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Technology development for human exploration of Mars ☆

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A B S T R A C T

Current plans call for the first human missions to Mars to be launched perhaps as early as 2035. The recently completed "Mars Design Reference Architecture 5.0" study defines a conceptual mission architecture and identifies enabling technologies. NASA is beginning long range development on key technologies needed for these missions because it will take many years for them to reach maturity. The ISS and the lunar outpost will be used as test beds for these technologies to reduce risk and prepare for human exploration of Mars.

NASA's Exploration Technology Development Program is maturing technologies and demonstrating operational scenarios for lunar exploration that are extensible to future human missions to Mars. These include entry, descent, and landing systems for large payloads; fission surface power systems; liquid oxygen–liquid methane propulsion systems; cryogenic fluid management; closed-loop life support; small pressurized rovers for surface mobility; in-situ resource utilization; radiation shielding; and optical communications. Advanced technologies will enable more affordable and sustainable Mars exploration.

1. Introduction

Mars may seem a distant goal for human exploration. Current plans call for the first human missions to Mars to be launched perhaps sometime after 2035 because the required technologies are not ready, and the missions would be far too risky and expensive without major technology advances. Although the goal is at least 25 years in the future, NASA is already beginning long range development of key technologies because it will take many years for them to reach maturity. Several of the same technologies are needed for lunar exploration. NASA's Exploration Technology Development Program (ETDP) is maturing technologies and demonstrating operational scenarios for lunar exploration that are extensible to future human missions to Mars [1]. One of the objectives for returning to the Moon is to use it as a test bed to prepare for Mars exploration.

To provide a framework for planning future system concepts and to identify enabling technology needs, NASA has conducted a series of Mars design reference mission studies. The studies also guide the development of an integrated exploration strategy that includes lunar exploration and robotic precursor missions to Mars. The latest study, the "Mars Design Reference Architecture 5.0 (DRA 5.0)", was published in 2009 [2].

2. Mars design reference architecture

Mars DRA 5.0 was derived from trade studies on a broad range of mission options. In the conceptual reference architecture, the mission would be conducted in two phases. In the first phase, cargo elements are predeployed to Mars and checked out to verify that they are functioning properly before the crew is launched 2 years later. The cargo elements consist of a surface habitat and a descent/ascent vehicle. Due to the large mass that must be

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launched for a human mission to Mars, four heavy-lift Ares V launches are required to assemble the cargo elements in low Earth orbit. Nuclear thermal rockets are used as the in-space propulsion system to transport the cargo elements to Mars orbit on a conjunction class trajectory lasting about 350 days. The cargo elements use aerocapture for Mars orbit insertion to reduce the amount of propellant needed.

The surface habitat remains in orbit for 2 years waiting for arrival of the crew. The descent/ascent vehicle lands on Mars, and deploys a fission surface power system. The nuclear reactor is used to power an in-situ resource utilization system (ISRU) that produces oxygen from the Martian atmosphere. The oxygen is liquefied and stored for use as propellant in the ascent vehicle and to replenish the air in the surface habitat's life support system.

In the second phase of the mission, a crew of six is launched to Mars 2 years after the cargo elements have been pre-deployed. Three Ares V launches are required to assemble the Mars transfer vehicle in low Earth orbit. The crew is launched separately, and they rendezvous with the transfer vehicle in Earth orbit. Nuclear thermal rockets are then used to propel the crew transfer vehicle to Mars on a fast-transit trajectory lasting 175–225 days to minimize radiation exposure.

When the crew arrives in Mars orbit, they rendezvous with the surface habitat and descend to the surface. The Mars transfer vehicle remains in orbit while the crew explores Mars for 500 days. Pressurized rovers are used to explore regions of Mars up to 100 km from the outpost on sorties lasting about 1 week.

To return home, the crew is launched into Mars orbit by the ascent vehicle, where they rendezvous with the Mars transfer vehicle. The transfer vehicle returns the crew from Mars, and they end the mission with a direct entry at Earth in a modified Orion crew exploration vehicle.

The entire mission lasts about 900 days. Missions of this length will require greater understanding of risks to the crew's health and performance from prolonged microgravity and radiation exposure, and developing the capability to perform remote medical care. NASA's Human Research Program is addressing many of the physiological, medical, and behavioral issues associated with long-duration space flight [3].

In addition to defining a conceptual mission architecture, the Mars DRA 5.0 study identified key technologies. These include nuclear power and propulsion; entry, descent, and landing systems for large payloads; liquid oxygen–liquid methane propulsion systems; cryogenic fluid management; closed-loop life support; small pressurized rovers for surface mobility; in-situ resource utilization; radiation shielding; planetary protection; and high-data rate communications.

3. Entry, descent, and landing technology

Advances in entry, descent, and landing (EDL) technology are required to land heavier payloads on Mars for future human and robotic missions. Existing EDL systems such as the Mars Science Laboratory's sky crane are not capable of landing payloads greater than 2 metric tons. Human exploration missions require surface payloads greater than 40 metric tons. To save weight, the launch shroud would also be used as an aeroshell for aerocapture and EDL of the cargo elements. This rigid aeroshell concept is called an "ellipsled" entry system (Fig. 1). Large diameter inflatable aeroshells could also be used to reduce peak heating rates.

NASA recently began a new project to develop EDL technologies for landing large payloads on Mars. Technology development includes thermal protection system (TPS) materials for rigid and inflatable aeroshells, aerothermal modeling and analysis tools, supersonic parachutes and aerodynamic decelerators, and supersonic retro-propulsion to brake the descent vehicle after it separates from the aeroshell.

In 2011, NASA will launch the Mars Science Laboratory (MSL) mission. The MSL aeroshell will be instrumented with temperature, pressure, and TPS recession sensors to acquire aerothermodynamic and heat shield performance data during Mars atmospheric entry. The data from the Mars EDL Instrumentation (MEDLI) experiment will be used to validate models and improve analysis tools needed for the design of future aeroshells [4].

In addition to atmospheric entry systems, the ETDP is developing Autonomous Precision Landing and Hazard Avoidance Technology (ALHAT) [5]. During descent, cameras image the lunar surface at high altitude and prominent features are compared with an onboard terrain database to determine the lander's trajectory. This technique is called terrain relative navigation. At low altitudes, a flash lidar sensor is used to construct a three-dimensional image of hazards in the landing zone. The lander maneuvers autonomously to avoid rocks and craters and to land within 30 m of its intended target The ALHAT system being developed for the lunar lander could also be used to enable autonomous precision landing on Mars so that the crew can land near the pre-deployed cargo elements. For current robotic missions, the uncertainty in the location of the landing site is on the

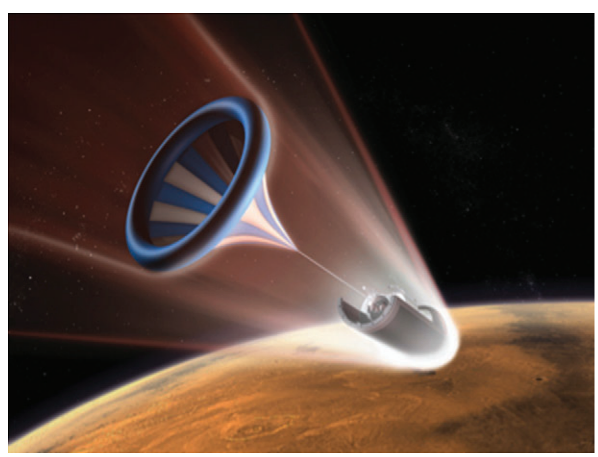

Fig. 1. Ellipsled rigid aeroshell with inflatable decelerator.

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order of tens of kilometers, so ALHAT would provide a substantial improvement in precision landing.

4. Nuclear propulsion and power

Nuclear thermal propulsion (NTP) is an enabling technology for human missions to Mars because it is capable of producing high thrust at high specific impulse (Isp 875–950 s), which is about twice that of chemical rocket engines. In a nuclear thermal rocket, a fission reactor is used directly to heat the liquid hydrogen propellant to generate thrust. Nuclear thermal propulsion was demonstrated in ground tests during the Nuclear Engine for Rocket Vehicle Applications (NERVA) program [6]. The Mars cargo and crew transfer vehicles would use a common propulsion module consisting of three 25,000 pound thrust nuclear thermal rockets.

For surface power, a nuclear fission reactor would be used to generate electrical power for the crew habitat and ISRU systems landed on Mars. NASA and the U.S. Department of Energy are developing concepts and technologies for a 40 kW fission surface power system for the lunar outpost that could also be used on Mars [7]. The reactor uses uranium dioxide for the nuclear fuel. Liquid sodium and potassium metals are circulated through the core to cool it. Stirling power convertors generate electricity from the heat produced by the reactor. The fission surface power system needs large deployable radiators to dissipate excess heat. The reactor would be emplaced in a hole distant from the lunar outpost and surrounded by lunar regolith to provide radiation shielding.

Several component technologies for a fission surface power system have been demonstrated. A 2 kW Stirling power conversion system was integrated with a liquid metal coolant loop, and power was generated from a simulated nuclear heat source at a thermal conversion efficiency of 32% (Fig. 2). A prototype radiator panel was also tested in a vacuum chamber, rejecting 10 kW of heat. The fission surface power systems project is working towards a non-nuclear systems-level demonstration in the next few years.

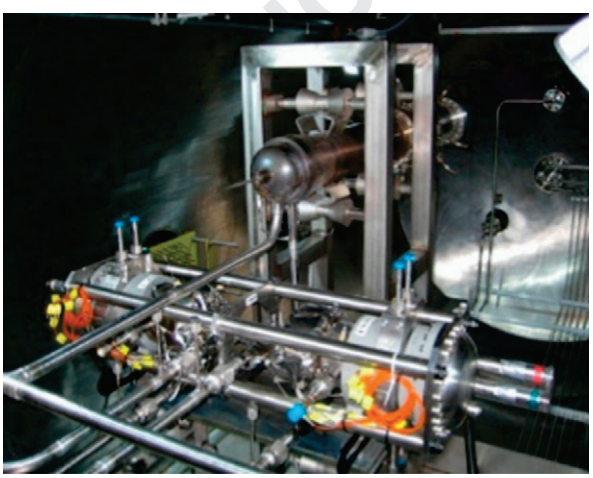

Fig. 2. Stirling power converters and liquid metal coolant loop for Fission Surface Power System.

5. LOX–methane propulsion and cryogenic fluid management

The Mars ascent vehicle would use a liquid oxygen (LOX)–liquid methane propulsion system. Methane and oxygen can be produced from the Martian atmosphere so that the propellants needed for the return trip do not have to be launched from Earth, greatly reducing the overall initial mass of the mission. Although hypergolic propellants can be stored at room temperature, they are toxic and require special handling procedures to insure crew safety. Cryogenic propellants such as LOX–methane are non-toxic, and they have higher specific impulse (Isp 330 s) than hypergolic propellants. The main drawback of cryogenic propellants is that they will boil off unless they are kept refrigerated and stored in insulated tanks.

To reduce the risk of using LOX–methane propulsion systems on Mars missions, NASA and Aerojet are developing a prototype LOX–methane engine for the lunar lander ascent stage [8]. The engine is pressure fed, has a film-cooled chamber, and produces 5500 lb thrust (Fig. 3).

NASA is also developing LOX–methane reaction control system (RCS) thrusters so that a separate propulsion system is not needed for attitude control. The RCS thrusters can be integrated with the main engine's propulsion system. A major technical challenge for these RCS thrusters is ensuring reliable ignition over a wide range of environmental conditions. Depending on the ambient temperature, the state of the propellants entering the thruster's injector could range from very cold liquids to warm gases. NASA is developing 100 lb thrusters capable of multiple short-duration pulses. The ignition risk has been greatly reduced in over 3000 thruster firings at various inlet conditions.

Cryogenic propellants must be stored on the surface of Mars for many months as the ISRU system is producing propellants from the Martian atmosphere for the ascent vehicle. To prevent boil off, the propellants must be actively cooled. NASA is developing concepts for broad area cooling systems to chill the propellant tanks. Other cryogenic fluid management technologies being

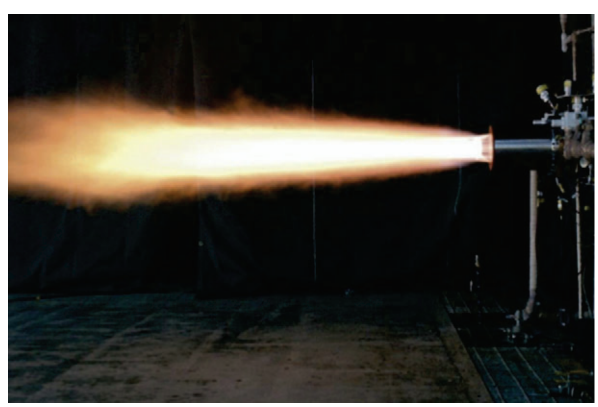

Fig. 3. LOX–methane 5500 lbf engine (~~aerojet~~)

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developed include thermodynamic vent systems to control tank pressure and temperature, liquid acquisition devices, and propellant mass gauging [9].

Other technical challenges include cryogenic fluid transfer and two-phase flow in partial gravity environments. To understand how gravity affects cryogenic fluids, fundamental research on fluid physics in microgravity is being conducted on the International Space Station (ISS). The ISS could be used as a test bed for cryogenic propellant storage and handling technologies to enable in-space propellant depots. A propellant depot in Earth orbit could refuel vehicles prior to departing for Mars.

6. Closed-loop life support

To minimize the mass of consumables such as oxygen and water that must be supplied from Earth, life support systems for Mars exploration will have to recycle air, water, and solid waste. The life support systems that are currently used on the ISS recycle less than 50%percent of their resources. The goal for Mars missions is to recycle greater than 95%.

A process called the Sabatier reaction can be used to revitalize the air and recover oxygen. In this process, the carbon dioxide exhaled by the crew is reacted with hydrogen to produce methane and water. The water can then be split into hydrogen and oxygen using electrolysis. The hydrogen is recycled to the reactor and the methane is vented overboard. Hamilton Sundstrand is developing a Sabatier reactor to produce water for the ISS [10]. If the methane is pyrolyzed at high temperature instead of being vented overboard, it can be converted to elemental carbon and hydrogen. This additional processing step would reduce the consumption of hydrogen. Another process called the Bosch reaction is also being developed to reduce carbon dioxide directly into elemental carbon, but it requires a higher temperature than the Sabatier process.

A water recovery system is being tested on the ISS. This system recycles about 93% of the water it collects from urine and sweat condensed from the cabin atmosphere [11]. The wastewater is distilled inside a rotating drum that generates an artificial gravity field to separate contaminants from the water vapor. The distilled water is filtered and fed into the oxygen production system for electrolysis. The ISS water recovery system is capable of recycling about 6000 lb of water per year.

A direct osmotic concentration process for purifying wastewater is also being developed. A permeable membrane allows the water to pass through under pressure but not the contaminants. Other techniques are being developed to recover water from solid waste. To remove the water, the waste is freeze dried or heated with microwaves.

The integration of oxygen production, oxygen recovery, water recovery, and waste processing systems can lead to greater closure of life support systems. Biological life support systems in which plants remove carbon dioxide from the air and provide food for the astronauts may enable life support systems that are fully closed.

7. Surface mobility systems

Astronauts will explore large areas of Mars in pressurized rovers that will allow them to travel far beyond the landing site. NASA is developing concepts for a small, pressurized rover to conduct similar surface exploration on the Moon. This rover is called the Lunar Electric Rover (LER). The LER consists of a pressurized crew compartment that is integrated with a six-wheeled rover chassis (Fig. 4).

Two astronauts drive the rover while seated in a comfortable shirt sleeve environment. The LER has large windows so that the crew can see ahead. Two space suits are attached to the exterior of the LER crew compartment at the rear end through an interface called a suit-port. The suit-port permits the astronauts to quickly enter the suit and detach from the rover for extravehicular activity (EVA). Keeping the suits outside the rover prevents dust from being tracked into the cabin where it could be hazardous to the crew's health [12].

Airlocks on each side of the crew compartment allow the LER to dock with habitat modules. Radiation shielding is provided by a reservoir of water in the roof of the crew compartment. The water also functions as a heat sink for thermal control.

The concept of operations is for two LERs to travel together on sorties lasting about one week. If one of the rovers breaks down, all four crew members would return to the landing site in the other rover.

The average driving speed of the LER is 10 km/h. It can cover about 60 km in a day, with a total range of about 100 km. To obtain this range goal, the rover will require advanced lithium-ion batteries with energy density at least 200 Wh/kg. Regenerative fuel cells may provide supplemental power.

8. In-situ resource utilization systems

Mars has many resources that could be exploited to make human exploration missions more sustainable and affordable. ISRU systems will produce propellants from the Martian atmosphere to fuel the ascent vehicle. The

Fig. 4. Lunar Electric Rover.

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atmosphere is mostly carbon dioxide, and the Sabatier process combined with electrolysis could be used to produce oxygen and methane. There are probably abundant sources of subsurface ice in the high latitudes of Mars that could be mined to supply water and oxygen for life support systems. Hydrogen and oxygen produced by ISRU systems could be used to store energy in regenerative fuel cells.

Initial development of ISRU technology has focused on oxygen production because it is a major constituent of the minerals in both lunar regolith and Martian soil, and a fairly simple hydrogen reduction process can be used to extract it. A prototype ISRU system for producing oxygen from lunar regolith has been demonstrated in field tests (Fig. 5). A batch of regolith is heated to about 900 °C in a rotating reactor while hydrogen gas is passed through it. The hydrogen reacts with the iron oxide in the regolith to form water vapor. The water is condensed and split into hydrogen and oxygen using electrolysis. The hydrogen is recycled back into the reactor and the oxygen is stored. The hydrogen reduction process yields about 2 kg of oxygen from 100 kg of regolith. The prototype oxygen production system can produce about 1 metric ton of oxygen per year, which is enough to replenish life support and EVA systems at the lunar outpost [13].

More efficient processes for oxygen production are also being developed, but these are less mature. The carbothermal process, which uses methane gas for reducing silicates in molten regolith, yields about 10 kg of oxygen from 100 kg of regolith. NASA and Orbitec, Inc. are testing a proof-of-concept carbothermal system that uses highly concentrated sunlight to melt a small volume of regolith.

The most efficient process for oxygen production is molten salt electrolysis, in which an electric current is passed through molten regolith. The byproducts of this process are refined metals such as iron, aluminum, and silicon, which could be used as construction materials or to fabricate spare parts. The molten salt electrolysis process yields up to 40% oxygen by mass.

Designing surface systems to use common reactants, propellants, and consumables can lead to high levels of integration between ISRU, life support, energy storage, and propulsion systems. Robotic and human missions to the Moon could be used to test these integrated systems in preparation for Mars exploration.

9. Communications

The crew exploring the surface of the Moon or Mars must be able to communicate with each other, with their base camp, with spacecraft in orbit, and with Earth. Concepts for the communications infrastructure are being demonstrated in desert field tests that simulate lunar surface operations. A portable communications relay terminal that can be deployed by the crew rover is a key element. When the rover travels beyond the range of direct communication with the outpost, the relay terminal is deployed on high ground. The relay terminal has a tall mast antenna so that it can provide line-of-site communications with the rover as it travels into craters and valleys. The relay terminal may link with the outpost or a communications satellite in orbit, which sends the signal to Earth.

A high data rate communications link with Earth would allow the public to experience the exploration of Mars through high definition television. NASA and MIT Lincoln Laboratory are developing an optical communications system that consists of a 0.5 W modulated fiber laser, superconducting photon-counting detectors, and a compact 10 cm gimbaled telescope to transmit and receive laser signals (Fig. 6). The optical communications system will be demonstrated in lunar orbit on the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission in 2012 [14]. This system will be capable of downlinking 622 MB/s to Earth. An array of four 0.4 m telescopes on the ground will receive the laser signals from LADEE.

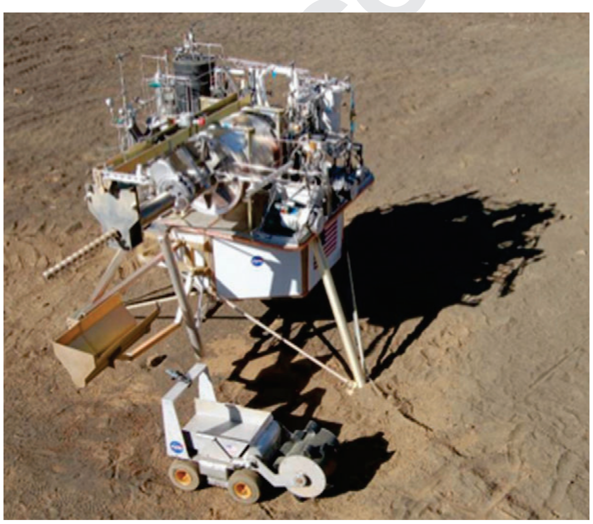

Fig. 5. Prototype ISRU system for producing oxygen from lunar regolith (Lockheed Martin).

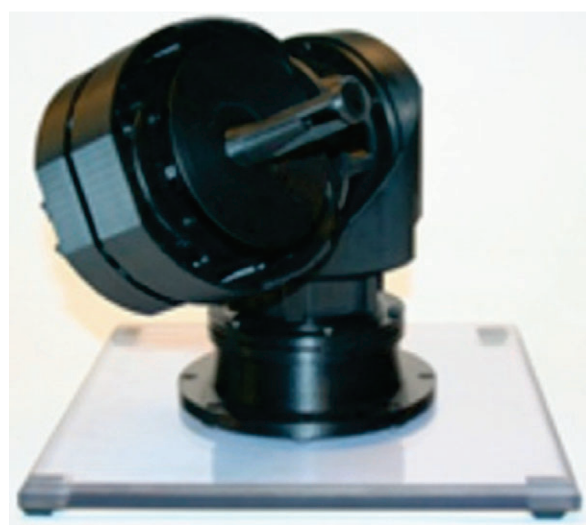

Fig. 6. Model of optical communications system for LADEE mission (MIT Lincoln Laboratory).

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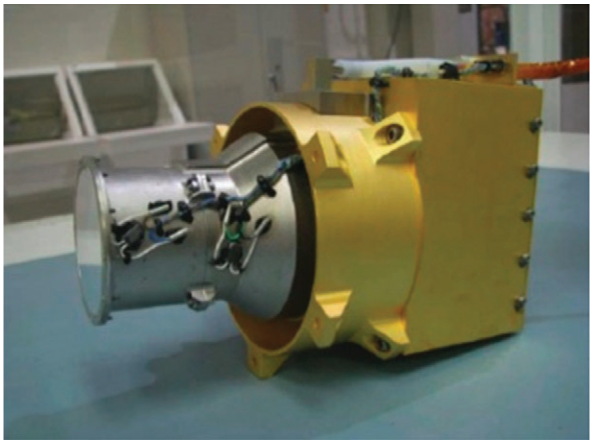

Fig. 7. Radiation Assessment Detector for MSL mission (Southwest Research Institute).

10. Radiation protection

On a mission to Mars, the astronauts will be beyond the Earth's protective magnetosphere, and they will be exposed to high-energy galactic cosmic rays and solar particle events. Radiation protection is a critical technology for long-duration missions because space radiation may increase the risk of cancer and have other harmful effects on crew health. Due to the large uncertainty in the risk of radiation exposure, radiation shielding has to be conservatively designed, and consequently it is very heavy. To reduce this uncertainty, the Human Research Program is investigating the biological effects of space radiation in particle accelerator experiments at the Brookhaven National Laboratory.

Materials with high hydrogen content are the most effective at attenuating the protons and heavy ions making up space radiation. Polyethylene is being studied as a lightweight shielding material because it contains long chains of hydrocarbons. The walls of the crew habitat could be lined with polyethylene. Water is also an effective shielding material. The crew could take refuge during a solar particle event inside a part of the spacecraft surrounded by water.

To characterize the surface radiation environment on Mars, the Southwest Research Institute and the German space agency DLR are developing a Radiation Assessment Detector (RAD) that will be carried onboard the Mars Science Laboratory (MSL) rover in 2011 (Fig. 7). The solid-state detector will measure the energy spectrum of charged particles, neutrons, and gamma rays [15]. These precursor radiation measurements for future human exploration missions are needed to understand questions related to habitability and the likelihood of sustaining life on the surface of Mars.

11. Preparing for Mars exploration on the Moon

Many of the systems, technologies, and operational scenarios needed for human missions to Mars can be tested on the Moon. The Moon is an extreme environment in which to prove the reliability of critical systems, and is remote enough that the crew must be self-sufficient. However, it is not so far away that they cannot return to Earth in a few days if something were to go wrong.

The Moon is also a good place to test techniques for planetary protection, which is a major gap in current capabilities. The primary reason for going to Mars is to search for signs of life that may have arisen there. Microbes brought from Earth would have to be contained so that they do not contaminate the scientific evidence for life. The lunar environment is sterile, so if microbes from Earth were released due to a failure of planetary protection techniques, it would not be catastrophic.

The advanced technologies we are beginning to develop now will enable more affordable and sustainable Mars exploration. By developing and testing technologies for lunar exploration that are extensible to human missions to Mars, we will learn how to operate more effectively and safely on long missions far from Earth.

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