

# Preliminary Surface Thermal Design of the Mars 2020 Rover

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The Mars 2020 rover, scheduled for launch in July 2020, is currently being designed at NASA's Jet Propulsion Laboratory. The Mars 2020 rover design is derived from the Mars Science Laboratory (MSL) rover, Curiosity, which has been exploring the surface of Mars in Gale Crater for over 2.5 years. The Mars 2020 rover will carry a new science payload made up of 7 instruments. In addition, the Mars 2020 rover is responsible for collecting a sample cache of Mars regolith and rock core samples that could be returned to Earth in a future mission. Accommodation of the new payload and the Sampling Caching System (SCS) has driven significant thermal design changes from the original MSL rover design. This paper describes the similarities and differences between the heritage MSL rover thermal design and the new Mars 2020 thermal design. Modifications to the MSL rover thermal design that were made to accommodate the new payload and SCS are discussed. Conclusions about thermal design flexibility are derived from the Mars 2020 preliminary thermal design experience.

## Nomenclature

<i>AFT</i>	=	Allowable Flight Temperature
<i>ChemCam</i>	=	Chemistry and Camera instrument (MSL instrument)
<i>DAN</i>	=	Dynamic Albedo of Neutrons (MSL instrument)
<i>DTE</i>	=	Direct-to-Earth
<i>DEA</i>	=	Digital Electronics Assembly
<i>EDL</i>	=	Entry, Descent and Landing
<i>ELEX</i>	=	Electronics
<i>FSW</i>	=	Flight Software
<i>HazCam</i>	=	Hazard Avoidance Camera
<i>HGA</i>	=	High Gain Antenna
<i>HRS</i>	=	Heat Rejection System
<i>IAR</i>	=	Instrument Accommodation Review
<i>IMU</i>	=	Inertial Measurement Unit
<i>ISRU</i>	=	In-Situ Resource Utilization
<i>JPL</i>	=	Jet Propulsion Laboratory
<i>LCE</i>	=	Landing Context Electronics (part of the Terrain Relative Navigation System)
<i>LIBS</i>	=	Laser Induced Breakdown Spectroscopy
<i>Ls</i>	=	Solar Longitude
<i>M2020</i>	=	Mars 2020 Project
<i>MAHLI</i>	=	Mars Hand Lens Imager (MSL instrument)
<i>Mastcam-Z</i>	=	Mast Camera with Zoom capability
<i>MCR</i>	=	Mission Concept Review
<i>MEDA</i>	=	Mars Environmental Dynamics Analyzer
<i>MGCM</i>	=	Mars General Circulation Model

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<i>MMRTG</i>	=	Multi-Mission Radioisotope Thermoelectric Generator
<i>MOXIE</i>	=	Mars Oxygen ISRU Experiment
<i>MSL</i>	=	Mars Science Laboratory
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>NavCam</i>	=	Navigation Camera
<i>PDR</i>	=	Preliminary Design Review
<i>PIXL</i>	=	Planetary Instrument for X-ray Lithochemistry
<i>PRT</i>	=	Platinum Resistance Thermometer
<i>RA</i>	=	Robotic Arm
<i>RAMP</i>	=	Rover Avionics Mounting Panel
<i>RBAU</i>	=	Rover Battery Assembly Unit
<i>RCE</i>	=	Rover Compute Element
<i>REMS</i>	=	Rover Environmental Monitoring System (MSL instrument)
<i>RIMFAX</i>	=	Radar Imager for Mars' Subsurface Exploration
<i>RIMU</i>	=	Rover Inertial Measurement Unit
<i>RIPA</i>	=	Rover Integrated Pump Assembly
<i>RLGA</i>	=	Rover Low Gain Antenna
<i>RMCA</i>	=	Rover Motor Controller Assembly
<i>RPA</i>	=	Rover Power Assembly
<i>RPAM</i>	=	Rover Power and Analog Module
<i>RPFA</i>	=	Rover Pyro Firing Assembly
<i>RSM</i>	=	Remote Sensing Mast
<i>RUHF</i>	=	Rover Ultra-High Frequency
<i>SCB</i>	=	Sample Caching Box
<i>SCBU</i>	=	SuperCam Body Unit
<i>SCMU</i>	=	SuperCam Mast Unit
<i>SCS</i>	=	Sampling Caching System
<i>SDST</i>	=	Small Deep Space Transponder
<i>SHERLOC</i>	=	Scanning Habitable Environments with Raman & Luminescence for Organics and Chemicals
<i>SMA</i>	=	Shape Memory Alloy
<i>Sol</i>	=	Day on Mars (duration is 24.66 Earth hours)
<i>SRR</i>	=	System Requirements Review
<i>SSPA</i>	=	Solid State Power Amplifier
<i>SuperCam</i>	=	Advanced Version of the MSL ChemCam Instrument
<i>TIR</i>	=	Thermal Infrared
<i>TRN</i>	=	Terrain Relative Navigation
<i>UHF</i>	=	Ultra-High Frequency
<i>UV</i>	=	Ultra-Violet
<i>WATSON</i>	=	Wide Angle Topographic Sensor for Operations and eNginneering

## I. Introduction

NASA is scheduled to launch the Mars 2020 (M2020) rover to Mars in July of 2020. After a 7-month cruise, the M2020 rover will touch down on the surface of Mars in February of 2021. The M2020 rover will go to a yet-to-be-selected Mars landing site (somewhere in the  $\pm 30^\circ$  latitude range) where it will investigate the geology of the site, assess the habitability of the site and look for signs of ancient Martian life. In order to carry out these investigations, the rover is equipped with 7 science instruments. This rover mission has an additional science objective that is to extract and cache a collection of soil and rock samples from the surface of Mars for a potential return to Earth by a future sample return mission. The M2020 Rover design is heavily derived from the MSL Rover design. Many of the changes that were made to the MSL Rover design for M2020 were driven by accommodation of the 7 science instruments and the Sampling Caching System (SCS). Fortunately, the thermal architecture that was chosen for MSL (and re-used for M2020) is flexible enough to absorb these changes and retain the original design integrity and performance.

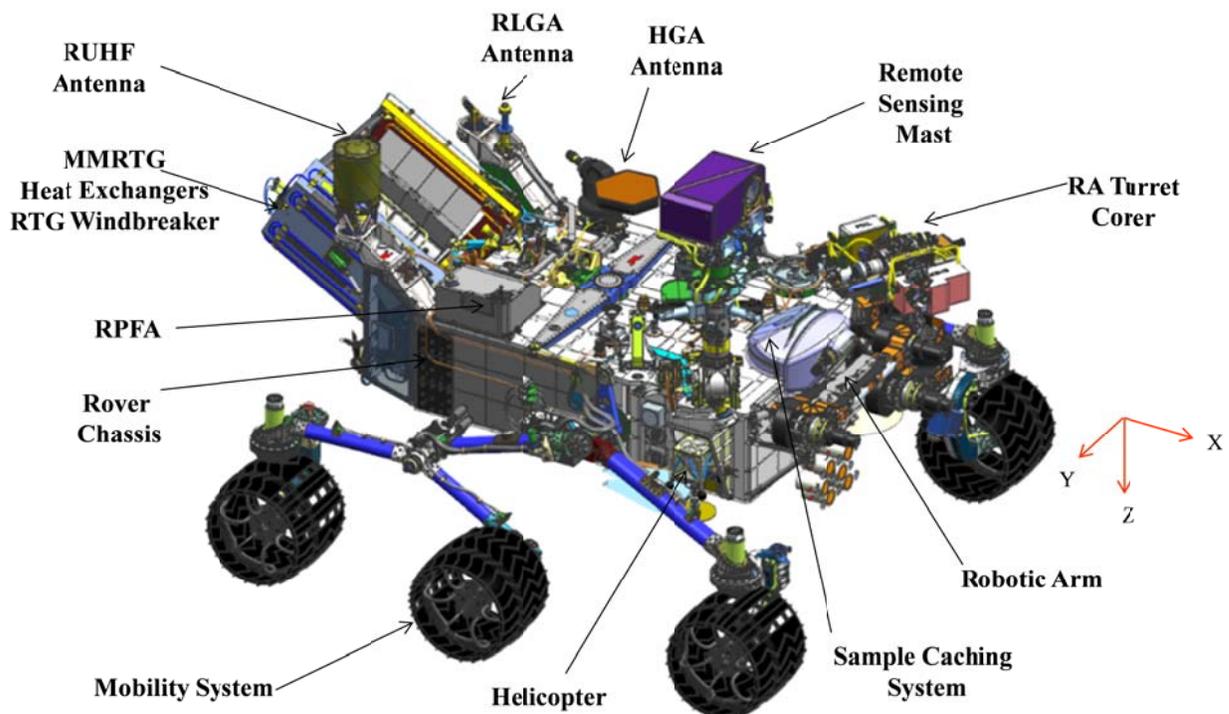
A considerable number of papers have been written to document the MSL Rover thermal design and its performance on Mars during the MSL mission.<sup>1-16</sup> The M2020 project has adopted a “build-to-print” philosophy, from the MSL design, wherever possible to keep costs and complexities down.

The M2020 project passed its Mission Concept Review (MCR) and System Requirements Review (SRR) in October, 2014 and completed the Instrument Accommodation Reviews (IARs) in March, 2015. The Thermal Preliminary Design Review (PDR) is scheduled for September, 2015 and the Project PDR is scheduled for December, 2015. This paper discusses the pre-PDR, M2020 rover thermal design. Since the M2020 Rover design is highly leveraged from the MSL design, much is already known about this design, even in its pre-PDR state.

The M2020 rover design will have to live with some of the same resource constraints under which the MSL Rover was developed. For instance, the M2020 spacecraft will use the same Cruise Stage, Descent Stage and Aeroshell as MSL, so the rover is tightly volume-constrained and is only allowed to grow incrementally in very local areas. The M2020 Rover mass is constrained by the capability of the existing EDL Sky-Crane landing system and the surface mobility system. M2020 will use the same MMRTG power source as MSL (electrical power output is approximately 110W) and therefore must operate under the same power and energy constraints. The avionics boxes, which house all of the Rover power switches and telemetry boards are the same as MSL, so the power switch and telemetry channel counts are the same.

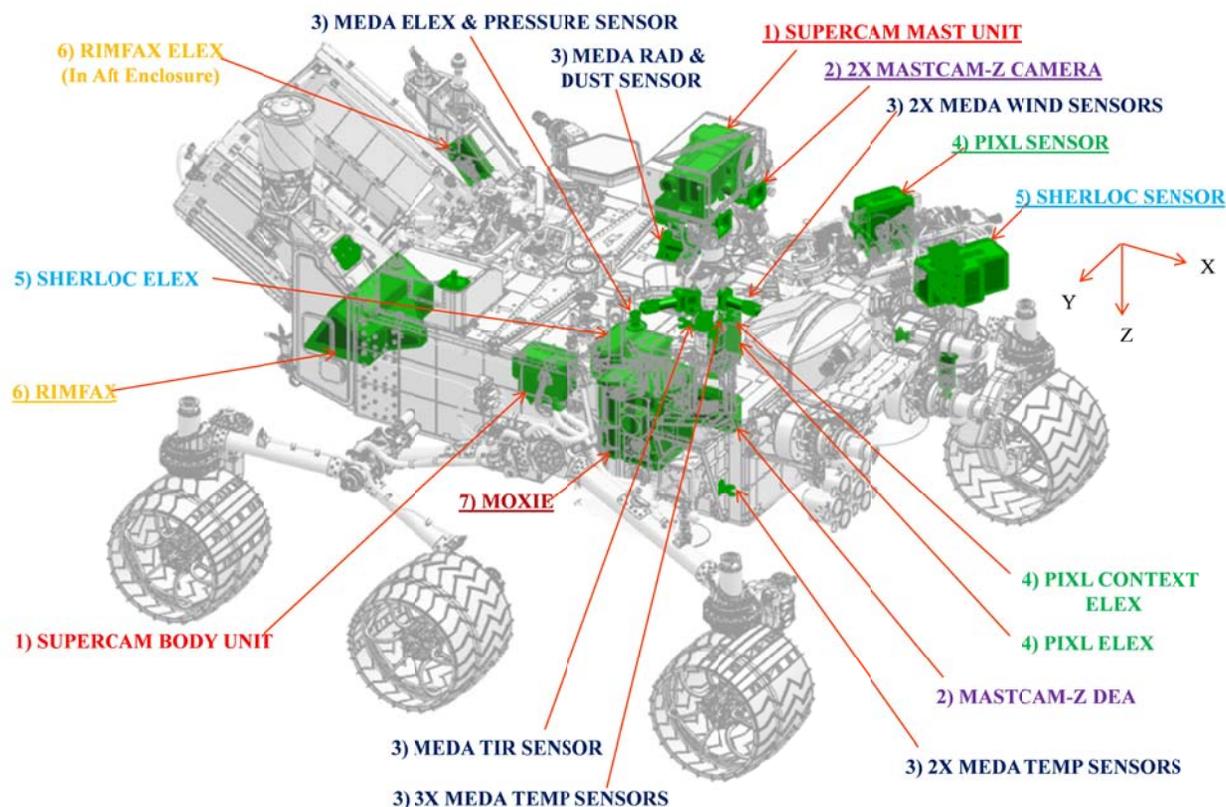
### A. Description of the M2020 External Rover Hardware

When the M2020 rover is fully deployed on Mars, it will have a wheelbase of 2.8 m long and 2.3 m wide, and a ground clearance of more than 60 cm. Engineering hardware, located on the outside of the Rover, is shown in Figure 1.



**Figure 1 - M2020 Rover and External Hardware**

There are many heritage hardware elements from MSL that will be re-used on M2020. Some of these are exact copies of MSL designs; others are MSL build-to-print designs with slight modifications. The M2020 mobility system, which has 6 drive motors and 4 steer motors, will be essentially the same as MSL. The MSL wheels, which sustained significant damage during traverses over sharp rocks inside Gale Crater, will be strengthened (at the cost of increased mass) for M2020. The MSL-heritage Remote Sensing Mast (RSM), which supports the Mastcam-Z and SuperCam science instruments, as well as the engineering Navigation Cameras, stands 2.2 m above the ground. The MSL-heritage Rover Pyro Firing Assembly (RPFA) is responsible for firing all rover launch locks and pyro release devices during Entry Descent and Landing (EDL) and after landing. There are 3 external telecommunications antennas, two operating in the X-band (the RLGA and the HGA) and one in the UHF-band (the RUHF). Direct-to Earth (DTE) communications are done in the X-band and rover-to-Mars-orbiter communications are done in the UHF-band. The M2020 rover is powered by a nuclear power source, the MMRTG, which dissipates ~2000W of thermal waste heat.



**Figure 2 - Locations of Science Instruments on M2020 Rover**

There are many other systems on the M2020 rover that will be completely new designs or extensive modifications of hardware that was previously developed for MSL. The M2020 SCS, which resides in the front of the rover, is responsible for collecting and caching Mars rock and soil samples in sealed sample tubes and placing them onto the Mars surface. These sample tubes may be picked up by a future rover mission and returned to Earth. The largest element of the SCS is a 5-degree-of-freedom Robotic Arm (RA). This M2020 RA may look similar to the MSL version (it has to fit in the same volume), but it may have new actuators in all 5 joints. New actuators may be necessary to deliver the fine-pointing accuracy and stability that is needed to operate the new turret-mounted science instruments (PIXL and SHERLOC). The Coring Drill will be located on the turret at the working end of the RA. The Coring Drill, having 6 actuators, will drill into rocks and soil to collect core samples. These core samples will be transferred into the Sample Caching Box (located under the rover top deck) which houses the Bit Carousel (2 actuators) and a Sample Handling Arm (4 additional actuators). All 12 of the SCS actuators (motor and gearbox pairs) for SCS will require warm-up heaters to allow operations in cold environments. All of the rover engineering cameras (4 NavCams and 8 HazCams) are being completely re-designed. NASA has asked the project to accommodate or keep open the option to accommodate the following additional items on the Rover: 1) WATSON, a context imager on the Robotic Arm turret, 2) a Terrain Relative Navigation (TRN) system with one camera on the outside of the rover and an electronics box inside the chassis, mounted to the RAMP, 3) an EDL Uplink Camera, 4) a Microphone and 5) the Heli-Scout, Mars helicopter. The Mars helicopter would be added to the outside of the vehicle between the right front chassis wall and the forward mobility rocker tube. The helicopter would be stowed for launch and deployed after landing. The helicopter would carry an onboard camera to be used for high resolution imaging of the potential drive path of the rover.

## B. Description of M2020 Science Instruments

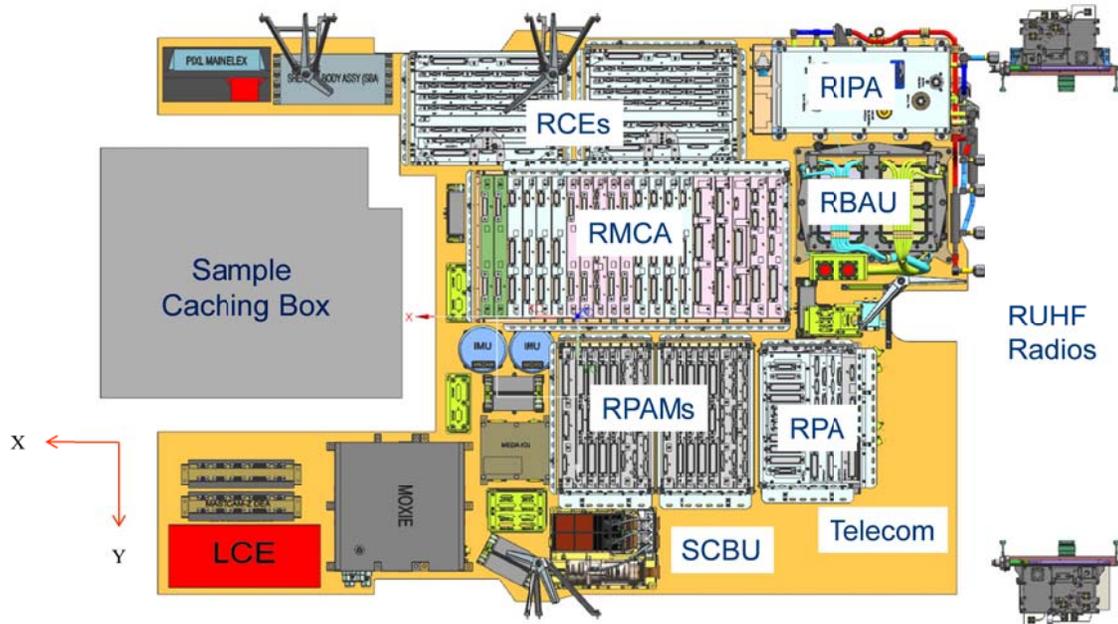
All 7 of the M2020 science instruments (see Figure 2) are new builds. Some of these instruments are enhanced (next-generation) versions of instruments that flew on the MSL Rover, and others are completely new designs that have never been flown before.

There are three instruments on the M2020 rover that are enhanced versions of instruments that flew on MSL: 1) SuperCam, a modified version of the MSL ChemCam, combines co-aligned Raman-fluorescence, visible/infrared reflectance, and laser-induced breakdown spectroscopy (LIBS) to provide imaging and analysis of rock chemical and mineralogical composition; 2) Mastcam-Z, a modified version of the MSL Mastcam camera, is a high resolution camera for panoramic and stereoscopic imaging with a new zoom feature; and 3) MEDA, an enhanced version of the MSL REMS instrument, is a weather station which includes sensors to measure wind speed and direction, atmospheric pressure, atmosphere and ground temperatures, relative humidity, and radiation and dust levels. The SuperCam Mast Unit, Mastcam-Z stereo pair cameras and MEDA wind sensors are all located on the MSL-heritage RSM.

The remaining four science instruments are completely new designs. Two of these science instrument sensors are mounted on the RA turret on opposite sides of the coring Drill: PIXL and SHERLOC. PIXL is a high-resolution X-ray fluorescence spectrometer used to determine fine-scale, elemental composition of rocks and soil. SHERLOC is a UV Raman spectrometer that uses a laser to determine fine-scale mineralogy and detect organic compounds. WATSON, attached to the SHERLOC body, is a potential reflight of the MAHLI microscopic imager from MSL. RIMFAX is a ground-penetrating radar that will provide centimeter scale images of the subsurface geologic structure at depths from 10 – 500 m. The RIMFAX antenna is mounted underneath the MMRTG. MOXIE is an In-Situ Resource Utilization (ISRU) technology demonstration instrument. MOXIE is designed to capture Mars ambient atmospheric CO<sub>2</sub> and convert it into oxygen. This instrument is an important step toward a human mission to Mars in which O<sub>2</sub> would be needed for astronaut life support and Mars Ascent Vehicle propulsion.

## C. Description of M2020 Internal Rover Hardware

All of the temperature-sensitive science instruments and avionics are mounted inside the rover chassis as shown in Figure 3. This figure shows a view of the internal box configuration that one would see, looking up from the



**Figure 3 - M2020 Rover Science Electronics and Avionics mounted on RAMP (Note: Sample Cache Box is attached to bottom of Rover Top Deck, not to RAMP)**

ground, after removing the rover belly pan. All of the boxes shown in Figure 3 (except the Sample Caching Box) are hard-mounted to the Rover Avionics Mounting Panel (RAMP) that serves as the main structural support inside the chassis. Note that the Sample Caching Box (SCB) is attached to the top deck of the rover, but is not enclosed inside the “warm” enclosure of the rover chassis. Like all of the other externally mounted hardware (e.g., actuators & cameras), the SCB will have to be qualified to go down to -135C in a non-operating condition. Any heat

dissipated in the SCB will have to be rejected to the Mars environment. All actuators and cameras in the SCB will need warm-up heaters. For planetary protection and contamination control reasons, the SCB is separated from the rest of the internal rover hardware. The RAMP is suspended below the rover top deck by a number of low thermal conductance flexures. Science instrument boxes bolted to the RAMP include: the MOXIE instrument and electronics boxes for SuperCam, PIXL, SHERLOC, MEDA and Mastcam-Z. The RIMFAX and Helicopter electronics boxes are housed (with the UHF radios) on separate HRS plates inside the rear rover tower structures (see Figures 7 & 8).

Engineering boxes (all identical to those flown on MSL) that are mounted to the RAMP include: the telecommunications boxes, (the X-band power amplifier (SSPA) and transponder (SDST)), the rover avionics boxes (the redundant flight computers (RCEs), the power and switching boxes (the RPA and RPAMs), the Rover Motor Controller Assembly (RMCA) and the Rover Inertial Measurement Units (RIMUs)). Two Li-ion batteries, also mounted to the RAMP, make up the Rover Battery Assembly Unit (RBAU), used to store electrical energy produced by the MMRTG. The final major hardware element mounted to the RAMP is the Rover Integrated Pump Assembly (RIPA). The RIPA, at the heart of the Rover Heat Rejection System (HRS), pumps liquid Freon through tubing imbedded in the RAMP to remove or replace heat as needed. The M2020 Rover HRS (which has the same architecture as the MSL HRS) is described in more detail in Section III.

## II. M2020 Thermal Design Drivers - Environment and Power Profile

There are two main factors that influence the temperatures predicted on the inside and outside of the M2020 rover: the external Mars environment and the power dissipation profile of the hardware inside the rover.

The Mars surface thermal environment is the ultimate thermal sink for the rover. 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 Level 1 requirement for M2020 landing site latitude range is from 30° South to 30° North. On the current list of the top nine M2020 landing sites, the most extreme southerly landing site is Holden Crater (at 27°S latitude) and the most extreme northerly landing site is Mawrth Vallis (at 24°N latitude). 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.

Environment predictions for the M2020 mission were taken directly out of the MSL Environmental Requirements Document from runs of the Mars General Circulation Model (MGCM).<sup>17</sup> Figure 4 shows the predicted atmosphere, ground and sky temperatures on the worst-case hot day for the M2020 mission (Landing site latitude = 27.5°S, Summer Solstice,  $L_s=270^\circ$ ). Figure 5 shows the predicted atmosphere, ground and sky temperatures on the worst-case cold day for the M2020 mission (Landing site latitude = 30°S, Winter Solstice,  $L_s=90^\circ$ ). The winter atmosphere temperature curve in Figure 5 shows that the atmosphere will be below -55°C for the entire Sol. Warm-up heaters are needed in order to bring the actuators up to operating temperature in the cold Mars winter environment.

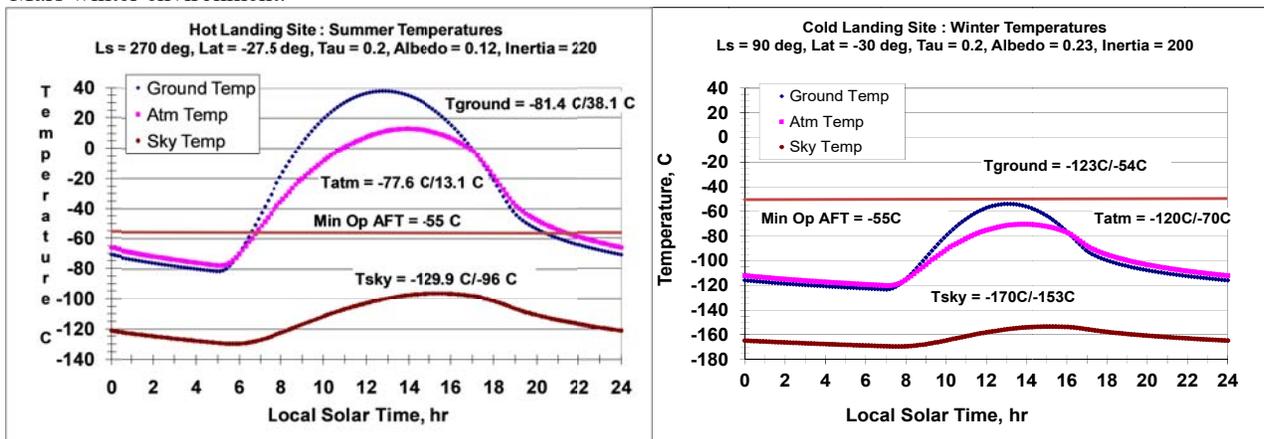


Figure 4. M2020 Mission Worst-Case Hot Diurnal Environment Profile.

Figure 5. M2020 Mission Worst-Case Cold Diurnal Environment Profile.

The M2020 rover will be designed to survive a surface thermal environment in which the wind speed could vary anywhere in the range of 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 hot, predicted rover internal and external daytime temperatures, 0 m/sec wind speed (free convection on exterior surfaces) will be assumed. To generate worst-case cold rover internal temperatures, 15 m/sec wind speed (forced convection on external surfaces) will be assumed. To generate the worst-case cold nighttime temperatures for external rover hardware, no wind at night will be modeled, since exterior surfaces view the cold night sky sink which is colder than the atmosphere sink.

Environmental solar loads will also be modeled. The peak incident solar load on the Mars surface in the worst-case hot environment (Summer Solstice at 27.5°S) is approximately 669 W/m<sup>2</sup> at solar noon. The peak incident solar load on the Mars surface in the worst-case cold environment (Winter Solstice at 30°S) is approximately 258 W/m<sup>2</sup>.

Power profiles for the M2020 Rover have not been developed yet. For some build-to-print hardware (e.g., the avionics and telecom boxes), the power dissipations are well known. For other new developments (e.g., science instruments) the power dissipations are still uncertain. By thermal PDR the worst-case hot and cold power dissipation profiles should be developed enough to use for preliminary design purposes. Since the power system for M2020 is very much like the MSL power system (same MMRTG power source and similar battery), it's highly unlikely that the maximum and minimum bounding power profiles for M2020 would be too much different than what was assumed for MSL. Certainly the available energy per Sol is essentially identical.

### III. Description of M2020 Thermal Design

In general, the rover internal hardware mounted on the RAMP has allowable flight temperature (AFT) limits of -40°C to +50°C. RAMP-mounted boxes will be qualified to operate over the wider temperature range of -55°C to +70°C.

In order to keep the RAMP-mounted avionics and science boxes within their AFT limits during flight, heat must be provided to them, when they are powered down and the environment is cold, and heat must be removed from them, when they are powered up and the environment is hot. The Rover HRS performs the functions of providing heat in the cold cases and rejecting heat in the hot cases. Papers describing the design and performance of the MSL Rover HRS in detail have been previously published.<sup>1-6, 8-10, 13, 15, 16</sup> Figure 6 is a schematic showing the Rover HRS system and its major components. In the cold case, the HRS pumps liquid Freon through tubes in hot plate heat exchangers, located on either side of the MMRTG, to pick up radiated waste heat from the MMRTG and bring it into the RAMP. In the hot case, the Freon flow is directed away from the HRS hot plates (using passively-actuated thermal control valves) and into heat rejection surfaces on the HRS cold plates and the rover top deck. The actuators inside the thermal control valves use the thermal expansion of oil to open and close the valves.<sup>4</sup> Figure 7 shows some of the HRS tubing on the rover top deck and cold plates (dark blue tubing), on the hot plates (yellow tubing on red plates) and the RAMP structure (light blue tubing running on the base of the yellow plate). Note that Figure 7 shows the old MSL RAMP, not the new M2020 RAMP which is still being designed.

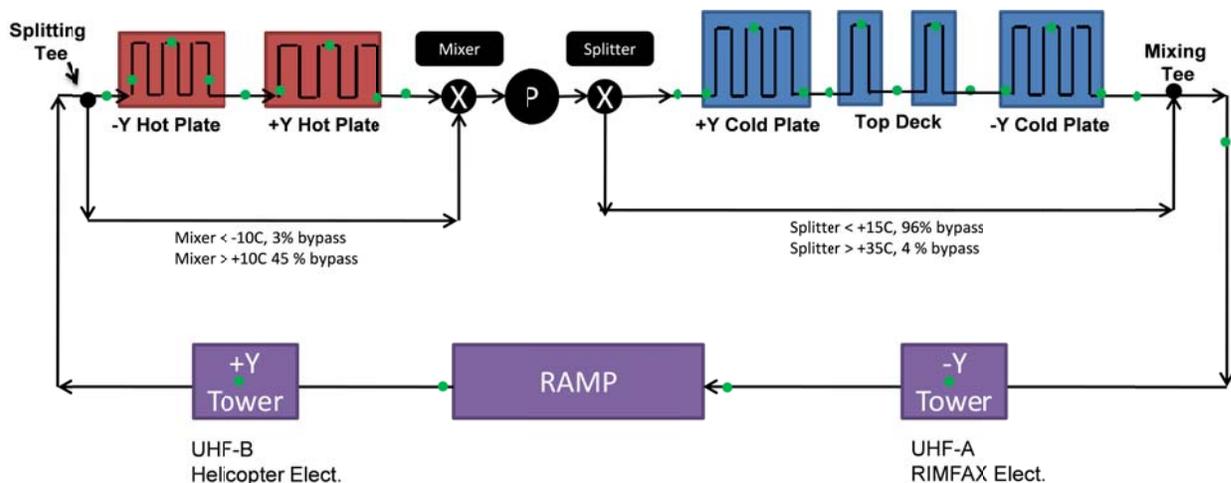
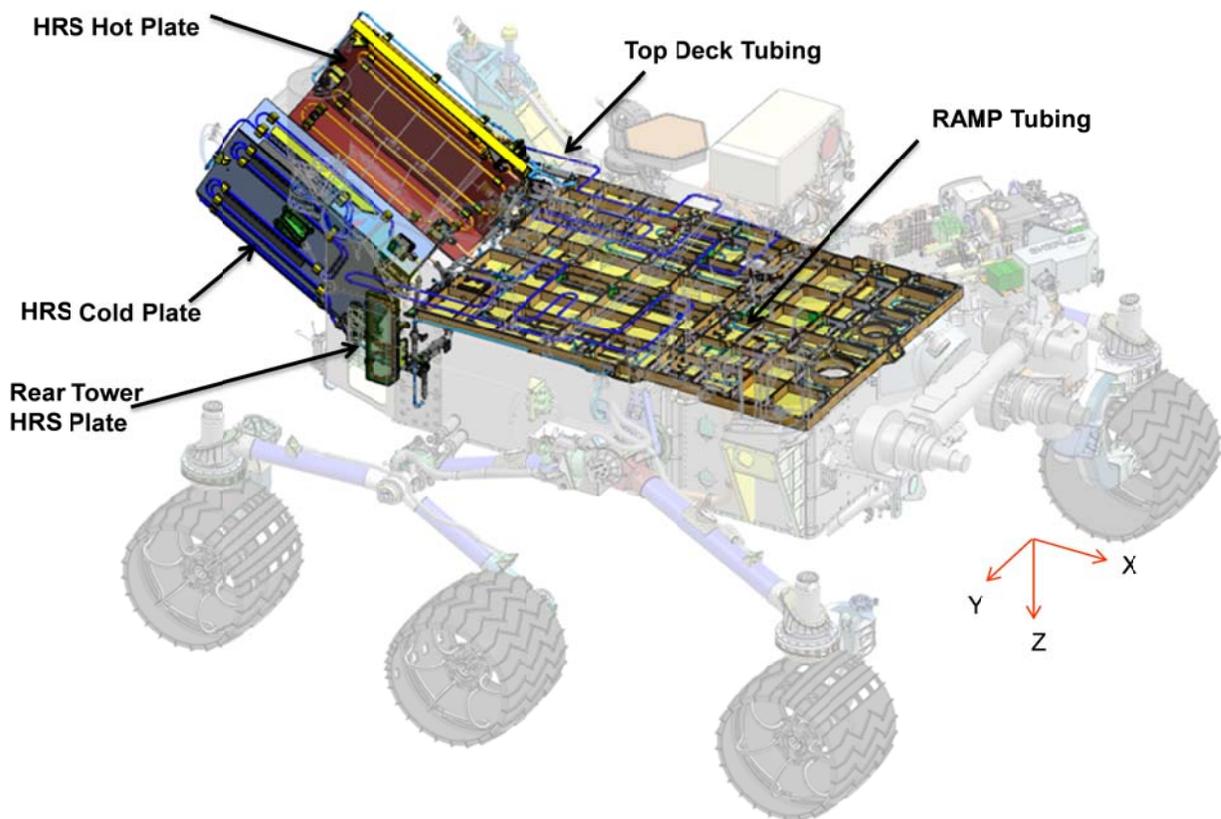


Figure 6 - M2020 Rover HRS Schematic

The rover battery, with tighter AFT limits (-20°C to +30°C) than the rest of the RAMP mounted hardware, has additional survival and warm-up heaters that are controlled by mechanical thermostats. CO<sub>2</sub> gas-gap insulation is

used inside the rover chassis to provide thermal resistance between the internal hardware and the external rover chassis walls.

PRTs will be used for temperature monitoring and for control of FSW-controlled warm-up heaters on the actuators and cameras. Survival heaters must be able to operate when the rover flight computer is asleep, so they will be controlled by mechanical thermostats to keep hardware above minimum non-operating AFT limits. The M2020 design has mechanical thermostats controlling survival heaters on the battery, Rover Pyro Firing Assembly (RPFA), SuperCam Mast Unit (SCMU) and the PIXL and SHERLOC sensor heads. The provisions for survival heating of turret-mounted science sensors are a departure from the MSL design, where no survival heating was needed on the turret. This puts an added load on the electrical power system and subtracts from the available energy for science, especially in the winter. Current estimates of wintertime survival heater energy consumption are 85 W\*hrs for PIXL and 36 W\*hrs for SHERLOC. An additional 4 thermostats will control the battery warm-up heaters and 4 more thermostats are used for Rover HRS pump fault protection. If the primary HRS pump fails, and the RAMP exceeds its maximum or minimum Flight Acceptance temperature limits (+55°C or -45°C) the HRS fault protection thermostats will close and turn on the backup pump.



**Figure 7 - HRS Tubing on MSL Rover - NOTE: Top deck structure removed to show RAMP below (yellow plate)**

A majority of the hardware mounted on the outside of the rover has been designed and tested to survive the cold nighttime temperatures of Mars without any survival heating. Most of the external hardware has AFT limits of -128°C to +50°C.

There are a number of hardware mechanisms and cameras on the outside of the vehicle that must be warmed up prior to use. While they can survive non-operating cold temperatures (as low as -128°C), they have minimum operating temperatures between -55°C and -40°C. The three science cameras (2 Mastcam-Z, and 1 WATSON) and 14 engineering cameras (4 front HazCams, 4 rear HazCams, 4 NavCams, 1 TRN camera and 1 EDL uplook camera) have Flight System controlled warm-up heaters to bring them up to operating temperature. The rover also employs 31 electric-motor driven actuators to perform a variety of engineering and science functions including: mobility,

camera pointing, telecommunications antenna steering, soil and rock sample coring and sample caching. When the Martian environment is cold, Flight System warm-up heaters are required to bring the actuators up to temperature (above  $-55^{\circ}\text{C}$ ) prior to use. A previously published paper describes the MSL actuator thermal design, testing and performance in detail.<sup>11</sup> Actuator and camera warm-up heaters are controlled by Flight Software (FSW) running on the Rover Compute Element (RCE) boxes.

#### IV. Thermal Design Modifications of MSL Rover for M2020

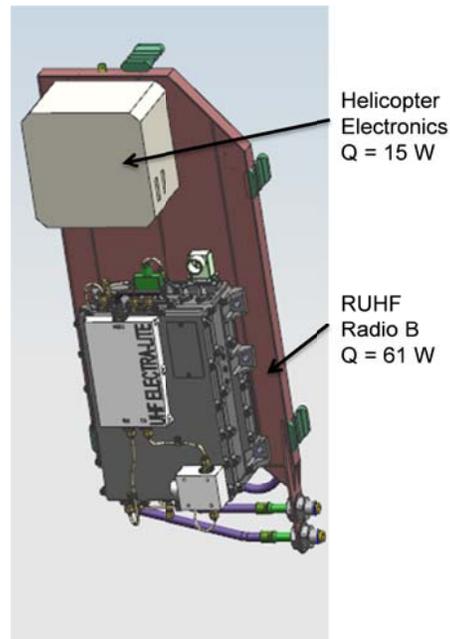
The M2020 Rover thermal design is derived from the MSL design. This section of the paper discusses the significant thermal design modifications of the MSL design that have been made for M2020.

The RAMP, which supports all of the avionics and science electronics hardware inside the rover, is still being designed for M2020. The SCS takes up a large volume on the front of the rover, creating a cutout in the RAMP (see Figure 3). The electronics boxes that need a temperature-controlled interface must be squeezed into the remaining chassis volume and RAMP surface area. Boxes have been moved around iteratively to different locations on the RAMP in order to find an optimal configuration for the existing volume and surface area. One of the key features of the HRS design is that boxes can be reconfigured on the RAMP with few thermal constraints being taken into account. Routing of the tubing underneath the boxes (to pick up heat under bolted interfaces) is one of the last RAMP design features to be worked. There are some constraints related to minimum tube bending radius, locations of bosses for threaded inserts and structural ribbing of the RAMP, but for the most part, tubing can be routed to virtually any location on the RAMP. This frees up configuration engineers to consider a number of different RAMP box layouts. One of the new science instruments, MOXIE has a very high thermal dissipation ( $\sim 120\text{W}$ ) and a correspondingly high heat flux on the RAMP ( $\sim 2900\text{ W/m}^2$ ). Additional HRS tube runs under MOXIE may be needed to carry away its heat.

Lack of RAMP surface area inside the main chassis drove the need to expand the rear tower HRS plates that were used for the DAN instrument on MSL. The enlarged M2020 HRS plates in the rear towers (see Figures 7 and 8) house the primary and redundant Electra-Lite UHF radios, the helicopter electronics and the RIMFAX electronics. These rear tower plates provide the same temperature-controlled mounting interface as the RAMP. Transfer of the backup UHF radio, from a bracket supported off the RAMP in the MSL design, out to the rear tower HRS plate in the M2020 design, actually improved its thermal performance, by moving its interface closer to the HRS fluid. The desire for more RAMP surface area also drove a design modification to put the PIXL Main Electronics Box and PIXL Context Camera Electronics on a “T” bracket, effectively turning these boxes on their sides. The downside of this move was that the AFT limit range of these boxes had to be expanded by  $\pm 5^{\circ}\text{C}$  (to  $-45^{\circ}\text{C}$  to  $+55^{\circ}\text{C}$ ) to account for the added thermal resistance of the bracket. Changes in the RAMP have had both positive and negative effects on its thermal performance. A decrease in RAMP surface area, reduced the area for heat loss, but a reduction in RAMP mass resulted in a shorter overall system thermal time constant. Preliminary analysis has shown that these changes will not have a large effect on the thermal performance of HRS-controlled boxes.

No changes to the HRS thermal control valve (splitter and mixer) setpoints are being considered, since the RIPA (where the valves are housed) is build-to-print. The existing MSL design has very little high temperature margin (hot case predictions are close to the maximum AFT limit of  $50^{\circ}\text{C}$ ), but still some margin to the min AFT limit of  $-40^{\circ}\text{C}$ . Maintaining cold temperature margin as a hedge against potential increases in heat leaks (due to an increase in cable copper cross-sectional area, a reduction in  $\text{CO}_2$  gas gap insulation thickness, etc.) is a prudent design strategy. Hot case margin can be recouped by trimming power profiles and avoiding operations during hot times of day. Cold case margin is much more difficult to build back into the design.

Overall, the MSL thermal design has performed quite well during Curiosity surface operations.<sup>13,15,16</sup> One residual concern, left over from the original MSL thermal design, was the potential for freezing of the HRS working fluid



**Figure 8 - Helicopter Electronics and UHF Radio on Right Rear (+Y) Tower HRS Plate**

(Freon) in the top deck HRS tubes, in the worst-case cold environment. This concern went away for MSL, when the Curiosity landing site was chosen. The Curiosity landing site (Gale Crater) is at 4.5° South latitude, a nearly equatorial landing site, with much more benign winters than the M2020 worst-case cold landing site at 30° South latitude. Options for warming up the M2020 top deck fluid include: 1) using an in-line electrical survival heater, 2) increasing the heat leak from the RAMP to the top deck and 3) re-routing of HRS fluid flow path so that cold fluid goes to the top deck first, before it is cooled by the cold plates.

Once the HRS tubing layout is fully realized in a solids model, hydraulic pressure drop calculations need to be done. The RIPA has a pump curve which describes the flow rate as a function of pressure drop. The existing pressure drop is in a flat area of the pump curve, so any reasonable increase or decrease in HRS tubing length and the corresponding change in pressure drop is not expected to result in a significantly different thermal performance. Performance of the splitter and mixer valves is also dependent on the back pressure of the lines on either side of the valve output (either in the main flow direction or in the bypass direction). These line pressures and valve performance parameters also need to be checked in the new M2020 HRS design.

The thermal design of the SCS is completely new. Consequently, it is one of the least-developed thermal designs in the M2020 rover. There is a science requirement to keep filled sample tubes at temperatures below a (yet to be determined) maximum temperature, to preserve any water in the sample and prevent any chemical reaction that might alter its natural state. This requirement drove the SCS out of the warm rover chassis and outside underneath the front portion of the top deck. There is no minimum temperature requirement for the coring sample. SCS has 17 new actuators that will need to be fitted with warmup heaters. The Coring drill has 6 actuators, the sample handling arm has 4 actuators, the bit carousel has 2 actuators and the RA has 5 actuators. The sample tube sealing technique has not yet been chosen. Options include a heated, SMA-actuated seal and a mechanically pressed seal. There are many thermal challenges to be resolved if the SMA thermally-driven seal option is selected. M2020 has decided to employ a sample caching technique that saves volume inside the rover by allowing the rover to place sample tubes individually or in “piles” onto the Martian surface shortly after they have been acquired. This technique is known as “adaptive-caching.” One of the thermal issues to be resolved is how to keep the sample tubes from exceeding their maximum allowable temperature after they have been placed onto the Martian surface, where the external surfaces of the sample tubes are exposed to dust and a solar load. This is another thermal design challenge posed by the M2020 sample cache system.

As shown in Figure 2, the RIMFAX antenna has been accommodated directly underneath the MMRTG. The antenna will see an MMRTG that runs as warm as 200°C. The instrument is robust to high temperatures; it has a maximum AFT limit of 95°C. The RIMFAX antenna has a very small effect on the maximum temperature of the MMRTG (increasing it by only 1°C in the hot case). The majority of the MMRTG heat loss occurs from the top of the MMRTG to the cold sky. The MMRTG view to the ground, now partially blocked by the RIMFAX antenna, does not drive MMRTG temperatures.

## **V. Possible Changes to the MSL Rover Thermal Design for Increased Operability**

Experiences with the complex operations of the Curiosity (MSL) Rover on Mars, and concerns with the amount of time and effort that it takes to operate the vehicle, have spawned an effort on the M2020 team to find ways to increase operability of the M2020 rover. Level 1 requirements specify required drive distances and numbers of samples that need to be collected over the course of the prime mission (1 to 1.5 Mars Years). In order to meet these requirements, the M2020 Rover must be operated more efficiently than the MSL Rover. Efficiency improvements, leveraging off the existing system design, are being considered across the entire Project (Flight System and Mission Operations). Since the vehicle operates at the system level with a variety of interacting constraints, each of the thermal design solutions presented here, must be evaluated in mission-level scenarios to understand the actual impact to increased performance they provide and therefore which ones ultimately will be implemented for M2020.

There is a desire on M2020 to drive more often and drive earlier in the day. The Operations team would like to warm up the mobility actuators faster, consuming less daylight time waiting for actuators to warm up and opening up more daylight time for driving. The thermal team has proposed adding 20W output heaters to the mobility actuators to speed up the warmups. The mobility actuators will warm up faster with more heat, but at the cost of increased energy expended. There are also concerns about consuming additional power switches and PRT telemetry channels that are needed to make this design change a reality.

Actuator warm-up sequences are written based on predictions of heating durations and target temperatures derived from test-correlated, analytical thermal models of the actuators. Because the MSL (and M2020) actuators are large, rotating, distributed-mass thermal systems, it is not possible to directly measure the temperature of the actuator internals (where the viscous lubricant lies inside of bearings and gears). Temperature sensors are mounted

on the external housings of the actuators. As determined by the analytical thermal models, actuator external housings must be heated to temperatures well beyond actuator minimum operating AFT limits (-55C) in order to drive heat into the actuator internal components.<sup>11</sup>

The thermal team has proposed a thermal test of an old MSL mobility life-test actuator that would be internally instrumented with thermocouples. Uncertainty in how heat moves through the gearboxes of the large actuators (in mobility, RA and RSM) has resulted in conservative assumptions for gas conduction and gear-tooth-to-gear-tooth conduction inside actuator analytical thermal models, which are used to predict heating parameters. This test would reveal how much more conduction exists inside the actuators and promises to reduce the predicted amount of time and energy it takes to warm up the actuators, with absolutely no design change whatsoever. This test is currently scheduled to take place in 2017.

Another way to reduce the energy needed to operate the vehicle is to lower the minimum operating AFT limit of the actuators. Currently, the minimum operating temperature limit for the actuators is -55°C (the minimum operating qualification limit is -70°C). By requalifying the actuators to -90°C, the project could take advantage of a -75°C minimum operating AFT limit. This lower operating temperature limit would open up larger windows of operation during which no heating was needed. In addition, the lower operating temperature limit would reduce the amount of heating required at times of day when the actuator is not naturally warmed up to operating temperature. No actuator design changes are currently planned or required to take advantage of the lower temperature capability that may already exist in the actuators. There is however, a risk that operating actuators at colder temperatures could increase actuator wear and shorten lifetime. Operating at colder temperatures will also certainly reduce torque margins due to the higher viscosity of the lubricant.

Finally, another proposal for reducing the time and energy required to warm up actuators has to do with the addition of a temperature sensor inside the output drive shaft of the actuator. This is somewhat problematic in the mobility drive actuators, which rotate through angles greater than 360 degrees, but could be accomplished with a slip ring to carry the temperature sensor signal across the rotating interface. In the other large actuators (mobility steer, RA and RSM) the range of motion on the output drive is less than 360 degrees. A temperature sensor could be placed in the output drive shaft without slip rings. If this sensor were placed where it reads the coldest temperature in the gearbox, this opens up the possibility of “event-driven” (as opposed to “time-driven”) operations. Event-driven sequencing is already done on the MSL rover in areas like mobility. The current baseline for M2020 is to use time-driven heating sequences, in the same manner as MSL. In time-driven operations, the rover planning team uploads sequences with conservatively long warmup heating times (derived from ground-based analytical thermal models) for actuators and cameras. This is not the most efficient way to heat actuators, but it is a safe and conservative way to do so. If the M2020 rover could look at a temperature sensor in real-time and know when an actuator was up to operating temperature, it could start an operation immediately thereafter. This would be a much more efficient way to operate the M2020 vehicle.

## **VI. Conclusion**

There is a significant amount of thermal design work left to do on the M2020 Rover in preparation for the Thermal PDR in September of 2105. M2020 is in a unique position, since there is a lot of inherited hardware, inherited design and flight experience from MSL that can and will be incorporated into the M2020 design. The MSL thermal architecture both outside (actuators and cameras) and inside (avionics and electronics boxes) the rover chassis is flexible enough to absorb the changes imposed by the accommodation a new science suite and the Sample Caching System. The warmup and survival heater architecture developed for the MSL rover is directly applicable and transferrable to the M2020 design. The HRS pumped-fluid loop, developed for the MSL mission, is flexible enough to accommodate (with a reasonable number of modifications) the M2020 payload and avionics. The flexibility of the HRS design allows the RAMP configuration to be iterated on until an optimal volume and interface area solution is achieved, with minimal thermal design constraints.

## **Acknowledgments**

The rover development described in this paper is being carried out 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 people who have supported the M2020 Rover thermal design work at JPL. Personnel at JPL who helped greatly during the design of the thermal subsystem are Jackie Lyra (M2020 Thermal/Mechanical Systems Product Delivery Manager) and Gordy Cucullu (M2020 Thermal Hardware Cognizant Engineer). We would also like to acknowledge our M2020 Project Management and Project Scientist: John McNamee (Project

Manager), Matt Wallace (Deputy Project Manager) and Ken Farley (Project Scientist). Copyright 2015 California Institute of Technology. Government sponsorship acknowledged.

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