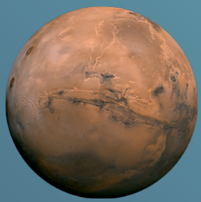
National Aeronautics and
Space Administration



2024
Moon to Mars
Architecture

white paper

Mars Surface Power Technology Decision

Introduction

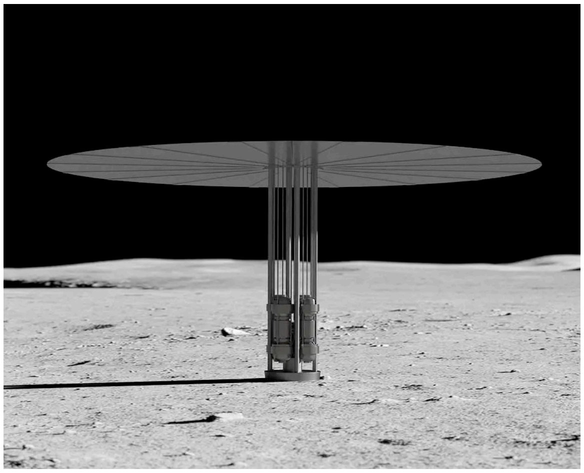
NASA has selected nuclear fission power as the primary surface power generation technology for crewed missions to Mars. The decision was adopted as part of the 2024 Architecture Concept Review cycle and will inform development of the Humans to Mars segment of the Moon to Mars Architecture.

This paper updates a white paper from the 2023 Architecture Concept Review, “Mars Surface Power Generation Challenges and Considerations.”[1] It summarizes the drivers and constraints that informed this architecture decision and provides an overview of NASA’s decision-making considerations.

Background

As part of the 2023 Architecture Concept Review cycle, NASA began identifying driving decisions needed to define initial human missions to Mars. This effort identified the selection of the primary Mars surface power generation technology as a key decision because of its down-flow impacts on NASA’s Mars architecture and Mars-forward considerations for NASA’s lunar architecture.

NASA involved numerous internal stakeholder communities (such as technology developers and safety experts) in its assessment process. ESDMD coordinated relevant data and technical expertise across NASA’s mission directorates and technical authorities, collating these inputs into a decision package for consideration by agency leadership at the 2024 Architecture Concept Review and subsequent meetings of the executive council. **These bodies reviewed the package and accepted the recommendation that nuclear fission serve as the primary Mars surface power technology.**



Selecting nuclear fission establishes the primary power generation technology for the Humans to Mars architecture segment but does not dictate funding for technology development or restrict other power technologies that could operate on the Martian surface. Instead, it offers an initial assumption for narrowing the architectural trade space and lays the groundwork on which flow-down architectural and implementation decisions may be made.

NASA’s selection of nuclear power technology over non-nuclear power technology was driven primarily by the need to mitigate the risk of loss of mission. To make the decision, NASA traded numerous power technologies, ultimately down selecting to nuclear fission systems versus photovoltaic arrays with energy storage (i.e., solar panels with batteries).

Although solar power may have a lower per unit cost, fission power is more robust and better suited to the Martian environment. Fission can provide consistent power generation for a wide range of potential landing sites, around the clock, and during global dust storms. It also offers advantages in landed mass and volume.

Image 1: *Artist concept of space fission surface power systems. (NASA)*

Note: *This paper is concerned with the primary power generation technology for an initial crewed Mars exploration campaign. The potential for supplementary, backup, and redundant systems remains an open area of architectural analysis.*

Mars Surface Power Considerations

After reaching and landing on the Red Planet, the first human Mars explorers must generate sufficient energy to power the systems they will need for a healthy and productive stay on the surface and their ascent back to orbit. Mars surface power needs may vary from one crewed mission to another depending on how long each crew plans to stay on Mars, surface mission objectives, and the requirements of surface assets and ascent vehicles.

Studies show that a modest mission of two crew members, conducting science and exploring the surface for no more than 30 days while living in a pressurized rover would require at least 10 kilowatts (kW) of surface power. (This includes propellant conditioning for a small crew ascent vehicle).

At the other end of the trade space, a larger crew complement, longer duration, propellant manufacturing, etc., would require hundreds of kW. Some architectures could require megawatt (MW)-class power systems.

Regardless of the architecture, a Mars surface power generation technology must address each of the unique environmental and operational challenges below:

Environmental Challenges

Dust Storms

Martian dust storms range from local dust devils to regional or global storms persisting for weeks or months. Local phenomena can evolve to global events in just a few Martian days. Atmospheric dust can reduce the solar energy that reaches solar arrays and the effectiveness of technologies requiring line of sight for power distribution, (e.g., power beaming). Dust settling out of the atmosphere can also collect on solar arrays, reducing performance. Sufficient accumulation can prevent them from generating keep-alive power, a situation that proved fatal for the solar-powered Opportunity rover.

Reduced Solar Energy Availability

Mars missions must account for reduced solar flux — the amount of solar energy that reaches an area — which is at most 45 percent of typical Earth values and varies significantly by location and season. The Martian day/night cycle also varies by location and season, with mid-latitude missions experiencing a 25-hour cycle and only illuminated for about 50 percent of that time. A Mars solar power system must simultaneously provide power for daylight operations while charging batteries to maintain night operations under this reduced solar energy availability.

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. Large solar array structures designed for lunar applications would need higher structural strength for deployment on Mars. The design of very large or vertical solar arrays must also account for Martian winds. While wind is a design consideration, it is insufficient to serve as a primary surface power source (see the trade space section below).

Operational Challenges

Autonomous/Remote Power System Operation

To mitigate landing risks, many proposed Mars architectures would land their crew ascent vehicles with empty or partially full propellant tanks and either transfer staged, Earth-origin propellant or manufacture propellant from Mars resources. Both approaches require abundant surface power to condition, transport, and/or manufacture fuel. Depending on a variety of factors (including the use of delivered versus in-situ propellant and Earth departure windows), power systems may need to be deployed years in advance and support several human missions.

Limited Repair Options

The sheer distance between Earth and Mars means that unplanned replacement units or repair parts will not be readily available unless already staged on or near the Red Planet. The reliability, redundancy, and repairability of a surface power technology will have flow-down impacts on the architecture. To ensure crew safety, a surface power technology must be sufficiently robust, have built-in redundancy, and/or consider maintenance and servicing in its concept of operations.

Plume-Surface Interactions

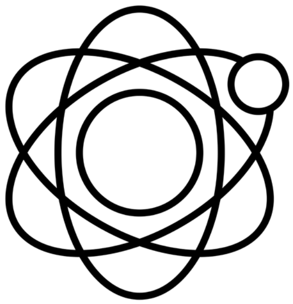
Descent and ascent engines can create plume-surface interactions, a known challenge for lunar landings that is exacerbated by the Martian atmosphere. Power systems must be shielded or separated from debris ejected by arriving or departing vehicles. This could require more extensive power distribution systems (e.g., autonomously deployed cabling) or mobility capabilities. Additionally, plume-surface interactions can loft dust that can cover solar panels a significant distance from a landing site.

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."[2] NASA is developing specific planetary protection guidelines for human missions to Mars; the primary power generation technology selected for Mars must adhere to these constraints.

Mars Surface Power Generation Trade Space

Despite Mars' many challenges, many promising power generation technologies are available or in development. While NASA considered many technologies as part of its surface power decision, two options in the trade space stand out as offering the most value: nuclear power and solar power.

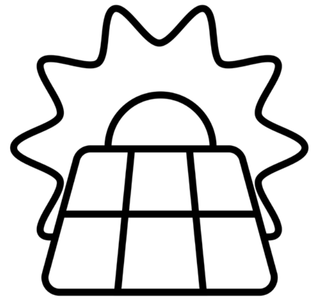


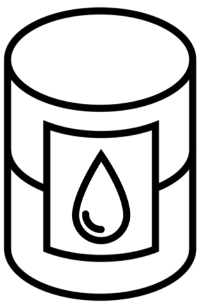
Nuclear Power

High energy density nuclear power — either Curiosity/Perseverance rover-style radioisotope power systems or nuclear fission systems — are unaffected by day/night cycles and reduced solar energy availability. Additionally, nuclear power systems would package well in volume-constrained spacecraft. Although current radioisotope power system designs only offer a few hundred watts, they may be applicable to applications with smaller power loads. For higher power needs (e.g., crew life support or ascent propellant manufacturing), fission surface power is readily scalable.

Solar Power

Solar power could be feasible if designed to address the challenges of dust accumulation and the day/night cycle. To clear accumulated dust from solar panels, NASA could augment them with robotic dust wipers, pressurized gases, mechanical array tilting, or electrodynamic or piezoelectric dust removal. However, surface dust removal would not mitigate the problem of reduced solar availability due to suspended atmospheric dust during lengthy storms. Nighttime power needs would require energy storage and simultaneous daytime charging and power distribution. Additionally, NASA would need to evaluate unique operational considerations — such as radiation keep-out and large array off-loading — for large-scale solar power system deployment on Mars.



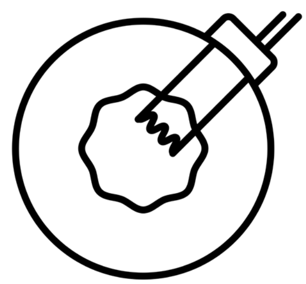


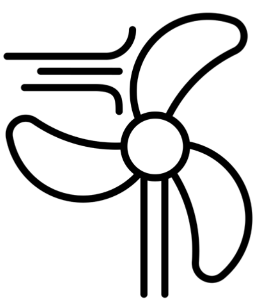
Fuel Cells

Fuel cells — which generate electricity through chemical reactions — are often proposed for Mars missions. In this paradigm, associated chemical fuel would be transported from Earth or generated in-situ on Mars. These systems do not trade well because they require large amounts of landed reactant mass and/or more energy to make reactants in-situ than the fuel cells could provide.

Geothermal Engergy

Geothermal energy has been proposed for use in eventual Martian settlements. However, NASA currently has limited data on local geothermal availability and has not matured geothermal technologies for Mars. Additionally, accessing geothermal energy would require heavy equipment to implement and may be geographically constrained to areas with easy access to geothermal sources. The autonomous robotic drilling and regolith-moving required to access heat sources would also require a separate power source. This makes geothermal energy generation less attractive for early missions.



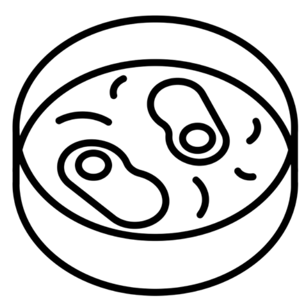


Wind Power

While some have proposed wind turbines as a potential Mars power generation technology, analysis shows that the Red Planet has insufficient sustained winds for reliable power production. While wind is a key design consideration for Mars surface power, it would not suffice for primary power generation for initial crewed missions to Mars.

Biogeneration

Biogeneration relies on microorganisms to convert organic feedstock directly into heat or another commodity, such as methane, that can then be used to generate power. This technology has been proposed as an option for Mars power generation but would be greatly complicated by planetary protection constraints.



Note: While multiple power systems may be integrated to support mission needs, this paper and its associated decision consider *primary* and not *supplementary* power generation technologies specifically for *initial* crewed missions to Mars.

The Moon as a Testbed for Mars

The Moon's proximity to Earth offers opportunities to demonstrate candidate Mars surface power generation technologies with reduced consequences of failure. To ensure extensibility to Mars, lunar surface power systems would need to account for the environmental differences, including Mars' atmosphere, increased gravity, shorter day/night cycle, wind loads, dust storms, communications delay, etc. While implementing Mars-forward technologies at the Moon could add cost or complexity, surface power technology demonstrations during the Artemis campaign would significantly reduce risk for initial crewed missions to Mars, serve as pathfinders for power system operations, and ultimately reduce the cost of implementing systems for Mars.

Summary

NASA examined the factors detailed above in developing the decision package for the primary Mars surface power generation technology. The team evaluated different power generation options across a variety of attributes, including:

- reliability and availability (i.e., their resilience to the environmental factors described above),
- ability to meet the power needs of a range of potential missions,
- extensibility to future segments,
- and key drivers of affordability.

The team consulted with stakeholders from across NASA's mission directorates and technical authorities, ultimately offering a recommendation that was approved by agency leadership.

Because of the advantages it offers in power availability and reliability, NASA will baseline nuclear fission power as the primary surface power generation technology for initial crewed Mars missions. This decision represents a significant step in defining the first human missions to the Red Planet and enables Mars-forward power considerations during lunar missions.

Image 2: *Artist concept of space fission surface power systems. (NASA)*

Key Takeaways

The minimum power required for a modest, short duration, human Mars surface mission with a limited crew complement is about 10 kW. More complex architectures leveraging significant in-situ resource utilization could require MW-class power systems.

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

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

Architecture Decision

NASA has baselined fission power as the primary surface power generation technology for initial crewed missions to Mars due to its robustness to surface environmental and atmospheric conditions as well as mass and volume advantages considering the power levels needed for human Mars exploration.

References

1. **Mars Surface Power Generation Challenges and Considerations, 2023 Moon to Mars Architecture White Paper**
   https://www.nasa.gov/wp-content/uploads/2024/01/mars-surface-power-generation-challenges-and-considerations.pdf?emrc=383a7b
2. **NASA Procedural Requirement 8715.24, Chapter 1**
   https://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_8715_0024_&page_name=Chapter1