International Conference on Environmental Systems

AIAA
The World's Forum for Aerospace Leadership

CFD Analysis For Assessing The Effect Of Wind On The Thermal Control Of The Mars Science Laboratory Curiosity Rover

Pradeep Bhandari & Kevin Anderson

Jet Propulsion Laboratory, California Institute of Technology

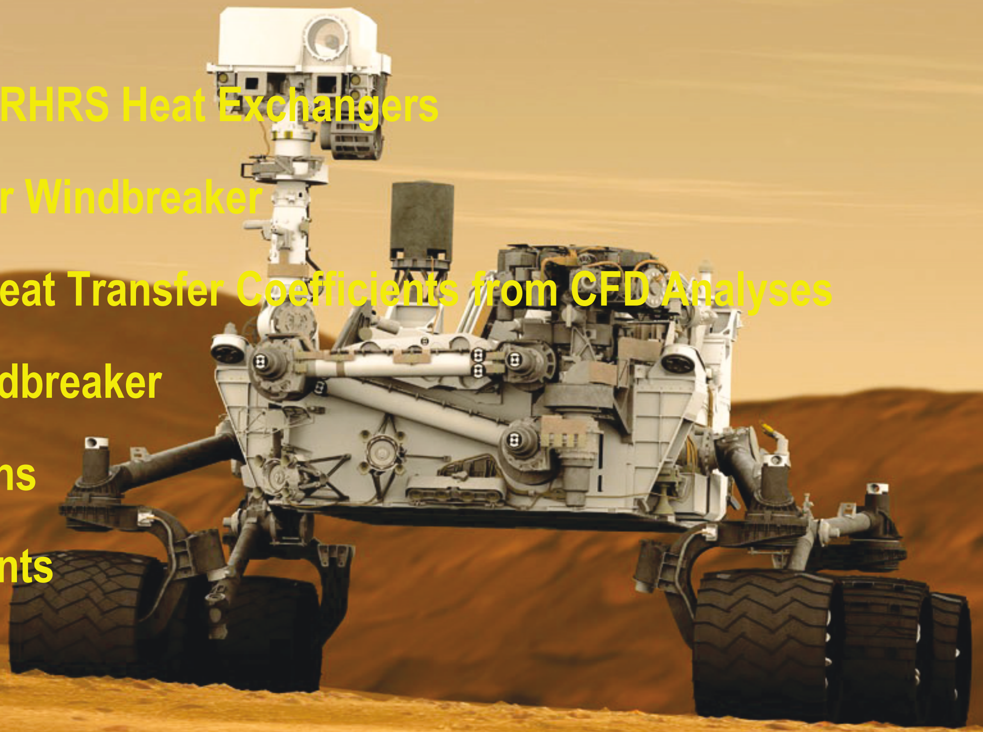
43rd ICES, 16th July 2013, Vail, Colorado

NASA

JPL
Jet Propulsion Laboratory
California Institute of Technology

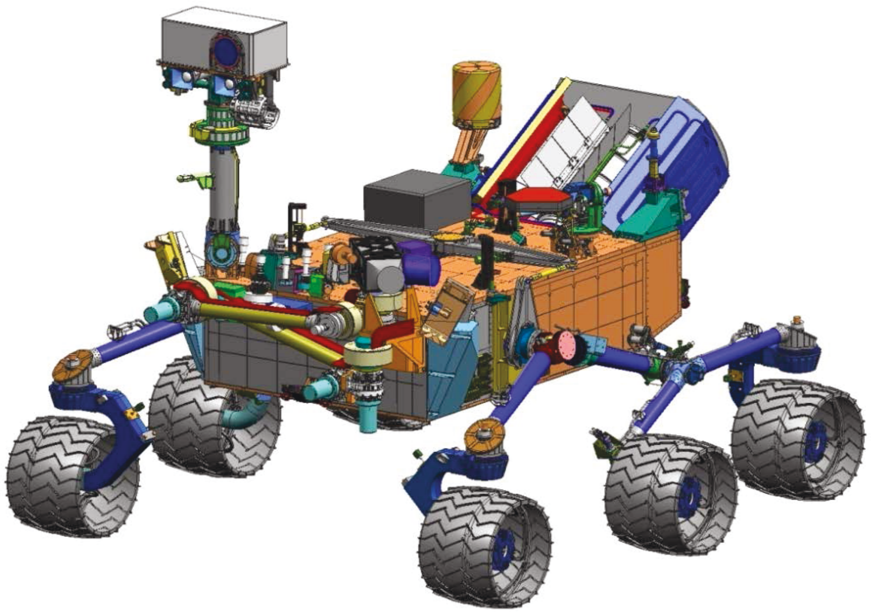
Agenda

- MSL Project Overview
  - Spacecraft & Rover Configuration
  - Overall Thermal Architecture
- Rover Heat Rejection System (RHRS) Overview
- Winds on Mars
- Windbreaker for RHRS Heat Exchangers
- CFD Analyses for Windbreaker
- Predictions of Heat Transfer Coefficients from CFD Analyses
- Tradeoffs of Windbreaker
- Major Conclusions
- Acknowledgements



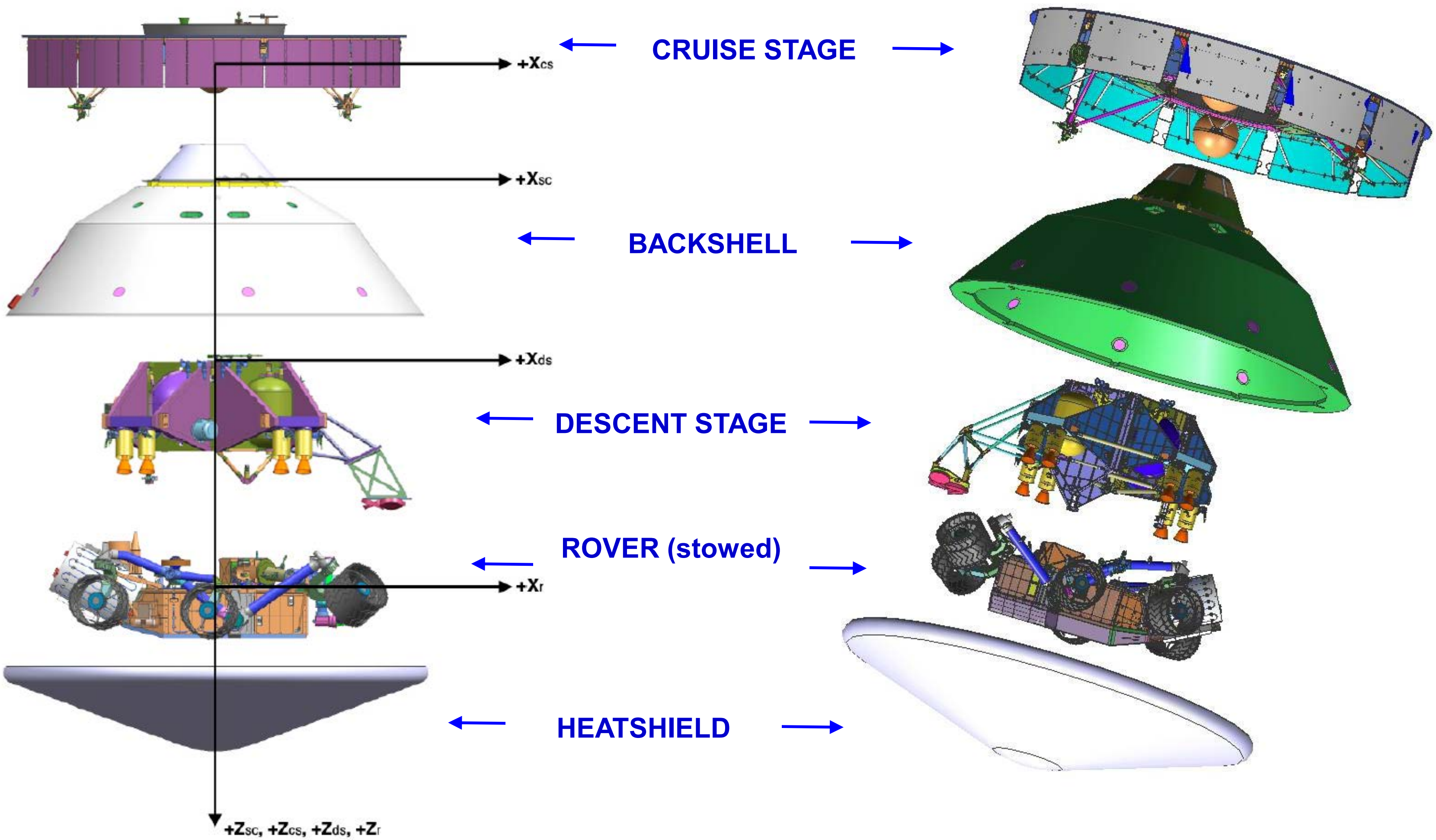
MSL Project Overview

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

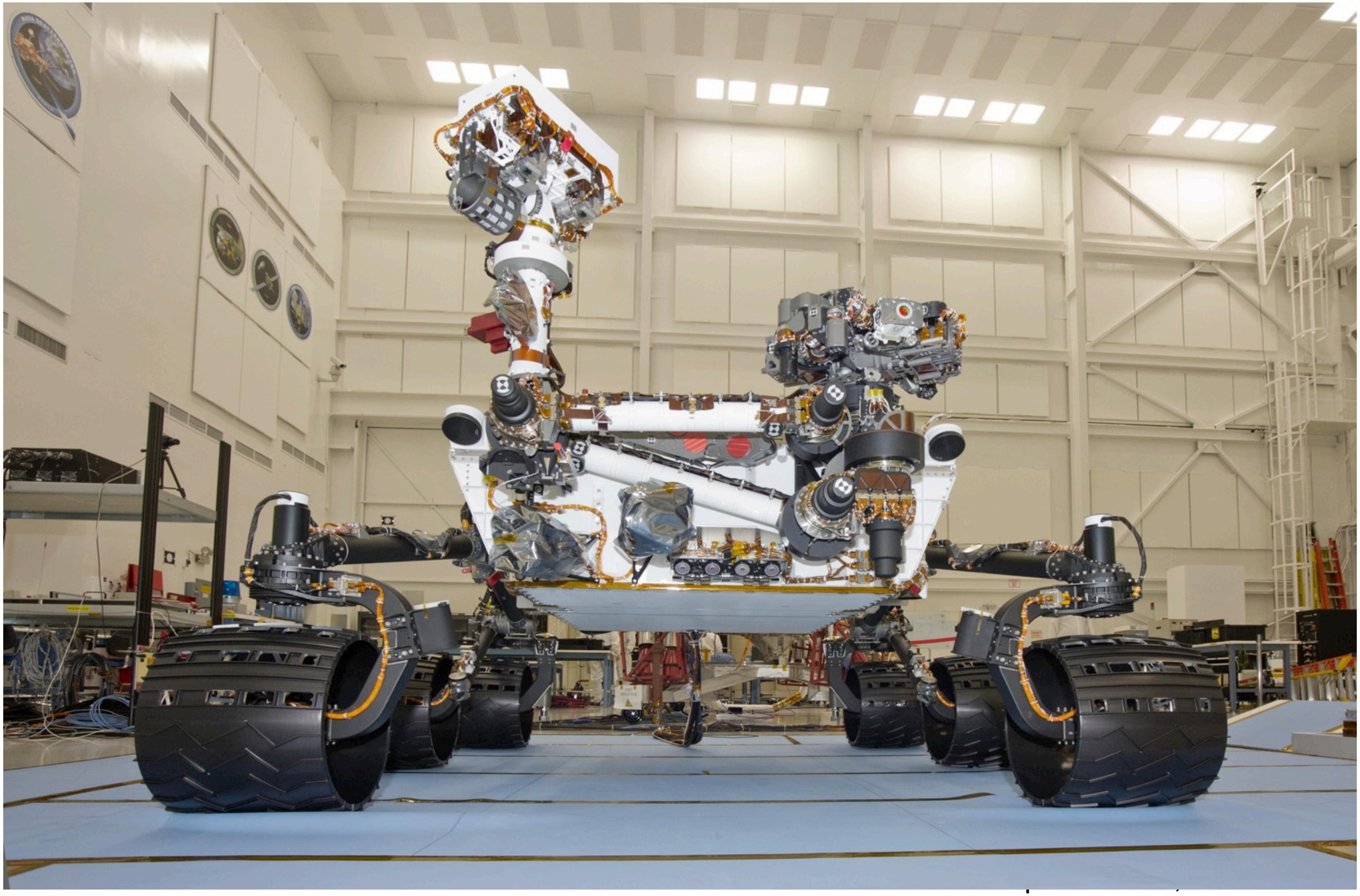


Science
- Mission science focuses on Mars habitability
- Next generation analytical laboratory science investigations (SAM & Chemin)
- Remote sensing/contact investigations (MastCam,ChemCam, MAHLI & APXS)
- Suite of Environmental Monitoring Instruments (DAN, REMS, MARDI & RAD)

MSL Spacecraft



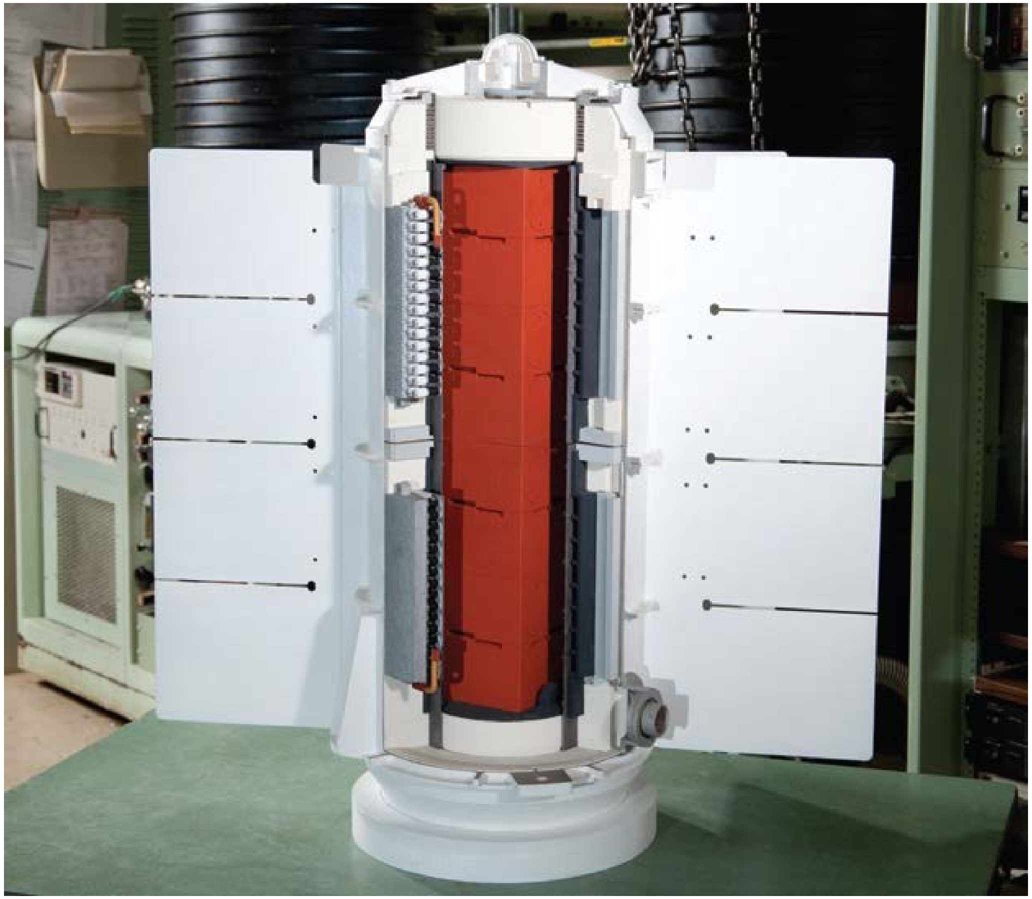
Curiosity 2011: *Terminator* on steroids…



Multi-Mission RTG

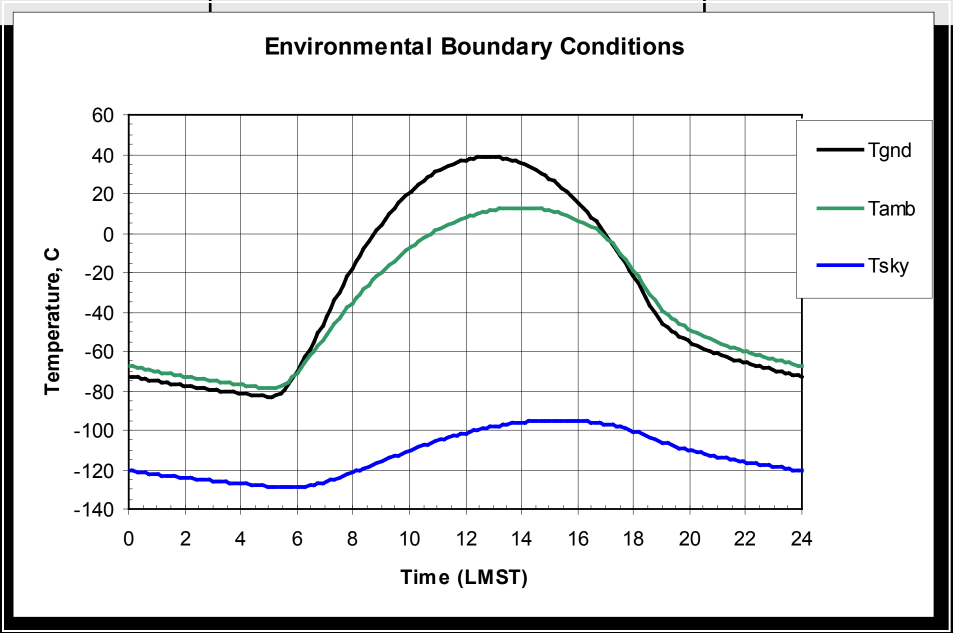
-Radioisotope Thermoelectric Generator

- 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!

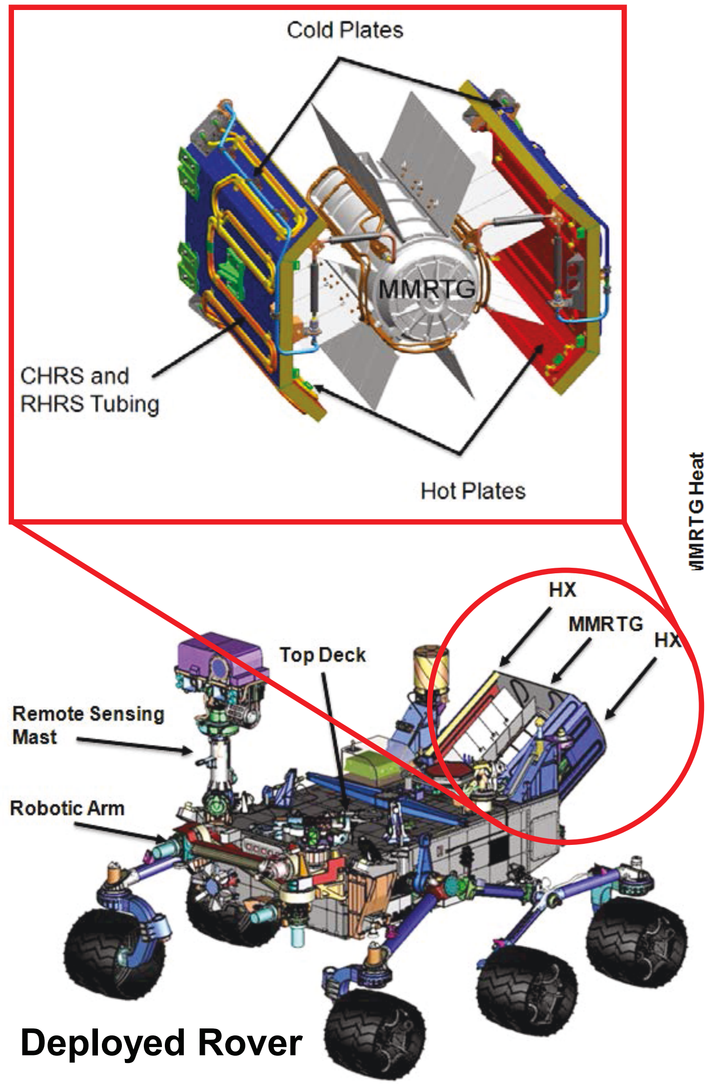
	Coldest	Hottest
Earth	-89 C Antarctica	57 C Death Valley, CA
Mars	-140 C	20 C
Spacecraft in Space	-160 C (Shade)	120 C (Sun Side)
Space	-273 C	na



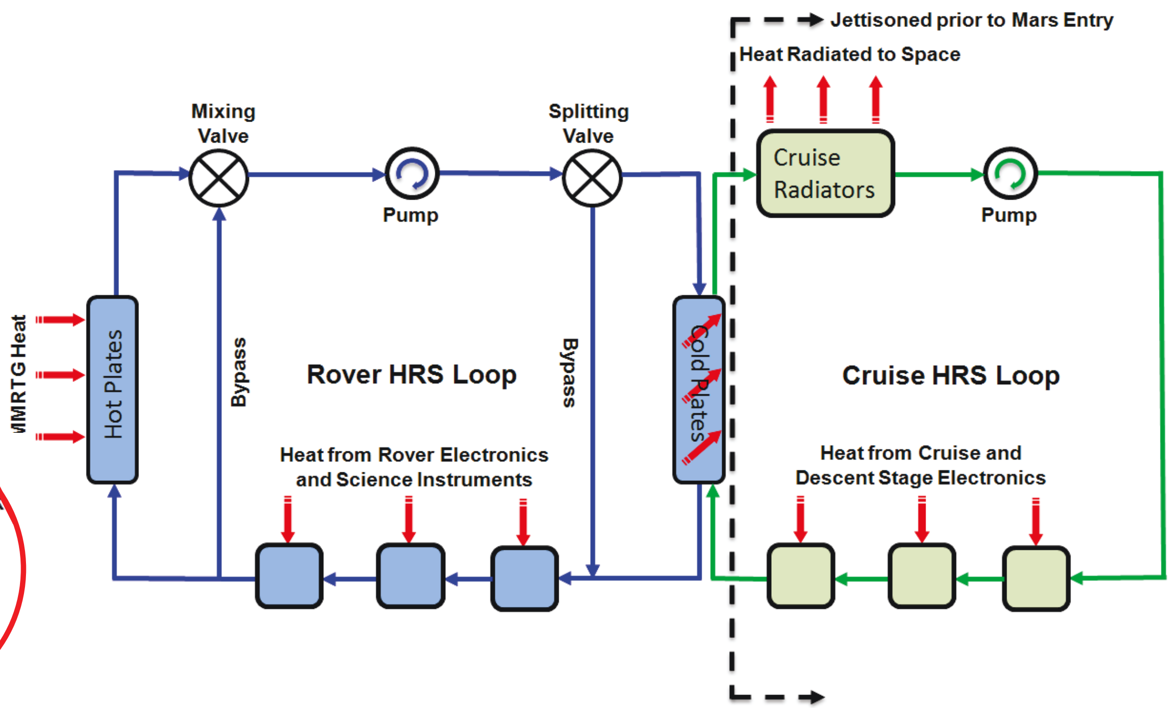
Thermal Control Challenges of MSL Rover

- 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

Mechanically Pumped Fluid Loop Heat Rejection System (HRS)

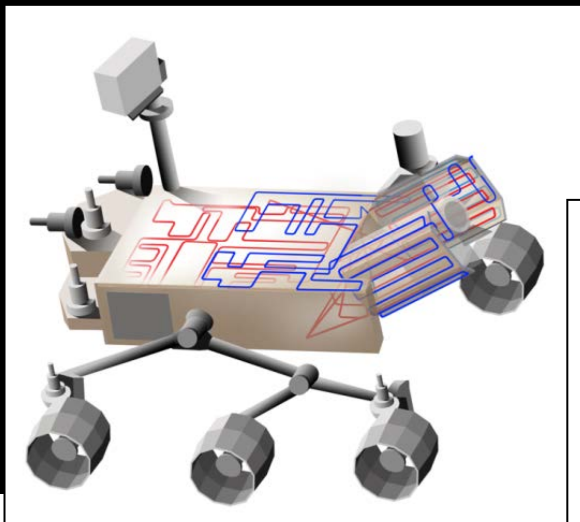


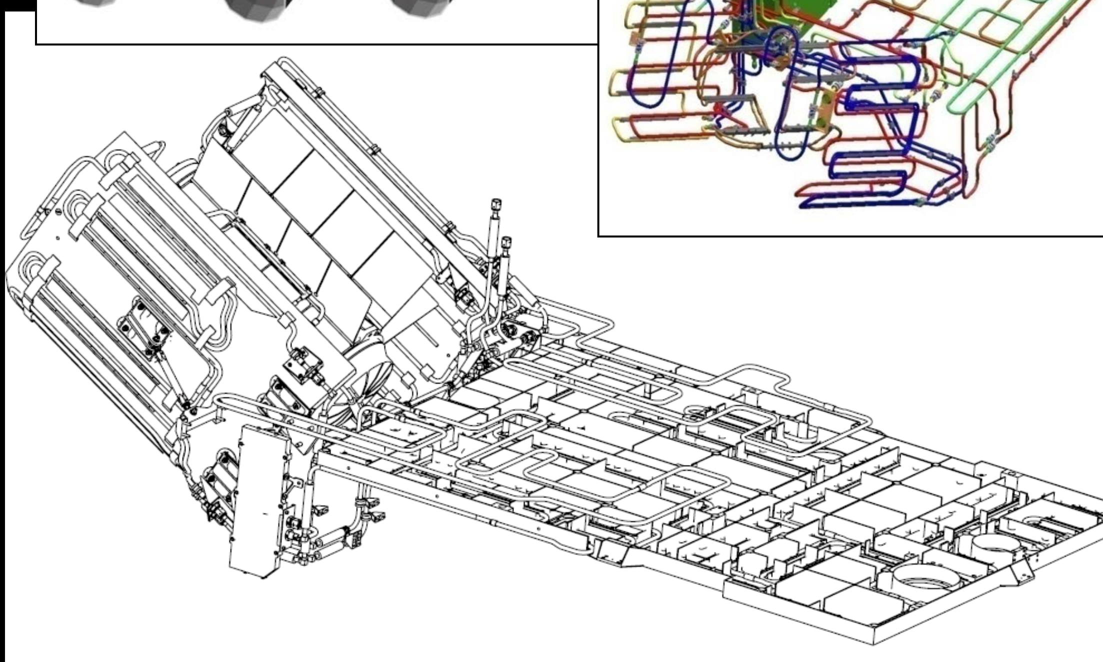
MSL Mechanical Pumped Fluid Loop Architecture

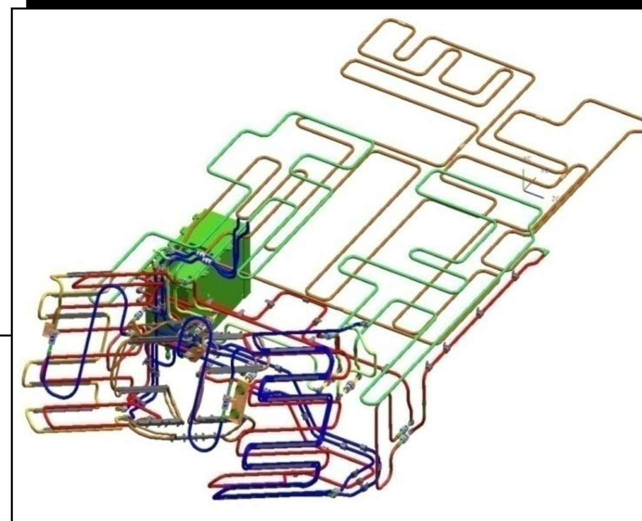


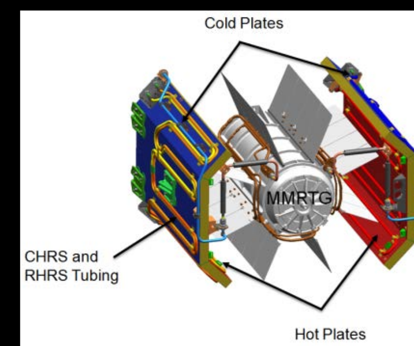
Simultaneously collect heat from MMRTG ***and*** reject waste heat to either the Cruise Loop or directly to Martian environment depending upon mission phase

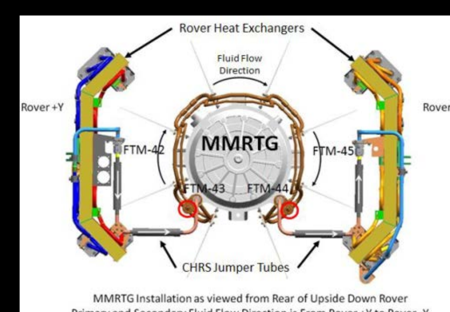
MSL RHRS Tubing Labyrinth!



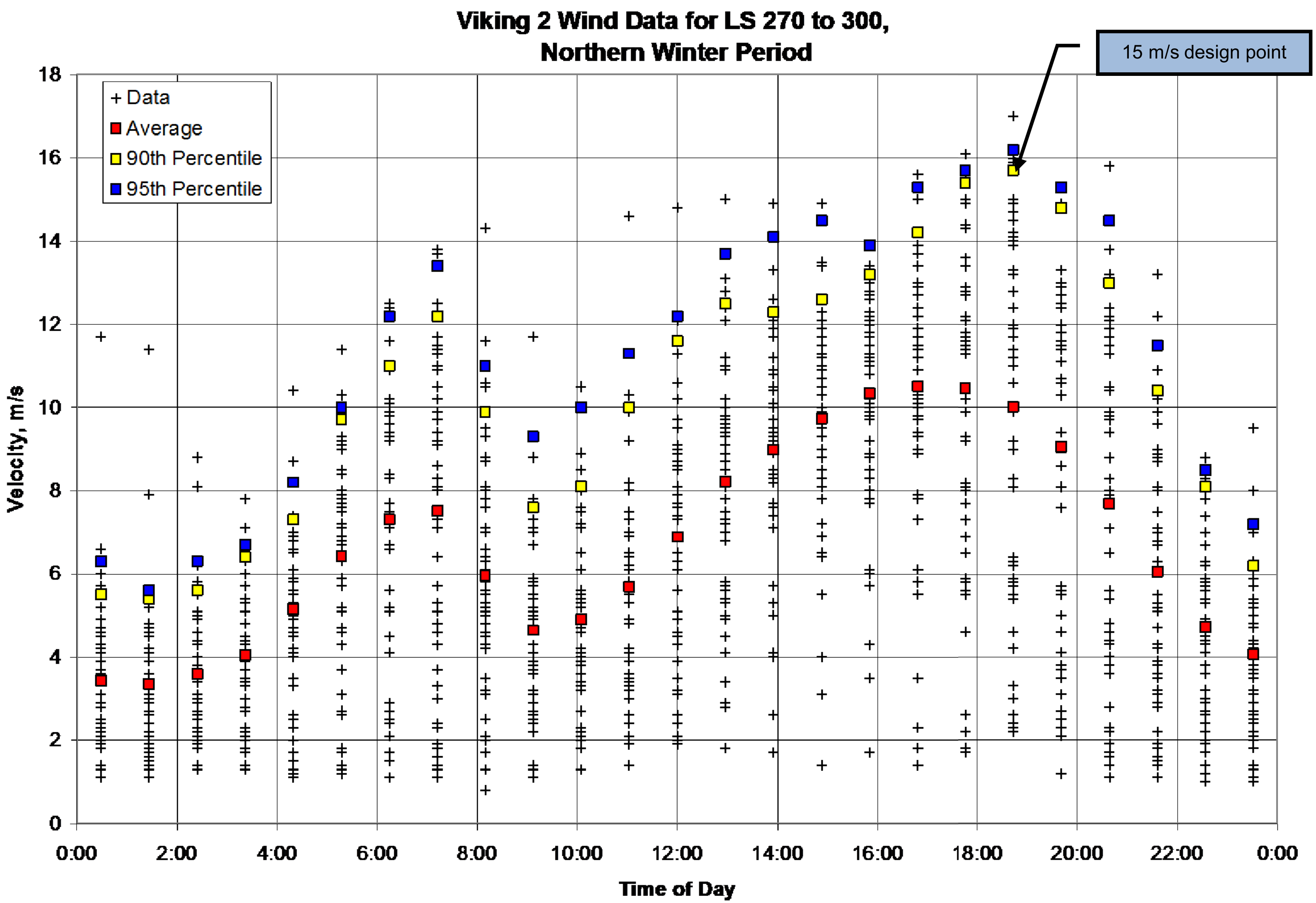








Winds on Mars



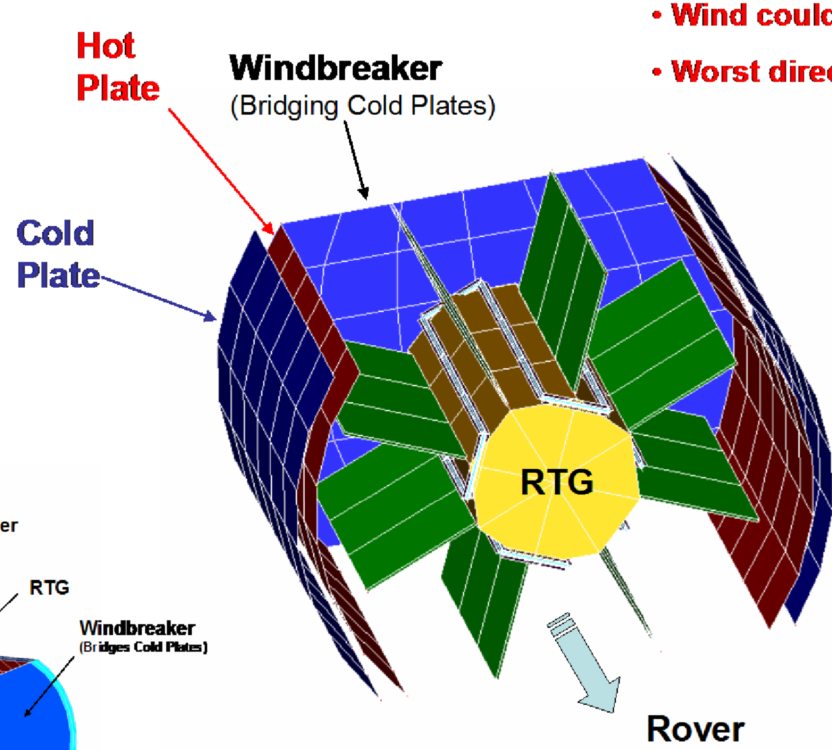
RTG Windbreaker

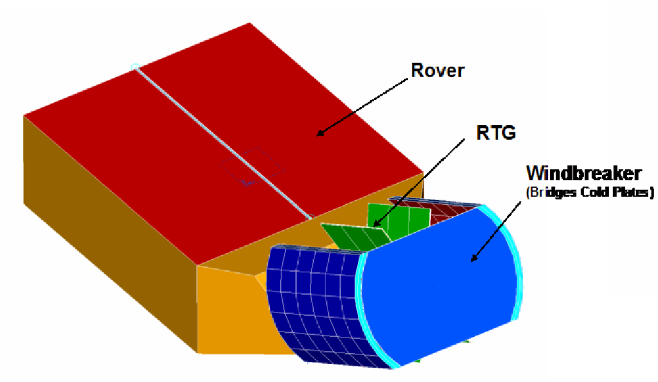
Concern: Wind would rob the RTG and the hot plates of heat and reduce the heat being transferred to the Rover Electronics/Payload

Solution: Use Windbreaker (Beta Cloth) to minimize this effect

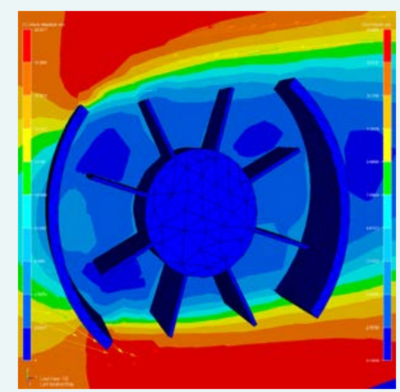
- **Wind could come from any direction**
- **Worst direction is wind blowing // to RTG axis direction**

block wind at least in perpendicular to RTG axis

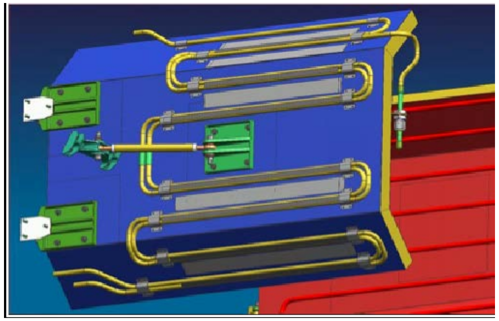


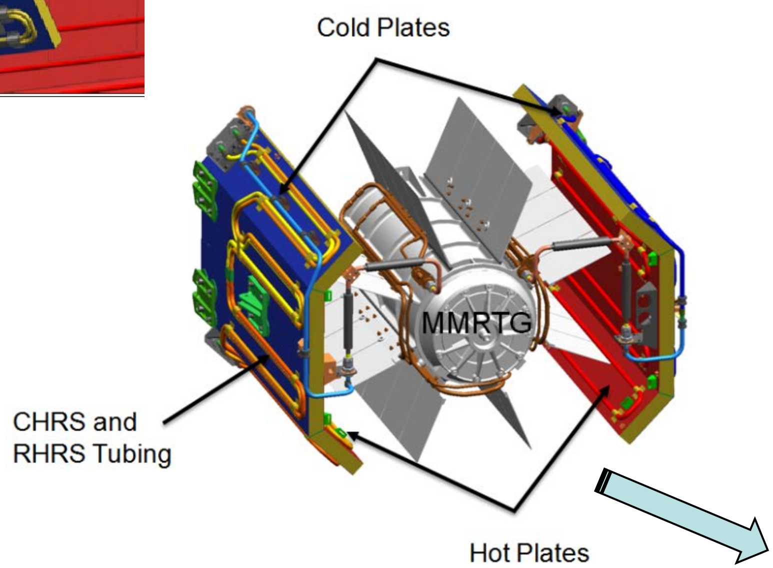


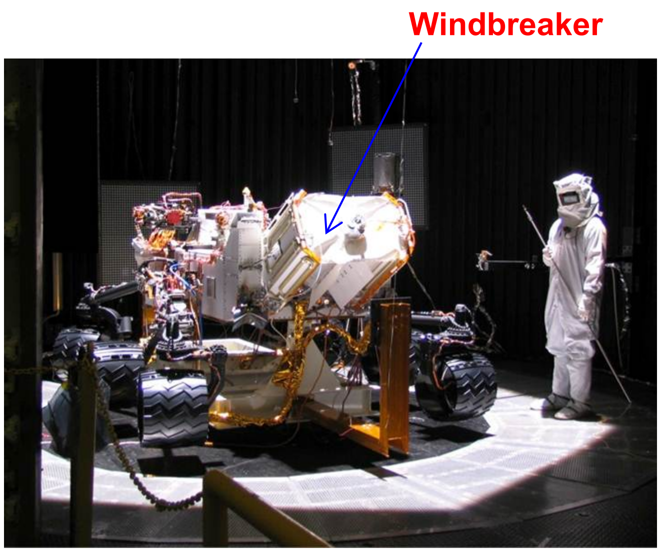
CFD Model Sample Output



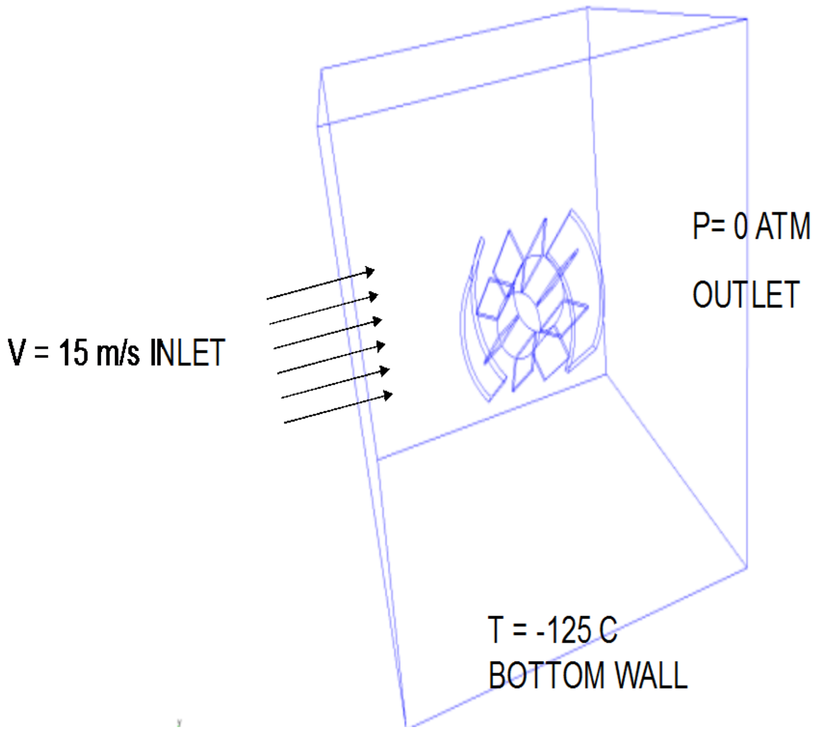
Windbreaker Implementation

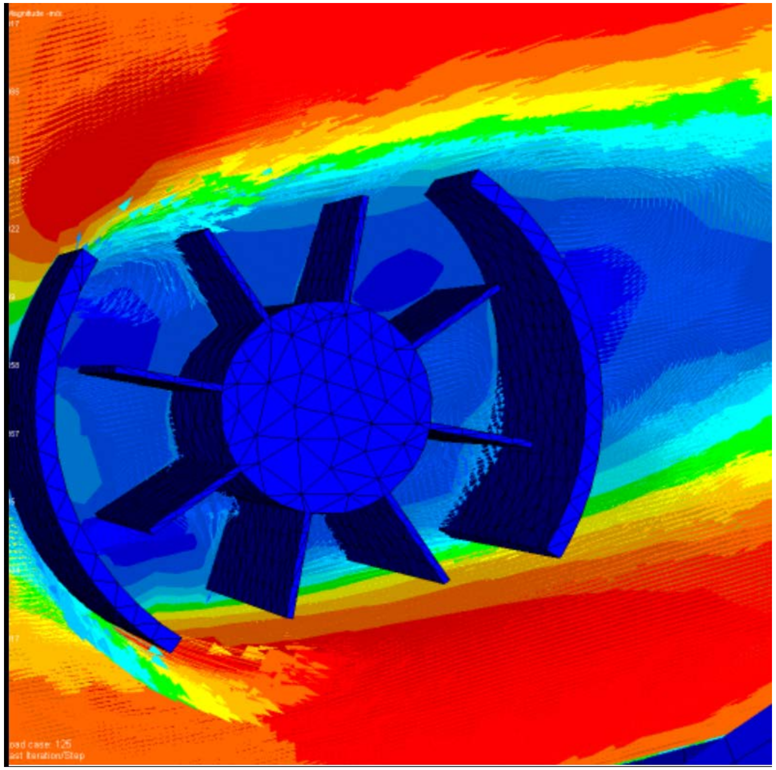






CFD Analyses





CFD Analyses Validation By Benchmarking

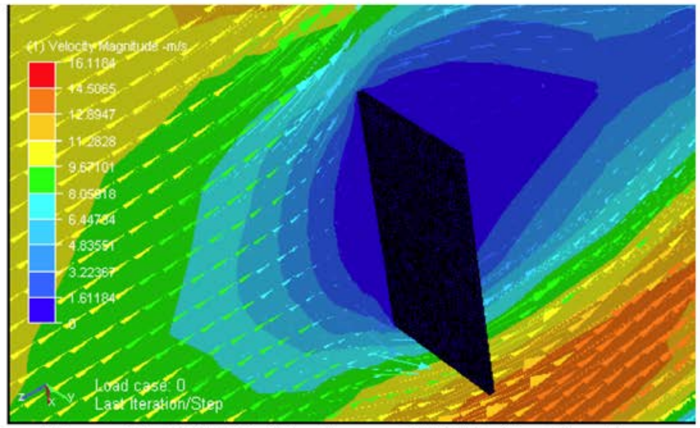


Figure 13. CFD Verification and Validation Case for Vertical Plate in Cross flow

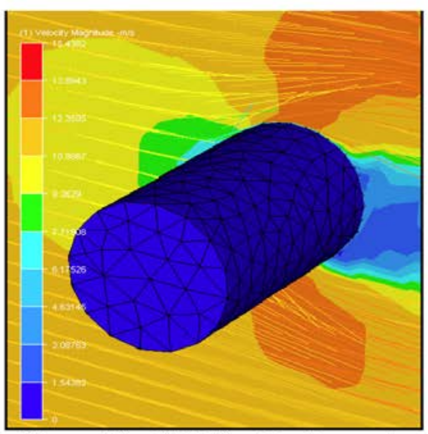
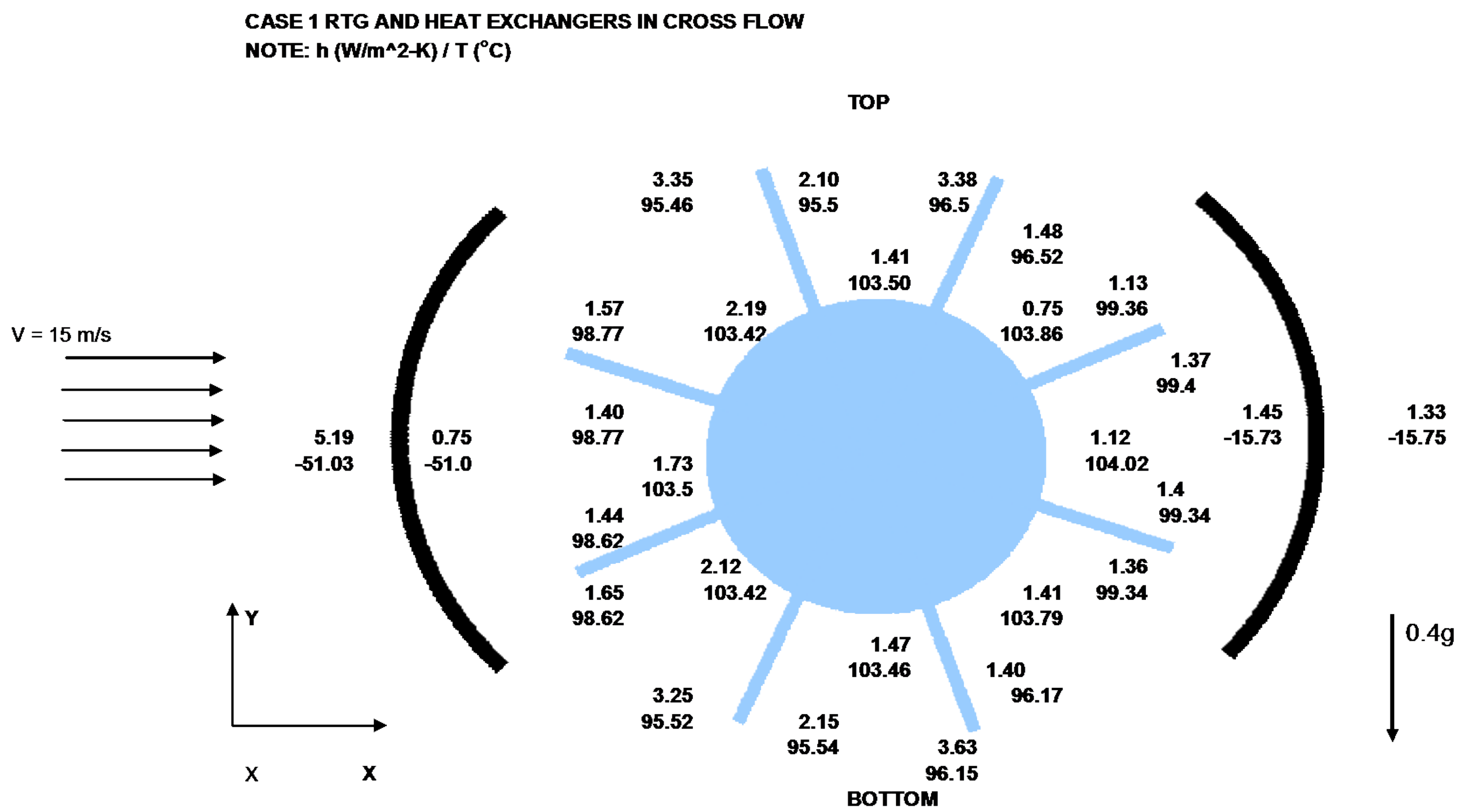
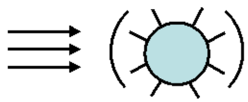
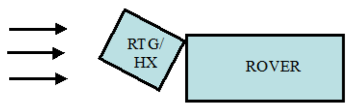
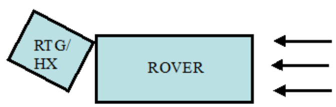
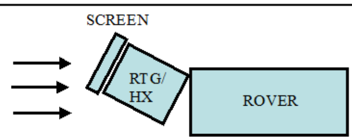
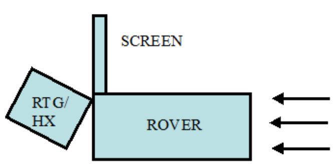
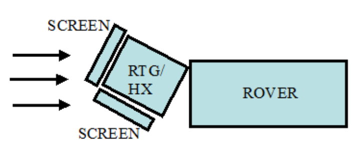


Figure 14. CFD Verification and Validation Case for Cylinder in Cross flow

CFD Predictions of Heat Transfer Coefficients Around MMRTG & Heat Exchangers

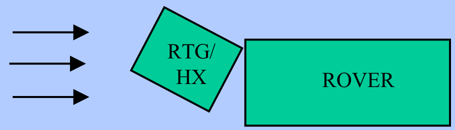
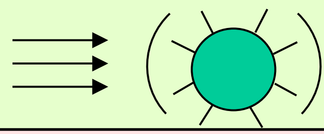
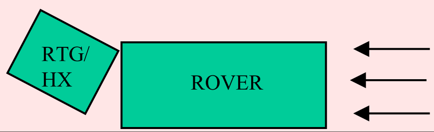
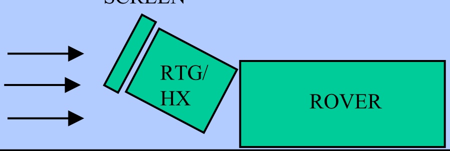
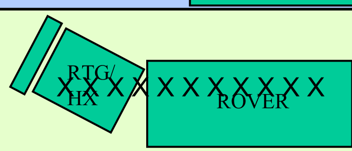
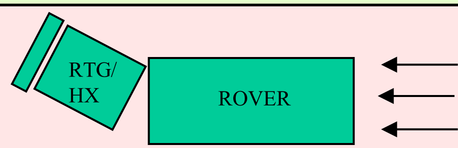


Predictions of Average Heat Transfer Coefficients in Windy Environments

	CFD SIMULATION CASE	Ave Conv Coef, W/m^{2}K
1		1.85 RTG 1.1 HP 3.26 CP
2		2.21 RTG 1.49 HP 1.28 CP
3		1.75 RTG 0.9 HP 1.58 CP
4		1.25 RTG 0.19 HP 1.47 CP
5		1.14 RTG 0.54 HP 1.26 CP
6		0.94 RTG 0.24 HP 1.79 CP

CFD Simulation Cases For Wind

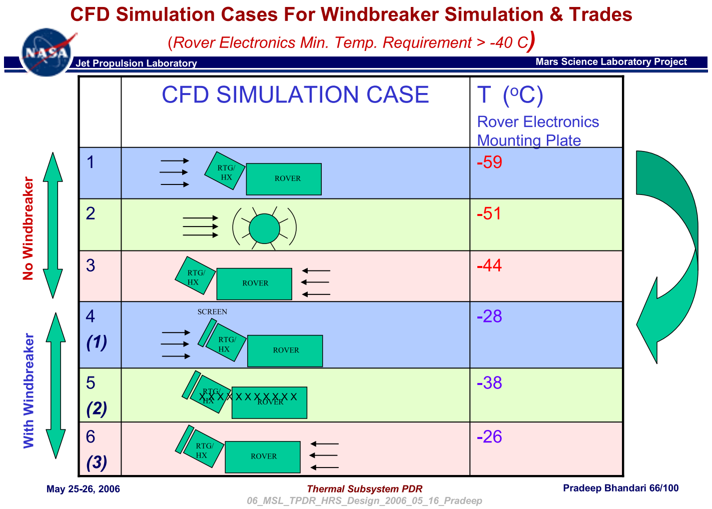
(*Rover Electronics Min. Temp. Requirement > -40 C*)

		CFD SIMULATION CASE	T (°C) Rover Electronics Mounting Plate
No Windbreaker	**1**		**-59**
No Windbreaker	**2**		**-51**
No Windbreaker	**3**		**-44**
With Windbreaker	**4** *(1)*		**-28**
With Windbreaker	**5** *(2)*		**-38**
With Windbreaker	**6** *(3)*		**-26**

PRE-DECISIONAL DRAFT; For planning and discussion purposes only

Conclusions on Windbreaker

- **Windbreaker leads to very significant (~30 C) improvement of Rover electronics worst case cold (minimum) temperatures**
  - in *windy* conditions
- **Rover electronics would be much below allowable limits without it**
- **Windbreaker should not pose problems of RTG overheating**
  - Windbreaker design accounted for in thermal analyses
    - 2 C penalty in RTG temp. during EDL
    - 5 C penalty in RTG temp. on Mars
- **No major integration heartburns**
- **Lightweight**
- **Does not attach to RTG**
- **Should survive Martian Entry**



Windbreaker Implementation

- Construction
  - Beta Cloth
  - White surface properties
    - Low absorptance (0.4), high emittance (0.85)
  - Grommets, Cable Ties (TBD) to be used to hold windbreaker from Cold Plates
  - Implemented by Thermal Subsystem: Mark Duran
- Lightweight
  - ~300 g mass (beta cloth)
- Does not touch RTG
  - Only bridges Cold-plate Heat Exchangers
- Integration
  - Installed after RTG integration and checkout
- Survival During Martian Entry
  - Dynamic pressure < 0.05 psi
    - 360 mph speed at 8 Torr
  - < 15 pounds force
  - Should pose no problem for beta-cloth
  - Should not fly away during EDL (tie downs)

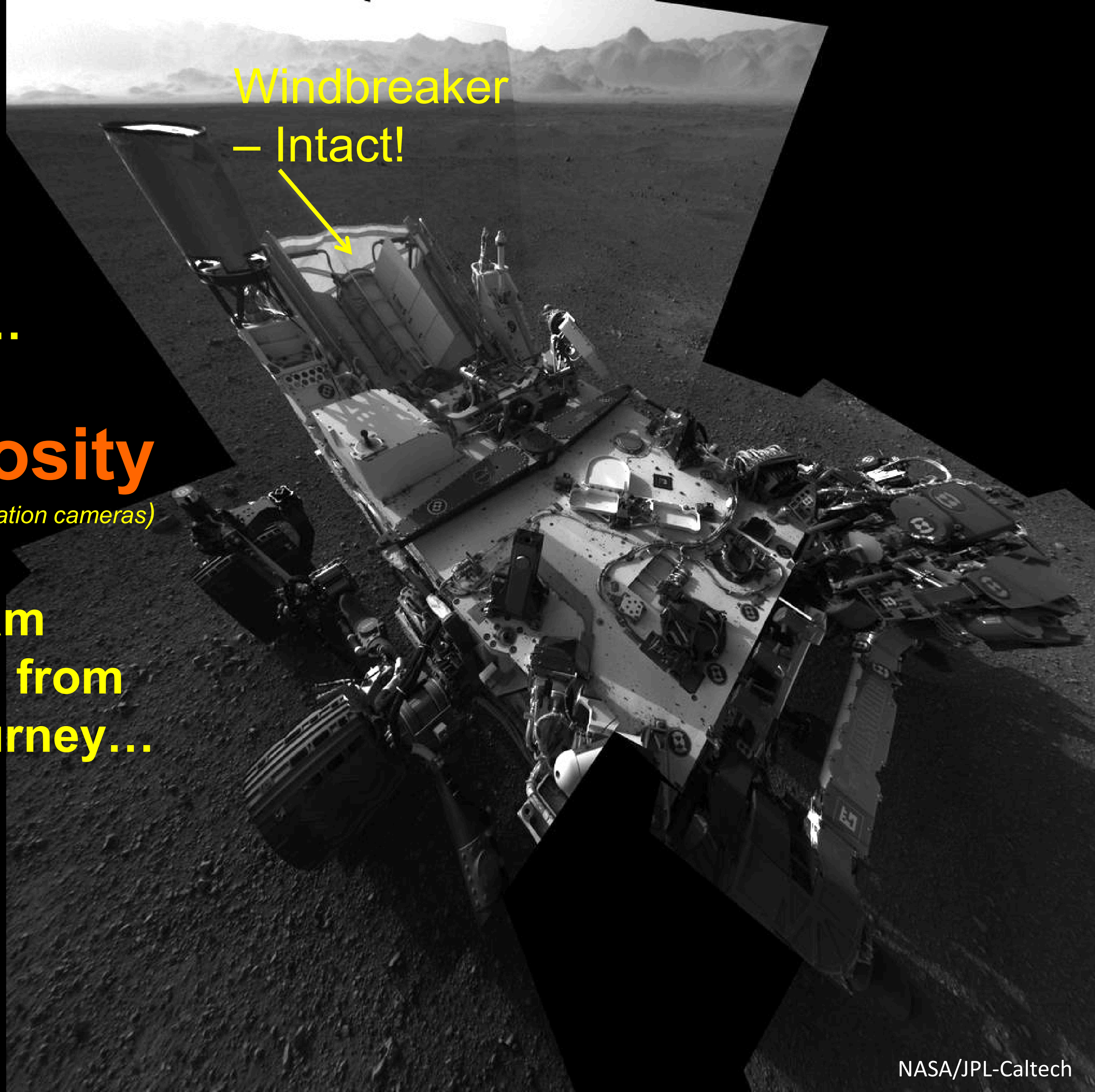
Final Installation of the Windbreaker at Launch Pad

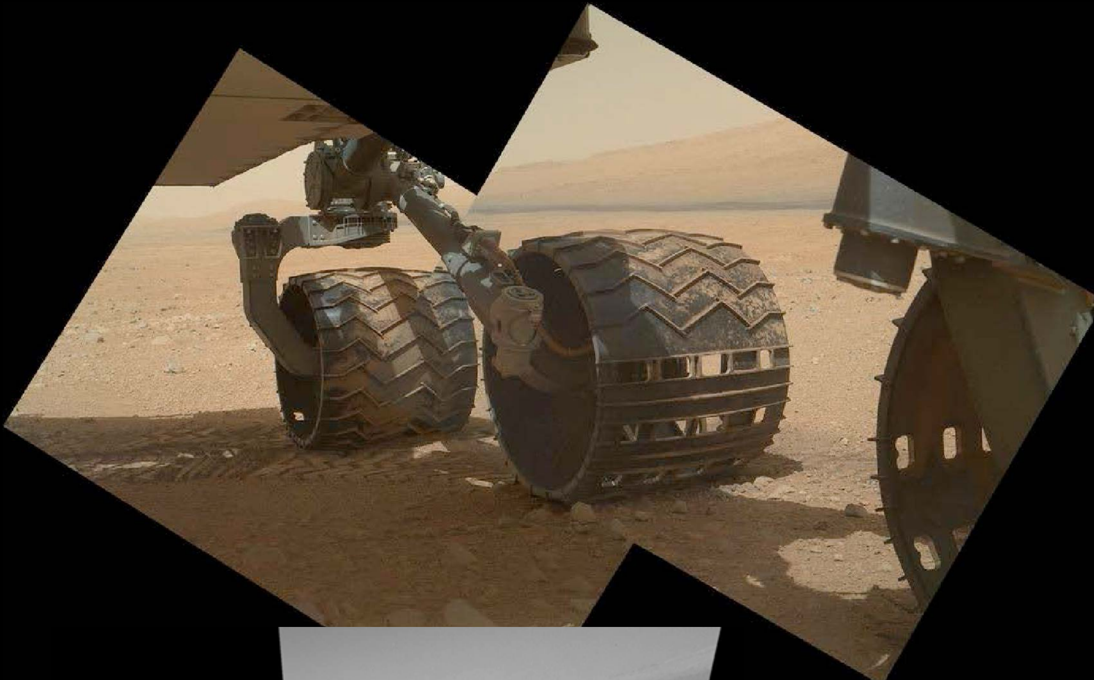
Hello, I am…

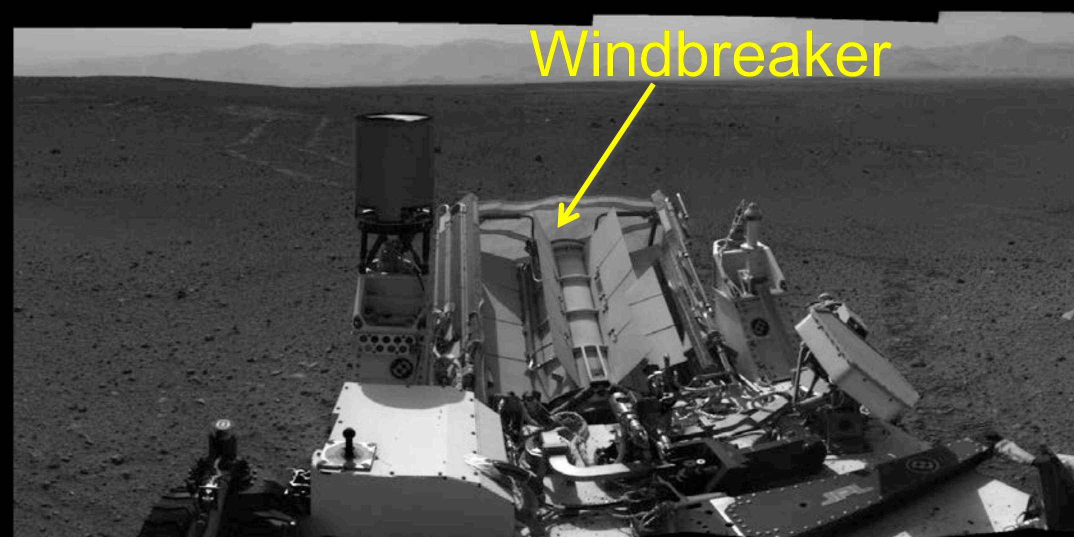
Curiosity

(self- portrait with navigation cameras)

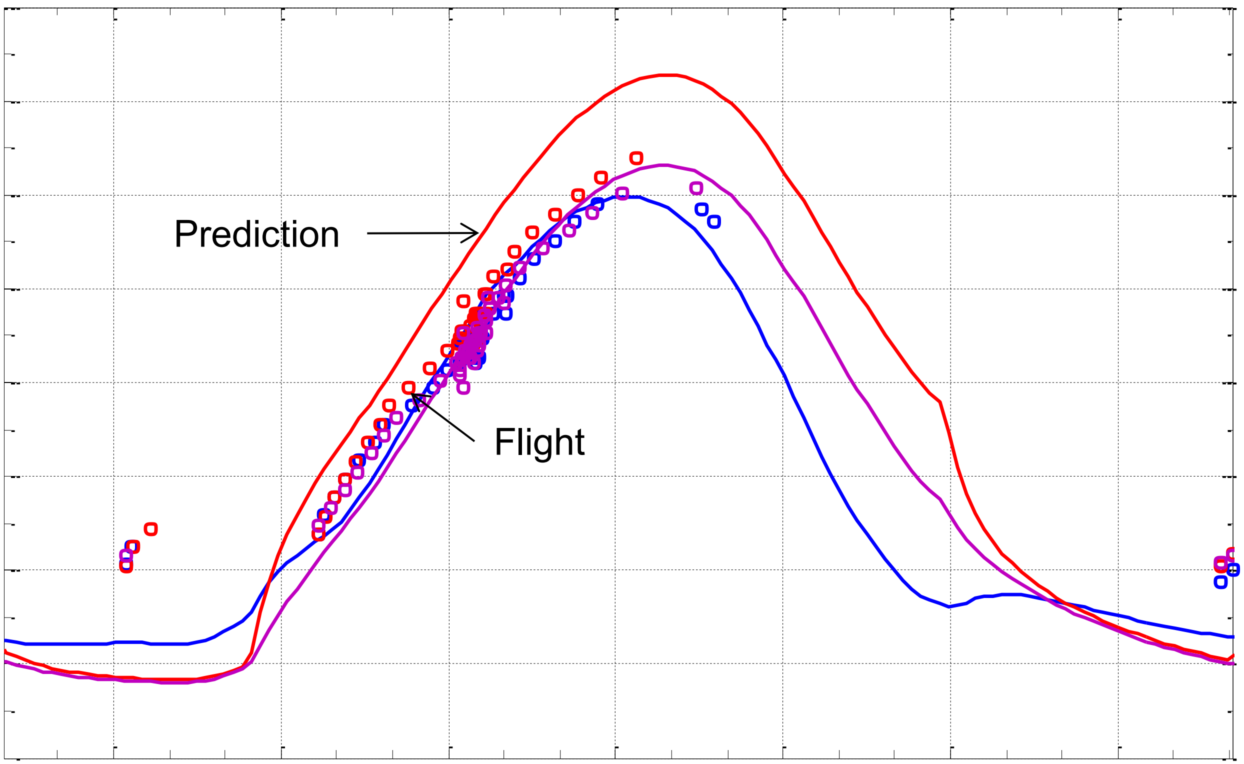
And I am exhausted from my long journey…





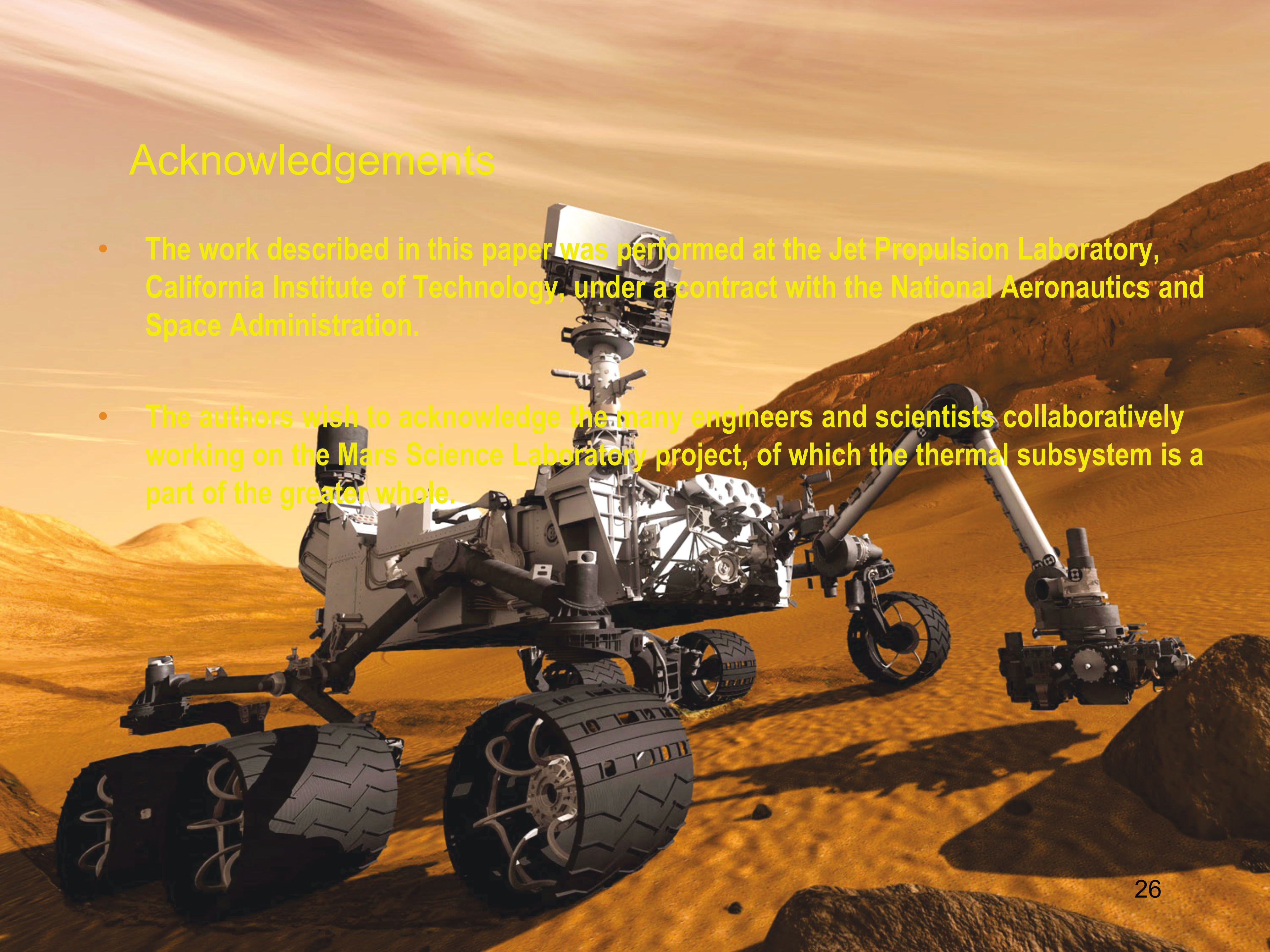

Windbreaker

Rover HRS Predictions vs. Flight (RHRS Controlled Components)



Major Conclusions

- The windbreaker was implemented on the MSL Curiosity Rover to significantly mitigate loss of heat pick up from the MMRTG in windy conditions
- It increased the Rover HRS controlled components temperatures by ~30 C in the worst case cold windy conditions
  - With an insignificant increase in their temperatures in hottest conditions
- It has a relatively small mass, was quite easy to implement out of beta cloth and landed on Mars intact after being subjected to Entry, Descent & Landing forces
- Hence a simple scheme to protect the RHRS from high speed winds was successfully demonstrated in the MSL Curiosity rover



Acknowledgements

- The work 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.

- 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.