Mars Surface Power Generation Challenges and Considerations

Background

Once the challenges of reaching and landing safely on Mars have been met, the first human explorers will be faced with the challenge of finding sufficient energy to power the systems they will need for a healthy and productive stay on the surface and for their ascent back to orbit. Surface power needs may vary from one human Mars mission to another depending on how long each crew plans to stay on Mars, their surface mission objectives, and the support services their surface and ascent vehicles will require.

Studies show that a very modest mission of two crew members, conducting science and exploring the surface for no more than 30 days while living in a pressurized rover — plus propellant conditioning for a small, storable-propellant crew ascent vehicle — will require at least 10 kilowatts (kW) of surface power. At the other end of the trade space, a larger crew complement, exploring the surface for a longer duration, use of cryogenic ascent propellant manufacturing and storage, etc., will require hundreds of kW, approaching megawatt (MW)-class power systems for some architectures.

Surface power system designs for early human Mars missions must account for not only crew life support, but ascent vehicle preparation, propellent quantities, and equipment keep-alive power. This white paper outlines some of the unique challenges that Mars poses to ensuring sufficient power is generated, particularly during the initial human Mars segment.

Unique Mars Environmental Surface Power Challenges

Dust Storms

Martian dust storms have been observed in sizes ranging from small, local dust devils to regional and even global storms. Regional storms can cover thousands of square kilometers and last for days to weeks, growing in size and moving from their points of origin based on atmospheric conditions and terrain features. Global dust storms encircle the entire globe, can persist for several weeks or months, and may evolve from a local phenomenon to a global event in just a few Martian days (called sols).

Because the atmosphere is so thin and dry, it takes much longer for fine dust particles to settle out of the atmosphere, which places solar array–powered systems at particular risk. Data collected by the Opportunity rover during its fatal encounter with a global Mars dust storm in 2018 demonstrates just how fast and furious Martian weather can be: from clear skies to as dark as Opportunity had ever previously recorded (4.9τ), within three Martian sols.

Opportunity then observed a virtual blackout (Figure 1A) just four sols later, with its final message reporting more than double prior recorded optical measurements. The 2018 storm shrouded the entire planet in such a thick blanket of dust (Figure 1B) that even the Curiosity rover, operating on the other side of the planet, reported significant optical degradation. However, unlike the solar-powered Opportunity, Curiosity's nuclear radioisotope power system was unaffected by the storm, allowing it to continue transmitting data to Earth.

The impact of Martian dust storms on surface power will depend on severity and duration. Regional and global storms pose significant risk to surface power systems in two ways: first, dust suspended in the atmosphere will reduce the amount of energy reaching surface power systems that rely on solar energy, such as solar arrays, and can disrupt power systems that require clear line of sight for distribution, such as power beaming technologies. Oversized arrays can compensate for some reduced array efficiency, but at very high solar obscuration even oversized arrays may not be able to collect enough solar energy for nominal surface operations and energy storage systems to wait out the dust storm event could be enormous.

The second problem is that dust settling out of the atmosphere can accumulate on solar

Figure 1a. *Simulated view of the Sun from Mars during a dust storm*

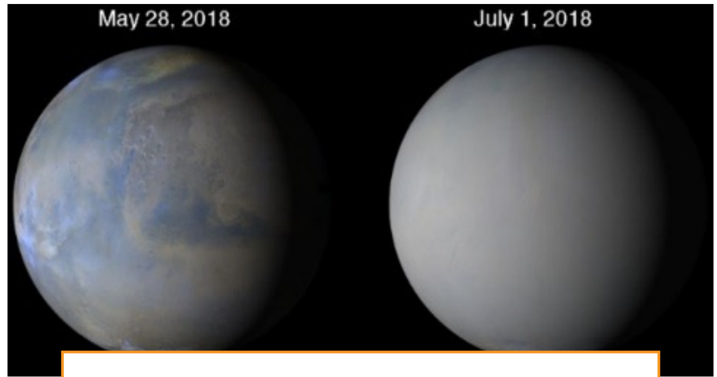

Figure 1b. *Global view of Mars during the 2018 dust storm*

arrays, further reducing their efficiency. For example, NASA's InSight Mars lander was able to achieve all of its primary science objectives, but heavy dust accumulation prevented the solar arrays from generating sufficient keep-alive power and forced controllers to suspend operations after the vehicle was no longer able to communicate with Earth.

Reduced Solar Energy Availability

Solar energy has long been the reliable choice for in-space power applications, but solar array designs on Mars must account for reduced solar flux, which is at most 45 percent of typical Earth solar flux values and varies significantly with geographic location and season. Figure 2 presents the maximum solar flux in orbit and at several different latitudes over a typical Martian year. The dashed curves in Figure 2 show the potential impact of dust storms on solar flux.

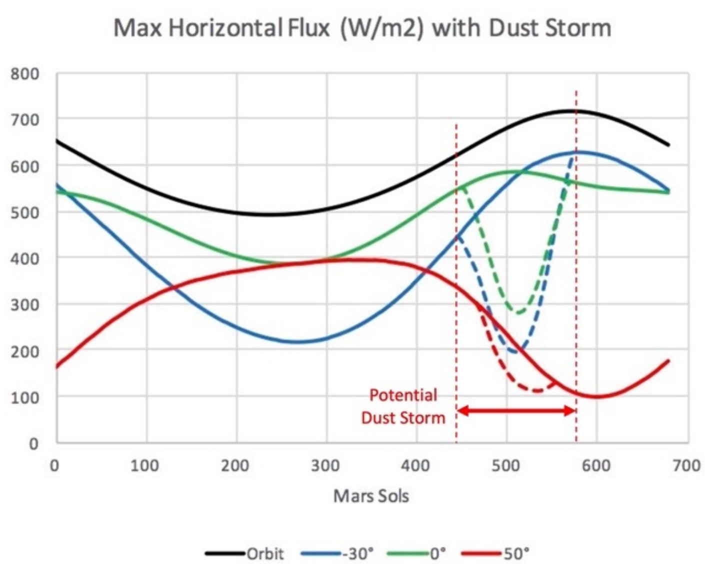

Figure 2. *Mars Solar Flux Variations*

The Martian day/night cycle also varies with location and season. Typical mid-latitude missions would experience a 25-hour cycle, with approximately 50 percent of the time spent under illumination. In practice, this means that a solar power system must be oversized to supply power for daylight operations while simultaneously charging the energy storage (batteries or regenerative fuel cells) to maintain night operations, all of which requires additional landed mass/volume and complexity.

Gravity and Wind Loads

Although Mars gravity is only about a third of that on Earth, Mars has about twice the gravity of the Moon, meaning that large array structures designed for lunar applications would need higher structural strength for deployment on Mars.

Unlike the Moon, Martian winds pose another unique challenge. The Martian atmosphere is very thin, and even very high wind speeds would impose lower forces than equivalent wind speeds on Earth. For example, the highest wind speed ever measured on the Martian surface was about 30 meters per second (m/s) at the Viking 2 Lander site, but the lower atmospheric density on Mars makes a solar array in that same wind feel like it is only in a 4 m/s terrestrial wind.

However, even though the pressures felt by a solar array are lower on Mars, they are still exerting forces in addition to gravity that can be quite substantial. The design of very large or vertical solar arrays must account for these forces.

Severe dust storms beg an obvious question: why not just harness the power of Martian wind? While winds must be accounted for structurally, the Martian atmosphere is too thin to generate sufficient wind power for crewed systems. Data collected by InSight reveals that winds at Elysium Planitia rarely reached a capable power threshold; the wind was even insufficient to reliably blow dust off of arrays. In short, Martian winds may be troublesome, but are insufficient to be harnessed.

Day/Night Cycle Temperature Variations

The Martian day/night cycle is comparable to Earth's; a Martian sol is about 39 minutes longer than an Earth day. This means that solar-based power systems must be augmented with overnight energy storage solutions. Mars surface temperatures also vary from as warm as 30 C to as cold as -140 C, depending on location and season.

Unique Mars Operational Challenges

Autonomous/Remote Power System Operation

Round-trip human Mars surface systems are dominated by the ascent vehicle needed to launch crew back to Mars orbit and return to Earth. In most mission architectures, the ascent vehicle is the largest and heaviest surface payload, making it difficult to land a fully fueled ascent vehicle.

To mitigate landing risks, many architectures rely on landing the ascent vehicle with empty or partially full propellant tanks and either transferring Earth-origin propellant that was delivered on a separate lander or manufacturing propellant from Mars resources. All approaches require abundant surface power.

At a minimum, a few kW will be needed to environmentally condition Earth-origin propellants until ascent vehicle use. In contrast, tens of kW will be needed to maintain cryogenic propellants. Additional power will be needed to transport propellants between landers. Manufacturing propellants from Mars resources will require tens to hundreds of additional kW.

To reduce crew risk, the ascent vehicle will ideally be ready prior to crew arrival, so whether ascent propellants are delivered from Earth or manufactured in situ, Mars surface power systems must be deployed, checked out, activated, and maintained without human intervention or assistance. Depending on pre-deploy mission timing (which will be constrained both by vehicle availability and the 26-month Earth departure windows of opportunity for Mars), and surface concepts of operations, surface power systems may need to be deployed years in advance of crew arrival and may need to support several crew missions over a years-long, multi-mission campaign.

Limited Repair Options

The sheer distance between Earth and Mars means that unplanned replacement units or repair parts will not be available. Critical crew safety capabilities, such as surface power, will drive reliability, redundancy, and possible spares provisioning mass, all of which will have flow-down impacts to other parts of the architecture and operations.

Because loss of surface power can lead to loss of mission/loss of crew risk on Mars, power system spares must also be considered in mass and volume calculations when comparing different power source options. This includes a variety of failure modes during the crewed landing phase concept of operations: dust storms could delay the crew's connection to existing surface power sources, or the crew could land farther away from the pre-deployed power source than planned.

Plume/Surface Interactions

A particular challenge for Mars surface assets, including power systems, is potential impact of descent and ascent engines' thrust plume debris, which is exacerbated by the Mars atmosphere. Power system separation from arriving/departing vehicles may require longer power distribution systems (e.g., power cabling) or power system handling and surface mobility. Because power systems must be deployed in advance of crew arrival, power system handling, mobility, and power distribution must also be performed autonomously or remotely without crew assistance. If sufficient separation distance (currently estimated at about 1 kilometer) is possible, surface power systems may require additional debris protection to mitigate potential debris impact damage.

Planetary Protection Constraints

Planetary protection refers to "the policy and practice of protecting current and future scientific investigations by limiting biological and relevant molecular contamination of other solar system bodies through exploration activities and protecting the Earth's biosphere by avoiding harmful biological contamination carried on returning spacecraft, as described in the Outer Space Treaty."[1]

Specific policy guidelines are being developed to establish quantitative and implementable planetary protection requirements for the safe and sustainable exploration and utilization of Mars. Eventual requirements may include sterilization goals to prevent the transmission of Earth-origin microorganisms to Mars, or operational constraints, such as limits on thermal output that could inadvertently create a more habitable environment for microorganisms.

Mars Surface Power Generation Opportunities

Surface Power Generation Technologies

Despite Mars' many challenges, promising power generation technologies are available or in development. High energy density nuclear power, either Curiosity rover-style radioisotope power system or fission systems, are unaffected by day/night cycles or weather and package well in volume-constrained spacecraft. Although current radioisotope power system designs only offer a few hundred watts, they may be applicable to smaller power load applications. For higher power crew life support or ascent propellant manufacturing needs, fission surface power is readily scalable.

Limited solar power may be feasible if augmented by robotic dust wipers, pressurized gases, mechanical array tilting, or electrodynamic or piezoelectric dust removal to clear accumulated dust from the solar arrays, although only for applications that are not crew safety critical, given that surface dust removal would not mitigate the problem of suspended atmospheric dust during lengthy storms. Unique operational considerations, such as radiation keep-out or large array off-loading, would need to be evaluated for Mars.

Lower technology readiness solutions may eventually offer additional options. For example, geothermal energy has been proposed for use in eventual Martian settlements, but data on its availability is limited. Accessing geothermal energy requires heavy equipment and time to implement and may be geographically constrained to areas with easy access to geothermal sources, making it less attractive for early missions. Implementation of geothermal technologies would require a separate power source for the robotic drilling and regolith-moving required to access the heat sources before the crew even arrives.

Fuel cells are often proposed, but they do not trade well for mass because they either require landed reactant mass or more energy and production mass to make reactants in-situ than the fuel cells provide. Biogeneration (relying on microorganisms to convert organic feedstock directly into heat or into another commodity, such as methane, that can then be used to generate power) has also been proposed as a power generating technology option. However, the introduction of microorganisms may be complicated by planetary protection constraints. Furthermore, additional safety/processing measures may be needed if feedstock/biomass replenishment involves use of Martian soil, due to the presence of perchlorates or other chemicals and their byproducts.

Regardless of the power source selected, it should be noted that multiple power systems could be integrated as needed to support higher power needs. This would allow the power system to be tailored to a specific mission, as more modest initial efforts evolve into more ambitious exploration.

The Moon as a Testbed for Mars

The closer proximity of the Moon offers an excellent opportunity to demonstrate candidate Mars surface power generation technologies with reduced consequences of failure. Lunar surface systems designed to be extensible to Mars would need to account for the environmental differences, including Mars' low-pressure carbon-dioxide atmosphere, increased gravity, shorter day/night cycle, reduced solar insolation, wind loads, dust storms, and increased distance from Earth that results in longer round-trip communication times.

The challenge is to ensure that lunar power generation systems remain Mars-forward without adding significant cost or complexity to either the lunar or Mars missions. Solar and fission surface power technology demonstrations could serve as pathfinders for power system launch, landing, autonomous deployment, maintenance, and sustained operations in challenging and dynamic environments.

Summary

Regardless of mission type, stay duration, or surface exploration objectives, human missions to Mars will require abundant, reliable surface power. Stationary power systems that produce at least ten kilowatts day and night, in varying weather conditions, will be needed for human ascent vehicles, habitats, propellant conditioning or manufacturing plants, and surface exploration activities.

NASA is working to advance the technology readiness of a range of surface power generation technologies and mitigate performance challenges that some of these options would have in the Mars environment. An overarching objective is to demonstrate the technologies in relevant mission environments to verify performance and functionality.

Power needs for humans operating on the Moon will have some commonality with Mars operations, opening up the possibility of common power technologies if strategic engineering choices are made and proper consideration is given to the different environments. Where practical, demonstrations can be performed directly on the Moon to gain operating experience on systems that will later be used on Mars.

Key Take-Aways

Safety-critical human needs on the surface of Mars pose additional challenges, such as higher availability over longer periods of time, versus robotic Mars or human lunar surface missions.

The minimum practical power level required for even a short-duration, two-crew, human Mars surface mission is about ten kW.

Maximum required power levels could approach MW class for very in-situ resource utilization-intensive architectures.

The Mars surface power generation technology selected for the initial human Mars segment must accommodate both anticipated operational needs and the unique challenges of the Mars environment, with limited repair or replacement options.

The Artemis missions offer an opportunity to test safety-critical Mars surface power generation technologies and operations on the Moon to reduce risk for later Mars crews.

Reference

1. NASA Procedural Requirement 8715.24, Chapter 1, https://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_8715_0024_&page_name=Chapter1