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Surface Rover: Exploration of Mars by Nasa's Curiosity Rover

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Abstract--- The Curiosity Rover is sent to Mars to explore different atmospheric and physical quantities such as pressure, temperature, surface features and others. It is found that the Martian atmosphere is thinner than that of the earth. Scientists have identified that earlier the Martian atmosphere was thicker than its present condition. Due to changes over time it has reached its present conduction. Carbon-dioxide is the main component of the Martian atmosphere and igneous basalt rock is the main component of the land surface. Several craters are also found on Mars and the weather is changing through the passage of time. Dust accumulation is also identified by the scientists by calculating the dust correction factor through this mission. The research study sheds light on the exploration of Mars by the Curiosity rover. Therefore, the purpose of this mission is also an important analysis of this research study. Furthermore, the strategy of the Mars mission to achieve all the goals of the mission is analysed in this research study. Apart from that, system engineering the processes of system engineering is very important for the exploration of Mars. Thus, the importance of system engineering in exploring Mars rovers is described in this research study significantly.

Keywords---Mars, Curiosity rover, RAD, atmosphere, dust, NASA, system engineering, exploration of Mars

I. INTRODUCTION

Rover is a device that helps to know about the condition of other planets and along with that rover is called a surface exploration device. Therefore, the rovers were designed by humans and there are different parts of the rover that make a complete planetary device. Thus, rovers are used for different missions and in different missions there are different names of the rovers (Gage *et al.* 2019). Furthermore, the rovers are important for making the mission complete and making another step for the development of the country. Thus, there are several rovers and those rovers have different efficiency. Apart from that, there are a lot of other advantages of rovers such as the rovers help the people to gain knowledge about other planets and the conditions of the planets. In addition to that, rovers can examine more efficiently as the rovers are designed like that. Furthermore, the rovers are helpful to gain knowledge about the interesting facts, weather and other conditions of the planets.

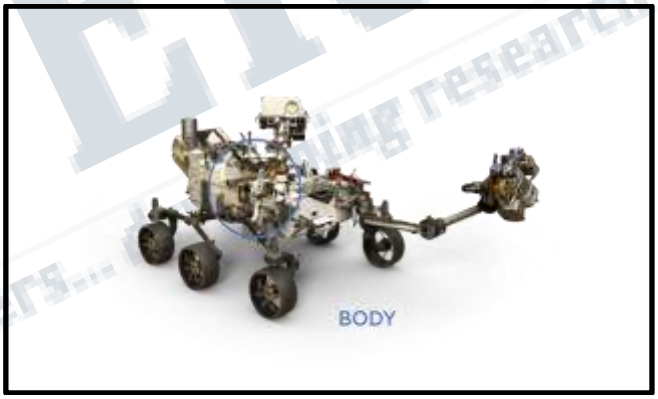

Figure 1: Rover body
(Source: Gage *et al.* 2019)

On the other hand, in this research study the researcher is discussing the Curiosity rover exploration of Mars. In the November month of the year 2011, the ***Curiosity rover*** was launched and this is one of the important rovers (Bell *et al.* 2017). Apart from that, the Curiosity rover helped to know several conditions of Mars and it was made by NASA. Along with that, system engineering is an important part for the Mars exploration Curiosity rover. Thus, the usage and importance of system engineering in Mars exploration rovers is analysed in this research study briefly. Apart from that, the overview of the mission such as the strategies for this Mars mission and findings from this mission is discussed in this research study significantly. In addition to that, the purpose of the Mars mission in the year 2011 and

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the causes of the mission is also described in the research study by the researcher. Furthermore, the findings that are gathered by the Curiosity Mars mission are another significant discussion in this research study.

Aim and objectives

The aim of this particular research study is to provide the exploration information of Mars by the usage of Curiosity rover

Objectives

The objectives of this research study are

- To analyse the purpose of the Mars mission by Curiosity rover
- To identify the benefit that is provided by Curiosity Rover over Surface Rover while conduction of exploration in Mars
- To understand the importance of system engineering in Mars exploration rovers
- To analyse the findings or information about Mars that are provided by the Curiosity rover

II. 2. OVERVIEW OF THE MISSION

2.1 Strategy used in the Mars mission

Strategies are very helpful to achieve the goals and an efficient strategy is always helpful for development. There are some strategies for exploration that help to achieve the scientific goals of the mission. In the case of the Curiosity Mars mission, NASA has adopted their own strategy that is called ***Follow the Water*** as their exploration strategy for the Mars mission (Mars Exploration, 2021a). Therefore, there are a lot of advantages to using this strategy for the Mars mission as the strategy helps to gain more knowledge about Mars and several conditions of Mars. Thus, the strategy can be helpful for knowing about the environment of Mars and even the recent environment of the planet. According to some scientists, once there was a vast ocean on Mars in the northern hemisphere and now the planet became dusty and dry (Mars Exploration, 2021b). Therefore, the strategy will help to know if there were any oceans and how the climate of Mars changed.

Hence, the strategy will help to know about the history of the climate of Mars and that will help NASA achieve the goals. Therefore, it will help to know if human exploration on Mars is possible (Verneil *et al.* 2018). Thus, it can be said that the used strategy is accurate for the Mars mission for achieving all the goals of the mission.

2.2 Purpose of the mission

There are some goals for Mars exploration and the purpose of the Mars mission was to achieve those goals. Therefore, there are specific four scientific goals that are fixed for Mars exploration and the selected strategy is based on those goals. Thus, the first goal is to investigate the Mars planet ***if there is any possibility to be alive on Mars***. Therefore, the second goal is to ***gain knowledge about the climate of Mars***. Hence, by achieving this goal the scientist will be able to know if the climate of Mars is appropriate for life. Apart from that, the third goal of this mission is to ***investigate the geology of Mars*** (Mars Exploration, 2021). Thus, by achieving this goal scientists will be able to gain knowledge if the climate of Mars ever can be accurate for life. Furthermore, the last and forth goal of this mission is to ***prepare for human exploration on Mars*** after the rover exploration. Hence, to achieve the last goal the scientists have to achieve the other three goals as knowing the possibility of life on Mars is important before human exploration on Mars.

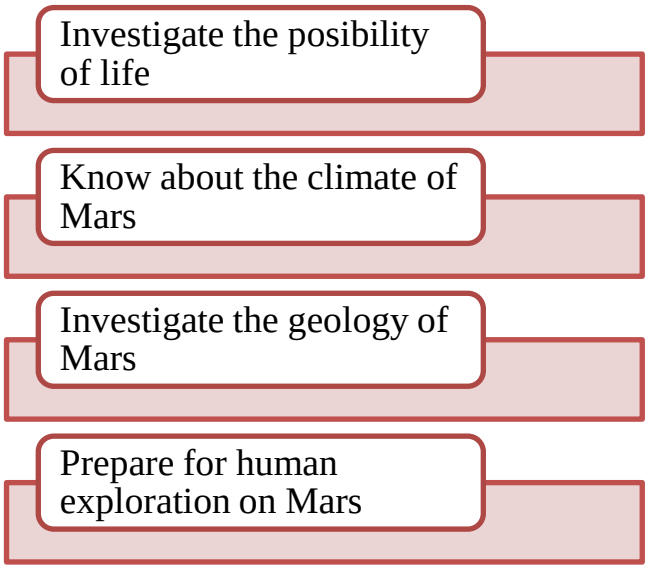

Figure 2.2.1: Purpose of the Mars mission
(Source: Mars Exploration, 2021)

2.3 Findings from the Mars mission

The Curiosity rover has been very helpful to know about the climate of Mars as the main motive of Mars mission is to gain knowledge about the climate and habitability on Mars. Therefore, in the year 2021 Curiosity has sent some interesting photos of Mars and those photos are exploring the environment of Mars. Thus, the Curiosity rover spotted clouds in Mars as the planet is always dusty and dry, capturing clouds is big news for the scientists. Furthermore, the Curiosity rover has spotted several types of cloud on Mars such as drifting clouds, twilight clouds and iridescent clouds (Shining Clouds on Mars, 202). Therefore, this is a positive sign for NASA to achieve the goals of the mission.

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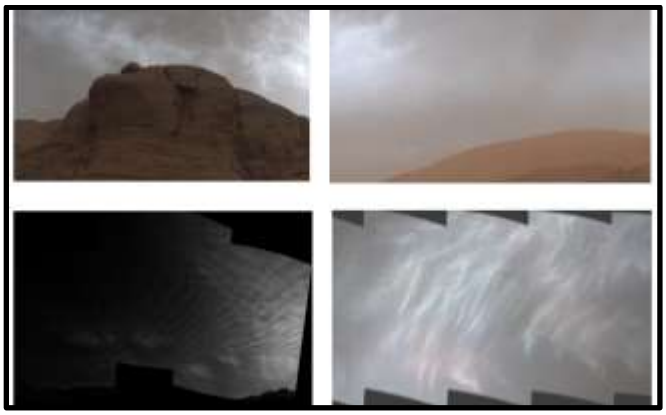

Figure 2.3.1: Different types of clouds in Mars
(Source: Shining Clouds on Mars, 202)

Apart from that, not only clouds but also organic salts are found on Mars and this is another chance to have an ocean on Mars. Moreover, it is also identified that the salts are chemical remnants that are made by organic compounds (Organic salts in Mars, 2021b). Thus, these salts are also very important for scientists as it helps to know about the geologic part of Mars.

Figure 2.3.2: Organic salts in Mars
(Source: Organic salts in Mars, 2021b)

On the other hand, there are lots of rocks that can be found by the Curiosity rover and among all of them the rover has sent a 360-degree viewpoint of Mont Mercou. Therefore, all the rocks on Mars are made of chemicals (Mont Mercou, 2021c). Thus, the Mont Mercou is one of the most important and beautiful rocks on the planet.

Figure 2.3.3: 360-degree viewpoint of Mont Mercou
(Source: Mont Mercou, 2021c)

Along with that, the Curiosity rover has found a location that is named Mary Anning. Therefore, the Curiosity rover has made three drill holes in the Mary Anning (Mary Anning, 2020). Apart from that, the robotic Curiosity rover took a selfie with the location on the red planet.

Figure 2.3.4: Curiosity rover with Mary Anning
(Source: Mary Anning, 2020)

Apart from that, the Curiosity rover has sent the weather report of Mars and that is helpful to gain knowledge about the climate change on Mars. In the month of June of the recent year the ***maximum temperature is -18°F*** and ***minimum temperature is -107°F*** on Mars. In addition to that, the ***average sunrise time is 06:10*** and the ***average sunset time is 17:56*** on the red planet according to the Curiosity rover (Mars Weather, 2021). Therefore, the Curiosity rover has sent several news about the temperature of Mars in the year 2021 that is analysed in the table. Thus, these are the findings or information from the Curiosity rover about several conditions on Mars.

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Date	Maximum Temp.	Minimum Temp.
May 27, 2021	-8°F	-107°F
May 29, 2021	-9°F	-107°F
May 30, 2021	-8°F	-108°F
June 1, 2021	-9°F	-108°F
June 2, 2021	-18°F	-107°F

Table 1: Temperature review of Mars in recent months
(Source: Mars Weather, 2021)

III. SYSTEM ENGINEERING IN MARS EXPLORATION ROVER

3.1 Mars Exploration Curiosity Rover

There are a lot of rovers that are made for Mars explorations such as Perseverance rover, Insight rover, Spirit rover, Opportunity rover, Ingenuity rover and others. These all rovers are very important for gaining knowledge about the red planet but among them the ***Curiosity rover*** is one of the most important rovers. Therefore, theCuriosity rover is sending pictures of several conditions of weather on Mars and pictures of climate change, therefore pictures of several locations and rocks from Mars. In addition to that, in the year 2011 the Curiosity rover was launched on 26th November and in the year 2012 the rover landed on Mars on 6th August. Therefore, the maximum speed of the Curiosity rover is ***0.14 km/h*** and about ***250 crores*** was spent to make this rover (Curiosity Overview, 2021). Thus, the Curiosity rover has been very efficient and effective to send pictures and news about the climate, temperature, locations, rocks and others on the red planet.

Figure 3.1.1: The Curiosity Rover
(Source: Curiosity Overview, 2021)

3.2 System engineering

System engineering is an important part of engineering that is based on designing, integrating and managing systems. Therefore, system engineering plays an important role in the development of system architecture and other operations. There are some models and processes in system engineering and those models are made by focusing on the concept of life cycle. In addition to that, the stages of the models or processes are also based on the stages of life cycle. The stages are concept then development therefore production then utilizing thereafter support and then retirement (Moro *et al.* 2020). These stages are the same as the life cycle stage. Furthermore, system engineering helps to manage the issues of world changing. Therefore, the models are helpful to avoid omissions and help to find out most efficient and effective solutions for the issues. Thus, system engineering is an important part of making rovers and the importance is analysed in this research study properly.

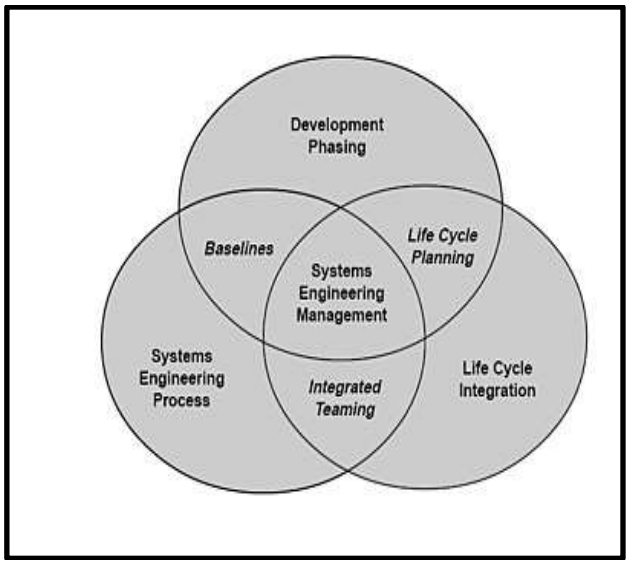

Figure 3.2.1: System engineering
(Source: Moro *et al.* 2020)

3.3 Usage of system engineering in Mars Exploration Rover

System engineering plays an important role in project management of rovers and Mars explorations. The adoption of the system engineering supports in enhancing shorter project cycles with help of a resilient system. According to (Donahue, 2019), adoption of resilient systems supports enhancing rate of functionality in operation. In the engineering process of Mars Exploration rovers, system engineering supports in conduction of functionality verification as lower down rate of defects. There are some processes under system engineering in project management of rovers such as ***system design process, product realization***

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process and ***technical management process*** (Systems Engineering, 2019). In the first process of system engineering, there are four steps of designing the system such as expectation definition, technical requirements, logical activities, and design solution. Therefore, in this first process of system engineering the goals and requirements will be set and then a design definition of the final system will be analysed.

Figure 3.3.1: Processes of system engineering
(Source: Systems Engineering, 2019)

On the other hand, in the second process there are five steps such as implementation of the product then integration of the product therefore verification of the product thereafter validation of the product and then transition of the product. These five steps are helpful to make efficient and effective products and this is an important process of system engineering. Along with that, the third and last process of system engineering has eight different steps to complete the process. Therefore, the steps are technical planning, management of requirements, management of interface, management of technical risks, management of configuration, and management of technical data, technical assessment and analysis of the taken decision (Yu *et al.* 2019). Thus, these processes are very important for the making of the rovers and exploration of Mars. Furthermore, there are some project management activities that are essential in system engineering such as creating a project team. Therefore, creating an efficient and effective project team is the most important part of project management for taking several decisions for the operation.

IV. MATERIALS AND METHODS

The Radiation assessment Detector (RAD) instrument was used by the ***Curiosity Rover*** to measure the extent of surface radiation in Mars. This instrument was equipped with a solid-state detector telescope and combined charged and neutral particle detector (Hassler *et al.* 2014). Apart from that plastic scintillator along with a CsI calorimeter is attached to detect the neutron. The detection of neutrons and γ- rays was done through an anti- coincidence logic in the detector. It is evident that the RAD is associated with a wide range of detection to measure ionic radiation of all charged particles on Mars's surface. Surface radiation with a geometry factor of approximately 0.9 cm^2 sr. is measured by the RAD instrument. Different fluxes to stop the charged particles were also quantified by this instrument. Particles with a maximum energy range of 95 MeV/nuc for protons and ^{4}He and 450 MeV/nuc for ^{56}Fe are measured in this regard.

A wide range of energy of radiation ranging between 10 MeV and 10 MeV were identified for neutral particles. The RAD used suitable dE/dx resolution to discriminate among major particles of radiation (Da Pieve *et al.* 2021). However, the resolution is measured in silicon and its dynamic range spans between 0.2 and 1000 KeV/μm of Linear Energy Transfer (LET) range in water. Biological effectiveness of a wide range of radiation was measured by convoluting the LET range with a quality factor. It is termed as ***Dose equivalent;*** that is a physical quantity having the unit of Grey. It signifies the capacity of energy absorption by biological tissues; having the unit of Sieverts. An observation was done on 11th April, 2013 to measure the radiation of ***Solar Energy Particles (SEP)*** on the Mars surface (Vicente-Retortillo *et al.* 2018). As per the dose rate shown in the following figure, that spectrum of energy was not able to produce ~30% of the Galactic Cosmic Rays on Mars surface.

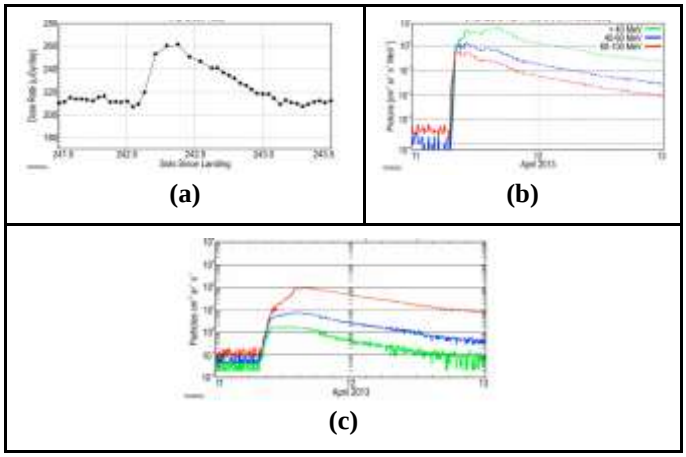

Figure 4.1: (a) RAD Dose rate, (b) 15 minutes data for STEREO B HET Protons, (c) 5 minutes data for GOES 13 proton flux
(Source: Vicente-Retortillo *et al.* 2018)

Above data of dose rate was observed on the Surface of Mars by RAD at the conjunction point of Mars with the Sun on Sol 242 as shown in figure (4.1 a). Another figure (4.1 b) depicts the observation taken by the spacecraft named STEREO- B placed in a magnetically aligned position with Mars. Figure (4.1 c) shows the SEP observed by the satellite named GOES-13 positioned on the earth orbit.

As per recent data the exploration programme is associated

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with two instruments termed as ***MAHLI*** and ***APXS;*** chosen for the analysis of nodular characteristics of ***Cladech*** (O'Connell-Cooper, 2021)**.** Apart from that these instruments are also used to conduct the analysis of a target of bedrock named ***Beauronne.*** It is found that the combination of these two arms helps the team in measuring the nodular feature of bedrock in respect of enrichment and depletion. The second bedrock target named as ***Lamourette*** is analysed by using the active mode of ***LIBS*** by the ***ChemCam.*** On the other hand, the passive mode is used to analyse ***Petit Bersac;*** the dark vein. A handful of data is gained through surveys by the Mastcam team regarding the intrigued texture of the workspace. This data is useful to monitor the environmental activities on the Mars surface to measure the amount of dust particles over the workspace.

Figure 4.2: Image of workspace taken by Curiosity on Sol 3138
(Source: O'Connell-Cooper, 2021)

Seasonal deposition of dust and lifting of these particles over the Mars surface is also observed by the curiosity rover. It is beneficial to study the effect of dust on the assets placed over the Martial surface. The Rover Environmental Monitoring system (REMS) associated with the Mars Science Laboratory (MSL) Curiosity Rover is equipped with a wide range of sensors to measure several physical quantities on the Martial surface. Parameters such as pressure, temperature of ground and air, wind speed along with the ultraviolet radiation in six bands ranging 200 to 380 nm are explored by the REMS (Millan *et al.* 2020). As the UV sensor is placed over the deck of the rover it is easily utilized to measure the amount of dust accumulation and its removal by the atmospheric process. Master camera is used to quantify the opacities of aerosol by using the Mars hand Lens Imager (MAHLI) camera. This instrument is used to measure the atmospheric process of dust accumulation on the rover surface.

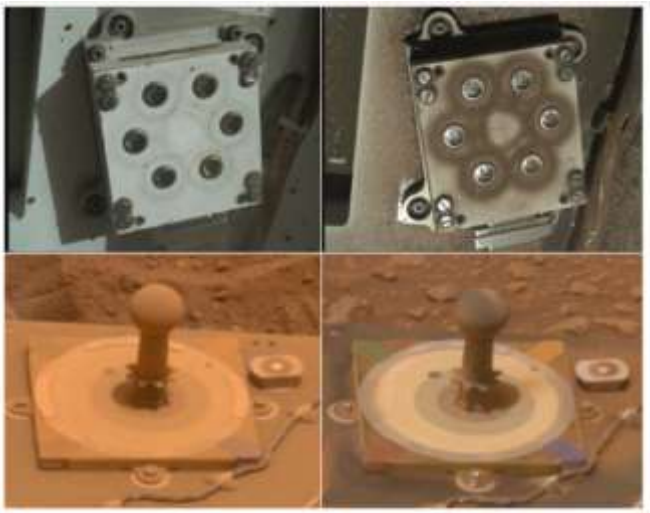

Figure 4.3: Dust accumulation observed by the MAHLI camera
(Source: Millan *et al.* 2020)

V. RESULTS AND DISCUSSION

The Curiosity rover landed on the Martial surface on 6th August, 2012 and the RAD started taking observations regarding the radiation on the Martial surface. These observations are reported based on the radiation Dose rate during the first 300 sols on Mars (Bell III *et al.* 2017). By using the single ended geometric factor and coincidence of two detectors the fluxes for charged particles are determined for both the cruise and Martial surface. It was observed that during the first 300 sols an average solar modulation was present over the Martial surface as compared to that on the cruise.

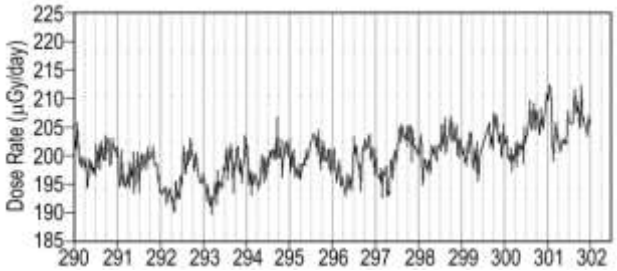

Figure 5.1: Image of Sols since landing
(Source: Bell III *et al.* 2017)

It is observed that differences in the dose rate occur under the influence of several factors such as shielding of the lower hemisphere and interaction between atmospheric

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nucleons and the primary GCRs (Ehresmann *et al.* 2021). In the following figure several observations conducted by the RAD measurement are represented along with the measured data.

RAD Measurement	Mars Surface	MSL Cruise	Units
Charged Particle Flux (A * B)	0.64 ± 0.06	1.43 ± 0.03	$cm^{-2}\ s^{-1}\ sr^{-1}$
Fluence Rate (B)	1.84 ± 0.34	3.87 ± 0.34	$cm^{-2}\ s^{-1}$
Dose Rate (Tissue-like) (E detector)	0.21 ± 0.04	0.48 ± 0.08	mGy/day
Avg. Quality Factor <Q>	3.05 ± 0.26	3.82 ± 0.30	(dimensionless)
Dose Equivalent Rate	**0.64 ± 0.12**	**1.84 ± 0.30**	**mSv/day**
Total Mission Dose Equivalent (NASA Design Reference Mission, DRM)	320 ± 50 (500 days)	662 ± 108 (2x180 days)	mSv

Figure 5.2: Measurement of radiation environment by MSL RAD
(Source: Ehresmann *et al.* 2021)

In recent times it is found by the two arms of MAHLI and APXS that ***Minzac*** is an area over the bedrock that occupies smaller space. This area is found as free from any kind of veins and nodular particles. ChemCam is used to shoot across the bedrock and the nodule to capture the target of ***Vayres*** (Nikiforov *et al.* 2020). It is also used to have a multispectral observation at that target while the Mastcam is used to acquire a small mosaic of ***Larzac.*** It is clear from the above observation that chemical composition and structure of several physical assets such as water, salt and organic matter extensively depends on the radiation of ionisation. As per latest findings heat and dust particles play a significant role in launching Martial water into space (Mars Exploration Program, 2021). Another instrument of NASA's Mars exploration named as ***MAVEN*** found pulsation of Martian night sky in ultraviolet rays.

Apart from that the most important incident happened on 21st April, 2021 by the extraction of oxygen done by the Mars rover for the first time (Mars Exploration Program, 2021). Apart from that NASA has started to search for a suitable place for humans to land, live and work on the Martial surface. It is expected by the scientists that liquid water could be extracted from the heap of ground ice. Water is also expected to be extracted from the atmosphere and hydrated minerals. The ***Curiosity Rover*** is also equipped with an instrument named as ***MOXIE*** for demonstrating the technological advance used in extracting oxygen on the Martial surface.

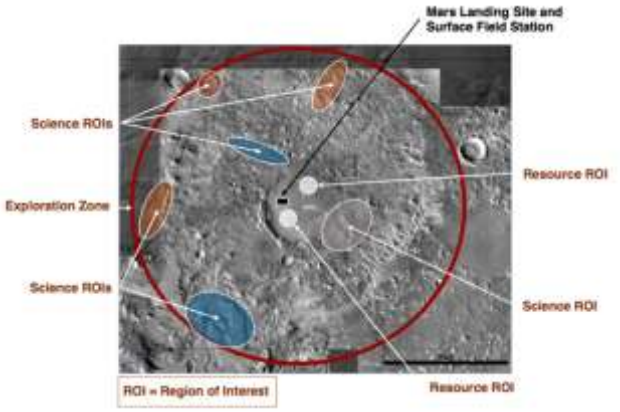

Figure 5.3: Layout of the exploration zone
(Source: Mars Exploration Program, 2021)

The scientists have also measured the amount of dust accumulated over the sensor of the REMS by means of calculating a parameter termed as ***dust correction factor (DCF).*** It is quantified by calculating the ratio between the fractions of the UV ray that reaches the photodiode through the dust accumulated to the fraction reached at the beginning. It is found that the DCF obtained by this calculator is evoluted in a temporal way for the UV radiation ranging 300 to 350 nm (Zhang and Guo, 2021). In the figure given below temporal evolution of the DCF obtained during the Martian year 31, 32 and 33 is represented.

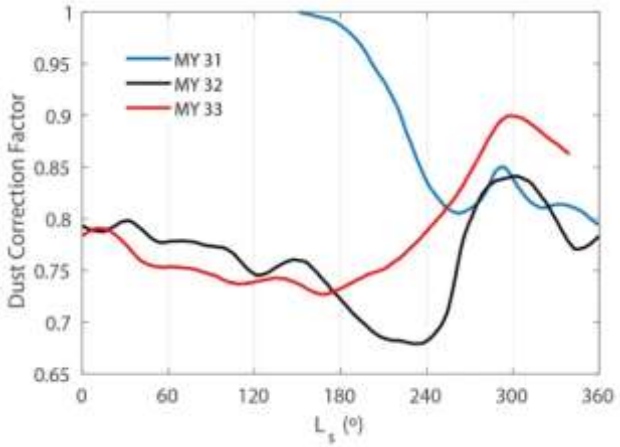

Figure 5.4: Temporal evolution of dust correction factor
(Source: Zhang and Guo, 2021)

Based on the above graph it can be stated that the dust accumulated over the sensor of the rover is not increased thought the mission as the dust cleaning events contribute to lower the DCF value below ~0.7. However, several atmospheric features are found by the scientist through the ***Crucial Rover.*** It is found that the Martian atmosphere is mainly composed of 96% carbon-di-oxide and other

constituents include gaseous substances such as nitrogen and argon (Mars Exploration Program, 2021). A thin atmospheric condition is also found that contributes to lower the atmospheric pressure of Mars about 0.6% that of earth. Scientists think that the Martian atmosphere was thicker in earlier times and due to a significant amount of atmospheric losses over time it became thinner and reached its present condition. Solar wind is identified as the major cause of atmospheric thinning on Mars by scientists.

A wide variety of rocks are found on Mars that includes the types of igneous basalt, sedimentary sandstone and evaporites, mudstones and impactites. Main constituents of these rocks are found as oilivine, amphiboles, carbonates, different forms of sulphates, phosphates hematite and others (Mars Exploration Program, 2021). Apart from the rocks a wide variety of landforms are also found over the Martian surface. It includes ***wind-formed dunes, transverse aeolian ridges and recurring slope lineae.*** Through this exploration mission scientists also make several analogies between different sites on the earth surface and the Martial surfaces. For instance, scientists compare the basalt rocks accumulated in Iceland with the basalt fired land on Martial surface. Cold and dry weather is compared with the atmospheric condition of Antarctica. Along with that basaltic shield volcanoes of Hawaii are compared with the ***Olympus Mons*** on Mars (Mars Exploration Program, 2021). Scientists have identified that there are no active tectonic plates present over the Martian surface as compared to earth. Moreover, there is no active global magnetic field and no source of stable liquid water on the Martian surface. A large number of craters are found over Martian surface in comparison to earth. Scientists have identified that due to change in weather conditions a huge span of the Martian surface has changed over time. Presently the programme is associated with ***propulsion and guidance technology*** along with a safe ***planetary protection technology*** (Mars Exploration Program, 2021). Such technologies are presently under in-space sterilization process to investigate and attain an appropriate development. Moreover, the development of technologies also contributes to exploring the planet through sending human beings rather than robots in the future.

VI. CONCLUSION

In conclusion, it can be said that the Curiosity rover is one of the most efficient and important rovers among all. Thus, it is very helpful to gain knowledge about several conditions of Mars. Therefore, the Curiosity rover helped to know the climate change system of the red planet from the year 2012 to the recent years. Furthermore, the Curiosity rover is helpful to gain knowledge about the regular temperature of the planet. Thus, the maximum and minimum temperatures in the recent months on Mars are described in this research study properly. Thereafter, the strategy that the NASA scientists use for the Mars exploration is analysed in this research study significantly. Along with that, the goals or purpose of the Mars mission is described briefly in this research study. Therefore, system engineering has a great impact on the exploration of Mars and rovers. Thus, those impacts are analysed in this research study properly. Thereafter, the processes under the system engineering that are used in project management of Mars exploration is another description of this research study. Thus, the methods that are used by the researcher in this research study are also described briefly in this research study. Therefore, the methods were helpful for the researcher to gather proper and accurate information about the research topic. Hence, it can be said that system engineering is important for the exploration of Mars.

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