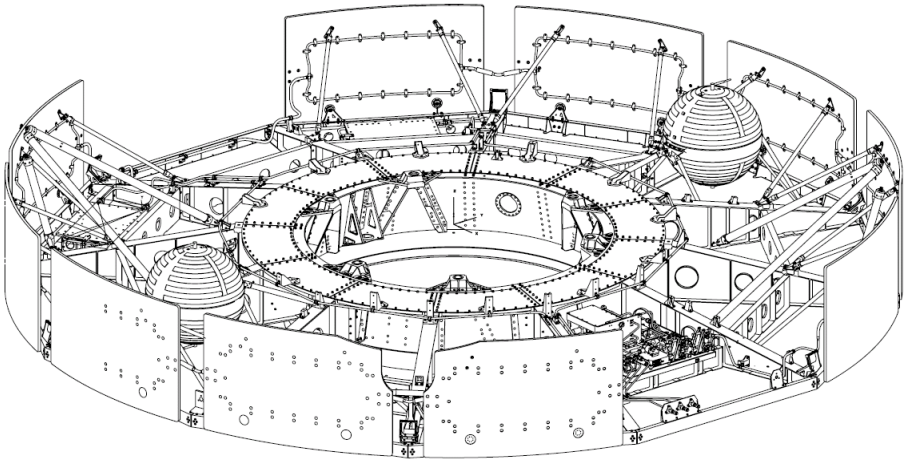
RIPA/RIPAS Design and Build

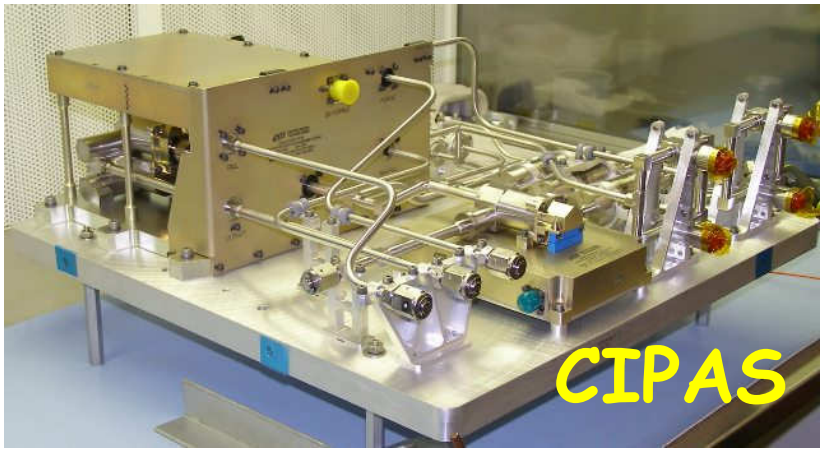


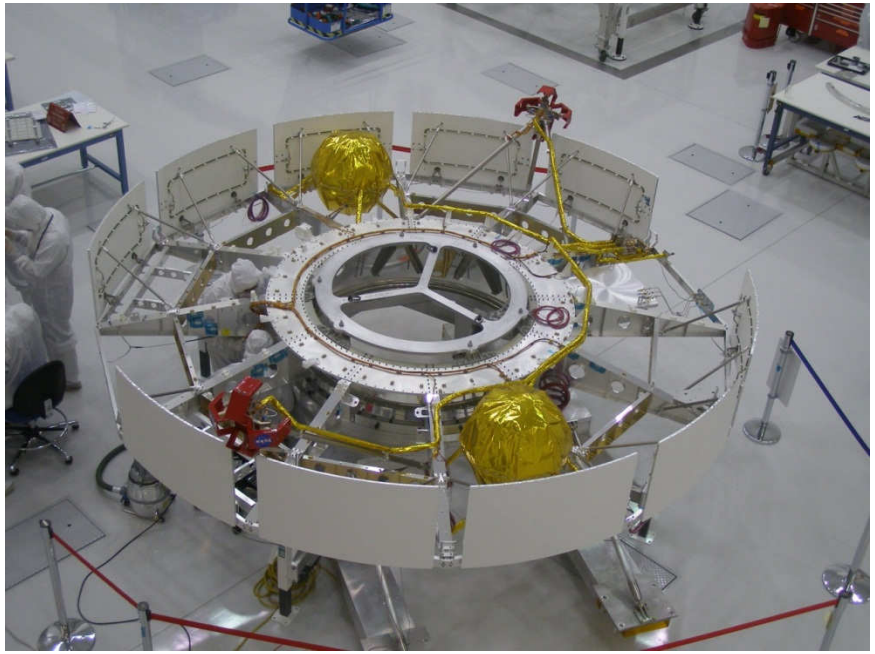




CIPAS & CHRS Fab/Install on S/C





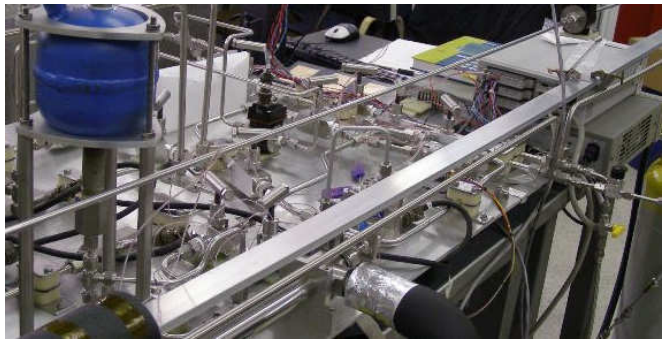


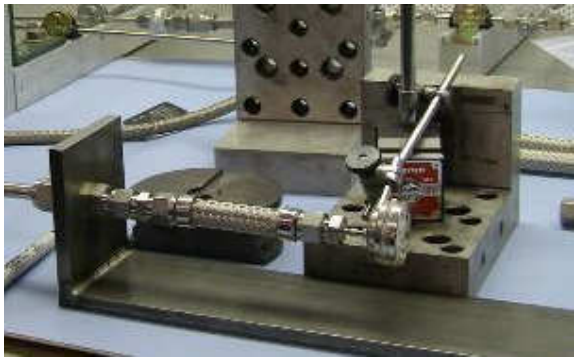
Mars Pathfinder Centrifugal Pump

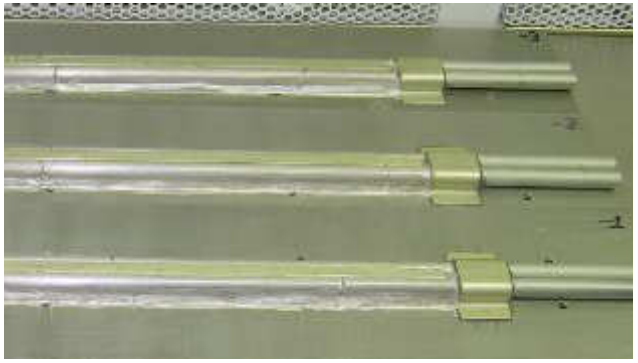
- Journal Bearings
- Hydro-Dynamically Lubricated
- 12,000 rpm
- 250 g
- All Stainless Steel Construction
- Permanent Magnet Embedded in Rotor
- Hall Sensors and Rotating Magnetic Field in Stator
- Pacific Design Technologies (PDT) Manufacturer

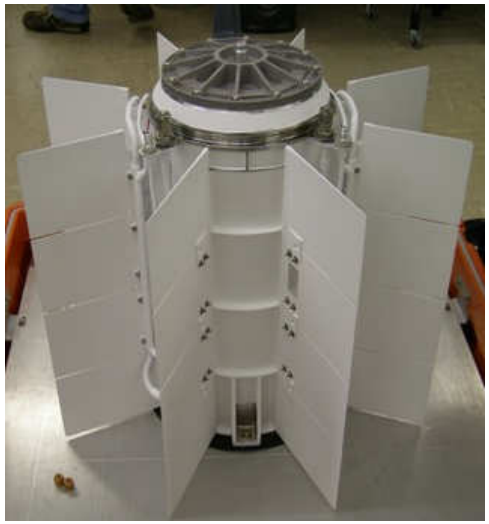
Key Changes during Design Phase

- Several significant changes had to made in HRS design
  1. Change of RAMP tubing from smooth to finned
  2. Flex lines in the loop to account for relative displacement
  3. Epoxy thermal conductivity lower than specified
  4. Adding of secondary tubes for ground cooling

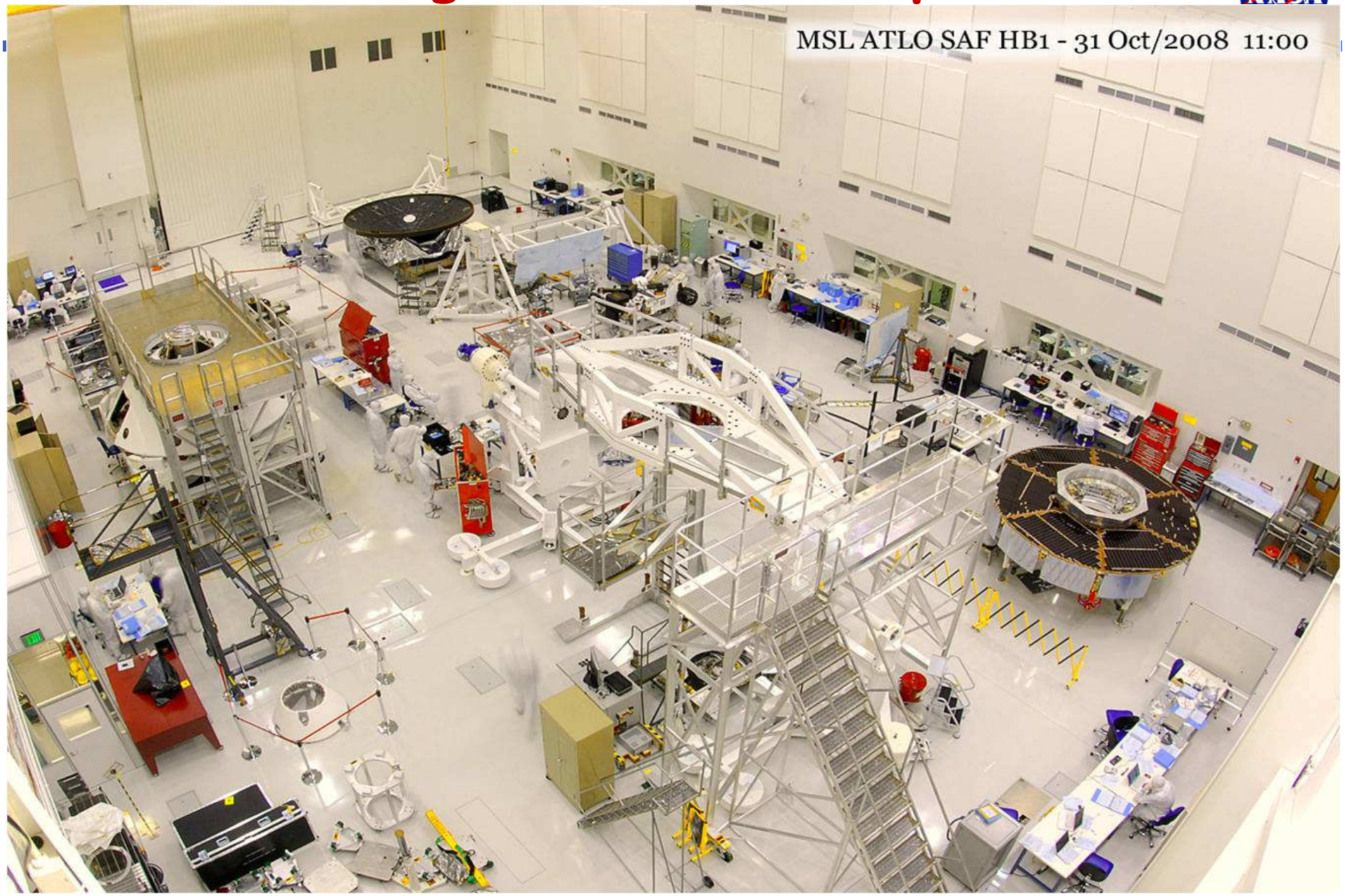








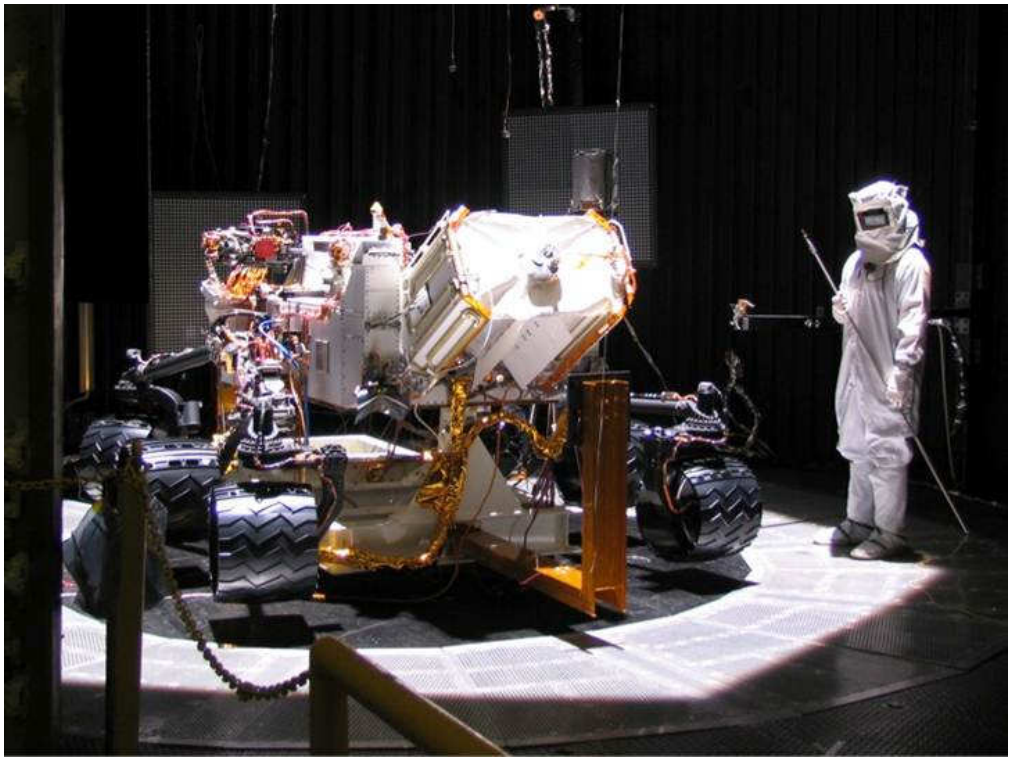
HRS Integration on the Spacecraft



System Level Testing of CHRS/RHRS

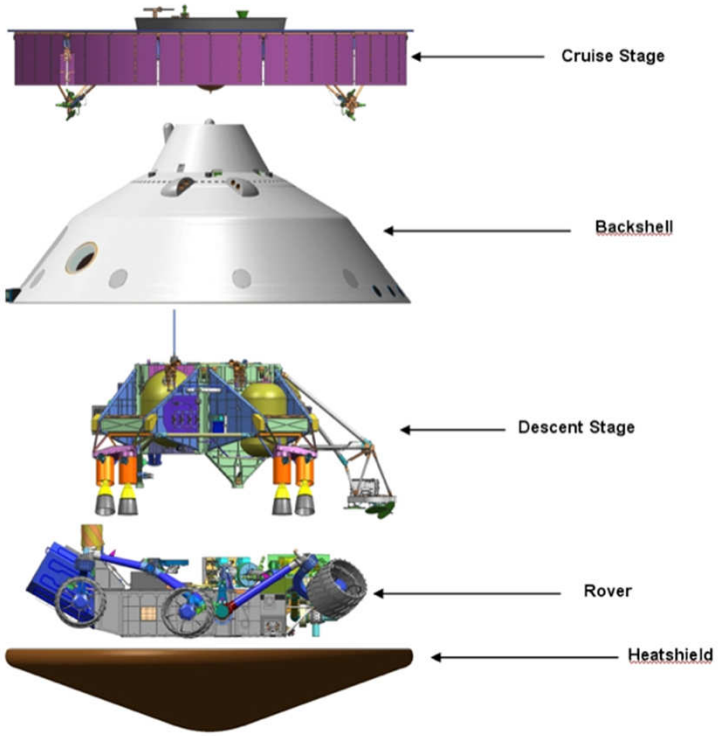
System Thermal Vac Test
(Cruise Phase)

System Thermal Test
(Surface Phase)



Integration of S/C…

Final Assembly of Spacecraft



Rocket Fairing – Atlas V

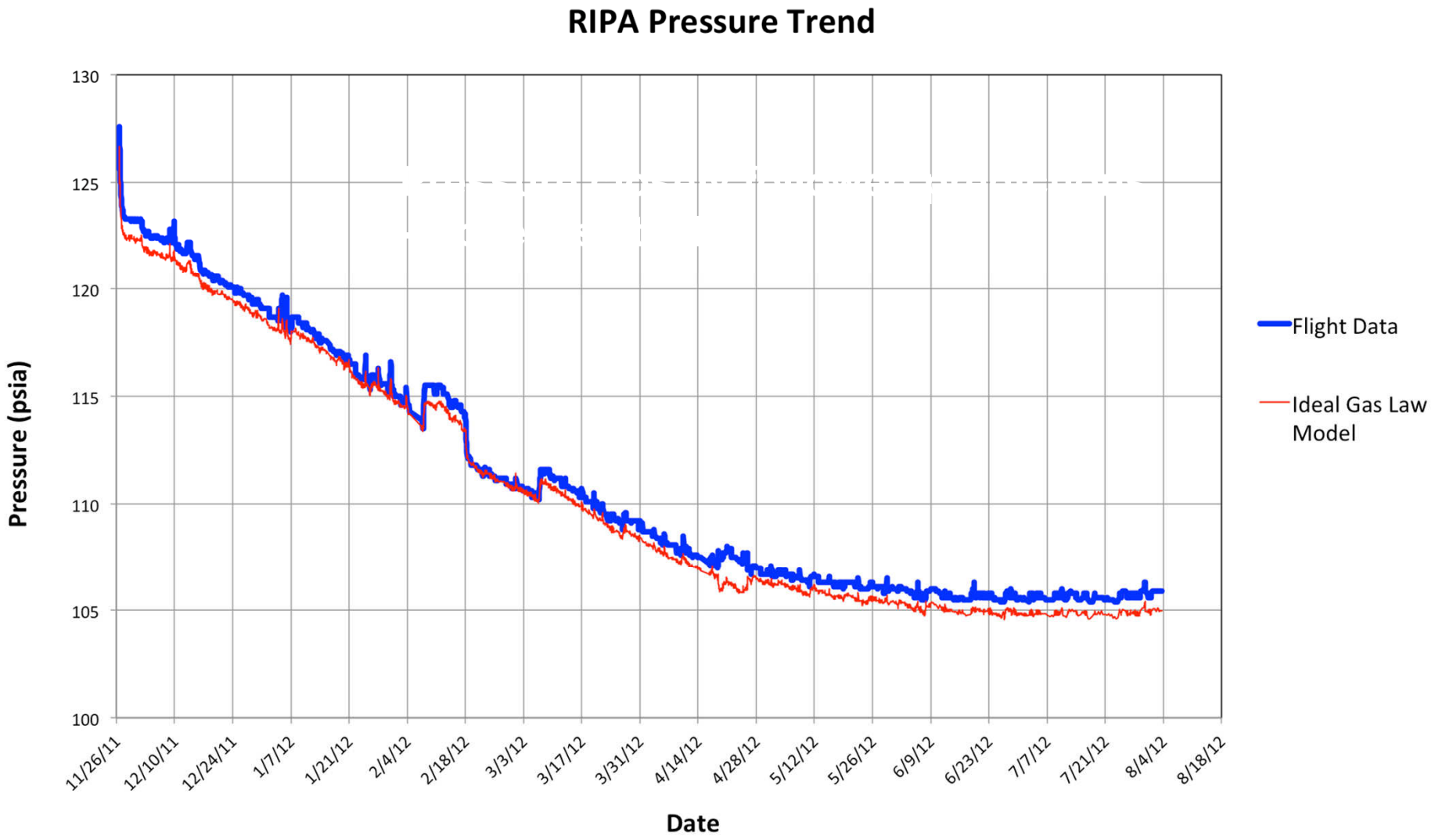
The Rocket.. Atlas V

MSL Launch: November 26, 2011

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

Rover HRS Pressure During Cruise



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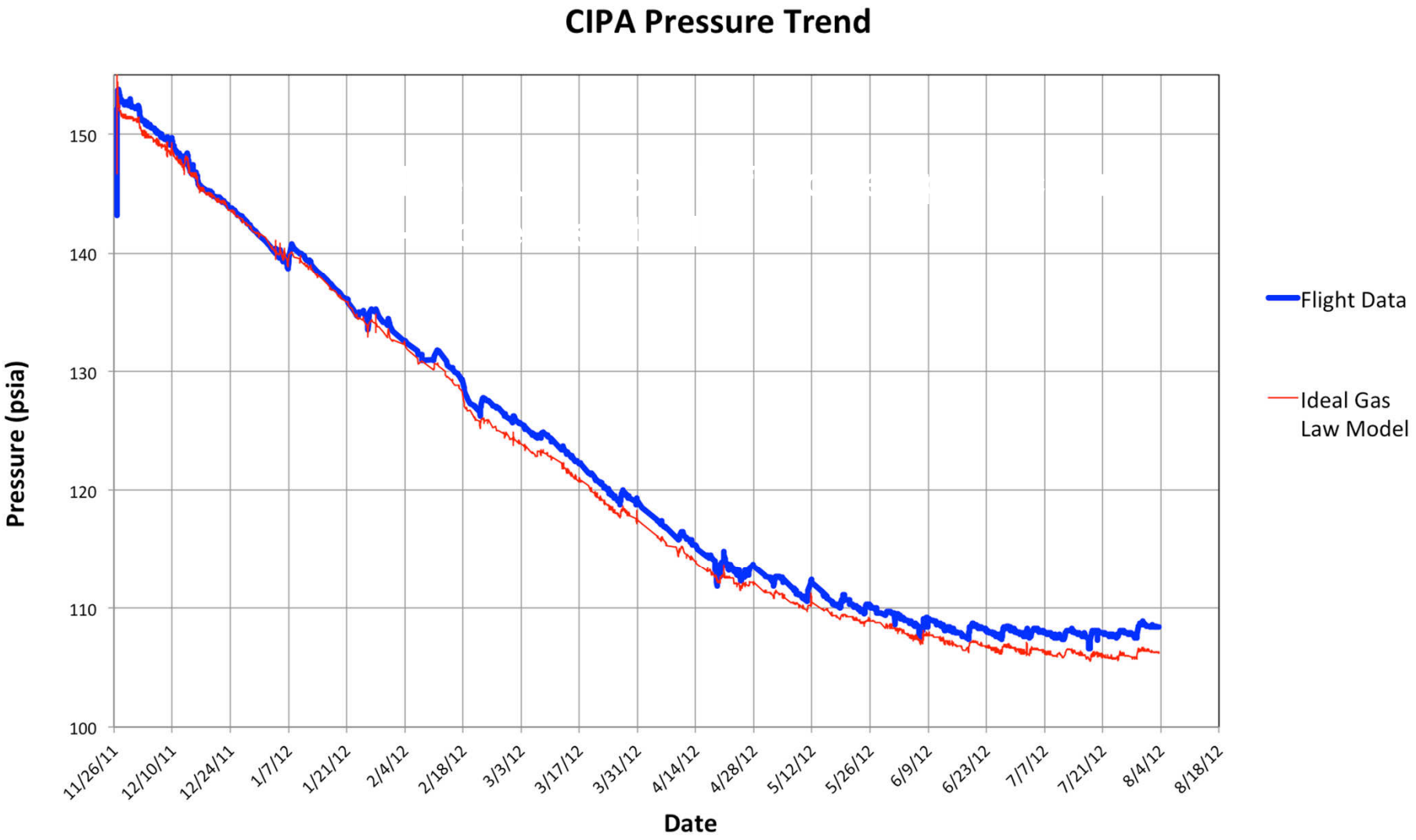
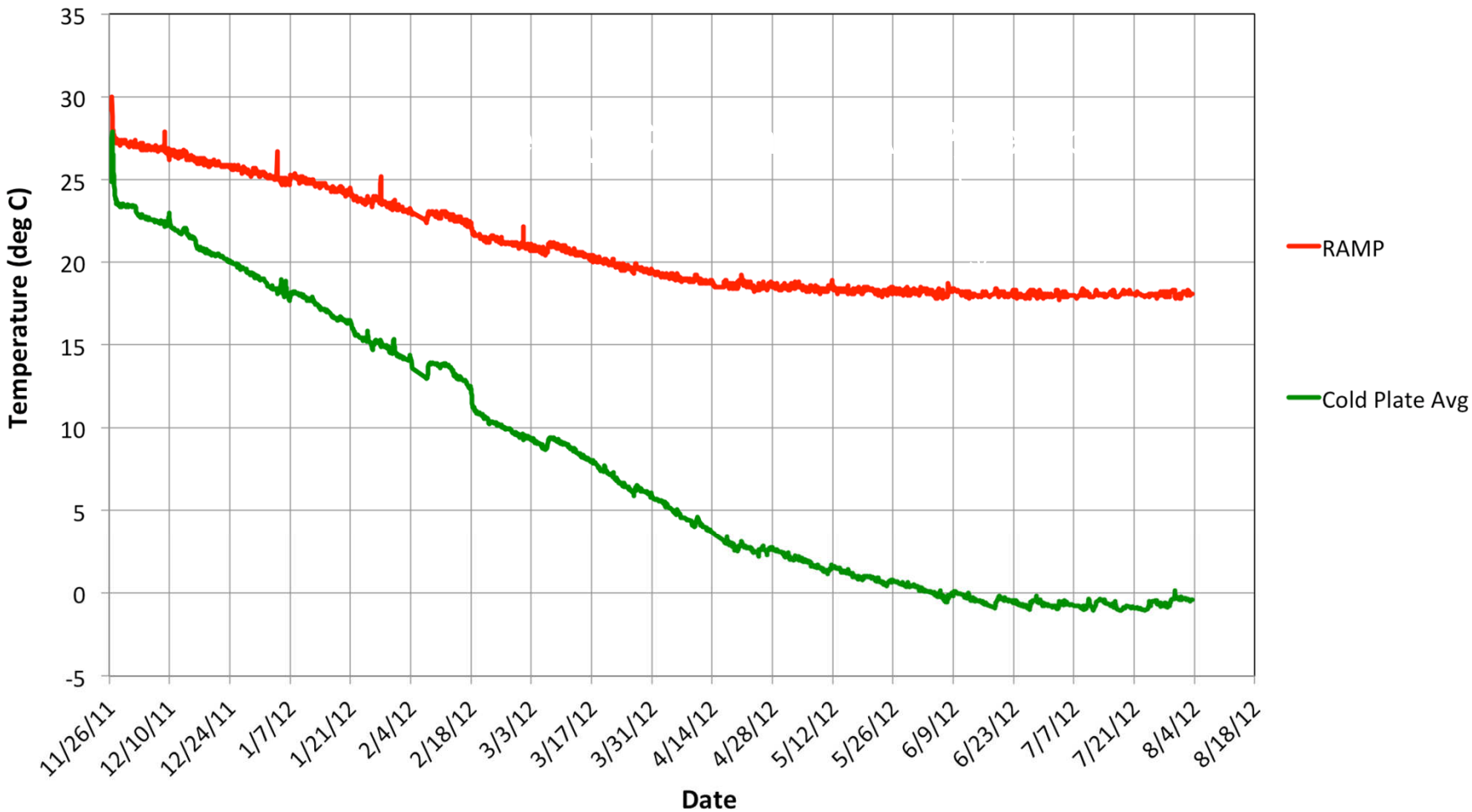
Cruise HRS Pressure During Cruise



44

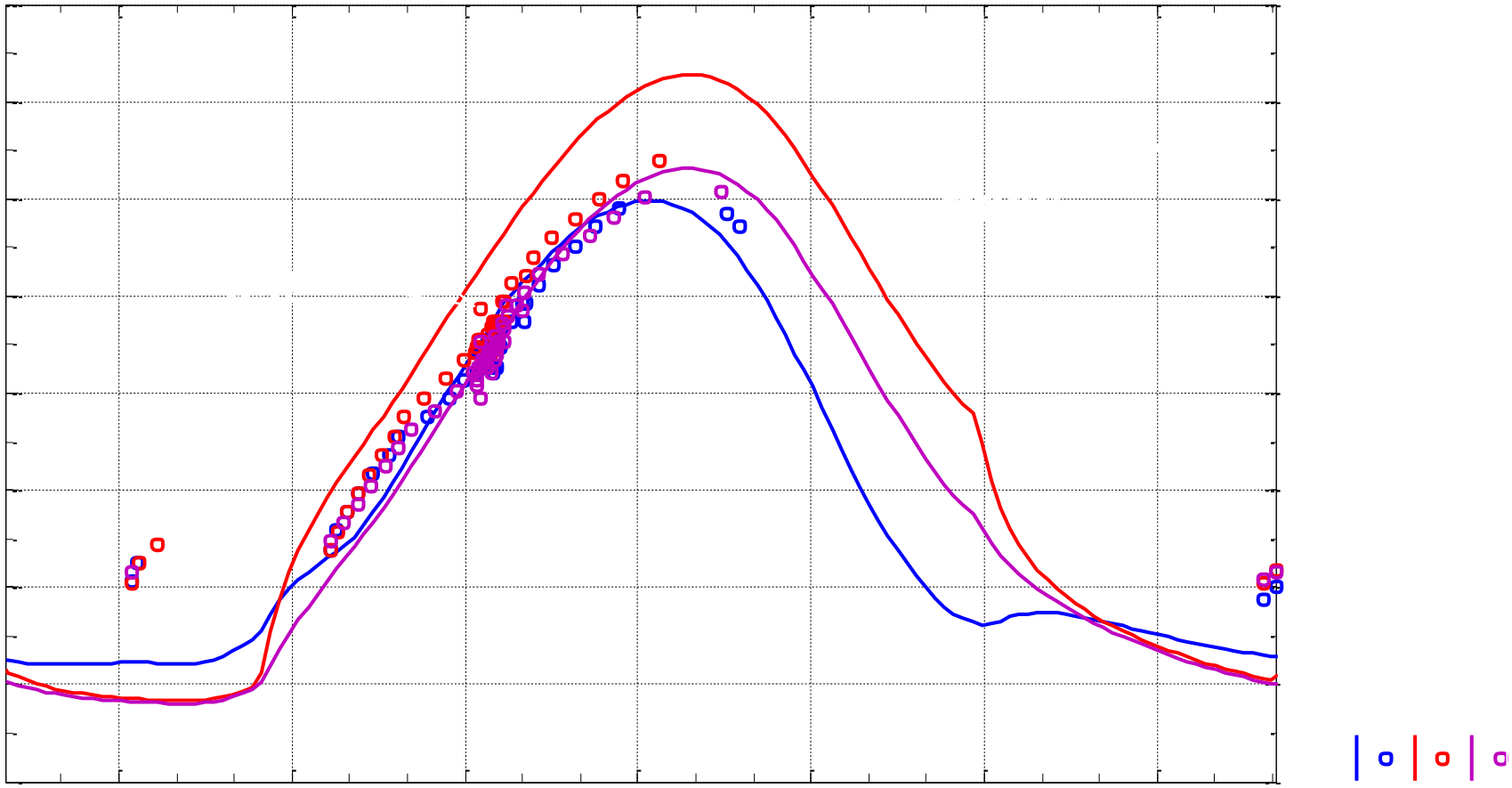
Rover HRS Controlled Temperatures During Cruise



Curiosity's Overall Thermal Performance

- The Curiosity rover has been on the surface of Mars for about 10 months since its landing on August 5th,
  - It landed in spring at the Gale landing site and is in the summer
- The active fluid loop has performed extremely well in all phases – Cruise, EDL, and Surface Operations
-
- All fluid loop components (pumps, accumulators, control valves, heat exchangers etc.) have performed well and are close to prediction made by the post-test correlated thermal models

Fluid Loop Controlled Temperatures on Mars



Lessons from MSL HRS Experience

- Challenging missions require "out-of-the box" ideas and involve significant risks in meeting the final goals

  MPFL Technology for Rover

- Strong commitments from the team members, flight system managers, and institution are very important

  Mars Focused Technology Program

- Large margins in design, schedule, and resources are a must

  Early Start, Mass & fund reserves

- Use simple quick experiments to verify new design

  Epoxy tests, finned tube test,

- Work closely with the vendors; allow sufficient schedule margins on vendors' services

  Pump assemblies, Chiller HX, flex lines, OmniSafe joints

- Team should be able to tackle unexpected problems

  Bellows, flex lines, welds

- Multi-disciplined diverse team is a must for such effort

  Designers, Analysts, hardware engrs., techs, young/older

- High morale, perseverance, and team spirit are key

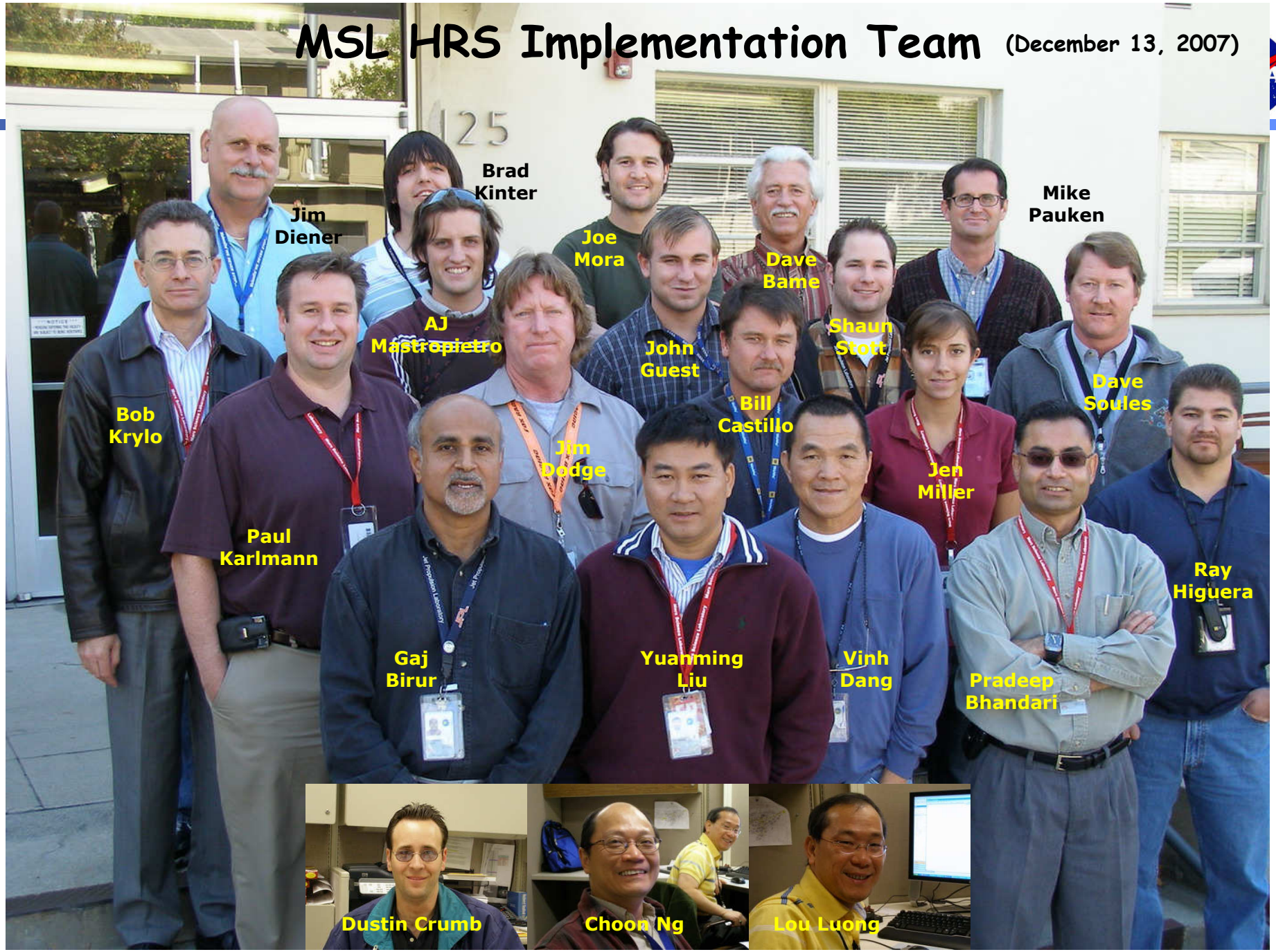
  The HRS gang kept up for over six years

Conclusions

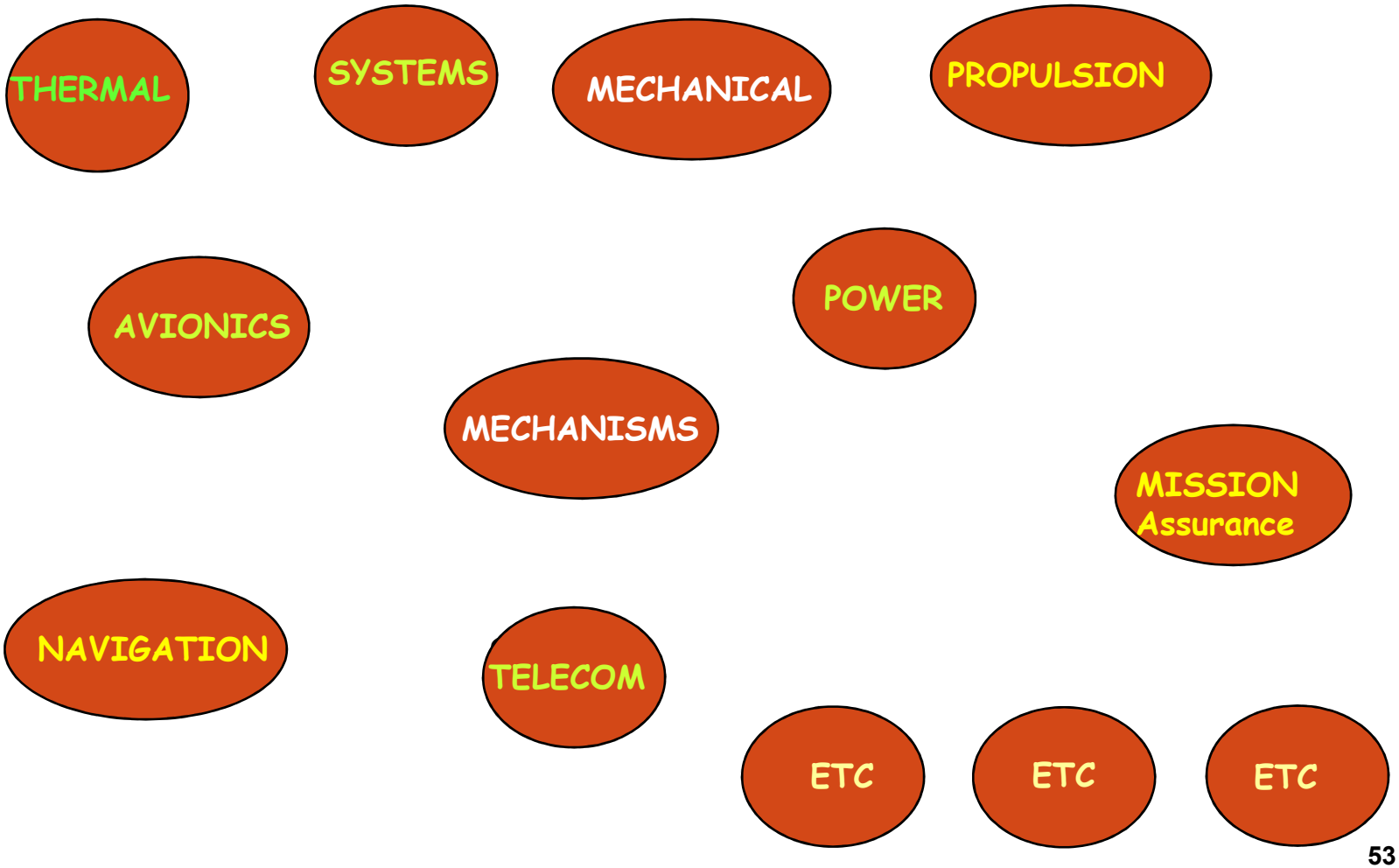
- MSL rover's many challenging thermal requirements during its surface operation could be met with MPFL
- Several advanced MPFL thermal technologies were developed in order to ensure a robust thermal control system for the rover operation
- MSL Rover MPFL based thermal architecture will pave way for its usage on future NASA missions, Commercial satellites, and military missions

Curiosity Thermal Team

MSL HRS Implementation Team (December 13, 2007)



MSL Rover Thermal Team

MSL Rover Project

~ 100's more Subsystems engineers make up the project