Mars Exploration Rover Surface Mission
Thermal Performance for More Than an Entire Martian Year

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The Mars Exploration Rover (MER) project landed two identical roving science vehicles on Mars in Jan. 2004; they have continued to perform geological science data collection well beyond their surface design lifetime of 90 sols.

- Today is sol 903A & Sol 883B

The missions launched in June & July of 2003 on separate Delta II class vehicles.

Each Flight System consisted of:

- A cruise stage and entry, descent and landing system (EDL) with inheritance from the Mars Pathfinder (MPF) development
- A rover based upon the Athena Rover developments undertaken for the Mars ‘01 and Mars Sample Return projects Athena Science Package, 5 science instruments to conduct remote and in-situ observations
Mission Overview

Launch/Cruise

EDL

Surface

Images From Mission Animation by Dan Maas
Rover Configuration - Deployed

- Navcams
- Pancams
- Pancam Mast Assembly (PMA)
- Magnets
- Rover Equipment Deck (RED)
- Instrument Deployment Device (IDD)
- Calibration target
- Low gain Antenna (LGA)
- UHF monopole antenna
- High Gain Antenna (HGA)
- Solar arrays
- Warm Electronics Box (WEB)
- Mobility Differential
- Mobility System
Rover Warm Electronics Box (WEB)

- UHF Radio
- IMU
- REM Structure and Electronic Slices
- X-Band Waveguide to HGA
- X-Band SSPA
- Mini-TES location (attached to RED)
- Battery Location on Bottom of WEB
- X-Band SDST
- Forward Cable Tunnel and Bulkhead
- Rear Cable Tunnel and Bulkhead
- Differential Shaft Connection to the Starboard Rocker Bogie
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Thermal Design Drivers

• Mars Surface Thermal Environment

• Hardware Temperature Limits

• Electrical Energy Usage Constraints

• High and Low Energy Operational Scenarios
Mars Surface Environment

- Design driven by landing site latitude (10°N to 15°S), time of year ($L_S = 328$ at BOM, $L_S = 30$ at EOM), ground albedo (0.12 to 0.25) and inertia (rock distribution), dust level ($\text{Tau} = 0.2$) in atm & elevation (-1.3km, MOLA)

- Global Circulation Model predicts ground, atmosphere & sky temps, solar insolation during day

- Wind speeds from Viking data (0 to 20 m/sec)
Hardware Temperature Limits

• **Temp Sensitive Hardware Located Inside WEB**
  
  – Li Ion secondary battery (-20°C/+30°C), charging at >0°C
  – Flight System Electronics (-40°C/+50°C)
  – Mini-TES Science instrument (-40°C/+45°C)

• **Temperature Robust External Hardware** - 9 cameras & 34 actuators (-105°C/+50°C)
  
  – Deployable Solar Arrays
  – Telecommunications antennas (High Gain, Low Gain, UHF)
  – Robotic arm with science sensors
  – Mobility system
  – Pancam Mast Assembly
  – Cameras (Optics and Electronics)
**Power System**

- 1.3 m^2 deployable solar array with triple-junction GaAs cells
- Two, 8 A*hr Li Ion rechargeable batteries
- 600 W*hrs electrical energy production per Sol
- Bus voltage maintained between 24V and 36V
- 120 W* hrs available for electrical heater power at night

**Operational Scenarios**

- Hot Case – maximum activity, early in mission, 4 hours of DTE comm, 716 W*hrs of dissipation in WEB (100W peak power)
- Cold Case – late in mission, minimum activity, charge batteries, 470 W*hrs of dissipation in WEB
Rover Internal Thermal Design

- **Maximize Thermal Time Constant** \((\text{Tau} = R \times C)\)
  - Slow down daytime temperature rises during times of high power
  - Slow down nighttime temperature drops during times of low power

- **Maximize thermal capacitance** \((C)\)
  - Concentrate thermal mass in WEB (36kg) by coupling together
  - Allow power sharing
Rover Internal Thermal Design

- Maximize WEB thermal resistance (R) to environment
  - Carbon-opacified aerogel insulation (k=0.012 W/m*K)
  - Low emissivity gold internal & external surfaces
  - Flex cables with lower copper cross-section
  - Cable tunnels for flex & coax
  - Battery thermal switches open when battery is cold
  - Stainless steel section of HRS tubing at egress
  - Low conductivity boron-epoxy tubes support H/W
WEB Thermal Hardware

- **Survival heaters** on REM, Battery & Mini-TES
  - Controlled by mech t’sstats
  - Operate when flight computer is OFF

- **Warmup Heater** on Battery
  - Controlled by mech t’sstats
  - Warmup to optimal charging temp (0°C)

- **Radioisotope Heater Units** (RHU’s) on REM (2) and Battery (6)
  - Dissipate 1.0 W each
  - Non-electrical heat source; cannot be turned off

- **Paraffin-actuated thermal switches** between battery & radiator
  - Close when battery temp > 20°C (G=1.0 W/°C)
  - Open when battery temp < 18°C (G=0.017 W/°C)
Rover External Thermal Design

- **34 Actuators** on Outside of Rover

![Diagram of Rover External Thermal Design](image-url)

- PanCam Filter Wheel (2)
- Camera Elevation
- HGA Elevation
- HGA Azimuth
- PMA Mast Drive Deploy
- Solar Array Deploy (5)
- Rock Abrasion Tool (3)
- Instrument Deploy Device (5)
- Mobility Steering (4)
- Mobility Drive (6)
- Rocker Deploy (2)
- Micro Imager Dust Cover
Rover External Thermal Design

- **9 Cameras on Outside of Rover**

  - PanCam (2)
  - NavCam (2)
  - HazCam (4) Front (2) & Rear (2)
  - Micro IMG (1) on IDD
External Thermal Hardware

• **No survival heaters necessary**

• **Warmup Heaters** (to –55C min op temp)
  – On all actuators (motors, gearboxes, bearings, harmonic drives)
    - Concern is viscosity of Braycote lubricant at cold temps
  – On all camera electronics boards
  – Allow early morning operations

• **Low a/e coatings**
  – Minimize effect of solar insolation
  – White paint on PMA mast
  – Silvered teflon on motors and gearboxes
  – Silvered teflon on camera electronics housings
Rover Analytical Thermal Model

• **Used in Mission Ops**
  
  – 375 Nodes
  – Correlated to STT test data and flight data (every 20 Sols)
  – 1 Sol transient runs in 1 minute
  – Predicts plotted and compared to flight telemetry in Excel
  – Used to predict allowable communications and necessary warmup durations
  – Temp predicts within 5C
  – Simplified version (10 nodes) used in Power model
Sol 14A

- Total energy dissipated = 767 W*hrs
- 2 hours of DTE X-band comm
- 30 minutes of UHF comm
- Internal electronics < 50°C, max AFT limit
- Battery < 30°C, max AFT limit
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Mars Exploration Rover

MER-A Flight Data – Battery Max & Min Temps

Battery AFT limits = -20C/+30C

1 Mars Year = 669 Mars Sols
687 Earth Days

MER-A Battery Temps

1 Mars Year =
669 Mars Sols
687 Earth Days
MER-A Flight Data – REM Max & Min Temps

MER-A REM Temperature

REM AFT limits = -40C/+50C
MER-A Flight Data – Solar Array Max & Min Temps

MER-A Solar Array Temperature

Solar Array AFT limits = -110°C/+90°C
Max allow survival energy = 120 W\text{*hrs}

Max Mini-TES Survival Heater Energy Utilized = 48 W\text{*hrs}

Batt surv htr first activated on Sol 869A; used 20 W\text{*hrs}

REM surv htr never activated

Peak Energy = 48 W\text{*hrs} on Sol 186A
**MER-B Robotic Arm Heater Anomaly**

Instrument Deploy Device (IDD) Warmup Heater Switch failed ON

- **Overtemperature Concern** (max non-op AFT limit = 110C)
- **Potential Energy Hit** ($Q_{IDD\ Az\ htr} = 15W$ for 24 hours = 360 W*hrs)
  - Mitigated by thermostat box (only on for 11 hours)
    - (close/open setpoints = -52.4C/-42.6C, tied to $T_{atm}$)
  - Further mitigation by Deep Sleep Mode (only on for 2 hours)
    - took battery off-line from 2000 to 0800
Deep Sleep Mode took battery off-line from 2000 to 0800

- Left Mini-TES with no survival heater at night
- Min temp experienced by Mini-TES in flight = -59C
- Min AFT limit = -40C
- Min Qual limit = -45C
- Instrument “requalified” during flight after 90-Sol primary mission completed
MER Lessons Learned

- Passive Thermal Design
  - Bias to protect from cold
  - Solve hot problem with op constraints
- Test Hardware beyond AFT’s
  - Show temp margin
  - May be used in flight
- Use temp sensors on every motor
  - Telemetry always better than predicts
- Use flexible adhesives under temp sensors
- Protect from stuck-on warmup heaters
- UHF Comm provides more bits per Watt*hr than X-band
Update on Rover Health

- **MER-A (Spirit) Rover has 1 drive motor with open circuit**
  - Dragging Right Front wheel since Sol 779A
- **MER-A has low energy**
  - Parked with arrays facing sun
  - Will not move again until August 2006
- **MER-B (Opportunity) Rover has 1 steering actuator failed**
  - No RF steer actuator
  - Wider turning radius
- **MER-B has higher current draw on robotic arm**
  - One motor winding is open
  - Actuator is still functional
- **External temp sensor failures on both vehicles – total of 11**

MER-A Sol 788A
Conclusion & Status

System Level Thermal Design
• Exceeded performance requirements
• Required low night heater energy
• Allowed full operability in hot environment
• Highly successful design

Current project status
• Rovers have lasted over 10X design life (today is Sol 903A & Sol 883B)
• Both rovers continue to explore Mars return valuable science data
• MER-A > 6.8 km, MER-B > 8.2 km traverse and still going
• Thermal design working very well
  – Contributing to High Science Output and Long Life of Rovers
Favorite Images

MER-B, (Opportunity) leaves Eagle Crater in Meridiani Planum,
Sol 60B, March 25, 2004
Favorite Images

MER-A, (Spirit) Image of Columbia Hills, 3 km east of landing site, Gusev Crater, Sol 8A, Jan. 11, 2004
Favorite Images

MER-A, (Spirit) Entire Traverse from Landing Site to Columbia Hills, Gusev Crater, Sols 1 - 860A (Jan. 4, 2004 to June 5, 2006)