AIAA 2014-3820

Propulsion and Energy Forum
July 28-30, 2014, Cleveland, OH
50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference

Mars Aerial Nuclear Global Landing Explorer: A Global Mobility and Multi-Mission Platform

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Abstract

This paper conducts a preliminary feasibility study on a novel global mobility and multi-mission Mars exploration platform, Mars Aerial Nuclear Global Landing Explorer(MANGLE). MANGLE is an aerial and ground system powered by nuclear propulsion to fly in Martian atmosphere with vertical take-off/landing capability. The Martian atmosphere, composed of 95.3% carbon-dioxide, will be used as propellant for an air-breathing engine heated by a fission nuclear reactor based on the open Brayton cycle. The engine will generate both thrust and accessory power. The cruise Mach number of MANGLE is 0.41. The engine power required is 2.1MW at takeoff/landing and 0.4MW at cruise. The total system mass is 899kg. The low weight of the vehicle is attributed to the lack of carried on propellant and radiator as well as the extremely high power and energy density of nuclear fission. The ultra-high lift co-flow jet flow control airfoil will be implemented on the blended wing-body configuration to achieve a cruise lift coefficient of 3.5, which is 5 to 10 times higher than a conventional airfoil. MANGLE will not only perform a scientific mission to investigate the Martian atmosphere, but will also land to collect soil samples at locations of interest observed from aerial survey. A deep drill of the soil sample up to 1 meter or more is possible due to the high shaft power from the air-breathing engine. MANGLE can transport the acquired ground samples to a base on Mars for sophisticated examination. The MANGLE mission period is one Martian year in order to investigate the seasonal variation of the atmosphere and surface soil. MANGLE will fly for 2/3 of the total mission time to survey the atmosphere and surface and the remaining 1/3 of the time will be spent on the ground for surface sample collection and examination. The range is sufficient to circle Mars 160 times during the mission.The preliminary feasibility study indicates that the MANGLE concept is feasible and the required technologies are achievable. MANGLE will revolutionize Martian scientific missions by enormously increasing the mobility in the atmosphere and on the ground, significantly benefiting mankind's efforts to explore the Martian planet.

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1 Introduction

One of NASA's major strategic goals is to expand the frontiers of knowledge, capability, and opportunity in space. Mars exploration has the high priority with the motivation to discover the possible existence of extraterrestrial life.

In 1999, NRC published the guideline for essential capabilities of space exploration[1]. The most important conclusion from their study is that "mobility is not just important for solar system exploration–it is essential. The case is exemplified for Mars, where spacecraft mobility would enable major advances in understanding climate change and geologic history and in searching for direct evidence of past life"[1]. The second conclusion from the NRC study is that the diversity of planetary environments to be explored requires simultaneous development of some combination of wheeled rovers, aerobots(balloons), aircraft, and touch-and-go orbiters. The NRC study requires the platform mobility to have extensive range and long lifetime. Furthermore, for soil sample acquisition and examination, it is necessary to remove the thin rind of weathered materials on the planet soil surface. Even though the compositions of the rinds are of great interest, they will not provide a reliable inventory of the elements present in the fresh material. The NRC study points out that it is extremely important to develop the capability to drill deep into the soil up to depth of one meter or more instead of just micrometers to a few center meters. The high mobility and deep drilling capability pose extreme challenges to the spacecraft, which is limited by their weight, size, power, and energy available. Current spacecraft still have not met the requirements outlined by the NRC study[1].

As the efforts of deep space exploration, NASA has sent landers, rovers, and orbiters to Mars to perform various scientific missions, including the recent Curiosity rover and MAVEN orbiter. These rovers have the ability to examine surface samples, but the range is at a "point" scale. The orbiters do have a global scale range, but the high altitude limits the observation resolution and there is no capability to examine near surface atmosphere, such as crustal magnetization, spatial variability, potential biogenic gases, volcanic gases, and Martian atmosphere's boundary layer, etc.

To bridge the gap between rovers and orbiters for science missions with high resolution survey from 1-2km kilometer range, many efforts have been made to develop Martian aircraft. There are two challenges in designing an aircraft for Mars: 1) low atmospheric density and low Reynolds number, which causes conventional airplanes to have low wing loading(i.e. large planform area); 2) the carbon-dioxide dominant atmosphere can not be used as an oxidizer for air-breathing engines to generate high thrust.

In the late 70's, comprehensive Mars airplane concepts were studied by DSI with NASA[2]. The "Mini-Sniffer", developed by Akkerman, proposes a hydrazine fuel engine with a propeller and made it to the final concept list. However, its scientific mission is limited due to the small payload and short range. Other power systems considered included battery and fuel cell systems, which were not feasible due to low power density.

The ARES(Aerial Regional-scale Environmental Survey of Mars)[3] airplane was a rigorous effort made by NASA in the early 2000's to achieve an advanced science mission. It cruises at Mach number 0.65, with an altitude of 1.5km and CL=0.5-0.7. ARES is powered by a rocket engine with a fuel payload of 48kg. ARES has a total mass of 175kg, flight range of 500km to 600km, flight time of 4.2 hours, and endurance time of 60-70 minutes.

Another potentially useful airborne system for Mars exploration is balloons, which either use the gases lighter than the ambient atmosphere or heat the enclosed ambient atmosphere gas. A balloon with the autonomous position, altitude control capability, and landing capability is termed an "aerobot". The balloons share many of the advantages of Martian aircraft. However, they have some serious disadvantages: 1) the payload is very limited due to the thin atmosphere on Mars and the large size of the balloons; 2) it is very difficult to control navigation, altitude changes, and landing in the Mars environment.

In general, the above platforms have a single mission. For example, the rovers can only examine a very small designated land area and can not survey the atmosphere. The low power radioisotope thermoelectric generator used to power rovers are not able to conduct deep sample drilling. The airborne systems of aircraft and balloons may have a regional scale range, but have no or very limited capability to examine the soil on Mars surface.

Since it is very costly to send any mass to Mars due to the long distance and travel time, it is appealing to send a robotic system with minimal weight that is able to perform multiple scientific missions to explore both the surface and atmosphere of Mars with global scale mobility. Such a system will revolutionize our venture to understand Mars and the ability to explore this neighboring planet. This paper proposes and studies such a platform.

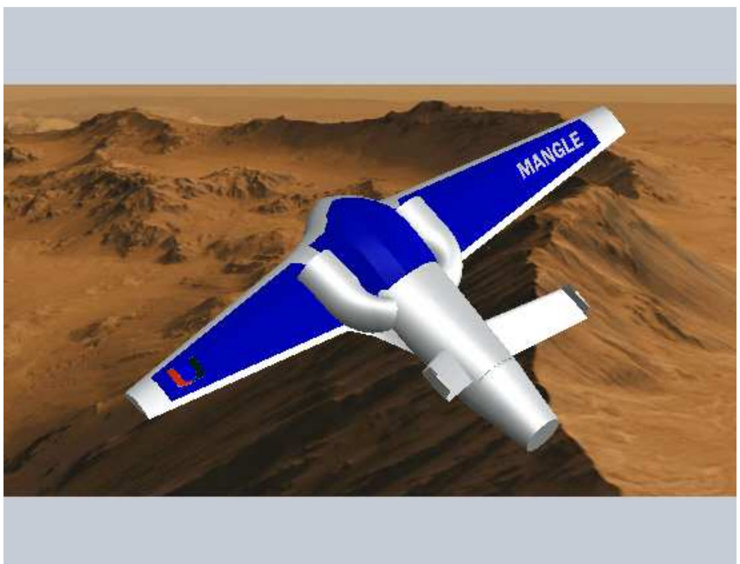

Figure 1: MANGLE at cruise.

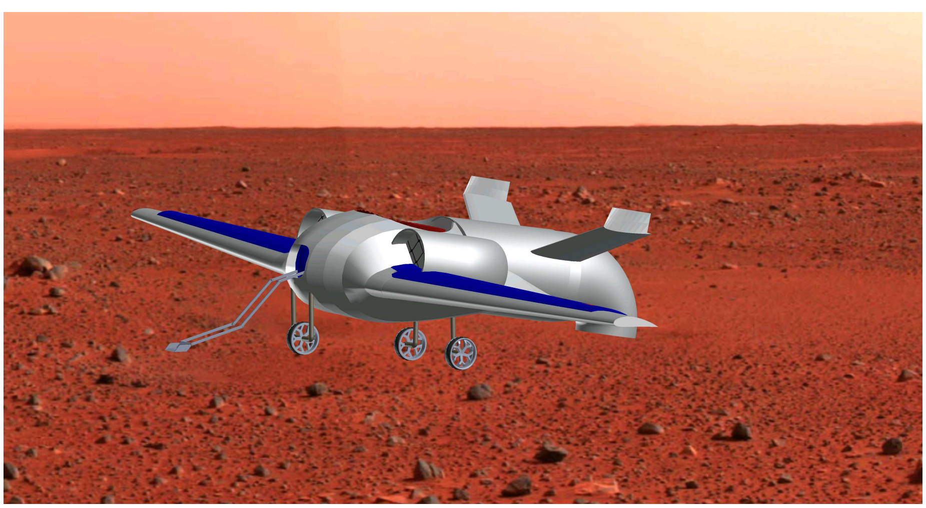

Figure 2: MANGLE vertical landing to take soil sample.

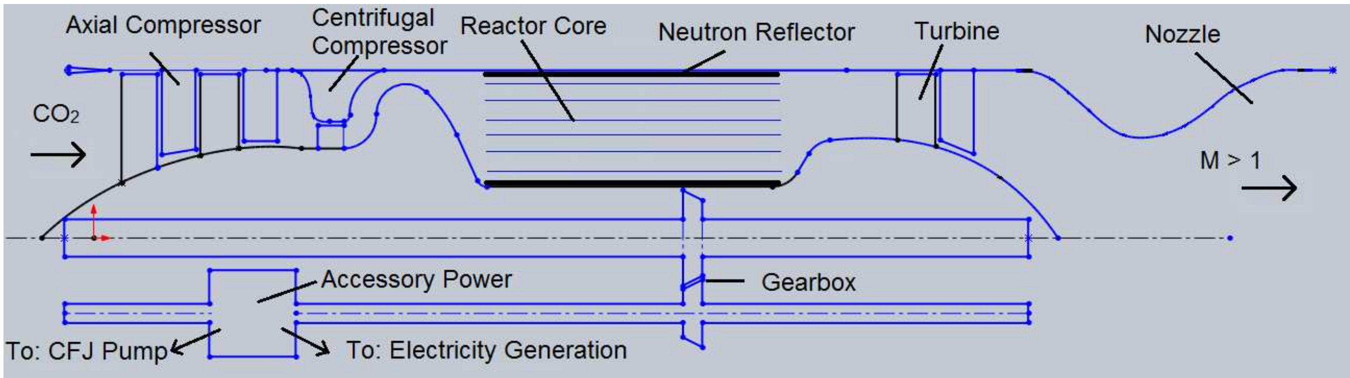

Figure 3: Carbon-Dioxide air-breathing engine sketch.

2 Mars Aerial Nuclear Global Landing Explorer Concept

This paper proposes a novel multi-mission Martian explorer platform with global mobility[4], the Mars Aerial Nuclear Global Landing Explorer(MANGLE). This is an aerial and ground system powered by nuclear propulsion to fly in Martian atmosphere as shown in Fig. 1 and 2. MANGLE has the vertical takeoff/landing capability realized by a lifting fan in the front and a vectored nozzle at the end of the engine. It is able to roam within a very short range on Martian surface to adjust its position for sample acquisition and examination. The 95.3% carbon-dioxide based Martian atmosphere will be used as propellant for an air-breathing engine heated by a fission nuclear reactor based on an open Brayton cycle as sketched in Fig. 3. The engine will generate both thrust and accessory power. The minimized weight of the vehicle is attributed to no carried on propellant and radiator as well as the extremely high power and energy density of nuclear fission. The ultra-high lift co-flow jet (CFJ) flow control airfoil, shown in Fig. 4, will be implemented on the blended wing-body configuration to achieve a cruise lift coefficient of 3.5, which is 5 to 10 times higher than that of a conventional airfoil. The multi-mission system requires a large amount of energy consumption, which is satisfied by the enormous energy capacity of the nuclear propulsion system.

2.1 Mission

MANGLE is a multi-mission robotic system. It will not only perform a science mission to investigate Martian atmosphere on crustal magnetization, spatial variability, potential biogenic gases, volcanic gases, and Martian atmosphere's boundary layer, but also land to collect and examine soil samples at the locations of interest determined from the aerial survey. MANGLE can transport the acquired ground samples to a base on Mars for a sophisticated examination. The MANGLE mission period is one Martian year to investigate the seasonal variation of the atmosphere and surface soil. MANGLE will fly for 2/3 of the total mission time to survey the atmosphere and surface and use remaining 1/3 of the time on land for ground-based surface sample collection and examination. The soil sample drill up to 1 meter depth or more is possible by the high power engine shaft on the ground, where no thrust and lift are needed. However, incorporating the drilling system is not included in this design and will be left for future study. The range is sufficient to circle Mars 160 times during the mission. The MANGLE concept can also lay a foundation for future manned vehicles used on Mars. It also has the potential to be used for Venus exploration due to the high concentration of CO_2 in the Venus atmosphere.

2.2 Impact

Realization of MANGLE will revolutionize our capability to explore Mars with enormous mobility and capability to examine atmosphere and soil samples. The MANGLE concept can also lay a foundation for future manned vehicles used on Mars. Out of all the previous Mars airplane and rover platforms studied in the past several decades, no air-breathing engine with nuclear propulsion concept has ever been considered or studied. The concept also has the potential to be used for exploration of Venus due to the high concentration of CO_2 in the Venus atmosphere. Furthermore, the MANGLE technology could be also used for high altitude long endurance surveillance aircraft on Earth, which can cruise and loiter for environment monitoring for years without landing.

3 Preliminary Feasibility Study

When the concept of MANGLE came to mind, the immediate questions asked were: Is this feasible? Is there a credible nuclear reactor that can be used to heat the thin air of Mars, which is mostly carbon dioxide? Is the heat transfer of the reactor sufficient to heat the CO_2 to the desired temperature to replace the combustor? What should the thermal cycle of the engine be? Will the system generate enough lift and thrust? What will a functional size and weight of MANGLE system be? How can the low Reynolds number flows prone to be stalled overcome?

To answer all these questions, a preliminary analysis of MANGLE system with aerodynamics, propulsion, thermodynamics cycle, nuclear reactor, heat transfer, and structure is conducted based on the first order principle of physics and existing technologies. The conclusion is: the MANGLE concept is feasible and the required technologies are challenging, but achievable. The guideline is to minimize the weight and size of the system by sacrificing some of the energy efficiency, which will be compensated by the abundance of energy from the nuclear reactor.

Table 1 is the summary of some of the preliminary conceptual design results. The constraint is that MANGLE must be fit to the size of the MSL Aeroshell with one simple fold of the wings. Fig. 1 and 2 show the design configuration. The MANGLE-MITEE uses the MITEE[5] nuclear reactor. All the calculations are based on Mars ambient density, pressure, temperature, and gravitational acceleration. Some of the basic formulations are given in Appendix A. The results in Table 1 demonstrate the feasibility of the concept with no optimization. It is expected that the system will have further reduced weight and size when a systematic optimization is conducted.

3.1 Weight analysis

The total weight of the system is crucial to determine the feasibility of the system. We have developed a weight analysis tool for each component based on structure analysis, materials, scaling from existing components, empirical data and correlations, etc. The preliminary system weight shown in Table 2 has all the mission essential components, including instrumentation suite, avionics system, communication components, landing gear, aircraft skin and structure support, air-breathing engine and its components(sand filters, compressor, turbine, nozzle, etc), nuclear reactor(fuel elements, control rods, reflectors, etc), nuclear shield for electronic components, battery and supercapacitor system, lifting fan, co-flow jet pumps, and miscellaneous weights. The weight analysis is an iteration process within the whole design procedure.

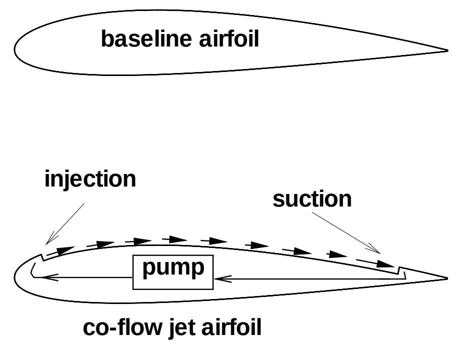

Figure 4: Co-flow jet flow control airfoil.

3.2 Propulsion system

The proposed propulsion system is an air-breathing engine as sketched in Fig. 3. The carbon-dioxide mass flow from the Martian atmosphere will be drawn into the compressor via the inlets to achieve a high pressure, then go through the numerous thin tubes(100 to 300 μm diameter) of the fission nuclear reactor as laminar flow to absorb the heat. The flow will then strike the turbine with high enthalpy and output power to drive the compressor and accessory power systems, expanding through a converging-diverging vectored nozzle at supersonic speed to generate thrust. Finally, it will be exhausted into the Martian ambient. A bifurcated engine inlet system is adopted to minimize the engine inlet flow interaction with the lifting fan inlet flow. A centrifugal sand filter will be installed at the engine inlet to avoid any possible flow blockage in the nuclear reactor. The engine and nuclear reactor will be completely shut down and remain cold during the travel to Mars and will be started after detaching from the launch vehicle by a high power supercapacitor within a few seconds. The initial deployment procedure similar to ARES will be utilized.

Due to the vertical takeoff/landing, the propulsion system requires a wide operating range to handle the disparity of performance at takeoff/landing and cruise. For example, the mass flow of the engine is 0.5kg/s at cruise and the reactor exit fluid temperature is only 1400K, but they are increased to 2kg/s and 1800K respectively at takeoff. The reactor temperature is intentionally chosen to be below 1800K to achieve high safety of the reactor system and easy cooling for the turbine downstream of the reactor. The MITTE reactor's design temperature is 3000k, which means that there is room to further increase the reactor temperature. A higher reactor temperature will lead to a higher power output, hence a lower mass flow rate required and a smaller engine size and weight. The optimal reactor temperature needs to be further studied with the specific engine technology to be adopted.

The proposed compressor is composed of a 2 or 3-stage axial compressor in the front and a centrifugal compressor aft to reach a pressure ratio of 50:1 in a compact space. The axial compressor will have an overall pressure ratio of 4-5 and the centrifugal compressor will have a pressure ratio of 10-13. The pressure ratio of 50 is not an essential requirement and can be as low as 30 to 40. The engine inlet will be ensured un-choked at take off due to the high mass flow rate. It does pose a challenge to the compressor with high subsonic inlet Mach number at takeoff. However all the performance requirements are within the current technology capability even though they are at the

Parameters	MANGLE-MITEE
Total system mass	899kg
Planform area	12m^2
Mach at cruise	0.41
Cruise Altitude	1.5km
L/D (lift/drag as efficiency)	8
CL (lift coefficient)	3.5
Engine Mass Flow(CO2)	0.5kg/s (cruise), 2kg/s (takeoff)
Engine Diameter	0.98m
Engine length	1.7m
Compressor pressure ratio	50
Nuclear reactor core mass	315kg
Nuclear Shield mass	274kg
Reactor exit temperature	1400K (cruise), 1800K (takeoff)
Max fuel temperature	1800K
Total thermal Nuclear Power	0.4MW (cruise), 2.1MW(takeoff)
Lifting Fan mass flow	3.6kg/s
Lifting fan diameter	1.3m
Lifting fan power required	0.4MW
Operating period	1 Mars year
Range(2/3 time flying)	4x10^6 km

Table 1: MANGLE performance summary

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Instrument/Item		Mass(kg)	Weight(N)
Instrumentation Suite	Magnometer (x2)	10	37.1
	Pamoramic Camera (x2)		
	Point Spectrometer		
	Mass Spectrometer		
	Air Data System		
	Barometer		
	Radar Altimeter		
Computer and Data Collection System		5	18.55
Communication Components	UHF Antenna	5.85	21.7035
Landing Gear		12.2	45.262
Aircraft Skin		30.88	114.56
Aircraft Structural Support		100.73	373.7083
Jet Engine	Dust Filter	10	37.1
	Engine Components	73.03	270.9413
	Shield	273.45	1014.487
	Fuel Assemblies (54)	154.6	573.566
	Control Assemblies (12)	18.27	67.7817
	Side Reflector (Inner and Outer)	116.4	431.844
	Top Reflector	25.4	94.234
Battery System	Capacitor	15	55.65
	Battery	8	29.68
Lifting Fan		15	55.65
Co-Flow Jet System		5	18.55
Radioisotope Heater Units (12)		0.5	1.855
Miscellaneous Weights		30	111.3
Weight Totals:		899.307	3336.43

Table 2: MANGLE system components and weight

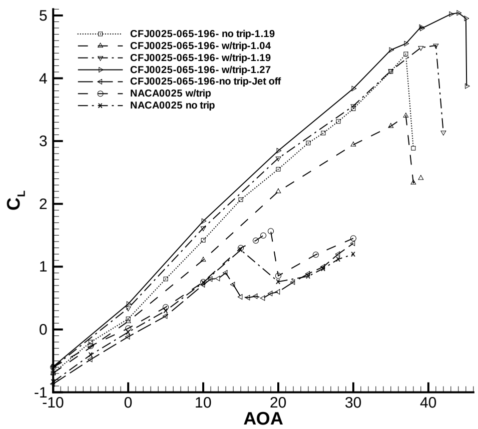

Figure 5: Measured lift coefficient of a CFJ airfoil in wind tunnel testing.

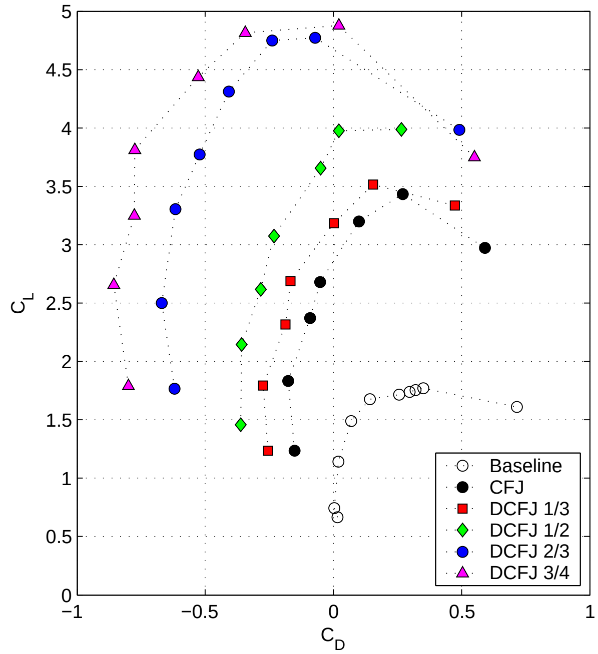

Figure 6: Comparison of the measured drag polars of discrete CFJ airfoils with different obstruction factors, $C_\mu^* = 0.25$ [6].

experimentally demonstrated to drastically

technology forefront and may be near the limits. The compressor power required is determined by:

$$P = \frac{\dot{m} C_p T_{t1}}{\eta} (\Gamma^{\frac{\gamma-1}{\gamma}} - 1) \tag{1}$$

Where $\dot{m}$ is the mass flow, C_p is the constant pressure specific heat, T_{t1} the total temperature at the compressor inlet, η the compressor efficiency, Γ the total pressure ratio, and γ the specific heat ratio of CO_2. The compressor is driven by the turbine via the engine shaft. The turbine will have 1 to 2-stages with an inlet temperature intentionally selected to be below 1800K so that conventional turbine cooling technology can be used to minimize the engine weight without a complex cooling system. A portion of the turbine power output will power the accessory components via a secondary shaft and gear system. The accessory components include the lifting fan for takeoff and landing, co-flow jet(CFJ) pumps at cruise, and charging the battery used for electronic equipment and the supercapacitor. The power required for lifting fan and CFJ pump also satisfy Eq. (1), but the pressure ratio is much lower. The nozzle is designed to be fully expanded to Mars ambient pressure to maximize the power output and thrust. The nozzle is a converging- diverging nozzle with an exit supersonic Mach number of 1.5 at cruise and 2 at takeoff and landing.

3.3 Airframe

The proposed airframe is a blended wing-body configuration using CFJ flow control airfoil at cruise altitude of 1.5km, Mach number of 0.4. The planform area is $12m^2$ with wing span of 9.8m, length of 4.3m, and the maximum fuselage height of 0.94m.

The CFJ airfoil is a compact high lift, low-energy expenditure, high control authority, zero-net mass-flux flow control method using fluidic actuators developed by Zha and his team[7, 8, 9, 10, 11, 12, 6, 13]. As illustrated in Fig. 4, a small amount of flow is withdrawn from the CFJ airfoil trailing edge, energized by a pressure pumping system, and then is injected tangentially to mix with the main flow from the leading edge. CFJ airfoil is experimentally demonstrated to drastically increase lift, reduce drag, and increase stall angle of attack(AoA)[10, 7, 9, 12, 6, 13]. Fig. 5 shows a measured CFJ airfoil lift coefficient with the maximum value of 5.0 at momentum coefficient C_μ of 0.3[9]. The stall angle of attack is increased form 19° to 45°. The lift coefficient can continue to go up and surpass the inviscid maximum lift coefficient limit with an increased momentum coefficient[10]. The CFJ airfoil reduces drag while increasing the lift. The drag reduction could be so large and very high thrust(negative drag) could be generated as shown by the measured drag polar in Fig. 6[10, 7, 9, 6]. The aerodynamic L/D is usually very large due to the small drag, or even could be infinity or negative when the drag is zero or negative(thrust). However, the CFJ pumping needs to consume energy. The L/D of 8 used in Table 1 is the effective L/D considering the pumping power for efficiency calculation, and is defined below:

$$\frac{L}{D}_{eff} = \frac{L}{D + P_{CFJ}/V_\infty} \tag{2}$$

where L and D on the right hand side of Eq. (2) are the measured lift and drag respectively, P_{CFJ} is the pumping power required for CFJ and V_∞ is the flight speed.

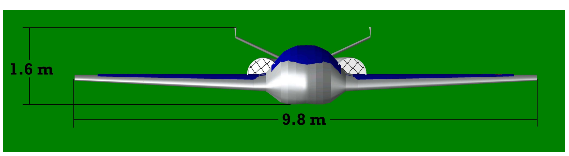

Figure 7: MANGLE front view.

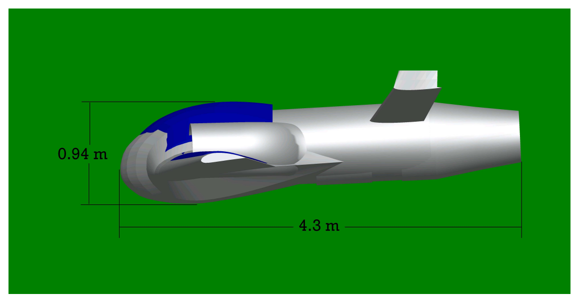

Figure 8: MANGLE side view.

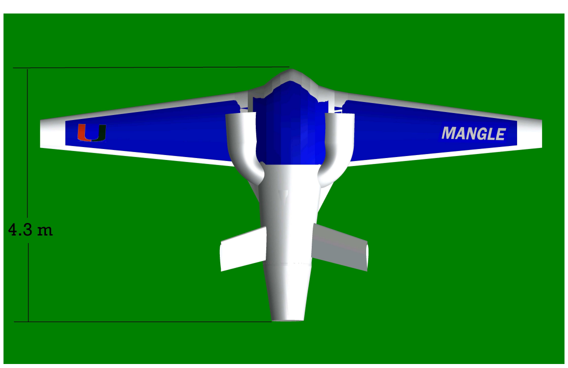

Figure 9: MANGLE top view for cruise.

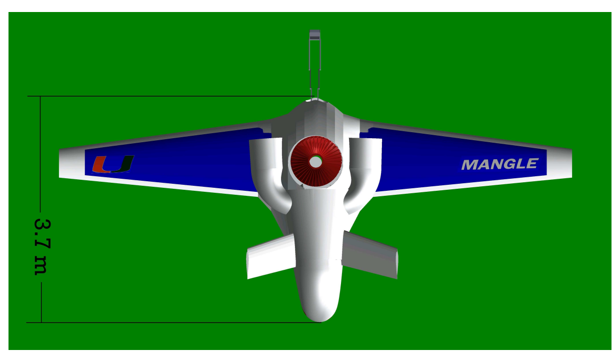

Figure 10: MANGLE top view for takeoff/landing with mechanical arm extending out and vectored nozzle bent downward.

It is particularly beneficial for the proposed MANGLE system to use CFJ, generate a high lift coefficient, and increase the stall margin to overcome the low Reynolds number effect. For the preliminary design, approximately 90% of the wing surface area uses CFJ and is colored in blue in Fig. 7 to 10. The cruise lift coefficient is 3.5 with a maximum lift coefficient of 5.0. The CFJ airfoil is the most effective way to generate high lift without using solid structure, but by consuming energy, the additional energy requirement is easily covered by nuclear powerplant. The planform area of $12m^2$ is sufficient to lift the mass of 899kg as shown in Table 1. The wing loading is nearly 3 times greater than that of NASA's ARES. In other words, if using the ARES concept, the size will be about 3 times greater. Furthermore, if the ARES's cruise Mach number is reduced from 0.65 to 0.4 as that of MANGLE, the size of ARES will be about 10 times larger than MANGLE. The cruise Mach number of 0.4 is selected to avoid the flow going into transonic regime, where the CFJ performance will be deteriorated due to shock wave-boundary layer interaction[13]. The lower cruise Mach number of MANGLE also benefits the frequent takeoff and landing to perform the multi-missions.

For vertical takeoff and landing, the lifting fan generates lift in the front, while the vectoring nozzle of the air-breathing engine generates lift in the back to form an overall lift system similar to the F-35. The preliminary study indicates that a lifting fan has a higher lift density per unit area than helicopter rotor blades and is more suitable to the compact system of MANGLE. The preliminary design has the lifting fan diameter of 1.3m located along the longitudinal axis close to the front of the blended wing-body configuration. The lifting fan will be covered during cruise flight. To avoid the engine inlet flow interaction with the lifting fan flow at takeoff/landing, a bifurcated engine inlet system with the two inlets on the side of the fuselage is adopted as shown in Fig. 7 to 10.

3.4 Nuclear Reactor

Nuclear powered propulsion is ranked as one of the most important areas of space technology development by the NRC recently[14]. Many studies have been conducted on nuclear thermal rocket (NTR) propulsion and space surface power generation[15]. The Rover/NERVA program successfully demonstrated the NTR and high specific impulse[16, 17]. However, the power density of NERVA that has the fuel rods embedded in graphite matrix and uses graphite moderator is not optimal for a small craft. In 1990, Ludewig et al at Brookhaven National Lab [18, 19] developed the Particle Bed Reactor (PBR) that demonstrated an increase of power density by 10 times to 30MW/liter under DOD/SNTP program. PBR uses small diameter (400 micron) coated HTGR type UC_2 fuel particles. The coolant flows directly through the fuel particles. The reactor has a weight of 350kg and maximum output power of 1000MW.

In the late 90's, Powell et al.[5, 20, 21, 22, 23] further developed a light version of PBR, namely MITEE(MIniature ReacTor EnginE), which has the weight of only 50kg(not including reflectors, etc.) dictated by the nuclear reaction criticality with reduced maximum power output of 100MW. Unlike the PBR, in MITEE, the fuel is contained as fibers or particles embedded in metal thin plates of perforated matrix composites, which form the multi-layered annular cylindrical fuel element. As in the PBR, there is a central hot gas channel, from which the coolant flows to exit the reactor. MITEE also has a very short start time of less than 10 seconds.

The MITEE reactor is proposed to be used for the MANGLE system. MITEE is designed to have exit flow temperature up to 3000K to achieve high specific impulse for rocket engines. The power required for MANGLE is less than 2.1MW as shown in Table 1. The maximum reactor fuel temperature will be less than 1800K, which is much lower than rocket engines. It hence will have high reliability for the mission and high safety to protect the fuel to avoid radioactive pollution of the Mars atmosphere. The designed power output of MITEE reactor is 75MW. For MANGLE, the power output will be reduced by controlling the neutron flux regulated by the control drums. MITEE has extraordinary large heat transfer areas with $63cm^2/cm^3$. The preliminary heat transfer calculation indicates that the laminar flow with Nusselt number of 4.0 ensures the CO_2 fluid has

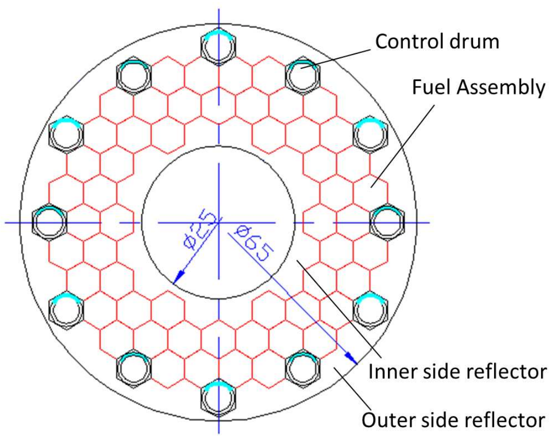

Figure 11: Annular core configuration of MANGLE reactor (unit: cm).

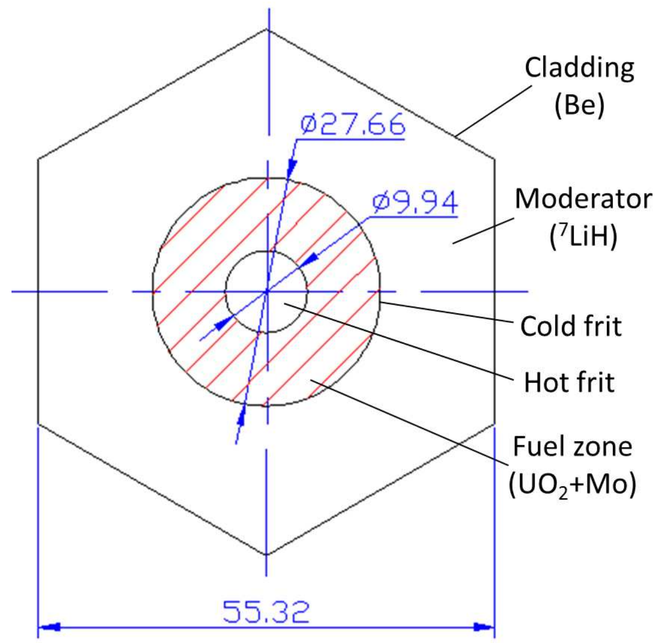

Figure 12: The configuration, main geometric parameters and material of Fuel assembly (unit: mm).

the temperature at the reactor exit equal to the reactor core surface temperature.

The reactor fuel is 93%-enriched UO_2. One fission of U-235 releases energy of about 200 MeV, that is, 3.2×10^{-11} J. For the MANGLE reactor with a conservative estimate of the averaged required thermal power of 1MW and a life time of 1 Mars year, the required mass of U-235 to carry in addition to the critical mass is:

$$m_f = \frac{PtM_{25}}{EN_a} = \frac{1.0 \times 10^6 \times 1.88 \times 365 \times 24 \times 3600}{3.2 \times 10^{-11}} \times \frac{1}{6.022 \times 10^{23}} \times 235.2 = 723g \tag{3}$$

Where, P is the thermal power of the reactor(W); t is the life time of the MANGLE reactor(s); E is the energy released by the fission of one U-235 atom(J); N_a is the Avogadros constant(mol^{-1}); M_{25} is the atomic mass of U-235(g/mol). As shown by Eq. (3), the carried on fuel for the lifetime of one Mars year is negligible compared to the overall mass of the system.

3.4.1 MITEE Annular Configuration Criticality

The original MITEE reactor has all the fuel elements bundled in a hexagonal core surrounded by a circumferential reflector with control shutters. The engine shaft connecting the turbine and compressor would needs to make a U-shape detour using a gear system to go around the nuclear reactor. This would increase the complexity of the engine system. To more efficiently accommodate the integration of the nuclear reactor with the air-breathing engine, it is desirable to have the fuel elements bundled in an annulus, which will allow the engine shaft to go through the reactor. The change of the fuel elements layout would affect the criticality of the nuclear reaction. A preliminary criticality analysis is conducted below.

A design configuration of the annular MANGLE reactor core is shown in Fig. 11. The length of the reactor core is 0.6m, and the inner and outer radii are 0.25m and 0.65m, respectively. The

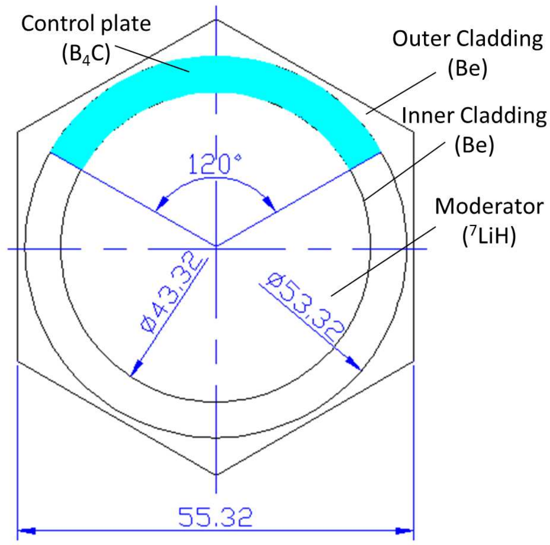

Figure 13: The configuration, main geometric parameters and material of Control assembly (unit: mm).

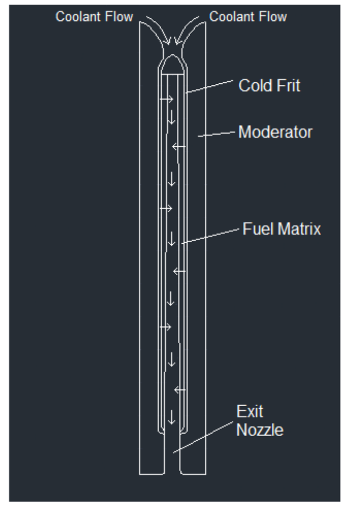

Figure 14: Longitudinal view of an individual fuel element.

whole reactor core is comprised of 54 fuel assemblies, 12 control assemblies, and reflectors. The top reflector, inner and outer side reflectors use beryllium. The thickness of the top reflector is 5cm.

The fuel assembly is composed of the Be cladding, ^{7}LiH moderator, matrix sheet composed of UO_2 fuel and metal molybdenum, and cold and hot frits, as shown in Fig. 12. The pitch of the fuel assembly is 5.532cm, and the ratio of the pitch to the outer diameter of matrix sheet is 2. The fuel is 93%-enriched UO_2 kernels with a diameter of 0.2mm which are diffused in metal Mo matrix sheet where the volume ratio of fuel to metal Mo is 0.5. The thickness of matrix sheet is 0.886cm, and the void fraction is 0.5 for coolant flow. The control assembly consists of Be cladding, B_4C control plate, and ^{7}LiH moderator, as shown in Fig. 13. Fig. 14 is the longitudinal view of an individual fuel element.

The annular MANGLE reactor can be critical for 2 Earth years with a thermal power of 1MW by preliminary criticality calculations using Monte Carlo method. For such a design, the total mass of the reactor core is approximately 315kg excluding the inner and outer vessels. The mass distribution of the reactor core is shown in Table 3. Compared with the original hexagon core design, the annular design needs more fuel and reflectors, especially the outer side reflector, because it has larger surface that leads to more potential neutron leakage. It is the trade off to gain the structure simplicity for the engine shaft. This increased weight is used for the feasibility analysis in this paper to be on the conservative side.

3.4.2 Shadow Shielding

Essential to the success of MANGLE is the protection of the instruments and soil sample collection and storage from radiation of the reactor. The "transient-radiation effects on electronics", or TREE, studies the effect of short term radiation on electronic instruments. While radiation hardened instruments greatly reduce the mass of shielding required, some method of shielding is still required. While alpha and beta particle radiation can be blocked by the casing of the reactor, shadow shielding is required to provide additional protection from gamma radiation and neutrons. The later causes movement of atoms from their original position within a crystal lattice. Furthermore, neutrons may cause structural elements to become increasingly brittle.

Structure	Material	Density [g/cm^3]	Mass [kg]	Total Mass [kg]
Fuel assembly (54 units)	UO_2	10.5	0.824	44.5
	Metal Mo	10.2	0.8	43.2
	^7LiH	0.78	0.745	40.2
	Metal Be	1.8	0.494	26.7
Control assembly (12 units)	B_4C	2.52	0.382	4.58
	^7LiH	0.78	0.69	8.28
	Metal Be	1.8	0.451	5.41
Side reflector (Inner and outer)	Metal Be	1.8	-	116.4
Top reflector	Metal Be	1.8	-	25.4
Total	-	-	-	314.7

Table 3: Mass distribution of the annular reactor core

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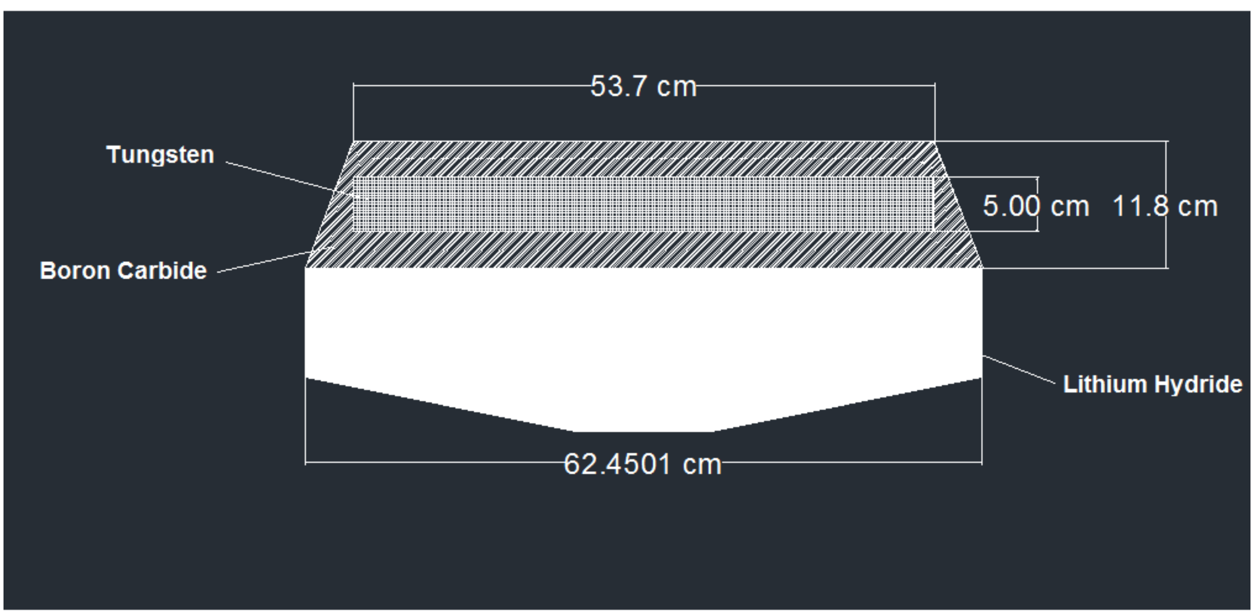

Figure 15: Cross sectional view of the shadow shield.

A shadow shield, as seen in Fig. 15, will provide sufficient shielding to the front of the aircraft where the instruments are located. The structure mirrors a design by Kowash[24] for the Small Ex-Core Heat Pipe Thermionic Reactor (SEHPTR). The first layer of the shield is comprised of a 0.068m B_4C plate which surrounds a 0.05m plate of tungsten. The B_4C reduces the radiation by a magnitude of 10^3 and the tungsten acts a gamma-ray shield, reducing radiation by a magnitude of 10^5. The second layer of the shield is made of LiH with a plate thickness of 0.15m. At half the designed thickness, LiH reduces the remaining radiation by one third. The total weight of the shield is 274kg. The mass attenuation coefficients found in literature are converted to linear attenuation coefficients using Eq. (4), where μ is the linear attenuation coefficient, ρ is the material density and μ_m is the mass attenuation coefficient.

$$\mu = \mu_m \rho \tag{4}$$

The outgoing radiation after each shield material is given by Eq. (5), where I is the outgoing radiation, I_o is the incoming radiation and x is the material thickness.

$$I = I_o e^{-\mu x} \tag{5}$$

The initial incoming radiation was determined by a full analysis of radiation emitted from fission reactions with U-235 and the final outgoing radiation was constrained to be less than 1Mrad, as specified by radiation hardened electronic specifications.

3.4.3 Sample Protection

The possibility of soil sample contamination by the radiation from the reactor is low and controllable. The drilling and sample examination area will be in front of MANGLE and is protected by the shadow shield. If the sample needs to be transported to an analysis center on Mars, the sample will be stored in a shielded metal box behind the shadow shield as an additional protection. The maximum thermal power of 2.1MW has very low average neutron flux in the reactor core, far less than the commercial reactors used on Earth. In addition to the shadow shield, the reactor core of MANGLE is already surrounded by thicker than 55mm Be reflectors in the front and peripheral of the reactor. The neutrons and gamma rays, especially the fast neutrons, which leaks from the reactor core through the reflectors and may cause radiation contamination of the samples, are minimal. Mars has high ambient background radiation at the level about 100-200mSv/a, which is about 50-100 times of the background radiation on Earth. The activation of the samples caused by the radiation from the reactor should not be an issue since the background radiation is already quite high. Furthermore, since surface soil is able to shield the radiation and we are more interested in the samples deeper than those on the soil skin, the likelihood to contaminate the sample beneath the soil surface is extremely low.

3.5 Martian Dust Filtering

The dust carried by winds within the Martian atmosphere must be filtered out before going into the engine. The dust has the potential to create blockage in the reactor coolant channels and could be disastrous. The dust could also pit the turbine blades due to the physical change under high temperature. The density of the particles on Mars is approximated as 2730 kg/m3, with the dust particles diameters ranging from 10-50μm [25].

A vortex filter such as the one designed and tested by Centrisep is able to remove the dust from the engine flow and protect the reactor[26, 27]. The atmosphere enters a duct where vortex generators force the fluid into a spinning motion. The centrifugal force pushes the dust particles to the wall of the duct where they are carried with a small amount of air out through openings along the duct wall. The majority of the filtered air continues through the duct. This filter can be placed in the intake ducts before the compressor stage of the engine. The filtering system is self-cleaning and virtually maintenance free. The particles that are not completely removed have a diameter less than $5\mu m$, which will not have serious effect since the reactor coolant channel will have the diameter from 100 to $300\mu m$ (more on the larger side) and the small particles will be carried by the coolant flowing out of the engine. Testing shows that the Centrisep vortex dust filter has a very small flow energy loss.

4 Conclusions

This paper conducts a preliminary feasibility study for a proposed multi-mission global scale range Mars explorer platform, Mars Aerial Nuclear Global Landing Explorer(MANGLE). This is an aerial and ground robotic system powered by nuclear propulsion to fly in the Martian atmosphere with vertical take-off/landing capability. The Martian atmosphere, mostly carbon-dioxide, will be used as propellant for an air-breathing engine heated by a fission nuclear reactor based on open Brayton cycle. The vertical takeoff/landing will be realized by a lifting fan and the vectored nozzle of the engine. The engine will generate both thrust and accessory power. The cruise Mach number of MANGLE is 0.4. The engine power required is 2.1MW at takeoff/landing and 0.4MW at cruise. The total system mass is 899kg. The low weight of the vehicle is attributed to no carried on propellant and radiator, and the extremely high power and energy density of nuclear fission. The ultra-high lift co-flow jet flow control airfoil will be implemented on the blended wing-body configuration to achieve a cruise lift coefficient of 3.5, which is 5 to 10 times higher than a conventional airfoil. MANGLE will not only perform a science mission to investigate the Martian atmosphere, but will also land to collect and examine soil samples at locations of interest observed from the aerial survey. A deep drill of the soil sample up to 1 meter or more is possible due to the high shaft power from the air-breathing engine, but is not considered in this study. MANGLE can also transport the acquired ground samples to a base on Mars for more sophisticated examination. The MANGLE mission period is one Martian year in order to investigate the seasonal variation in atmosphere and surface soil. MANGLE will fly for 2/3 of the total mission time to survey the atmosphere and surface and the remaining 1/3 of the time will be spent on land for surface sample collection and examination. The range is sufficient to circle the Mars 160 times during the mission.

The feasibility study includes the weight analysis for all the components and science mission equipment, airframe sizing and high lift capability with CFJ airfoil, engine thermodynamics cycle analysis, lifting fan power consumption and sizing, dust filtering, nuclear reactor selection, criticality and heat transfer analysis, shield and sample protection methods, etc. The conclusion finds that the MANGLE system to be feasible based on the existing technologies even though there will be many technical and engineering challenges. MANGLE's capability will significantly surpass all the previously studied Mars aircraft systems and balloon systems with its multi-mission function. It has a great potential to revolutionize Mars science missions by enormously increasing the mobility in the atmosphere and on the ground, therefore significantly benefiting mankind's efforts to explore the Martian planet.

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