# Mars Science Laboratory Rover Actuator Thermal Design

Keith S. Novak[1] and Yuanming Liu.[2]
*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109*

Chern-Jiin Lee[3]
*Applied Sciences Laboratory, Inc. Baldwin Park, CA 91706*

*and*

Steven Hendricks[4]
*Garrad Hassan America, Inc, San Diego, CA, 92123*

**NASA will launch a 950 kg rover, part of the Mars Science Laboratory (MSL) mission, to Mars in October of 2011. The MSL rover is scheduled to land on Mars in August of 2012. The rover employs 31 electric-motor driven rotary actuators to perform a variety of engineering and science functions including: mobility, camera pointing, telecommunications antenna steering, soil and rock sample acquisition and sample processing. This paper describes the MSL rover actuator thermal design. The actuators have stainless steel housings and planetary gearboxes that are lubricated with a "wet" lubricant. The lubricant viscosity increases with decreasing temperature. Warm-up heaters are required to bring the actuators up to temperature (above -55ºC) prior to use in the cold wintertime environment of Mars (when ambient atmosphere temperatures are as cold as -113ºC). Analytical thermal models of all 31 MSL actuators have been developed. The actuators have been analyzed and warm-up heaters have been designed to improve actuator performance in cold environments. Thermal hardware for the actuators has been specified, procured and installed. This paper presents actuator thermal analysis predicts, and describes the actuator thermal hardware and its operation. In addition, warm-up heater testing and thermal model correlation efforts for the Remote Sensing Mast (RSM) elevation actuator are discussed.**

## Nomenclature

*AFT* = Allowable Flight Temperature
*APXS* = Alpha Particle X-Ray Spectrometer
*CDR* = Critical Design Review
*ChemCam* = Chemistry & Camera Instrument
*CheMin* = Chemistry & Mineralogy Instrument
*CHIMRA* = Collection and Handling for Interior Martian Rock Analysis
*DAN* = Dynamic Albedo of Neutrons Instrument
*DC* = Direct Current
*DRT* = Dust Removal Tool
*DTE* = Direct-to-Earth
*EDL* = Entry, Descent and Landing
*GC* = Gas Chromatograph
*GCM* = Global Circulation Model
*HGA* = High Gain Antenna

[1] Senior Engineer, Thermal & Cryogenics Engineering, 4800 Oak Grove Dr., Pasadena, CA 91109, M/S 125-123.
[2] Senior Engineer, Thermal & Cryogenics Engineering, 4800 Oak Grove Dr., Pasadena, CA 91109, M/S 79-24.
[3] Consulting Engineer, Applied Sciences Laboratory, 13111 Brooks Drive, Baldwin Park, CA 91706.
[4] Consulting Engineer, Asset Management and Optimization Division, 9665 Chesapeake Drive, Suite 435, San Diego, CA 92123.

| | | |
|---|---|---|
| *HGAS* | = | High Gain Antenna System |
| *JPL* | = | Jet Propulsion Laboratory |
| *LIBS* | = | Laser-Induced Breakdown Spectrometer |
| *LPHTA* | = | Low-Power, High-Torque Actuator |
| $L_s$ | = | Solar Longitude |
| *LST* | = | Local Solar Time |
| *MAHLI* | = | Mars Hand Lens Imager |
| *MARDI* | = | Mars Descent Imager |
| *MastCam* | = | Mast Camera |
| *MMRTG* | = | Multi-Mission Radioisotope Thermoelectric Generator |
| *MSL* | = | Mars Science Laboratory |
| *NASA* | = | National Aeronautics and Space Administration |
| *NavCam* | = | Navigation Camera |
| *PRT* | = | Platinum Resistance Thermometer |
| *QMS* | = | Quadrupole Mass Spectrometer |
| *RA* | = | Robotic Arm |
| *RAD* | = | Radiation Assessment Detector |
| *REMS* | = | Rover Environmental Monitoring Station |
| *RMI* | = | Remote Micro-Imager |
| *RSM* | = | Remote Sensing Mast |
| *SAM* | = | Sample Analysis at Mars Instrument Suite |
| *SA-SPaH* | = | Sample Acquisition - Sample Processing and Handling |
| *Sol* | = | Day on Mars (duration is 24.6 Earth hours) |
| *Tau* | = | Optical Depth of the Atmosphere (a measure of dust load in the atmosphere) |
| *TLS* | = | Tunable Laser Spectrometer |
| *TOD* | = | Time of Day |
| *XRD* | = | X-ray Diffraction |
| *XRF* | = | X-ray Florescence |

# I. Introduction

NASA will launch the MSL Rover to Mars in October of 2011. The MSL rover will touch down on the surface of Mars in August of 2012. The MSL rover will robotically explore a particular Mars landing site to determine the planet's ability to support microbial life in the past or present. In order to investigate the question of Mars habitability, the rover is equipped with 10 science instruments. These science instruments will perform investigations to accomplish the 4 main science objectives of the MSL mission: 1) look for organic carbon compounds, 2) characterize the geology of the landing site, 3) investigate the processes that could have made Mars habitable in the past (including the influence of water) and 4) characterize the radiation environment of Mars.

## A. MSL Rover

This paper presents the thermal design of actuator hardware on the MSL rover (see Fig. 1). Papers about the overall thermal architecture of the entire spacecraft (including the Cruise Stage, Descent Stage and Rover) have been previously published. [1-5] The MSL rover is designed to last an entire Martian year (669 Sols). The Rover is capable of landing in a wide range of latitudes (± 30 degrees) on Mars. The Rover has been qualified to execute a long cumulative traverse (up to 20 km) over its lifetime. There are 10 science instruments located on the rover. The science instruments cover a range of science investigation types: 1) remote sensing, 2) contact science, 3) laboratory sample analysis, and 4) environmental sensing.

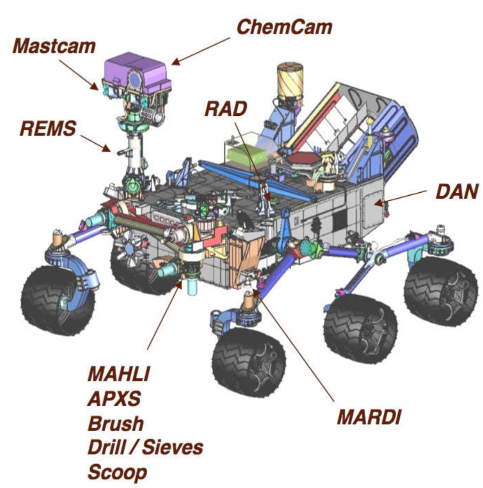

**Figure 1. MSL Rover and External Science Instruments.**

The remote sensing instruments, located at the top of the Remote Sensing Mast (RSM) are: 1) Mast Camera (Mastcam), left and right eye cameras that can acquire panoramic, color, multispectral and stereoscopic images and 2) Chemistry &

Camera (ChemCam), consisting of the first planetary science Laser-Induced Breakdown Spectrometer (LIBS) and a Remote Micro-Imager (RMI), which uses a laser to ablate the top layer of rock and soil targets and analyzes the returned spectra to remotely determine target elemental composition. The contact science instruments, located on the end of the Robotic Arm (RA) are: 3) Alpha Particle X-Ray Spectrometer (APXS), a spectrometer that uses X-ray Emission and X-ray Fluorescence (XRF) techniques to determine elemental chemistry of rocks and soil and 4) Mars Hand Lens Imager (MAHLI), a focusable color camera with a working distance range from 22mm to infinity. The analytical laboratory instruments, located inside the rover body, are: 5) Chemistry & Mineralogy (CheMin), the first ever, space-borne, powder X-ray Diffraction (XRD) instrument that also has XRF capabilities for identifying and quantifying the minerals present in Martian rocks and soil and 6) Sample Analysis at Mars (SAM), a suite of three instruments, a Quadrupole Mass Spectrometer (QMS), a Gas Chromatograph (GC), and a Tunable Laser Spectrometer (TLS) capable of detecting organics, and analyzing gas samples from the atmosphere as well as evolved gases from pyrolysis of Mars rocks and soil samples. The environmental instruments are: 7) Dynamic Albedo of Neutrons (DAN), located inside the rover body, which uses a neutron spectrometer to measure the abundance and depth distribution of H- and OH-bearing materials (water) in the Martian soil at depths up to 1 m, 8) Radiation Assessment Detector (RAD), located on the top deck of the rover, which detects and analyzes energetic particle radiation at the surface of Mars, 9) Rover Environmental Monitoring Station (REMS), with sensors on the top deck of the rover and attached to the RSM mast, which will record wind speed/direction, pressure, relative humidity, atmosphere temperature, ground temperature, and ultraviolet radiation and 10) Mars Descent Imager (MARDI), attached to the external side wall of the rover, which is a fixed-focus color camera that will take images of the landing site for 2 minutes during EDL, from the moment of heatshield separation until touchdown.

### B. MSL Actuators

There are a total of 31 rotary actuators on the MSL rover. The actuators provide all of the articulation needed to move and point the science cameras, to move and point the communications antenna, to drive and steer the rover, and to collect, process and deliver solid samples to the laboratory science instruments inside the rover body.

Each actuator consists of an electric brushless DC motor, a brake, an encoder, a gearbox and an output resolver (see Fig. 2). The electric motor provides the energy to move the mechanism. The gearbox reduces the high output speed of the motor (200 to 8000 rev/min) to a reduced speed and higher torque at the output shaft. Each stage of the gearbox consists of a sun gear that spins inside a ring of planetary gears. Some gearboxes are a single stage, while others have as many as 6 stages. The encoder measures the position of the motor shaft. The output resolver measures the position of the output shaft. The brake is used to hold the motor in a desired position.

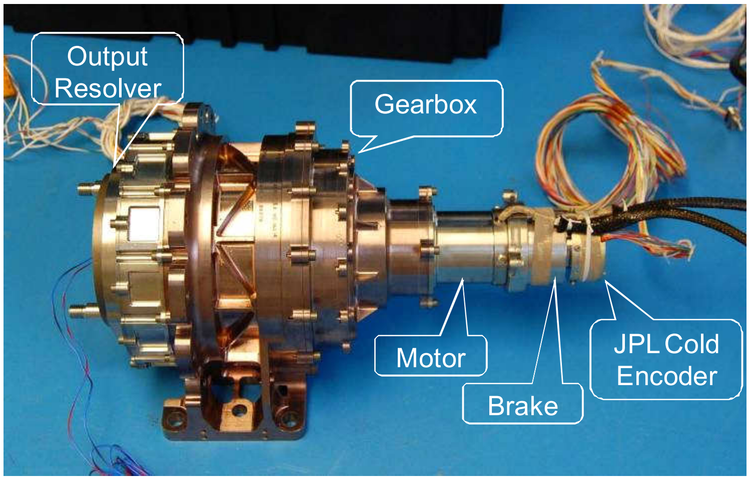


**Figure 2. Typical MSL Actuator.**

The actuators articulate all of the mechanisms on the rover (see Fig. 3). The Remote Sensing Mast (RSM), with 3 actuators, provides a pointing platform for the MastCam and ChemCam science instruments, as well as the engineering navigation cameras (NavCams). The RSM deploy actuator brings the mast out of its stowed position to a fully deployed position on the rover top deck. This RSM deploy actuator will only be used once during the mission. The RSM azimuth and elevation actuators are used throughout the mission to point science and engineering cameras at targets on Mars. The High Gain Antenna System (HGAS) is the mechanism that provides pointing of the X-Band High Gain Antenna (HGA) which allows high speed, Direct-to-Earth (DTE) communications, for both command upload and telemetry downlink. The HGAS points the HGA and tracks the Earth with 2 actuators, an azimuth actuator and an elevation actuator. Once the MSL Rover has touched down on Mars, it is ready to start driving across the Martian terrain in search of high value science targets. The mobility subsystem contains 10 actuators capable of driving and steering the rover as it moves in commanded and autonomous traverses. There are 6 drive actuators, imbedded inside the 6 wheel hubs, and 4 steer actuators, located above the corner wheels.

The remaining 16 actuators are located inside the Sample Acquisition – Sample Processing and Handling (SA-SPaH) subsystem.[6-7] The SA-SPaH subsystem is tasked with collecting rock and soil samples with a scoop and a percussive Drill, pulverizing the samples, sieving them into particles of the proper size and delivering them to the analytical laboratory instruments (SAM & CheMin) located inside the rover. The largest element of SA-SPaH is the 5 degree-of-freedom Robotic Arm (RA). The RA has 5 actuators that include an azimuth and elevation actuator at the shoulder joint of the arm (where the arm attaches to the rover structure front panel), an elbow actuator, located halfway down the arm, and wrist and turret actuators, located at the end of the arm. The azimuth, elevation and elbow actuators are the largest and most massive actuators on the entire vehicle, measuring 285 mm in length and 125 mm in diameter with a mass of 7.4 kg. When the RA is fully extended, the turret is 1.9 m from the shoulder joint at the base of the arm. The RA is capable of preloading the Drill onto a rock target with up to 300N of force prior to starting a drill operation. Two science instruments are mounted on the RA turret, APXS and MAHLI along with 3 engineering mechanisms that are part of SA-SPaH, the percussive Drill, the Collection and Handling for Interior Martian Rock Analysis (CHIMRA) and the Dust Removal Tool (DRT).

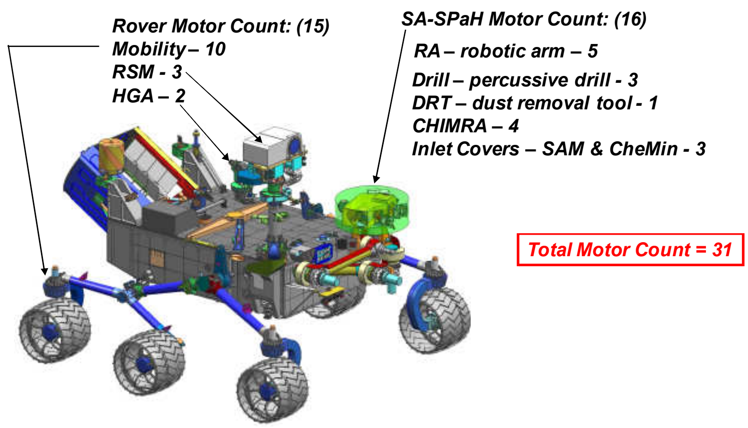


**Figure 3. Locations of Rotary Actuators on MSL Rover.**

The Drill uses a magnetic voice coil to percussively hammer through rock targets and create powered samples.[8] There are 3 rotary actuators on the Drill: a translation actuator to move the drill bit forward as it progresses into the rock, a rotate actuator to spin the bit around and a chuck actuator that allows a used bit to be discarded and a new bit to be installed. The CHIMRA is a mechanism capable of scooping its own soil samples from the Martian surface or receiving powdered rock samples from the Drill.[9] CHIMRA, with internal sieves that sort the samples into fines, portions the samples before transferring them into the analytical instruments. There are 4 actuators inside CHIMRA: scoop, portion, vibe and thwack. The scoop actuator enables CHIMRA to collect loose soil samples directly from the Mars surface. The portion actuator takes sieved samples and creates sample portions of the proper volume for deposition into the analytical lab instruments. The vibe actuator is used to vibrate the mechanism and cause powdered sample to progress in a gravity driven direction through the sample path. The thwack mechanism is used to rap the sieves inside CHIMRA and clean them after a sample has been processed. The DRT has a single actuator inside it. The DRT actuator is the smallest and least massive of all the actuators on the entire vehicle, measuring 114 mm in length and 66 mm in diameter with a mass of 0.35 kg. The DRT is designed to remove dust and debris from the top layer of a rock, so that the rock surface can be examined by the imagers and spectrometers on the turret. The final mechanisms in the SA-SPaH suite are the solid sample inlet covers. The SAM instrument has 2 sample inlets and the CheMin instrument has one. There are 3 covers on the top deck of the rover with 3 actuators to open the covers. Normally the covers will be kept closed. When it is time for CHIMRA to transfer solid sample into one of the science instruments, the proper cover will open, sample will be deposited into the inlet and the cover will close.

## II. History of MSL Actuator Thermal Design Effort

The thermal environment on Mars is quite harsh (with diurnal surface temperatures ranging from -81ºC to +38ºC in the summer and from -117ºC to -42ºC in the winter) over the landing site latitude range (± 30 degrees) of interest for MSL. Actuators, located external to the rover body, must be able to survive and operate in this harsh thermal environment.

Early in the MSL project design phase, it was decided to embark on an actuator development effort that had the potential to eliminate the need for actuator heaters. The cold actuator design would be capable of operating in any season, at any time of day (qualified to operate as cold as -135ºC). Actuators with titanium gearboxes and a dry lubrication system were fabricated and tested. Life testing of this actuator design revealed rapid wear inside the gearbox, leading to failure well before the required design life. The dry lubrication process selected appeared to work well in the bearings, but was insufficient to provide adequate life for the gears. The motor steel input pinion interface to the titanium gearbox was the highest loaded gear-pair, and neither the dry lubrication process nor a heritage wet lubricant could prevent rapid wear at this location. More time was needed to test titanium gear protective hard coatings and a more effective dry lubrication method. Investigations were complicated by the observation that the low thermal conductance of the titanium gears would result in temperature gradients within the gearbox, tightening the gear mesh under load.

Concerns about the cold actuator design were discussed at the Mechanical Critical Design Review (CDR) in May of 2007. The MSL Project decided to cancel the cold actuator development and return to a more traditional actuator design employing high strength steel gearboxes and a wet lubricant (Braycote). Braycote has a viscosity that increases with decreasing temperature, significantly so below -55°C. If the lubricant is too viscous, it will rob the actuator of its ability to produce the proper output torque and speed. The revised actuators were limited in how cold they could operate and still meet the mission requirements, so would most of them would need to have heaters to warm them up prior to operating in a cold environment.

Many of the MSL actuators are quite massive. For example the actuators used in the RA shoulder and elbow joints have masses of 7.4 kg. It would take an excessive amount of energy (> 180 Wh) to completely warm just one of the 5 RA actuators from an initial cold temperature of -100ºC to an operating temperature of -55ºC. Consuming large amounts of energy to warm actuators would leave little energy to perform the other critical functions of the rover (science data collection, driving, communicating, imaging, etc.). It was decided that the best way to reduce energy consumption of the heaters was to heat the high-speed, low-torque, input side of the actuator (motor, encoder, brake, 1st and 2nd stage gearboxes) to -55ºC and allow the lower speed and high torque output stages to run colder (at -65ºC). Significant energy savings were realized by this design strategy. By November of 2007, the "input-only" heating strategy had been baselined for all high and medium torque actuators in the MSL design. Smaller low torque actuators would be heated entirely to their operating temperature of -55ºC.

In some cases (e.g., daytime use in the summer season) it is acceptable to employ a "wait-to-use" actuator strategy, allowing natural warm-up of the environment to bring the actuators above their operating temperature limits. However actuator usage in the early morning, even in the summer season and for large portions of the day in the winter season requires a "heat-to-use" strategy to allow actuator operations. "Heat-to-use" extends the "wait-to-use" operating window and increases operating flexibility in the summer season. In the winter season, "heat-to-use" enables usage of actuators when there would be no operating window in the "wait-to-use" case.

## III. Actuator Thermal Design Requirements

The actuator thermal design is driven by the temperature requirements, usage requirements and resource constraints imposed by the hardware, materials, rover system and Mars surface environment. A discussion of these design drivers is presented in this section of the paper.

### A. Temperature Requirements

The allowable viscosity of the Braycote lubricant drove the minimum temperature limits for the actuators. It was determined that the minimum allowable temperature for the Braycote is -70ºC. All actuators have been qualified to operate at a soak temperature of -70ºC. Temperature margin of 15ºC was added to the minimum qualification temperature to derive the minimum Allowable Flight Temperature (AFT) of -55ºC. Actuator heaters must be powerful enough to bring the coldest internal component of the input stage of the actuators above -55ºC. The output portion of the actuators has a minimum AFT limit of -65ºC. Temperature limits for the RSM actuators are shown in Table 1.

**Table 1. RSM Actuator Temperature Limits**

| Remote Sensing Mast | Temperature, ºC | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Allowable Flight | | | | Protoflight or Qual | | | |
| | Operational | | Nonoperational | | Operational | | Nonoperational | |
| | min | max | min | max | min | max | min | max |
| RSM Deployment Actuator | -55 | 50 | -128 | 50 | -70 | 70 | -135 | 70 |
| RSM Azimuth Actuator | -55 | 50 | -128 | 50 | -70 | 70 | -135 | 70 |
| RSM Elevation Actuator | -55 | 50 | -128 | 50 | -70 | 70 | -135 | 70 |
| RSM Encoder | -65 | 85 | -128 | 100 | -80 | 105 | -135 | 120 |
| Motor and Brake Windings | -55 | 130 | -128 | 70 | -70 | 150 | -135 | 90 |

In addition to these absolute temperature limits, there were also temperature gradient requirements that needed to be considered. The temperature gradient from the inside of the gearbox to the outside housing of the gearbox was a significant concern. When internal components are warmer than external housings, compressive forces inside the gearbox can cause excessive wear. A gearbox maximum radial temperature gradient (from inside to outside) of 15ºC was adopted as a requirement. When the actuator is heated only at the input stages, temperature gradients are generated that run axially down the length of the actuator toward the output stage. No axial temperature gradient requirement was levied on the actuators; it was determined that there was enough tolerance margin in the axial direction of the actuators such that even large temperature gradients (>100ºC) would not cause a problem.

**B. Usage Requirements**

The heater design for the actuators was implemented in order to expand the operating window of the actuators, especially in cold environments experienced in the early morning and during the Martian winter. There were a number of derived requirements that drove the actuator thermal design:

1) The warm-up time must be reasonable (1 to 3 hours, maximum).
2) The warm-up times for individual actuators must be balanced across the entire mechanism. (For instance all 5 RA actuators should warm up at approximately the same rate.)
3) The heaters must have full functional redundancy. Failure of a single heater, temperature sensor or heater switch should not preclude the ability to safely warm the actuator up to temperature.
4) Heaters must be capable of being powered on when the flight computer is off. Nominally, the flight computer turns on to close a heater power switch, but then turns itself off to minimize energy consumption during the warm-up.
5) Heaters must be capable of thermostatic control when the flight computer is on. Redundant PRT's were added to the actuators to allow temperature feedback on the actuators for computer-based thermostatic control of the warm-up heaters.
6) Heater control setpoints must be capable of being modified during operations. During actuator warm-up, control setpoints can be high to facilitate fast warm-up. During temperature maintenance portions of heating sequences, control setpoints can be reduced to save energy. Also, as flight data is received and processed, desired control setpoints could change.
7) Maximum allowable heater power density is 0.78 W/cm$^2$ at maximum bus voltage of 32.8V. This is to keep the heater from damaging itself at high voltage and temperature.
8) Manufacturing tolerance on heater resistance is ± 5%.
9) Kapton film heaters can only be mounted on smooth, continuous surfaces of actuators. This was a challenge simply because mass reduction efforts on the gearbox housings often left irregular surfaces that were impossible to mount a heater on.
10) Minimum Kapton film heater heater width is 12.7 mm, due to manufacturing constraints.
11) Heater lead orientation must facilitate bundling of wires back into the flight harness and provide sufficient clearance to nearby hardware.
12) Heater sizes should be standardized wherever possible to facilitate design usage on multiple actuators.
13) Account for spacecraft bus voltage variation. Design with heater power at nominal expected voltage of 28V; check maximum heater power density at maximum bus voltage of 32.8V.
14) Each mechanism has a required operating time of day (TOD) range applicable for all seasons. In the winter, the HGAS has the widest required operational TOD requirement, from 1100 to 1700 Local Solar Time (LST), while the SA-SPaH subsystem had the narrowest operating TOD requirement, from 1400 to 1700 LST. The TOD requirement for the RSM in the winter is from 1300 to 1700 LST. Operating outside these ranges is possible at warmer times of the Martian year.

**C. Resource Constraints**

In addition to the usage requirements listed above, the rover flight system had its own constraints that influenced the actuator heater design. The following Flight System resource constraints also drove the actuator warm-up heater design:

1) The rover utilizes a MMRTG as its power source. This MMRTG produces roughly 104W of continuous power at end of mission. The Power subsystem also has an 86 A·hr, lithium-ion, secondary battery, used to store excess energy and deliver power when the instantaneous loads on the bus exceed the capability of the MMRTG. Total energy production per Sol is approximately 2500 Wh. Energy is consumed by the flight

system to do just about every activity on the rover. On a typical day, the flight system will consume about 550Wh (22%) to support operations (for example, operating the flight computer, power avionics, telecom transceivers, etc.). Keeping the rover in a sleep state (the baseline minimum power state, with survival heaters operating) over the course of the day consumes about 1100 Wh (44%). This leaves about 350 Wh (14%) of discretionary energy, to be used for science and 500Wh (20%) to be used for actuator heating. If additional energy is needed for heating or science, the resources of the battery may be used by temporarily drawing down the battery state of charge.

2) The Flight System has a finite number of power switches available. This constrains the number of heater zones that can be defined for use in warming up the actuators.
3) The Flight System also has a finite number of telemetry channels available for reading flight temperature sensors. This also limits the number of heater control points in the warm-up heater system.
4) Cabling also imposes constraints on the actuator warm-up heater design. Much of the system utilizes flex cables to deliver power to remote units at the top of the RSM and on the end of the RA. Voltage drops through flex cables can be significant and need to be accounted for in the heater design. Available traces on flex cables also limited the power levels and numbers of heaters that could be accommodated by the design.
5) Number of pinouts on connectors also limited the number of heaters that could be individually powered by the system.
6) Current carrying capacity of spacecraft power switches also limited the amount of power that could be dissipated by a single heater string. Allowable current through heater switches varied from 2A to 10A.

### D. Mars Thermal Environment

The Mars surface thermal environment defines the ultimate thermal sink for the rover and its actuators. Since all of the actuators are imbedded in mechanisms attached to the outside of the rover, they are at the mercy of the Mars external environment. The MSL landing site latitude range is from 30 degrees South to 30 degrees North. The proposed landing site with the lowest southerly latitude is Holden Crater, at 26.37 degrees South. Southerly landing sites will have the most extreme environments (hottest summers and coldest winters) due to the eccentricity of the Mars orbit. Southern summer occurs near perihelion and southern winter occurs near aphelion. The other three potential MSL landing sites are in higher latitudes and have more benign thermal environments than Holden Crater.

Environment predictions for the MSL mission were generated using the Mars Global Circulation Model (GCM).[10] The GCM was run with the appropriate input parameters (landing site latitude, ground albedo and thermal inertia, time of year, landing site elevation and atmosphere optical depth) to determine the worst-case hot and cold surface thermal environments for the MSL rover. Figure 4 shows the predicted atmosphere, ground and sky temperatures on the worst-case hot day for the MSL mission (Landing site latitude = 27.5 deg S, Summer Solstice, $L_s$=270 degrees). The summertime atmosphere temperature curve in Fig. 4 shows that the atmosphere will be below -55ºC (the minimum operating AFT limit of the actuators) for about 9 hours each Sol, in the night and early morning. Figure 5 shows the predicted atmosphere, ground and sky temperatures on the worst-case cold day for the MSL mission (Landing site latitude = 27.5 deg S, Winter Solstice, $L_s$=90 degrees). The wintertime atmosphere temperature curve in Fig. 5 shows that the

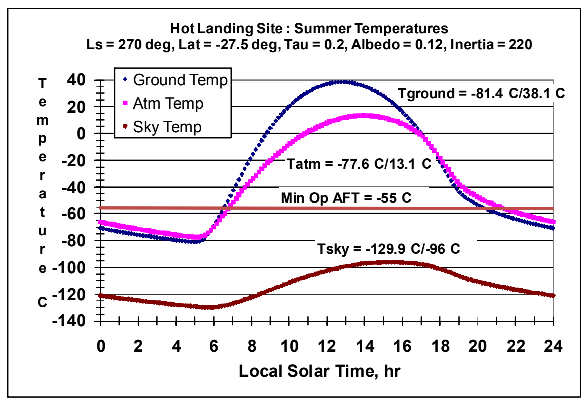


**Figure 4. MSL Mission Worst-Case Hot Diurnal Environment Profile.**

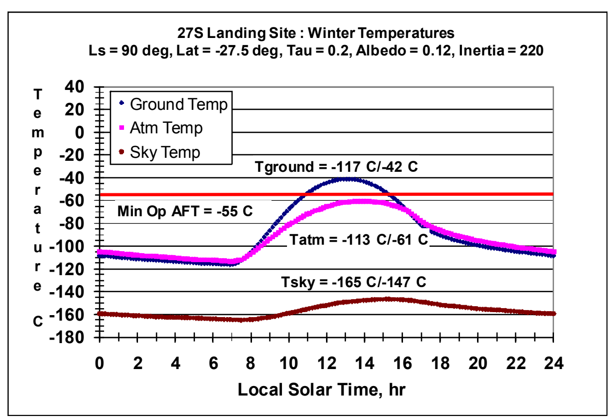


**Figure 5. MSL Mission Worst-Case Cold Diurnal Environment Profile**

atmosphere will be below -55ºC for the entire Sol. Clearly, heaters will be needed in order to bring the actuators up to operating temperature in the Mars surface design environments.

Excluding dust storm data, wind speeds recorded by the Viking 1 and Viking 2 landers reached sustained levels as high as 15 m/sec.[11] The MSL rover was designed to survive a surface thermal environment in which the wind speed could vary anywhere in the range between 0 m/sec to 15 m/sec at any time of day or night. The surface wind speed determines the heat transfer coefficient on external surfaces of the rover. To generate worst-case predicted daytime temperatures, 0 m/sec (free convection on exterior surfaces) and 15 m/sec (forced convection on external surfaces) wind speeds were adopted for the analytical hot and cold design cases, respectively. No wind at night was modeled since this was thermally conservative for exterior surfaces viewing the cold night sky sink which is colder than the atmosphere.

Environmental solar loads were also modeled. The peak incident solar load on the Mars surface in the worst-case hot environment (Summer Solstice at 27.5 S latitude) is approximately 700 $W/m^2$ at solar noon. The peak incident solar load on the Mars surface in the worst-case cold environment (Winter Solstice at 27.5 degrees South latitude) is approximately 400 $W/m^2$.

## IV. Warm-up Heater Sizing Procedure

Detailed thermal models of each actuator were integrated into thermal models of each articulating mechanism. The actuator thermal models included internal heat conduction paths through solid metal, across bolted joint interfaces and through bearings in the motors and gearboxes. Figure 6 shows a cutaway view of the LPHTA (used in the shoulder and elbow joints of the RA). Each stage of the gearbox consists of a sun gear that rotates inside the center of a carrier which houses planetary gears. Teeth of the planetary gears contact the sun gear in the middle of the carrier and the fixed ring gear at the largest internal diameter of the gearbox housing. Motor shaft, carriers and planetary gears are all supported inside the gearbox on bearings. Bearing thermal conductances are difficult to calculate and characterize.[12-13] A thermal test was done on a typical actuator (instrumented internally with thermocouples) in order to determine the internal heat paths in the actuator. Bearing conductances were calculated from the test data. Contact conductance across gear teeth is also hard to characterize and very uncertain. For model conservatism, the conductance path across gear teeth was neglected. Planet and sun gears were included in the thermal mass of the actuator. Motor, brake and encoder were also modeled. Cable heat transfer was also accounted for in the model.

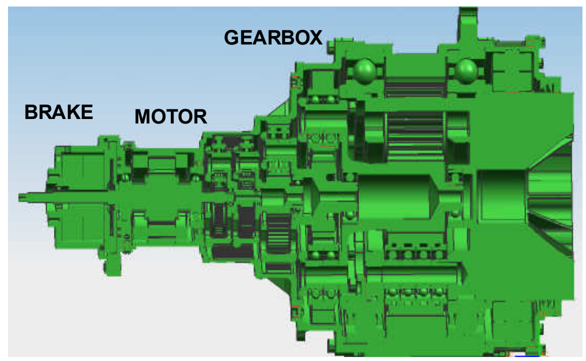


**Figure 6. LPHTA Cross-Section**

The general actuator warm-up heater sizing procedure proceeded as follows:

1) Put the largest heater possible on the motor. Size the heater such that it will not exceed the maximum power density of 0.78 $W/cm^2$ at a maximum bus voltage of 32.8V.
2) Add a heater to the input gearbox on the 1st or 2nd stage gearbox housing. This heater should increase the temperature on the input gearbox housing so that the external to internal temperature gradient is positive. This prevents binding of the gears during warm-up.
3) Add heaters to the output if necessary. Figure 7 shows the heater locations and heat flow paths from the outside of the LPHTA gearbox to the internal components.
4) Iterate on the heater design until the heaters deliver a reasonable warm-up capability (raising the coldest internal gearbox carrier above -55ºC), an operating time of day window consistent with usage requirements and a balanced warm-up capability across the mechanism.

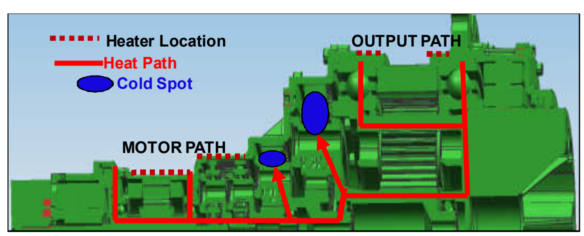


**Figure 7. LPHTA Heater Locations and Heat Flow Paths**

## V. Case Study – Remote Sensing Mast Elevation Actuator Warm-up Heater Design

In order to illustrate the entire actuator design process, a case study of the RSM elevation actuator is presented. The process includes heater sizing through analytical modeling, specification of thermal hardware, performance predictions, thermal characterization testing, model correlation to test results and final flight performance predictions. The RSM Elevation actuator controls the elevation angle of the cameras (ChemCam, MastCam and NavCam) mounted to the top of the RSM (see Fig. 8).

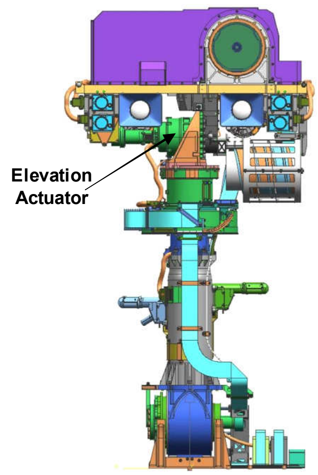


**Figure 8. Location of Elevation Actuator on RSM**

### A. Design Constraints

The RSM elevation actuator mass is 3.6 kg. Its maximum overall diameter is 100 mm and its length is 220mm. Two rover power switches were allocated for primary and redundant input stage heaters on the elevation actuator. Each of these switches had a maximum current carrying capability that limited the heater power on each circuit to 20W at 28V. There was one additional switch (also with a maximum allowable power of 20W) allocated to the elevation actuator for an output gearbox augmentation heater. If the input heating was not capable of bringing the actuator up to temperature, the augmentation heater could be used as well. Two PRTs were allocated to the elevation actuator to use as feedback control on the warm-up heaters.

### B. Thermal Design Features

As shown in Fig. 9, the final thermal design of the elevation actuator consisted of three Kapton film heaters, mounted to the motor (6W), 1st/2nd stage gearbox housing (5.5W) and 3rd/4th stage gearbox housing (9W), that made up the input heater circuit. These heaters were wired in parallel, so that a single heater open failure would not result in the loss of the entire circuit. Heaters were fabricated in 2 layers to allow redundant heater elements. An augmentation heater (20W) was added to the output housing to provide additional heat, if the input heating was not sufficient to raise the actuator temperature into the operating temperature range.

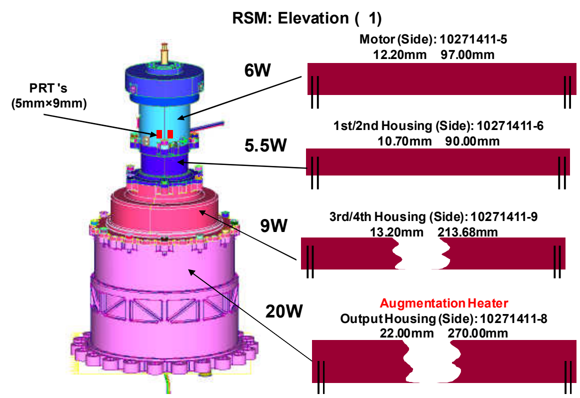


**Figure 9. Locations of Heaters and PRTs on RSM**

### C. Performance Predictions

An analytical thermal model of the RSM, which included all three RSM actuators, was used to predict heater performance and energy consumption in all seasons at the 27.5°S landing site location. The "input-only" heaters have enough power to meet the design requirements (minimum operating AFT limit = -55ºC) and time of day requirements (operating by 1300 LST) and bring the azimuth and elevation actuators up to operating temperature in the worst-case cold winter day in a free convection environment. As shown in Fig. 10, it will take 2.4 hours of heating (starting at 0900 LST and ending at 1124 LST) to warm the elevation actuator up to its operating temperature. After this initial warm-up, the elevation input heater will have to be cycled on and off at an 80% duty cycle in order to maintain the actuator at temperature during a 1-hour operation. The total energy cost to bring both the azimuth and elevation actuators up to temperature and maintain them at

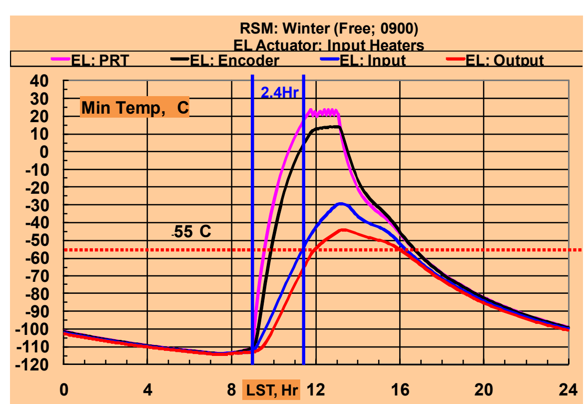


**Figure 10. RSM Elevation Actuator Warm-up Prediction in Winter Environment**

temperature during a 1-hour operation is 132 Wh. This is well under the 500 Wh of energy available for actuator heating. In a forced convection environment, the total energy cost is 133 Wh. Convective heat losses are higher in the forced convection environment, but the initial actuator temperature is colder in the free convection environment.

### D. Testing and Test Results

An engineering model of the RSM was thermally tested in a 10-foot diameter thermal vacuum chamber at JPL. The engineering model was very high fidelity and had flight-like actuators installed in the mechanisms. The RSM and its actuators were fully instrumented with thermocouples. One of the primary test objectives was to thermally characterize the warm-up heater performance. To this end, a test case was run in which the RSM was cooled down to -120ºC, in a 10 torr GN2 atmosphere, and then heated to steady state using the "input-only" warm-up heaters at a nominal bus voltage of 28V. During the entire thermal test, chamber shrouds were maintained at -120ºC. The peak steady-state elevation motor temperature achieved in this test was 22ºC. An additional test case was done using the entire-actuator heating (input heaters plus augmentation heaters). Pre-test predicts had shown that actuators would overheat if "entire-actuator" heating were done at 28V, so this test was run with the heaters energized to 19.8V. The entire-actuator heating case was run to steady state and then followed by a transient cooldown.

### E. Model Correlation and Flight Predicts

Test data obtained in the thermal characterization test of the RSM was used to correlate an analytical thermal model that had been originally developed to produce design predicts. The thermal model will be used to generate system level test predicts and eventually flight predicts for use in mission operations. Steady state test data, with heaters on, allowed the thermal designer to adjust the conduction resistances in the thermal model. After fixing the resistances in the model, the transient cooldown and warm-up cases were used to correlate the capacitances in the model. Figure 11 shows the test data (solid lines) and model predicts (dashed lines) after the model was correlated. Critical components of the actuators were correlated within ± 5ºC. The major adjustments that were made to correlate the model to test data included: 1) substitution of nitrogen in the test model for $CO_2$ in the flight design model, 2) adjustment of surface emissivities to account for Kapton tape coverage over bare metal surfaces and 3) most importantly, higher conductances inside the gearboxes to account for gear-to-gear and gas conduction heat flow paths that were previously neglected in the design model. Although the gearboxes were not instrumented internally with thermocouples (to do so would have rendered the gearboxes unusable), examination of the test data led to the conclusion that this internal conduction was an important part of the total heat flow through the actuator. Slower local heating rates on the outside of the actuators indicated that more of the internal mass of the actuator was participating in the warm-up. Although the external temperatures were lower than expected, the internal temperatures were higher than expected, leading to shorter warm-up times and lower overall energy consumption during the warm-ups. The correlated model, put back into a flight-like, worst-case cold, Martian Winter environment, predicts 14% less energy consumption and a 26-minute shorter warm-up time than had been predicted by the uncorrelated model. Energy savings in the correlated model is a benefit derived from lowered warm-up target temperatures and reduced warm-up times, both of which are direct results of the increased thermal coupling between the actuator housings and the interior gearbox components (planet gears and carriers).

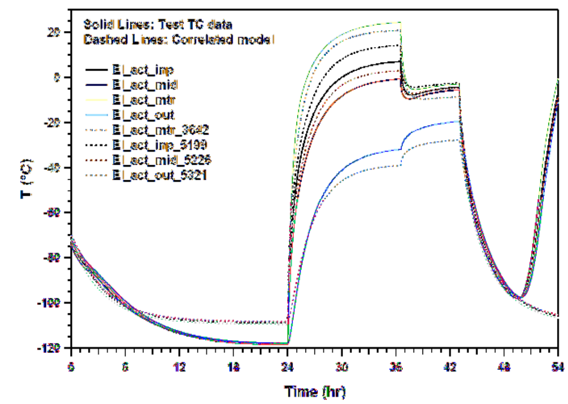


**Figure 11. RSM Elevation Actuator - Comparison of Test Data & Correlated Model Predicts**

## VI. Conclusion

Results from thermal testing of the RSM actuators has shown that internal heat paths (through gas conduction and gear-to-gear contact) are significant enough to change the thermal performance of the actuator warmup heaters. These conduction paths were accounted for in the correlated thermal model that will be used in flight. A lesson learned from this testing effort is that gearbox internal conduction paths should be estimated and modeled in future actuator heater design thermal models.

Actuator warm-up heater designs have been developed and implemented on all 31 of the MSL actuators. These heaters will be used at cold times of day and in the cold seasons to warm the actuators into their operating temperature range. Without these heaters, rover operators would have to wait for the ambient environment to warm actuators up naturally before they could be used. This would mean short operating windows in the spring and fall and no operating windows in the cold of the Martian winter. These heaters will open up larger operating windows for all of the mechanisms that are critical to the engineering and science operations of the rover. Actuator heaters will help to maximize the functionality of the rover (driving, communications, imaging, sample acquisition, processing and handling) and allow for more flexible and productive surface operations. Ultimately the actuator warm-up heaters will play an active role in maximizing the utility and science return of the MSL rover.

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