Engineering Journal
issn: 0125-8281

Review

A Comprehensive Review of Thermal Control of Moveable and Non-Moveable Spacecraft in Mars Sample Collecting Mission

Sahatsawat Mahattanavuttakorn[1], Keyyapat Tiputhai[1], Pathorn Senivong[1], Nutchaphol Putsa[1], Warin Namkotr[1], Chatchawan Tancharoensup[1], and Wares Chancharoen[2,*]

1 Sirindhorn International Institute of Technology, Thammasat University, 99 Paholyothin Rd., Khlong Nung, Khlong Luang, Pathum Thani 12120, Thailand
2 Princess Srisavangavadhana College of Medicine, Chulabhorn Royal Academy, 906 Kamphaeng Phet 6 Rd., Talat Bang Khen, Lak Si, Bangkok 10210, Thailand
*E-mail: wares.cha@cra.ac.th (Corresponding author)

Abstract. Space exploration has been the focus of scientists for centuries. Among all the planets, Mars is the closest to our planet that has the potential of discovering traces of life signs. The planet has critical environmental conditions which are from either the planet itself or the Sun. Nowadays, there are several spacecrafts sent to Mars for specific purposes. One of the current missions is Sample Collecting Mission, which collects Mars samples and sends them back to Earth. A current rover for this mission, Perseverance, was launched by NASA with the main purpose of collecting samples on the planet for at least a two-year mission period. Sample Retrieval Lander will be operated within around six months for receiving the samples collected by the rover and sending them back to the Earth. Each spacecraft also needs different kinds of power sources and thermal management systems based on their mission objectives and periods. The overview and consideration points for selecting each source of power and thermal control are investigated and discussed based on our perspectives.

Keywords: Mars sample collecting mission, perseverance mission, sample retrieval lander, thermal control system, space exploration.

ENGINEERING JOURNAL Volume 27 Issue 11
Received 5 May 2023
Accepted 20 November 2023
Published 30 November 2023
Online at https://engj.org/
DOI:10.4186/ej.2023.27.11.85

DOI:10.4186/ej.2023.27.11.85

1. Introduction

Space exploration is an investigation of the environment beyond the Earth's atmosphere regions by on-Earth innovation, such as telescopes [1], or launching either manned or unmanned spacecraft [2]. The exploration aims to gain knowledge of outer space and benefit human habitats [3]. Since 1957, many spaceships have launched to several asteroids and planets, and Mars is one planet in which scientists pay attention due to its feasibility of presence of water [4]. Scientists then started to manufacture spacecrafts and send them to Mars to investigate life signs and collect Mars surface samples. Mars sample collecting mission is one mission of looking for, picking up, and launching back of Mars samples, such as rock and soil. To complete its objective, the mission mainly includes a rover, Perseverance, and a lander, Sample Retrieval Lander.

Perseverance is the current rover that NASA launched on 30th July 2020, and landed on Mars on 18th February 2021 [5]. The purpose of Perseverance is to explore Mars, collect surface samples, recognize rock with signs of biosignature, and investigate suitability for human habitation [6], [7]. The operation will take place for a minimum of 1 year on Mars, which is roughly 2 years on Earth. Meanwhile, Sample Retrieval Lander (SRL) is the next spacecraft that NASA is planning to land on Mars after Perseverance. The launch date will be around 2028 and land date will be in 2030s [8]. The purpose of SRL is to receive the samples that were corrected by perseverance and prepare for the transportation from Mars surface to Mars orbit [9].

Surviving on Mars with the different environmental conditions leads to different heat transfer proportions. Internal and external heat sources must be balanced to ensure that the spacecraft's temperature stays optimal. Internal heat sources come from components inside the spacecraft and the power generator, while external sources include solar radiation, albedo, and planetary radiation. Thermal control technologies are essential for Mars spacecrafts. The radioisotope thermoelectric generator (RTG) is an extremely reliable and compact power system that is used to generate electrical power. Another power source is the solar PV panel, which is activated by absorbing the energy in sunlight. Lithium-ion batteries are the current technology used for secondary power resources and have an average lifespan of around ten years.

To manage the heat, passive thermal control technology is important for maintaining the appropriate temperature of spacecraft without the use of mechanical moving parts or input power. This system involves designing the system, selecting materials with appropriate properties, and coating the surfaces. Active thermal control technology can deal with higher amount of heat to be managed. It, hence, is applied in spacecraft that generate or need to reject such capacity of heat. In this review paper, the technical information of thermal control technologies used in the mission as well as the overview and consideration of selecting those technologies for each spacecraft is provided and discussed.

2. Heat Management

Due to the fact that the environment on Mars is very different compared with Earth, it results in different proportions of heat transfer, convection, conduction, and radiation. The amount of heat being transferred to the rover must be calculated differently from the Earth because of the lower atmosphere density on Mars [10]. Both external and internal heat sources are necessary to be considered as major heat sources, and they need to be balanced to ensure survivability of the rovers.

To control and manage the amount of heat the rover receives from heat sources, the rover must reject and compensate for the excess heat to balance the temperature to be in the optimal range [11]. The amount of heat or energy that the rover has to balance is determined by the following equation:

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

2.1. Internal Heat Sources

As the spacecraft operates, heat may be generated from components inside the spacecraft when being used, as well as the power generator of the spacecraft. From the equation above, $\dot{Q}_{in}^{int}$ is the heat input from the internal source described as

$$\dot{Q}_{in}^{int} = \dot{Q}_{e} + \dot{Q}_{Power\ source} \tag{2}$$

$\dot{Q}_{e}$ is the heat input from internal electronic devices, and $\dot{Q}_{Power\ source}$ is the amount of heat input from the spacecraft's power source.

2.2. External Heat Sources

Apart from the internal heat sources like internal components and power generators, other heat sources are those from environment in which it can be calculated by

$$\dot{Q}_{in}^{ext} = \dot{Q}_{sun} + \dot{Q}_{albedo} + \dot{Q}_{p} \tag{3}$$

where $\dot{Q}_{in}^{ext}$ is the summation of heat input from the external sources including solar radiation, albedo, and planetary radiation.

2.2.1. Solar radiation

The first source of external heat source is from radiation called "Solar radiation"; it is the energy in the form of electromagnetic waves emitted from the Sun to the rover. The thermal power of radiation being transmitted to the rover is calculated from the following equation: Apart from the internal heat sources like internal components and power generators, other heat sources are those from environment in which it can be calculated by

$$\dot{Q}_{sun}=\alpha I_s A_{solar} F_{s/r}\cos\beta \tag{4}$$

where α is the absorptivity of the surface, $F_{s/r}$ is the factor of view between the solar flux and planar surface, β is the tilted angle, and A_{solar} is the area of the surface projected to the Sun [12]. The solar intensity I_s is calculated from $I_s=\frac{P}{4\pi d^2}$, where P is the emitted power from the Sun [11]. As the planet rotates continuously, there is an eclipse period which means there is no heat transmitted from the Sun, $F_{s/r}$ is then considered to be 0.

2.2.2. Albedo

An albedo radiation or albedo effect is an effect from reflecting of solar energy from a planet's surface to the spacecraft. The intensity of albedo generally relies on the planet's surface and atmosphere properties. Heat flux from albedo effects can be calculated in similar manner to solar radiation as

$$\dot{Q}_{albeo}=b\alpha I_s A_{solar} F_{s/r} \tag{5}$$

where b is an albedo factor. The albedo factor on Mars can be varied upon its region in which in the volcanic rock basalt region indicates the albedo factor around 0.15 and the dust-covered surface has the factor of 0.4. The average albedo factor, however, of 0.29 is used for calculation in thermal system design [11]. Figure 1 shows the apparent surface albedo where blue area represents the basaltic region and red shows the dust-covered surface [13], [14].

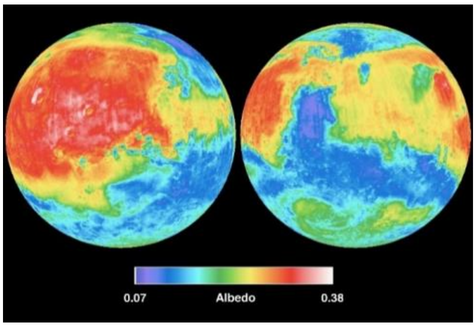

Fig. 1. Albedo Effect on Mars.

2.2.3. Planetary radiation

Planets and moons commonly radiate their absorbed heat out in the form of infrared wavelength with the fourth power of the absorbed temperature. The planets partly absorb the sun's heat radiation and re-emit as blackbody radiation to the spacecrafts [11]. Hence, the planetary radiation is one heat input to the spacecraft where its heat flux can be calculated as

$$\dot{Q}_p=\varepsilon_b A_b F_{b,p}\varepsilon_p\sigma T_p^4 \tag{6}$$

where ε_b is body surface absorptance, A_b is body area, $F_{b,p}$ is factor of view from body surface to planet surface, ε_p means planet emissivity and T_p is surface temperature radiation [12].

2.3. Heat Output

2.3.1. Convection

Even though the atmospheric pressure on Mars is very small compared to the Earth. There is also a process of heat convection since the planet still has ambient air as medium for the convection. $\dot{Q}_{conv}$ is the heat transfer from convection described as

$$\dot{Q}_{conv}=h(T_{s/c}-T_{amb})A_{sph} \tag{7}$$

where A_{sph} is the surface of a sphere, h is the convection coefficient [11].

2.3.2. Radiation

From Eq. (1), $\dot{Q}_{out}$ is the heat output in the radiative term which the S/C has to reject using heat rejection system integrated in it, and it can be calculated as

$$\dot{Q}_{out}=\sigma\varepsilon_{S/C}\left(T_{s/c}^4-T_{amb}^4\right)A_{sph} \tag{8}$$

where $\varepsilon_{S/C}$ is the emissivity of the spacecraft, σ is the Stefan-Boltzmann and $T_{s/c}$ is the spacecraft's equilibrium temperature [11].

3. Thermal Control Technology in Mars Sample Collecting Mission

3.1. Power Sources

Power sources are some kinds of sources providing useful power in many forms such as heat and electricity. Power can be generated using a generator or gathered from the surrounding environment and transformed into a suitable form for the application or stored in a device for future usage.

3.1.1. Radioisotope thermoelectric generator

The RTG is an extremely reliable and compact power system. It is used to continuously provide electrical power to the rover. The RTG generated the electricity by using the decay of radioisotope to generate heat for creating temperature differences. This temperature difference is later used to produce electrical power via thermoelectric generator, which is then supplied to other devices [15].

The heat source is called the General-Purpose Heat Source (GPHS). Nowadays, the heat source material is Plutonium-238 due to its characteristics of being able to produce sufficient heat and sustain that for a decades-long mission. The RTG has been used in multiple spacecraft such as the New Horizon spacecraft, Cassini, and Curiosity rover. As of now, there are 3 iterations of GPHS as shown in Fig. 2: Step-0, Step-1, and Step-2 of GPHS [16]. Each iteration introduced an improvement in strength, and Step-2 also considered the return mission. Multiple GPHS modules are stacked together to form the heat sources of RTG as shown in Fig. 3. Perseverance and Curiosity use the Step-2 GPHS RTG Also called the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) [16].

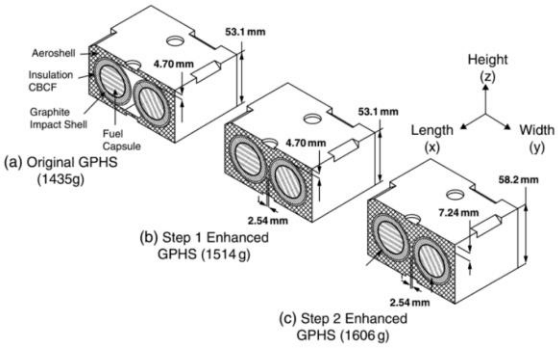

Fig. 2. Step-0, Step-1, and Step-2 of GPHS [16].

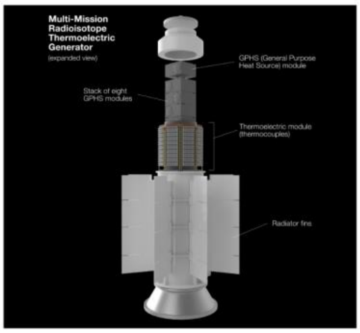

Fig. 3. Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) [11].

3.1.2. Solar PV panel

Solar PV panels are one of the main power sources for spacecraft since space has unlimited solar power and high solar intensity. On the surface of Mars, shielding radiation from the planet's atmosphere is estimated at 20 grams/cm^2, and a day on Mars, or sol, is relatively longer than a day on Earth [17]. Therefore, the solar PV panel is an appropriate power source since it can generate sufficient power to supply the spacecraft during the day as well as recharging the batteries [18]. Usually, the panels are installed on top of the spacecraft that looks like a wink [19]. The PV panel is activated by absorbing the energy in sunlight, then the energy will create electrical charges that move according to the internal electrical field in the cell, this leads to electricity flow [20]. One example of solar panel on the International Space Station (ISS) as shown in Fig. 4 [21].

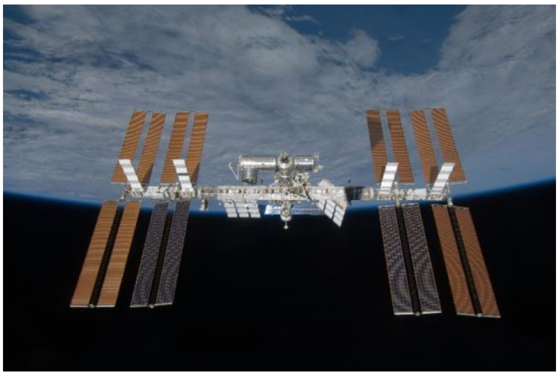

Fig. 4. Solar panels on spacecraft [21].

3.1.3. Battery

Batteries have been used for the second primary power resource for a long time. The batteries are normally recharged using spacecraft's main power sources, whether from MMRTG or solar PV panels [22]. The Lithium-ion batteries are the current technologies that currently been used across space operations [23]. According to Table 1 [24], Lithium-ion batteries provide a higher specific energy and energy density compared to old technologies (Nickel Metal Hydride Battery) [25]. The new Lithium-ion batteries have an average lifespan of around 10 years or 60,000 charge cycles [26]. The operational temperature condition of batteries on Mars surface needs to be maintained between -10 to 40 ℃ [27]. Figure 5 illustrates the Lithium-ion battery used as power source in spaces [28].

Fig. 5. Battery used on spacecraft [28].

Table 1. Comparative properties of battery types [24].

Properties	Lithium-ion	Nickel Metal Hydride
Cell Voltage (V)	3.6	1.2
Specific Energy (Wh/kg)	3-100	1-80
Specific Power (W/kg)	100-1000	<200
Energy Density (kWh/m^3)	80-200	70-100
Power Density (MW/m^3)	0.4-2	1.5-4
Efficiency (%)	99	81

3.2. Active Thermal Control Technology

Active thermal control requires power, including heat rejection and temperature control. Active thermal control technologies like mechanically pumped fluid in closed-loop circuits are mainly used to collect heat, transfer heat, and reject heat while heaters are used for heat generation [29].

3.2.1. Mechanically pumped fluid loop (MPLF)

Mechanically pumped fluid loop is a fluid loop system that operates with working fluid circularly. The loop consists of tubes which are connected to every part of a spacecraft as shown in Fig. 6 [30]. The tubes receive heat load from the attached electronic devices and carry it to rejection system of the spacecraft. The MPFL contains several advantages compared to other TCSs: flexibility of positioning inside the S/C, capability to absorb and dissipate heat from various locations, easy to detect the thermal performance, and ability to choose a proper working fluid to the thermal environment [31]. Typically, the material used for the loop tubes is either aluminum or stainless steel since it has properties of high strength, low density, and corrosion resistance [32].

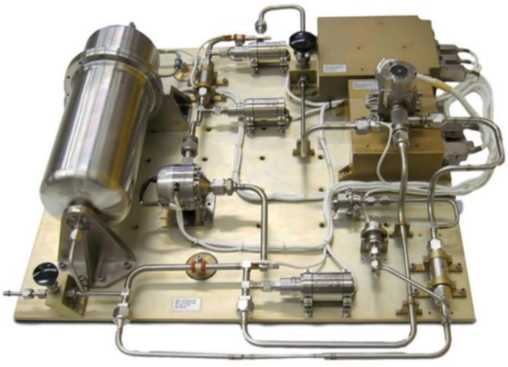

Fig. 6. Mechanically Pumped Fluid Loop [30].

In order to increase the reliability of the MPFL, the selection of working fluids is come up with the condition that the fluid must remain in liquid state throughout the operation. The fluid should also have high thermal conductivity properties and specific heat with low viscosity. The capacity to carry the heat load for a specific mass flow rate will increase with the high specific heat. Besides, high thermal conductivity affects the high heat transfer rate in receiving and rejecting heat from the loop. Low viscosity can help pressure rise across pumping states, leading to lower energy required. Additionally, low vapor pressure property benefits decreasing pressure inside the MPFL to prevent unexpected situations that may occur [31].

Many fluids are taken into consideration and compared to be used in the MPFL, they are deionized water, ethylene glycol aqueous solution, Freon 11, Thermion 59, and Syitherm XLT. Concerning the freezing point of fluid properties shown in Table 2 [31], water, ethylene, and Therminol 59 are not appropriate choices because the Mars ambient temperature at night can be decreased to -140 °C. Since the TCS must have high reliability, the system must be confirmed to operate for the entire lifespan, so concerning freezing point is one important criterion. Moreover, between the two other fluids, the Freon 11 has lower vapor pressure and dynamic viscosity with comparative thermal conductivity. This results in using Freon 11 as working fluid in MPFL on some heritage on the planet.

3.2.2. Heater

To keep the temperature of the devices on spacecraft during the night, multiple Radioisotope Heater Units (RHUs) were integrated into spacecraft [33]. The RHUs or survival heaters are devices that use the decomposition of Plutonium-238 to generate extra heat to keep the temperature of spacecraft at acceptable level [34]. The size of the RHUs is exceedingly minor compared to the others type of heaters, length of RHUs is about 31.95 mm and diameter of RHUs is approximately 25.95 mm. Each heater can supply a thermal output around 1.1 watts, at the start of mission the heaters hold 2.66 grams of Plutonium-238 [35], [36].

Fig. 7. Plutonium-238 [36].

Table 2. Properties of working fluids in mechanically pumped fluid loop [31].

Properties	**Water**	**Ethylene Glycol, 50% Wt**	**Freon 11**	**Therminol 59**	**Syltherm XLT**
Freezing point (℃)	0	-35	-111	-45	-111
Vapor pressure (MPa)	0.48	0.32	2.11	0.003	6.8
Specific heat (kJ/kg*K)	4.3	3.9	1.0	2.1	2.0
Thermal conductivity (W/m*K)	0.69	0.39	0.05	0.11	0.08
Dynamic viscosity (mPa*s)	0.18	0.37	0.16	0.75	0.34

3.3. Passive Thermal Control Technology

Passive thermal control system controls maintain heat for spacecraft without requiring any power input to operate. Passive thermal control may include layout designing, surface coating, and material selection which is considered by its properties such as specific heat, conductivity, and density [37].

3.3.1. CO_2 gas gap

For the purpose of isolating spacecrafts from the planet's environment, one special innovation called gas gaps has been chosen. This insulation gap is between internal devices and the spacecraft's chassis as shown in Fig. 8. The gap thickness is a case-by-case assessment. The assessment method consists of 3 processes. First, calculate and evaluate the heat loss characteristics from the equation shown below. The second process is to analyze the setup using Computational Fluid Dynamics (CFD) in various expected operating conditions to find the optimal gas gap. The graph in Fig. 9 shows the result from CFD as well as the calculation from the first process. The last process is to test the optimal gap within an actual test chamber with the lander design restriction [38]. The optimal insulation gaps are designed with a thickness of approximately 5 centimeters and filled by carbon dioxide, CO_2, which is the highest amount of gas on Mars. According to the research, thickness of the gap larger than this does not increase thermal isolation because of the existing of heat convection, whereas the smaller one allows purely heat conduction [39].

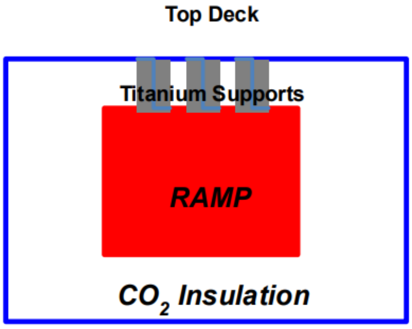

Fig. 8. Depiction of CO_2 gas gap in heritage on Mars [38].

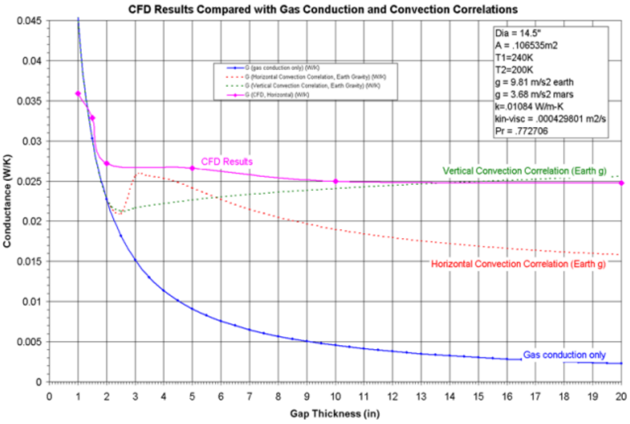

Fig. 9. Comparison of results from the CFD analysis [38].

3.3.2. Selective black surface

In order to enhance the ability of heat absorption from the sun, black color is used for covering spacecrafts due to its properties of high solar absorptivity and low infra-red emissivity. Radiation heat transfer rate can be calculated using Stefan-Boltzmann law. However, emission and absorption of radiated heat are practically coincident. The temperature of objects and surroundings influences the net rate of radiation heat transfer [40]. The net rate of radiation heat transfer can be determined by

$$\frac{Q_{net}}{t} = \sigma e A(T_2{}^4 - T_1{}^4) \qquad (9)$$

where σ is the Stefan-Boltzmann ($5.67\times10^{-8} J\cdot m^2\cdot k^4/s$);

A is the object's surface area in square meters;

T_2 is surrounding temperature in kelvin or degree Celsius;

T_1 is object temperature in kelvin or degree Celsius;

e is emissivity, which indicates absorption heat's ability with values between 0 to 1. In ideal, black body has e = 1 while perfect reflector has e = 0 [40].

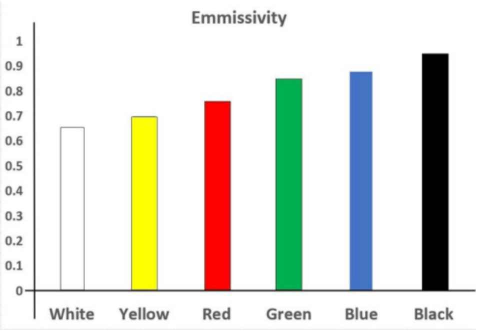

Fig. 10. Graph showing emissivity of colours [41].

According to Fig. 10 [41] and the Stefan-Boltzmann equation, black color has the highest emissivity, ℯ, indicating that black surface has more ability to absorb heat than other colors. Therefore, selecting black color for spacecraft parts can increase heat absorption, which can be utilized for internal components instead of heat from the heat generator.

3.3.3. Heat exchanger

A heat exchanger is a mechanical device that operates based on the process of heat exchanging between two fluids according to the differences of their temperature [42]. One purpose of using it on spacecrafts, heat exchanger is used similarly to a radiator. In other words, it is a device for receiving excess heat from the spacecraft and rejecting it to the environment. Generally, there are several designs of heat exchanger but one design that is the heritage which used by Curiosity is two facesheets heat exchanger [43].

The two-face sheet heat exchanger separates into Cold Plates and Hot Plates, and they are collocated as panels surrounding S/C power source. The inner side of the face sheets is called Hot Plate since it faces the source of power and mainly absorbs heat from the power source. Meanwhile, the exterior side is a surface for rejecting heat out, and it is known as Cold Plate. However, the design criteria of the two plates are that the heat from Hot Plates to the Cold Plates must be sufficient to prevent freezing of Cold Plates fluid in cold conditions. Besides, the heat transferred from the Hot Plates must be limited to prevent lacking heat inside the rover [43].

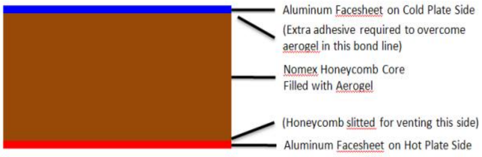

Fig. 11. Cross section of heat exchanger sandwich panel [43].

In order to have high compactness, the heat exchanger should have high in-plane but low through-thickness thermal conductivity. Such that, its layout is designed as a sandwich panel of two face sheets and core materials. The two face sheets are made from aluminum alloy due to their high thermal conductivity, high strength, low density, and ease of forming. On the other hand, the scheme for the core part comes up with 1/8 inch of Nomex honeycomb to lower the through-thickness thermal conductivity and optimize heat between the two face sheets. To suppress the radiative heat transfer, the honeycomb is filled with carbon-filled aerogel or Opaque aerogel because it has properties as heat transfer preventing and extremely low density, that later beneficial in minimizing launch cost [43].

Fig. 12. Nomex honeycomb filling with Opaque Aerogel [43].

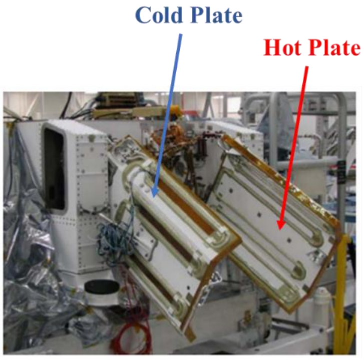

Fig. 13. Cold and Hot Plate of heat exchanger [43].

As shown in Fig. 13, it can be seen that both Hot Plates and Cold Plates are also attached with heat rejection system tubes in which it is a media to receive heat from heat sources on the rover to reject out. The material for tubing is required to have high thermal conductivity and compatibility with the working fluid. Hence, the tubing material is chosen to be aluminum in areas requiring effective heat transfer and stainless steel in sections requiring higher strength such as joints [43].

3.3.4. Annealed pyrolytic graphite thermal doubler

Due to the fact that the size and weight capability of spacecrafts are quite constant but electronic devices become to be more complex which means they create more heat and pose difficulty for space missions. Advanced material such as Annealed Pyrolytic Graphite (APG) have been invented and experimented to be utilized in this field. The APG can increase the heat rejection location's effectiveness and reduce the spacecraft bus's weight and size [44].

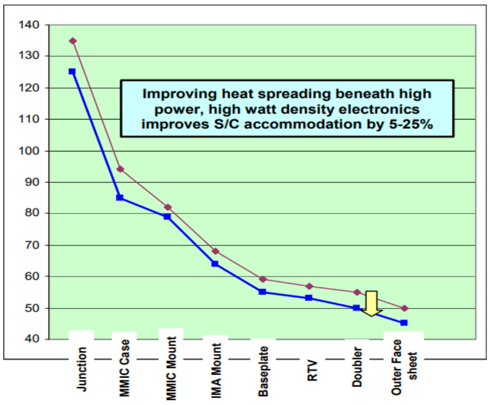

Fig. 14. Temperature profile of electrical component when attaching to a support with and without APG [44].

APG is a material produced from a process called Chemical Vapor Deposition (CVD) which is decomposition of a hydrocarbon gas in a high vacuum furnace, and after it is encapsulated with aluminum shell, its increases thermal conductivity to be more than 1400 W/mK, lower mass density, increase stiffness to be more than 50 Msi [45]. As a result, it provides many advantages for the spacecraft including using as material for thermal doublers or mount for internal electrical components. Adding APG reduces the operating temperature of electronics mounted on doublers by 2-5 °C as shown in Fig. 14, a weight saving of 15-45% compared to normal material, and therefore leads to cost saving [44].

4. Overview of TCS on Spacecrafts for Mars Sample Collecting Mission

Since thermal control system is one important and necessary system for every spacecraft, in order to select the suitable device for the system, several considerations should be concerned and discussed. According to Fig. 15 shown below, the highest priority to design to the lowest are operational, engineering, and economical factors respectively. The operational factors of spacecrafts can be varied based on their mission objectives whether they are being able to move, having robotic parts, or having ability to launch other spacecrafts. In terms of thermal aspect, the factors affecting the operational limitations are the amount of heat to be either stored or rejected and the spacecraft mission durations.

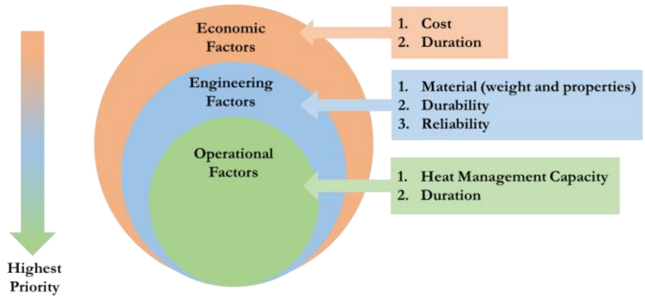

Fig. 15. Consideration factors for selecting thermal control system for spacecrafts.

Engineering factors concern selecting appropriate material for constructing thermal control technologies, as well as the thermal architecture or the designing layout of devices on each part of the spacecraft. The properties of material selected material are generally low density, good in either thermal conductivity or resistivity, and high strength. Aside from the material for construction, the type of working fluid in some TCS is also important to consider. The working fluid in some thermal control systems, such as the fluid loop, should have proper freezing and boiling point, vapor pressure, specific heat, and dynamic viscosity depending on the condition of its working environment. This aspect enhances durability and increases the reliability of TCS of spacecrafts.

Following the engineering factors, economic factors concern cost-effectiveness and the worthiness of choosing proper TCS for each spacecraft. This involves mission duration, production, operating, and launch costs. The economic point duration is quite different from the operational factor. For instance, in choosing thermal control systems, some systems may fit in operational factor but for economic factor, they might be overkill whereas some might be not. If the spacecraft is meant to be used for only a short amount of time, some technology may have high production costs which may not be worth using for just a short period. Weight of the spacecraft also has an impact to the launching cost of it, the heavier the spacecraft, the higher the cost might be. Consequently, picking those systems might increase the project budget which is considered worthless.

4.1. Perseverance

The purpose of Perseverance is looking for possibility of past and current life signs, testing oxygen production, and most importantly collect core rock and soil samples [6]. The duration is supposed to be at least 2 years [46]. Multiple engineering components were integrated to the Rover to serve the mission's purposes, including multiple types of cameras and sensors, drilling arm, and collecting arm [47].

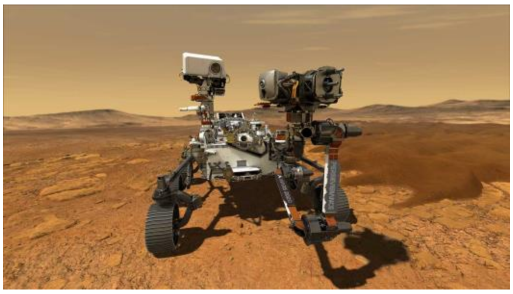

Fig. 16. Perseverance Rover [5].

Based on mission purposes and duration, Perseverance rover needs a power source that can provide a large amount of energy daily, MMRTG is the only technology that satisfies that condition. Moreover, the MMRTG uses the decay of radioisotope to generate electricity above 110 watts in small increments, its design ensures that a high degree of safety was taken into account, and with the rover's lifespan of higher than 14 years [47]. Due to its safety and longevity, MMRTG is highly reliable and durable. The total cost of MMRTG is relatively a lot cheaper than using solar PV panel as the major power source. By comparing the power produced in Watt to the weight of the system, the MMRTG has the value of 2.44 Watt/kg, whereas the panel has 1 Watt/kg. Moreover, the cost of fuel, operation, and maintenance for MMRTG is comparatively lower [48]–[51]. Besides MMRTG, rover also have second source of power which is batteries. Lithium-ion batteries that have an approximate lifespan of 10 years can definitely operate covering the mission duration. In addition, the batteries have been developed and become commonly used in many devices on Earth, so their price is reachable and acceptable for integration on the rover. For these reasons, using them as the alternate power source is reasonable.

Since the rover carried a lot of electronic components, the heat was generated from using all the devices and the MMRTG generated heat as a byproduct. So, the rover needs active thermal control technology to reject excess heat. Mechanically pumped fluid loop is one of the most reliable technologies, it has been proved with the previous rover (Curiosity) that it can transfer large loads of heat, have high durability and able to last more than 15 years [32]. Beside the mechanically pumped fluid loop, several survival heaters are installed to ensure that the cameras and sensors can safely operate during the harsh environment. The heaters can be relied on because they use the decay of radioisotope similar to MMRTG. The size of the heater is small, so the cost of each heater is worth investing. Not only the active thermal control system was integrated but also the passive thermal control system. Heat exchanger is one of the passive technologies that are used to reject excess heat from rover to environment. CO2 gas gap is used for separating the rover's electronic components from the planet environment. Both of these technologies are used in the previous rover and have been proven to satisfy the heat management conditions. Because of it is part of the heritage, it can be relied on and has a potential to last as long as it can the rover. Furthermore, passive thermal control technologies are also cheaper than active thermal control technologies.

4.2. Sample Retrieval Lander

The Sample Retrieval Lander (SRL), shown in Fig. 17, is a lander whose mission is continuing the mission from Perseverance. The lander will be sent to complete the purpose of collecting those samples from Perseverance and return them back to the Earth [52]. The rover has expected mission duration to complete its task of 150 Mars sol or around six months on Earth [53]. Inside the lander, there is a vehicle called Mars Ascent Vehicle which will store the collected sample and will be transferred to the planet's orbit before launching the sample to Earth's orbit [54].

Since the purpose of lander doesn't require large amounts of energy and it's a short-term mission. Solar PV Panels can generate just enough power to supply the lander. The durability of panels is trustworthy, and their reliability is enough for the short mission duration. Its lifespan can last 15 years without anything interrupting the panel [55]. Even though the transport cost of large Solar PV Panels from Earth to Mars is higher than MMRTG, due to its weight, the construction and operating cost considering the mission duration is moderately lower. Similar to Perseverance, the lander also has batteries for critical situations where main power is insufficient.

In perspective of heat generated, the only heat generator inside the lander is heaters and electrical devices. The heaters are known as survival heaters since they are a secondary heat source for extreme cases only. Due to a small amount of heat generated compared to the heat from MMRTG, the lander doesn't require such thermal control technology to reject any large amount of heat. Such that, the MPFL and heat exchanger would increase the project budget, and therefore not necessary. The major heat source selected for the lander is solar thermal energy. The lander has a selective black surface that benefits the heat absorbance from the environment to the internal part of the lander. During the night time that temperature is very low, the lander has to store the absorbed heat inside itself. The CO2 gas gap has been integrated to achieve this objective. For the internal devices on the lander, its temperature is thermally managed by APG thermal doublers. With the advantages of the material and its reliability, it has been merged with supporting parts of the devices. This also results in decreasing cost with is examined that it is more worthy than using active thermal control.

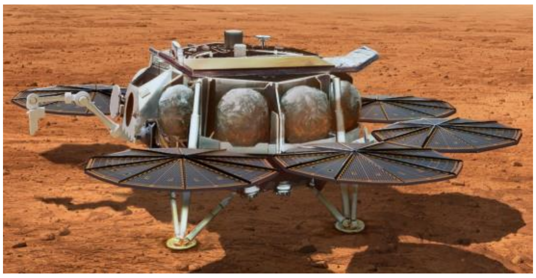

Fig. 17. Sample Retrieval Lander [9].

Table 3. Overview of thermal control systems on Perseverance and Sample Retrieval Lander.

	Perseverance	Sample Retrieval Lander	Ref.
Mission	1. Collecting core rock and soil samples. 2. Identifying the past environments. 3. Looking for the possibility of past microbial life. 4. Testing oxygen production.	1. Receiving sample and preparing the delivery container. 2. Maintaining inside rocket temperature and being a launching station.	[5] [6] [9] [27]
Duration	2 years	6 months	[46] [53]
Power sources	1. MMRTG 2. Batteries	1. Solar PV panels 2. Batteries	[11] [27]
Heat Sources	1. MMRTG 2. Electrical devices 3. Ambient	1. Electrical devices 2. Ambient	[11] [27]
Thermal Control System	1. Mechanically pumped fluid loop 2. Heat exchanger 3. Heater 4. CO_2 gas gap	1. Heater 2. CO_2 gas gap 3. Selective black surface 4. APG	[11] [27]

5. Conclusion

To summarize, every spacecraft has its own specific mission which may require different components to operate, the thermal control system then must be designed to meet their specific needs. To select suitable thermal control devices for the system, many considerations must be made depending on the spacecraft's purpose and design. The highest priority consideration to be made is that the thermal control device must be able to handle enough heat long enough through their mission duration. After that, it must be designed to serve its best by using engineering design such as material properties and reliability. Lastly, the design must consider any possible cost and worthiness of it. Any unmatched or unsuitable selection may increase production, operating, and launching costs. In example, for the SRL, its mission is only to deliver the sample to the orbit of the planet, which is a short period mission, a generator may not be needed, only a battery and solar panel is sufficient. Battery itself does not generate a lot of heat compared to a generator like MMRTG, it does not need a large capacity thermal control system like mechanically pumped fluid loop, passive thermal control technologies and simple heaters can be used instead, which are cheaper and easier to construct. Furthermore, since the mission period is short, sending an expensive system to be used for a short period may not be the greatest decision. Therefore, important factors like operational, engineering, and economic factors should be considered to make the TCS selection more suitable for the spacecraft.

References

[1] Encyclopedia of Science, Technology, and Ethics, "Space Exploration." Accessed: Apr. 30, 2023. [Online]. Available: https://www.encyclopedia.com/science-and-technology/astronomy-and-space-exploration/space-exploration/space-exploration

[2] J. M. Logsdon, "Space exploration," Accessed: Apr. 30, 2023. [Online]. Available: https://www.britannica.com/science/space-exploration

[3] D. Hengeveld, M. Mathison, J. Braun, E. Groll, and A. Williams, "Review of modern spacecraft thermal control technologies," *HVAC&R Research*, vol. 16, pp. 189–220, Mar. 2010, doi: 10.1080/10789669.2010.10390900.

[4] J. Wilson, "Mars Overview," NASA. Accessed: Apr. 30, 2023. [Online]. Available: http://www.nasa.gov/mission_pages/mars/overview/index.html

[5] mars.nasa.gov, "Mars 2020 Perseverance Rover - NASA." Accessed: Apr. 30, 2023. [Online]. Available: https://mars.nasa.gov/mars2020/

[6] K. A. Farley et al., "Mars 2020 Mission Overview," Space Science Reviews, vol. 216, no. 8, p. 142, Dec. 2020, doi: 10.1007/s11214-020-00762-y.

[7] R. C. Moeller et al., "The sampling and caching subsystem (SCS) for the scientific exploration of Jezero Crater by the Mars 2020 perseverance rover," *Space Science Reviews*, vol. 217, no. 1, p. 5, Dec. 2020, doi: 10.1007/s11214-020-00783-7.

[8] mars.nasa.gov, "Concepts for Mars sample return | Missions," NASA Mars Exploration. Accessed: Apr.

30, 2023. [Online]. Available: https://mars.nasa.gov/mars-exploration/missions/mars-sample-return

[9] mars.nasa.gov, “Sample Retrieval Lander - NASA.” Accessed: Apr. 30, 2023. [Online]. Available: https://mars.nasa.gov/msr/spacecraft/sample-retrieval-lander/

[10] A. V. von Arx and A. Delgado Jr., “Convective heat transfer on Mars,” *AIP Conference Proceedings*, vol. 217, no. 2, pp. 734–739, Jan. 1991, doi: 10.1063/1.40133.

[11] G. Quattrocchi, A. Pittari, M. D. L. dalla Vedova, and P. Maggiore, “The thermal control system of NASA’s Curiosity rover: a case study,” *IOP Conference Series: Materials Science and Engineering*, vol. 1226, no. 1, p. 012113, Feb. 2022, doi: 10.1088/1757-899X/1226/1/012113.

[12] B. Beynek, “Satellite thermal control systems and application to a cubesat,” 2020.

[13] “Global Albedo Map of Mars.” Accessed: May 1, 2023. [Online]. Available: https://www.isro.gov.in/Albedo.html

[14] NASA. “Mars Albedo.” NASA Jet Propulsion Laboratory (JPL). Accessed: May 1, 2023. [Online]. Available: https://www.jpl.nasa.gov/images/pia02816-mars-albedo

[15] “Radioisotope Thermoelectric Generators (RTGs) | Cassini – NASA Solar System Exploration.” Accessed: May 1, 2023. [Online]. Available: https://solarsystem.nasa.gov/missions/cassini/radioisotope-thermoelectric-generator/

[16] S. E. Davis, “End-to-end assembly and pre-flight operations for RTGs,” in *The Technology of Discovery*, 2023, pp. 151–182. doi: 10.1002/9781119811398.ch7.

[17] G. Landis, T. Kerslake, P. Jenkins, and D. Scheiman, “Mars solar power,” Dec. 2004, doi: 10.2514/6.2004-5555.

[18] mars.nasa.gov, “The Rover’s Energy - NASA.” Accessed: May 1, 2023. [Online]. Available: https://mars.nasa.gov/mer/mission/rover/energy/

[19] mars.nasa.gov, “Power - NASA.” https://mars.nasa.gov/mer/mission/technology/power/ (accessed May 01, 2023).

[20] “How Does Solar Work?,” Energy.gov. https://www.energy.gov/eere/solar/how-does-solar-work (accessed May 01, 2023).

[21] M. Garcia, “About the Space Station Solar Arrays,” NASA, Jul. 31, 2017. Accessed: May 1, 2023. [Online]. Available: http://www.nasa.gov/mission_pages/station/structure/elements/solar_arrays-about.html

[22] mars.nasa.gov, “Electrical Power - NASA.” Accessed: May 1, 2023. [Online]. Available: https://mars.nasa.gov/mars2020/spacecraft/rover/electrical-power/

[23] S. Ware, “Recharging rovers -- how batteries enable (and limit) our exploration of Mars and beyond,” ZME Science, Oct. 06, 2022. Accessed: May 1, 2023. [Online]. Available: https://www.zmescience.com/space/recharging-rovers-how-batteries-enable-and-limit-our-exploration-of-mars-and-beyond/

[24] “Lithium vs NiMH Battery Packs - Cost Effective Battery Pack Designs.” Accessed: May 1, 2023. [Online]. Available: https://www.epectec.com/batteries/lithium-vs-nimh-battery-packs.html

[25] J. A. Zaragoza-Asensio, S. Pindado, and J. Pérez-Álvarez, “Li-ion battery for space missions based on COTS cells: Mechanical analysis and design,” *The Egyptian Journal of Remote Sensing and Space Science*, vol. 24, no. 2, pp. 311–317, Aug. 2021, doi: 10.1016/j.ejrs.2020.12.005.

[26] “Batteries in Space | Arbin Instruments,” Arbin.com. Accessed: May 1, 2023. [Online]. Available: https://arbin.com/batteries-in-space/

[27] P. Bhandari, R. Kandilian, K. Novak, J. Miller, S. Morellina, J. Lyra, R. Somawardhana, and K. Singh, "Overall thermal architecture & design of the Mars sample return lander mission," in *51st International Conference on Environmental Systems*, July 2022, doi: 10.48577/jpl.QXQXCR.

[28] “ESA - Nobel-winning lithium-ion batteries powering space.” Accessed: May 1, 2023. [Online]. Available: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Nobel-winning_lithium-ion_batteries_powering_space

[29] “Active Thermal Control System (ATCS) Overview.” Accessed: May 01, 2023. [Online]. Available: https://media.labxchange.org/xblock-uploads/lb-LabXchange-6158be73-lx_document-1/473486main_iss_atcs_overview.pdf

[30] “Mechanically Pumped Fluid Loop | satsearch.” Accessed: May 1, 2023. [Online]. Available: https://satsearch.co/products/bradford-mechanically-pumped-fluid-loop

[31] A. D. Paris, G. C. Birur, and P. Bhandari, “High temperature mechanically pumped fluid loop for space applications: Working fluid selection,” *SAE Transactions*, pp. 892-898, 2004. [Online]. Available: https://hdl.handle.net/2014/38408

[32] P. Bhandari, B. Dudik, G. Birur, P. Karlmann, D. Bame, and A. J. Mastropietro, “Design of accumulators and liquid/gas charging of single phase mechanically pumped fluid loop heat rejection systems,” in *42nd International Conference on Environmental Systems*, 2012, p. 3515. [Online]. Available: https://hdl.handle.net/2014/44985

[33] mars.nasa.gov, “The Rover’s Temperature Controls - NASA.” https://mars.nasa.gov/mer/mission/rover/temperature/ (accessed May 01, 2023).

[34] “Light-Weight Radioisotope Heater Unit | Thermal Systems,” NASA RPS: Radioisotope Power Systems. Accessed: May 1, 2023. [Online]. Available:

https://rps.nasa.gov/power-and-thermal-systems/thermal-systems/light-weight-radioisotope-heater-unit

[35] A. J. Zillmer and A. Gates, "Overview of light weight radioisotope heating unit (LWRHU) user's guide," Idaho National Lab. (INL), Idaho Falls, ID, USA, Rep. no. INL/CON-22-65864-Rev000, May 2022. [Online]. Available: https://www.osti.gov/biblio/1871345

[36] The European Space Agency. "Radioisotope Heater Unit." Accessed: May 1, 2023. [Online]. Available: https://99estec-objects.esa.int/object-items/34

[37] S. Caldwell. "7.0 Thermal Control." NASA. Accessed: May 1, 2023. [Online]. Available: http://www.nasa.gov/smallsat-institute/sst-soa/thermal-control

[38] P. Bhandari, P. Karlmann, K. Anderson, and K. Novak, "CO_2 insulation for thermal control of the Mars Science Laboratory," in *41st International Conference on Environmental Systems*, 2011, p. 5119. 2011. [Online]. Available: https://hdl.handle.net/2014/42173

[39] P. Bhandari et al., "Thermal architecture of a conceptual Mars sample return lander during cruise and on Mars," in *International Conference on Environmental Systems*, 2020. [Online]. Available: https://hdl.handle.net/2014/53044

[40] "14.7: Radiation," Physics LibreTexts. Accessed: May 1, 2023. [Online]. Available: https://phys.libretexts.org/Bookshelves/College_Physics/Book%3A_College_Physics_1e_(OpenStax)/14%3A_Heat_and_Heat_Transfer_Methods/14.07%3A_Radiation

[41] G. Hanington, "Professor Hanington's Speaking of Science: It's not the heat, it's the color," *Elko Daily Free Press*, Jun. 25, 2021. [Online]. Available: https://elkodaily.com/lifestyles/professor-haningtons-speaking-of-science-it-s-not-the-heat-it-s-the-color/article_f36789f8-09b3-5788-97b4-005a1fc9db36.html

[42] C. Balaji, B. Srinivasan, and S. Gedupudi, "Heat exchangers," in *Heat Transfer Engineering*, C. Balaji, B. Srinivasan, and S. Gedupudi, Eds. Academic Press, 2021, ch. 7, pp. 199–231, doi: 10.1016/B978-0-12-818503-2.00007-1.

[43] A. J. 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. [Online]. Available: https://hdl.handle.net/2014/45114

[44] S. Kugler, "Aluminum encapsulated APG high conductivity thermal doubler," presented at *the 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 16th AIAA/ASME/AHS Adaptive Structures Conference, 10th AIAA Non-Deterministic Approaches Conference, 9th AIAA Gossamer Spacecraft Forum, 4th AIAA Multidisciplinary Design Optimization Specialists Conference*, 2008, p. 1861.

[45] M. Montesano, "Spacecraft thermal management solutions using annealed pyrolytic graphite," presented at *the 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 16th AIAA/ASME/AHS Adaptive Structures Conference, 10th AIAA Non-Deterministic Approaches Conference, 9th AIAA Gossamer Spacecraft Forum, 4th AIAA Multidisciplinary Design Optimization Specialists Conference*, 2008, p. 1958.

[46] "NASA's Perseverance rover: Everything you need to know about the new Mars rover." Accessed: May 1, 2023. [Online]. Available: https://www.rmg.co.uk/stories/topics/mars-nasa-rover-perseverance-facts-dates

[47] "Powering Curiosity: Multi-Mission Radioisotope Thermoelectric Generators | Department of Energy." Accessed: May 1, 2023. [Online]. Available: https://www.energy.gov/ne/articles/powering-curiosity-multi-mission-radioisotope-thermoelectric-generators

[48] "Sunlight-on-Mars.pdf." Accessed: May 1, 2023. [Online]. Available: https://www.firsttheseedfoundation.org/wp-content/uploads/2016/08/Sunlight-on-Mars.pdf

[49] N. Allen, "Solar Panel Size And Weight: A Comprehensive Guide," Forbes Home. Accessed: May 1, 2023. [Online]. Available: https://www.forbes.com/home-improvement/solar/solar-panel-size-weight-guide/

[50] "MSR (Mars Sample Return)." Accessed: May 1, 2023. [Online]. Available: https://www.eoportal.org/satellite-missions/msr-mars-sample-return-mission#msr-mars-sample-return-mission

[51] The Solar Energy Portal, "Solar panel per square meter," The Solar Energy Portal. Accessed: May 1, 2023. [Online]. Available: https://photovoltaicsolarenergy.org/solar-panel-yield-per-square-meter/

[52] B. M. M. Kumar and R. N. Annavarapu, "Conceptual design of mars sample return mission using solar montgolfieres," presented at *the 2021 IEEE Aerospace Conference (50100)*, IEEE, 2021, pp. 1–10.

[53] B. Muirhead et al., "Sample retrieval lander concept for a potential mars sample return campaign," presented at *the Ninth International Conference on Mars*, 2019, p. 6369.

[54] S. Morellina, "Thermal design of the Mars ascent vehicle for the Mars sample return mission," in *51st International Conference on Environmental Systems*, 2022. doi: 10.48577/jpl.VVY57Y.

[55] "Inside a solar cell." https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Inside_a_solar_cell (accessed May 01, 2023).

Appendix

Nomenclature

APG = Annealed Pyrolytic Graphite,
CFC-11 = Freon 11
CO_2 = Carbon dioxide
GPHS = General Purpose Heat Source
NASA = National Aeronautics and Space Administration
MPFL = Mechanically Pumped Fluid Loop
MMRTG = Multi-Mission Radioisotope Thermoelectric Generator
RAMP = Rover Avionics Mounting Panel
RHU = Radioisotope Heater Unit
RTG = Radioisotope Thermoelectric Generator,
SRL = Sample Retrieval Lander
TCS = Thermal control system

Sahatsawat Mahattanavuttakorn was born on January 1st, 2000, in Chiang Mai province, Thailand. He is currently a student in B.S. degree in mechanical engineering with an energy management minor at Sirindhorn International Institute of Technology, Thammasat University, Thailand.

Keyyapat Tiputhai was born on November 27th, 2000, in Chonburi province, Thailand. He is currently a student in B.S. degree in mechanical engineering with an energy management minor and M.S. degree in logistics and supply chain systems engineering at Sirindhorn International Institute of Technology, Thammasat University, Thailand.

Pathorn Senivong was born on May 14th, 2001, in Bangkok, Thailand. He is currently a student in B.S. degree in mechanical engineering with a general mechanical engineering minor and M.S. degree in logistics and supply chain systems engineering at Sirindhorn International Institute of Technology, Thammasat University, Thailand.

Nutchaphol Putsa was born on July 18th, 2000, in Satun province, Thailand. He is currently a student in B.S. degree in general mechanical engineering at Sirindhorn International Institute of Technology, Thammasat University, Thailand.

DOI:10.4186/ej.2023.27.11.85

Warin Namkotr was born on November 4th, 2000, in Buriram province, Thailand. He is currently a student in B.S. degree in general mechanical engineering and M.S. degree in logistics and supply chain systems engineering at Sirindhorn International Institute of Technology, Thammasat University, Thailand.

Chatchawan Tancharoensup was born on March 15th, 2001, in Bangkok province, Thailand. He is currently a student in B.S. degree in mechanical engineering with an energy management minor at Sirindhorn International Institute of Technology, Thammasat University, Thailand.

Wares Chancharoen was born on November 18th, 1989, in Bangkok province, Thailand. He received the B.S. degree in mechanical engineering from King Mongkut's University of Technology Thonburi, Thailand, in 2012 and the M.S. and Ph.D. degrees in information science at Nagoya University, Japan. He is currently the lecturer at Princess Srisavangavadhana College of Medicine, Chulabhorn Royal Academy, Thailand. His research interests include space medicine, space engineering, mechanical engineering, and medical device design. In 2018, he awarded the Emerging Space Leadership (ESL) from the International Astronautical Federation (IAF), France. In 2019, he got the recognition award from the Deep Space Food Challenge as the one of international team around the world from phase 1, which conducted by The National Aeronautics and Space Administration (NASA), the Canadian Space Agency (CSA) and the Methuselah foundation.