The thermal control system of NASA’s Curiosity rover: a case study

PAPER • **OPEN ACCESS**

The thermal control system of NASA's Curiosity rover: a case study

To cite this article: Gaetano Quattrocchi *et al* 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1226** 012113

IOP Conf. Series: Materials Science and Engineering 1226 (2022) 012113 doi:10.1088/1757-899X/1226/1/012113

The thermal control system of NASA's Curiosity rover: a case study

Gaetano Quattrocchi[1], **Andrea Pittari**[1], **Matteo D.L. dalla Vedova**[1] **and Paolo Maggiore**[1]

[1] Department of Mechanics and Aerospace, Politecnico di Torino, Turin 10129, Italy

E-mail: gaetano.quattrocchi@polito.it

Abstract. In any space mission, maintaining subsystems temperature within the allowed limits is a difficult challenge. Parts exposed to the Sun need to be cooled because temperatures rise extremely high, while parts not directly exposed to the Sun need to be heated, because temperatures can drop dramatically. The vacuum does not conduct heat, so the only way to transfer energy is through electromagnetic radiation, generated by the thermal motion of particles in matter. Operating on a planet surface allow convective dissipation and, to a lesser extent, conductive heat dissipation. Furthermore, Mars' thin atmosphere mitigates the strong temperature gradients that would occur in a vacuum. Nevertheless, external parts of the rover are exposed to temperature ranging between -123^oC - $+40^oC$. In this paper, the thermal control system of NASA's Curiosity rover will be presented, analyzing the challenges of maintaining suitable operating conditions in Martian environment and the solutions adopted to allow safe operations.

1. Introduction

The Mars Science Laboratory (MSL) is a robotic space probe mission to Mars launched by NASA on the 26th November 2011, while Curiosity landing was on the 6th of August 2012, at Gale Crater. The objective of the space mission included the investigation on Mars' habitability, the collection of data useful for future manned missions to Mars, and the evaluation of Martian geology and climate [1]. Furthermore, the investigation of the role of water and carbon, nitrogen and other fundamental elements for life was carried out. Many scientific instruments are on board to perform the required scientific experiments, including cameras [2, 3, 4, 5], spectrometers [6], radiation detectors [7], environment monitoring station [8] , soil samples acquisition systems [9, 10, 11].

The focus of this paper is to describe the Thermal Control System (TCS) of the Mars Rover Curiosity, which is a fundamental element of this mission. The interesting peculiarity of Curiosity is the adoption of a multi-mission radioisotope thermoelectric generator (MMRTG), which is a type of radioisotope thermoelectric generator (RTG) specifically developed for NASA space missions [12].

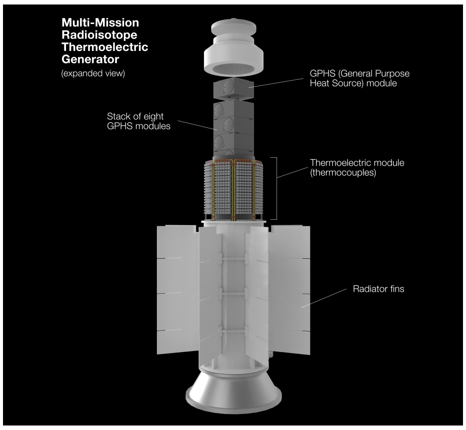
The particularity of MMRTGs is the intimate relation between energy generation and TCS, since their principle of operation is based on a not very efficient thermoelectrical conversion, so a large amount of waste heat has to be dissipated; for Curiosity, the electrical power generated is about 110 W_{el}, while the thermal power is about 2000 W_{th} at beginning of life. However, the

IOP Conf. Series: Materials Science and Engineering 1226 (2022) 012113 doi:10.1088/1757-899X/1226/1/012113

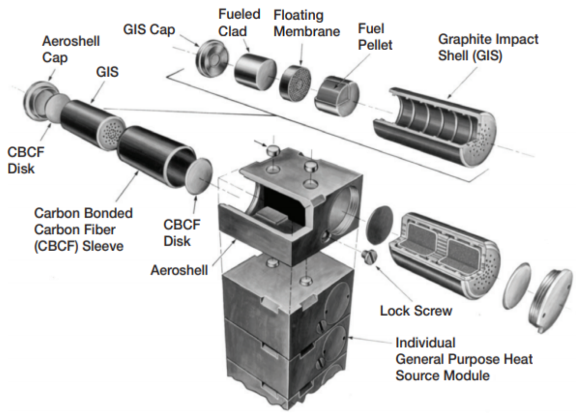
waste heat can prove useful to maintain a tolerable operative environment during cold conditions, e.g. during martian nights.

2. MMRTG

The Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is a type of Radioisotope Thermoelectric Generator (RTG) developed and provided to NASA for civil space applications by the U.S. Department of Energy (DOE). An MMRTG produces almost 2000W of power at the beginning of life. Still it is not very efficient in converting heat into electricity: the most used combination of materials, such as plutonium-238 with Si–Ge TE cells, give about 7% conversion efficiency of the total generated power, about 110W. The Heat Rejection System (HRS) uses some of the remainders to keep electronics warm to maintain temperatures in the operating range. Some of the waste heat is dissipated back to space or planet's surface via a radiator. An MMRTG is made up of different parts, each of which performs several functions:



(a) Multi-Mission Radioisotope Thermoelectric Generator schematics.

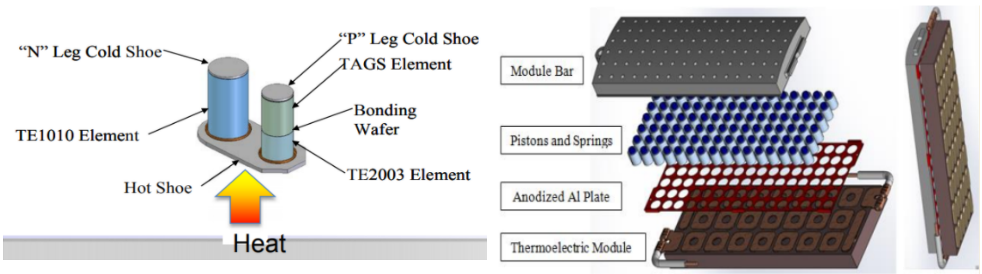


(b) Illustration of a GPHS module.

Figure 1: Details of the Heat Rejection System of Curiosity.

- GPHS module: it is the fundamental building block for the MMRTG, and it is designed to survive launch accidents because these modules contain the fuel, such as Plutonium-238. In Fig. 1b all the constituent parts of GPHS module are visible:
  - Fuel Pellet: the fuel is produced into ceramic pellets of Plutonium-238 dioxide, $^{238}PuO_2$, encapsulated in a protective casing of a ductile, high-temperature iridium-based alloy, which blocks the alpha particles emitted in the decay, known as Fueled Clad. Besides, even if the pellets undergo high forces to break them, it will break into large blocks rather than dust that could be inhaled;
  - Graphite Impact Shell: fuel clads, in turn, are encased and protected by graphite sleeves;
  - Aeroshell: the mentioned above elements are, in turn, enclosed and protected within nested layers of high stiffness and high chemical resistance carbon-fiber material, known as Aeroshell.
- Thermoelectric modules: solid-state devices convert heat flux into usable electricity, when any two dissimilar materials are maintained at different temperatures, through the Seebeck effect. A pair of conductive materials joined in this way is called Thermocouple. A typical MMRTG has 16 thermoelectric modules connected in electrical series, and each module

contains 48 thermocouples in an electrical series-parallel configuration for fault tolerance, increasing reliability. A thermocouple has a "hot shoe" and a "cold shoe", which is, in turn, separated into two parts: N-Leg and P-Leg (Fig. 2a). The thermocouple's hot shoes is pressed by a spring loading system, mechanically integrated with the cold shoes (Fig. 2b), to the heat distribution block typically made of Graphite, while cold shoes touching the outer shell of the MMRTG and its convecting-radiating fins. The N-Leg Cold Shoe consists of PbTe (Lead Telluride) alloy named TE1010, while the P-Leg Cold Shoe is made up of $PbSnTe_4$/TAGS5. Besides, P-Leg is divided into two parts optimized to stay in contact with the hot and cold parts respectively, which typically operate at the temperature of 520 °C, for hot shoes, and 75 °C for the cold shoes.



(a) Thermocouple schematics.

(b) Thermoelectric modules assembly.

Figure 2: Thermoelectric modules of an MMRTG [13].

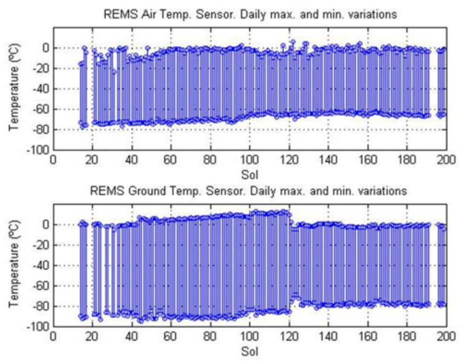
- Cooling tube: a fluid heat exchanger is used to dissipate the waste heat. Aluminium tubes (Al 6063) are used in MMRTGs that are designed to work in both vacuum and atmospheric conditions. The temperature can not fall below -269 °C (4K) to not create strong temperature gradients in the materials.
- Insulation: The thermocouples are surrounded and protected by insulating materials that minimize waste heat to the outside and reduce the sublimation rate of the thermoelectric materials. Different solutions have been proposed, such as using a Sol-Gel coating6 of aluminium oxide (Al_2O_3), titanium oxide (TiO_2), or silicon (SiO_2): these materials strongly reduce the sublimation rate, but the coating is non-uniform and does not reach the required density to stem sublimation of the thermocouples material and to ensure good insulation. The problems of Sol-Gel process can be solved using the Atomic Layer Deposition (ALD) technique, based on a gas phase coating process which allows angstrom level precision, ensures very thin films and uniform coating, repeated to produce a thickness of 30-40 nm of Al_2O_3.
- Fins: As mentioned above, the MMRTG produces 110W to power the electronic systems, the remaining part is used to create the correct thermal operating environment, and some of the waste heat is dissipated to the outside. The only way to increase the heat flow is to increase the exchange surface area and to do so it is essential to install finned walls on the surface to be cooled, or if necessary to be heated. In Figure 2.1 are shown the technical specifications of an MMRTG.

3. Thermal environment

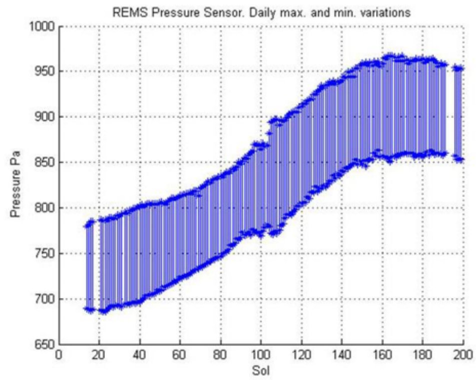
Martian environment is very different from typical Earth conditions. In particular, as visible from Figures 3a and 3b, there are very significant daily oscillations in temperature and pressure. Furthermore, there is a marked change of the pressure values during the year. The great daily excursions of temperature poses challenges in the thermal management of the spacecraft, which should be kept in a relative small temperature envelope during the whole day; it means that during the night the need of heating crucial elements such as the batteries might arise, while during the day there might be a need to reject excess heat.

In addition, the very low air pressure (less than 1/100 of Earth) greatly reduces the amount of heat that can be rejected from atmospheric convection.

The main heat sources will now be described.



(a) Typical Martian temperature profile.



(b) Typical Martian pressure profile.

Figure 3: Evolution of temperature and pressure on Mars during the year.

3.1. Solar radiation

The fundamental aspects of solar radiation of interest are: the spectral distribution, which can be considered constant throughout the solar system; the intensity of the radiation, which is not constant and varies with wavelength, approximating a black body at 5777 K. Most of the solar energy (99%) is between 150nm and 10 μm wavelength, with a maximum near 450nm. The solar intensity depends on the distance from the Sun and can be calculated from the following relationship $I_s = \frac{P}{4\pi d^2}$, where P is the total power emitted by the Sun, while df is the distance. The thermal power of solar radiation absorbed by a flat surface of area A is calculated using the following expression: $\dot{Q}_{sun} = \alpha I_s A_{solar} F_{s/r}$, where α is the absorptivity, since the rover is not a blackbody, but absorbs only a fraction of the incident energy; and $F_{s/r}$ is the view factor between the solar flux and rover's planar surface, which varies over time and according to latitude.

3.2. Albedo

The albedo is the fraction of solar radiation that is reflected from the surface or atmosphere of a planet and its value depends on the local properties of the surface and atmosphere. It is one of the factors that determine planetary surface temperature. For Mars, it varies from a maximum of 0.4 in dust-covered surface regions to a minimum of 0.15 in regions with volcanic rock basalt on the surface. However, the average value that can be used for thermal design purpose is 0.29. Thermal flux due to albedo (b) of solar radiation is: $\dot{Q}_{albedo} = b\alpha I_s A_{solar} F_{s/r}$

3.3. Planetary radiation

Mars radiates all its heat at infrared wavelengths (for this reason, the radiation is often referred to as thermal radiation). Some of the radiation is reflected, partly absorbed and then re-emitted as IR radiation or blackbody radiation. The heat exchange between two radiating surfaces is represented by $\dot{Q}_{IR} = J_p A_{planetary}$, where J_p is function of the planet temperature and can be approximated by $J_p = \varepsilon_{pl} \sigma T_{eff}^4$, assuming an emissivity of the planet Mars of 0.71 ($\varepsilon_{pl} = 1 - b$).

4. Thermal balance

Spacecraft and, more specifically, rovers are generally very complex structures within which temperatures vary continuously as a function of position and time, and their detailed calculation is very complex. The approximate solution presented in this section allows the orders of magnitude involved to be understood and a preliminary analysis to be carried out.

The net heat absorbed per unit time is given by the following equation:

$$\dot{Q}_{in}^{ext} + \dot{Q}_{in}^{int} - \dot{Q}_{conv} = \dot{Q}_{out} \tag{1}$$

where the external heat input can be assumed to be the sum of four different terms (sun irradiation, albedo, thermal radiation as described previously and thermal conduction through the wheels-ground interfaces). In particular, the conduction heat is $\dot{Q}_{cond} = 6 \cdot \frac{T_{gnd} - T_{rov}}{R_{gnd} + R_{susp}}$. since there are 6 wheel-ground interfaces.

The internal heat input is the sum of two thermal powers, i.e. $\dot{Q}_{in}^{int} = \dot{Q}_e + \dot{Q}_{MMRTG}$, where the electrical contribution varies in function of the active instruments, while the thermal contribution from the MMRTG can be assumed constant in first approximation.

The convection term $\dot{Q}_{conv}$ is the heat transfer from convection; it can be approximated by Newton's Law, i.e. $\dot{Q}_{conv} = h(T_{rov} - T_{amb})A_{sph}$ where A_{sph} is the surface of a sphere with equal surface to the rover, while h is the convection coefficient which is hard to evaluate, but for this case a realistic value of 1 $W/(m^2K)$ is assumed.

Finally, the heat output is the radiative term. To evaluate it. the Stefan-Boltzmann law is used, i.e. $\dot{Q}_{out} = \sigma\varepsilon_{rov}(T_{rov^4} - T_{amb}^4)A_{sph}$, with ε_{rov} the emissivity of the rover, while σ is the Stefan-Boltzmann constant.

Finally, solving the system of equation yields the only unknown term T_{rov} which is the rover equilibrium temperature, assuming white paint (low α/ε [14]).

Using the values reported in Figs. 4 and 5, we obtain the two equilibrium temperatures of $T_{rov,h} = 331.7K$ and $T_{rov,c} = 262.3K$. This prelminary analysis justifies the use of active heat rejection system that will now be described.

Worst case HOT condition	
Boundary conditions	
T_{gnd} [K]	292.790
T_{amb} [K]	270.730
D_{sph} [m]	1.426
EXTERNAL HEAT INPUT	
Direct Solar Radiation	
I_s [W/m^2]	587.424
α [−]	0.2
$F_{s/r}$ [−]	1
$A_\perp$ [m^2]	1.598
$\dot{Q}_{sun}$ [W]	187.688
Indirect Solar Radiation	
b [−]	0.4
$F_{s/r}$ [−]	1
$A_\perp$ [m^2]	1.598
$\dot{Q}_{albedo}$ [W]	75.075
Planetary Radiation	
J_p [W/m^2]	70.72
$A_\perp$ [m^2]	1.598
$\dot{Q}_{IR}$ [W]	112.979
Conduction Radiation	
λ_{alum} [W/mK]	130
λ_{tit} [W/mK]	17
θ [rad]	0.785
r_{wh} [m]	0.250
r_{susp} [m]	0.083
L_{wh} [m]	0.500
L_{susp} [m]	0.390
A_{wh} [m^2]	0.079
A_{susp} [m^2]	0.022
R_{gnd} [K/W]	0.049
R_{susp} [K/W]	1.052
$\dot{Q}_{cond}$ [W]	−212.342
INTERNAL HEAT INPUT	
$\dot{Q}_e$ [W]	301.988
$\dot{Q}_{MMRTG}$ [W]	2000
HEAT OUTPUT	
Convection Radiation	
h [W/m^{2}K]	1
A_{sph} [m^2]	6.390
$\dot{Q}_{conv}$ [W]	389.851
Thermal Radiation	
$F_{r/e}$ [−]	1
ϵ_{rov} [−]	0.85
A_{sph} [m^2]	6.390
$\dot{Q}_{rad}$ [W]	2075.540
Balance temperature	
T_{rov} [K]	331.738 (58.588 °C)

Figure 4: Data used for worst case hot conditions

5. Heat rejection system

The rover's heat rejection system (RHRS) must be able to dissipate the large amount of heat produced by the MMRTG that is not converted into electrical energy that can be used to power the various subsystems. A Mechanically Pumped single-phase Fluid Loop (MPFL) is used for

Worst case COLD condition	
Boundary conditions	
T_{gnd} [K]	178.868
T_{amb} [K]	183.2305
D_{sph} [m]	1.426
EXTERNAL HEAT INPUT	
Planetary Radiation	
J_p [W/m^2]	16.881
$A_\perp$ [m^2]	1.598
$\dot{Q}_{IR}$ [W]	26.9686

Conduction Radiation	
λ_{alum} [W/mK]	130
λ_{tit} [W/mK]	17
θ [rad]	0.785
r_{wh} [m]	0.250
r_{susp} [m]	0.083
L_{wh} [m]	0.500
L_{susp} [m]	0.390
A_{wh} [m^2]	0.079
A_{susp} [m^2]	0.022
R_{gnd} [K/W]	0.049
R_{susp} [K/W]	1.052
$\dot{Q}_{cond}$ [W]	−455.039

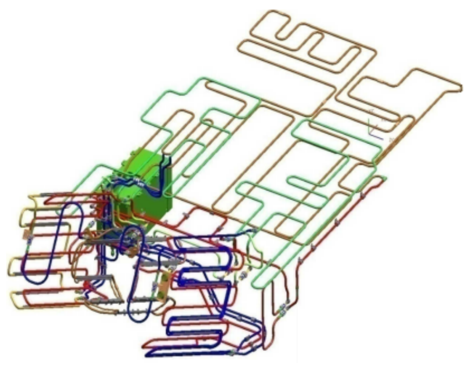
INTERNAL HEAT INPUT	
$\dot{Q}_e$ [W]	45
$\dot{Q}_{MMRTG}$ [W]	2000
HEAT OUTPUT	
Convection Radiation	
h [W/m^{2}K]	1
A_{sph} [m^2]	6.390
$\dot{Q}_{conv}$ [W]	505.468
Thermal Radiation	
$F_{r/e}$ [−]	1
ϵ_{rov} [−]	0.85
A_{sph} [m^2]	6.390
$\dot{Q}_{rad}$ [W]	1111.460
Balance temperature	
T_{rov} [K]	262.331 (−10.819 °C)

Figure 5: Data used for worst case cold conditions

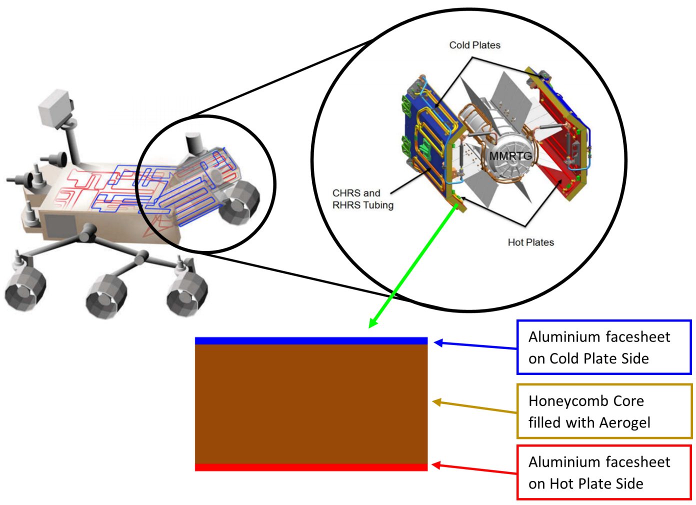
different reasons, including scalability in heat rejection, ability to absorb and supply heat at different points in the rover, flexibility in positioning all the equipment needed to dissipate heat and adaptability to last minute changes in design.

The working fluid is CFC-11, an artificial type of fluid, typically called Freon, which has: high density, both in the aeriform and liquid phases; high enthalpy of vaporisation; high thermal capacity; and high stability under operating conditions.

The Rover Integrated Pump Assembly (RIPA) is the heart of the rover, as it pumps fluid to all parts of the rover that need to be warmed and cooled. It also contains a large reservoir, which allows the Freon to expand as it heats up. The system consists of two honeycomb sandwich panel Heat Exchangers (HXs) at the back of the rover on either side of the MMRTG, which have a coil of tubes attached on both sides. On the inward-facing side of each HX is the hot plate, through which the fluid picks up waste heat from the MMRTG and returns to the pump. While, on the outward-facing side is the cold plate, where the fluid dissipates excess heat. A layer of Aerogel is placed between the two plates (Fig. 6b), thermally separating the hot inner face from the cold outer face.



(a) Rover heat rejection system schematics [15].



(b) Heat exchangers details [15, 16].

Figure 6: Details of the Heat Rejection System of Curiosity.

The working fluid system can handle temperatures between -97 °C and 170 °C, with a system pressure of about 1.36MPa to prevent boiling, and operates correctly if the diurnal fluctuation of the plate temperature is less than 60 °C (Fig. 6b). So, when the internal temperature is outside the allowable limits, the pump transfers the heated fluid from the MMRTG through the tubing connected to the RAMP, vice versa if the temperature is high, the pump sends the fluid from the RAMP to the cold plates on the outside of the HXs.

The two side heat exchangers, the body and a windbreaker on the back protect the MMRTG from the Martian wind (especially during the colder winter months) and other external factors that could affect its proper functioning and deprive it of the heat it needs to survive. Also due to the fail-safe principle, it is extremely vital to safeguard the health of the rover and thus it is essential to redundant the pump (only one is powered at any time) and the two mixing and splitter valves.

The mixer and splitter valves operate passively and work independently of any onboard computers, controlling the flow of fluid to the hot and cold plates, allowing the system, respectively, to heat or cool as needed. The mixer and splitter valves allow the heat rejection system to selectively heat or cool the Freon as needed. For rover safety, they work independently of any computer, operating passively in response to the temperature of the fluid flowing through them. The mixer valve controls the amount of flow across the rover's hot plates.

If the mixer valve falls below a temperature of –10°C, it opens all the way, sending 97% of the fluid through the hot plates. If the mixer valve measures a temperature of 10°C, it closes to its minimum setting of 55%, which runs just enough fluid in the hot plates to keep the fluid temperatures below 90°C (Fig. 7). The splitter valve controls the flow to the cold plates and top deck. When its temperature rises above 35°C, it opens all the way to 96%; it closes to its minimum setting of 4% at 15°C. If the mixing valve measures a temperature below -10 °C, it opens fully, transferring 97% of the working fluid through the hot plates, while if the temperature exceeds 10 °C, it closes at its minimum setting of 55%, flowing only 45% of the fluid, just to keep fluid temperatures below 90 °C. Whereas, when the splitter valve measures a temperature above 35 °C, it opens fully at 96%; it closes at its minimum setting of 4% below 15 °C.

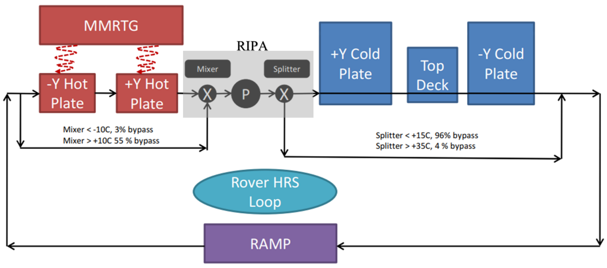


Figure 7: Rover HRS Loops. The circuit remains the same even during cruise with the rover inside the Cruise Stage, except that the fluid also passes through the CHRS radiator to perform the CHRS loop, which is not taken into account in the following analysis [17].

6. Conclusions

In this paper, an overlook of the Thermal Control System of Curiosity rover has been presented, focusing on the functioning of the MMRTG, presenting its advantages and disadvantages, highlighting the real problem with MMRTG is the low energy conversion efficiency due to the materials used for the hot shoes and cold shoes of the thermocouples.

Furthermore, a preliminary thermal balance of the spacecraft has been carried out, both in worst case hot and worst case cold conditions; the value obtained justifies the adoption of an active heat management system as adopted in the real project. In particular, the rover heat rejection system (RHRS) has been described and the principle of operation detailed, including advantages and disadvantages of the solution.

References

[1] John P Grotzinger et al. "Mars Science Laboratory mission and science investigation". In: *Space science reviews* 170.1 (2012), pp. 5–56.

[2] J Maki et al. "The Mars science laboratory engineering cameras". In: *Space science reviews* 170.1 (2012), pp. 77–93.

[3] Roger C Wiens et al. "The ChemCam instrument suite on the Mars Science Laboratory (MSL) rover: Body unit and combined system tests". In: *Space science reviews* 170.1 (2012), pp. 167–227.

[4] Kenneth S Edgett et al. "Curiosity's Mars hand lens imager (MAHLI) investigation". In: *Space science reviews* 170.1 (2012), pp. 259–317.

[5] Michal C Malin et al. "The Mars Science Laboratory (MSL) mast cameras and descent imager: Investigation and instrument descriptions". In: *Earth and Space Science* 4.8 (2017), pp. 506–539.

[6] CS Dickinson et al. "Apxs on mars science laboratory-first results from post-landing checkout". In: *International Workshop on Instrumentation for Planetary Missions*. Vol. 1683. 2012, p. 1035.

[7] ML Litvak et al. "The dynamic albedo of neutrons (DAN) experiment for NASA's 2009 Mars science laboratory". In: *Astrobiology* 8.3 (2008), pp. 605–612.

[8] Victoria E Hamilton et al. "Observations and preliminary science results from the first 100 sols of MSL Rover Environmental Monitoring Station ground temperature sensor measurements at Gale Crater". In: *Journal of Geophysical Research: Planets* 119.4 (2014), pp. 745–770.

[9] David Blake et al. "Characterization and calibration of the CheMin mineralogical instrument on Mars Science Laboratory". In: *Space Science Reviews* 170.1 (2012), pp. 341–399.

[10] Emily Lakdawalla. *The design and engineering of curiosity: How the Mars rover performs its job*. Springer, 2018.

[11] Paul R Mahaffy et al. "The sample analysis at Mars investigation and instrument suite". In: *Space Science Reviews* 170.1 (2012), pp. 401–478.

[12] Fred Ritz and Craig E Peterson. "Multi-mission radioisotope thermoelectric generator (MMRTG) program overview". In: *2004 IEEE Aerospace Conference Proceedings (IEEE Cat. No. 04TH8720)*. Vol. 5. IEEE. 2004, pp. 2950–2957.

[13] David Woerner. "The Mars Science Laboratory's MMRTG: a missions perspective". In: (2012).

[14] Wiley J Larson and James Richard Wertz. *Space mission analysis and design*. Tech. rep. Torrance, CA (United States); Microcosm, Inc., 1992.

[15] Gajanana Birur. "Thermal control of MSL rover'Curiosity'using an active fluid loop". In: (2013).

[16] AJ Mastropietro et al. "Design and Preliminary Thermal Performance of the Mars Science Laboratory Rover Heat Exchangers". In: *40th International Conference on Environmental Systems*. 2010, p. 6194.

[17] Keith Novak et al. "Thermal Response of the Mars Science Laboratory Spacecraft during Entry, Descent and Landing". In: 46th International Conference on Environmental Systems. 2016.