

COMMON POWER AND ENERGY STORAGE SOLUTIONS TO SUPPORT LUNAR AND MARS SURFACE EXPLORATION MISSIONS

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Future human exploration missions on the moon and Mars will require a new generation of power sources to sustain crew members and leverage in-situ resources. Long-duration human missions to the lunar and Martian surface will likely include large-scale landers, crew habitats, pressurized rovers, and in-situ propellant production plants. The power demands for these surface elements, whether on the moon or Mars, will be similar starting with robotic precursor missions in the multi-kilowatt range scaling to tens of kilowatts as the crew presence expands and local propellant production is established. While the power requirements may be similar, the vastly different environments on the two surfaces present unique challenges for power generation and energy storage systems. Candidate technologies to satisfy the surface power needs include deployable solar arrays, regenerative fuel cells, and small fission reactors. This paper presents strategies for power system architectures with elements that can be used on the moon and are extensible to Mars with features that make them resilient to either environment.

I. LUNAR SURFACE MISSION CONCEPTS

On-going studies are being performed by the National Aeronautics and Space Administration (NASA) and industry to define a new lunar exploration campaign for the twenty-first century. The National Space Council has given direction to pursue an initial human lunar landing by 2024 and a sustainable presence by 2028¹. NASA has responded with plans for Commercial Lunar Payload Service (CLPS) robotic missions as early as 2020 and an aggressive Human Lander System (HLS) development program with multiple contractor teams.

The early, short-lived robotic and human surface missions can likely be performed with available power technologies, but longer-term presence and increased mission dependence on In-Situ Resource Utilization (ISRU) will require new and innovative power approaches. Power levels are likely to increase from hundreds of watts for robotic landers to tens of kilowatts or more for human habitation, mining operations and propellant production. Operational system lifetimes will also increase from days to years, possibly including long periods of dormancy between use. The preferred implementation strategy is likely to include a diversity of power technologies that can be used to meet an evolving mission need with multiple, distributed surface users.

Early Robotic Missions

NASA awarded nine contracts to potential CLPS vendors including three initial lander contracts to Astrobotic, OrbitBeyond, and Intuitive Machines. Two separate lander payload solicitations have resulted in a

total of 24 scientific and technology demonstration payloads that are being considered for future lander missions^{2,3}. One of the selected technology demonstration payloads for CLPS is the Photovoltaic Investigation on Lunar Surface (PILS) which plans to evaluate advanced solar cell performance in the lunar surface environment.

The CLPS landers are being developed by industry and the power systems are still being defined, but are expected to use predominantly off-the-shelf power components. The Astrobotic Peregrine lander uses lithium-ion (Li-ion) batteries and a top-mounted solar array configured to support mid-latitude surface missions. A derivative version for polar missions will likely re-position the array to be vertical to capture low angle, sunlight on the lunar horizon. Intuitive Machines' Nova-C lander is derived from technology developed under NASA's Morpheus lander project. It uses side-mounted solar arrays and commercially-available batteries. Both landers are slated to land during the day and not survive the lunar night. Future, more advanced power systems and thermal management is needed to achieve lunar night missions.

Initial Human Landing

The HLS Program seeks to land humans on the moon by 2024 in support of Space Policy Directive 1 as issued by the President and the National Space Council⁴. The details of the human-class lander are still being formulated within NASA and through independent studies by government contractors. The current NASA reference concept envisions a three-element architecture comprised of a transfer vehicle,

descent module, and ascent module. The transfer vehicle delivers the crewed lander from the cislunar Gateway orbit to low lunar orbit. The crew would then descend to the surface for a multi-day stay during lunar daylight and return to Gateway via the ascent module, as shown in Figure 1.



Fig. 1: Lunar Lander Concept

Each of the three elements have their own dedicated power system consisting of solar array wings and batteries. It would be beneficial to utilize common power components for the three elements to save cost and reduce risk. The power system sizing is heavily influenced by the propulsion system, as active thermal management of cryogenic propellants would be a major power driver. Initial estimates indicate 6 kWe for a liquid oxygen/liquid hydrogen (LOX/LH₂) stage or 2 kWe for a LOX/liquid methane (LOX/LCH₄) stage. A two-person crew aboard the ascent module adds about 1 kWe for life support. Li-ion batteries would be used for docking operations near Gateway, lunar orbit eclipse, deorbit burn and descent coast to the lunar surface. The ascent stage solar arrays would be gimbaled for sun-tracking during the surface mission and reused for transit during the crew return to Gateway.

Key questions that surround the lunar lander solar arrays include methods to maximize low-angle polar sunlight collection, landing load and dust plume survivability, array deployment accommodations (and possibly retraction), extreme temperature operations (e.g. lunar surface temperatures may exceed 375K during the day and drop to 100K at night), and commonality with future off-loaded, surface-mounted solar arrays used for long-duration outposts.

Sustained Human Presence

A goal has been set for sustainable operations on the lunar surface by 2028, possibly with long-lived surface assets that are capable of supporting extended crew campaigns, perhaps as long as one year or more. There is still debate whether to establish a single outpost location with assets that could be reused on multiple missions, or pursue several distributed sites to expand the exploration footprint. One option considered in the

past, is to robotically move the assets between crew missions to minimize down-mass while maximizing the number of places visited, although this introduces challenges on system autonomy and remote teleoperations. Major power users among the early human surface elements include crew habitats, environment control, life support, and rover recharging. Using the International Space Station as an analogy would lead one to project power needs for a 4-person crew on the moon at 10 kW or more. Environmental control on the moon could be a major factor with large heating and lighting requirements during the night and large cooling requirements during the day. If closed-loop life support systems and local food production are introduced, power requirements could rise sharply.

Architectures that leverage ISRU-derived propellants would likely be consolidated at a single, ice-rich location. That site would include the infrastructure to extract and transport raw material, process the material in to useful products, and store the material for future use. Lunar ISRU propellant production, as depicted in Figure 2, is projected to provide considerable benefits for the lander propulsion architecture but has major implications on power. Among the major power users are the ISRU plant systems to separate water from regolith, electrolyze water in to hydrogen and oxygen gas, and liquify the hydrogen and oxygen for propellant. The mining rovers that acquire and move the material to the plant would likely use energy storage systems that require recharging power at the plant. ISRU power requirements are expected to be in the 10 to 20 kW range to produce metric ton quantities of lunar propellant.

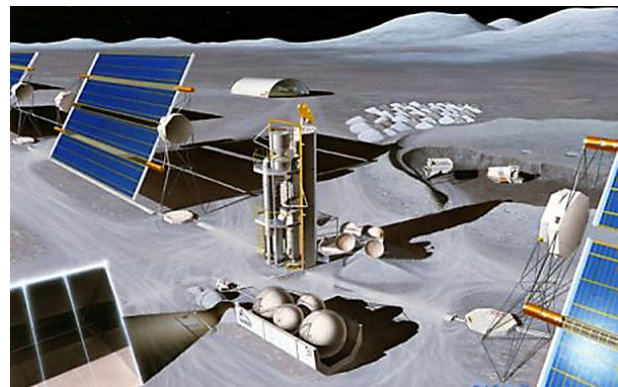


Fig. 2: Lunar ISRU Concept

II. MARS SURFACE MISSION CONCEPTS

There are two major schools-of-thought on how to undertake a human Mars mission. The first is to focus all the resources on getting to Mars directly while minimizing distractions that might come with intermediate destinations or practice missions. Some might argue that this is the fastest and lowest cost path

to Mars. The other approach, and the one favored by NASA, is to use the moon as a testbed to demonstrate critical technologies so that increased confidence can be gained with those systems before they are needed in the more demanding Mars mission. This approach may cost more and take longer, but the overall risk would be reduced. The closer proximity of the moon allows technology demonstrations to occur with reduced consequences of failure.

The moon and Mars differ in many ways, but strong arguments can be made to use the moon as a proving ground for human Mars missions. Among the technologies that could be demonstrated on or around the moon are space propulsion and propellant management, rendezvous and docking, crew habitation and life support, surface mobility, ISRU, and surface power. Lunar surface systems designed to be extensible to Mars would need to account for the environmental differences including the low-pressure carbon-dioxide (CO₂) atmosphere, increased gravity, shorter day/night cycle, reduced solar insolation, wind loads, and dust storms.

Human missions to Mars have been studied extensively in the past by NASA and industry, most notably Mars Design Reference Architecture 5.0⁵ and its variants defined during the NASA Evolvable Mars Campaign (EMC). Many previous mission studies assumed a pre-crew robotic mission to emplace assets that produce the propellant needed for the crew return phase before the crew ever leaves Earth.

Robotic Asset Pre-deployment

Mars transportation architectures are dominated by the propellant that must be carried to Mars to allow the crew to land, ascend, and return to Earth. Most studies show significant benefits of delivering equipment to make propellant at Mars rather than bringing propellant from Earth. A popular ISRU strategy is to generate LOX from the Martian CO₂ atmosphere and combine that with Earth-delivered LH₂ or LCH₄ for the ascent vehicle. This scenario would require the Mars ISRU plant to produce approximately 30t of LOX for a 4-person ascent vehicle. The process of producing oxygen from low-pressure, atmospheric CO₂ is being demonstrated on a small scale by the Mars 2020 rover via the Mars Oxygen ISRU Experiment (MOXIE). Another option is to mine water ice at Mars, presumed to be concentrated in the higher northern latitudes, and produce both LOX and LH₂ for the return mission. This approach is similar to the ISRU strategy that could be implemented on the moon.

Earth-to-Mars mission opportunities occur approximately every 26 months, and the CO₂-to-LOX ISRU plant, shown in Figure 3, would likely be delivered to Mars on the mission opportunity that proceeds the first crewed mission. Ideally, the LOX

production would be completed in the time period after the assets are delivered and before the crew leaves Earth on the next mission opportunity. That sets the time allocated to produce the required LOX propellant load at about 19 months, or about 1.6 t/month. The power required to produce the LOX in the allocated time with continuous day and night production is estimated at about 30 kW, which increases to about 100 kW for day-only production. In this scenario, the power system and ISRU plant would need to be delivered, deployed and operated without local human intervention, thus requiring high levels of autonomy and fault tolerance.

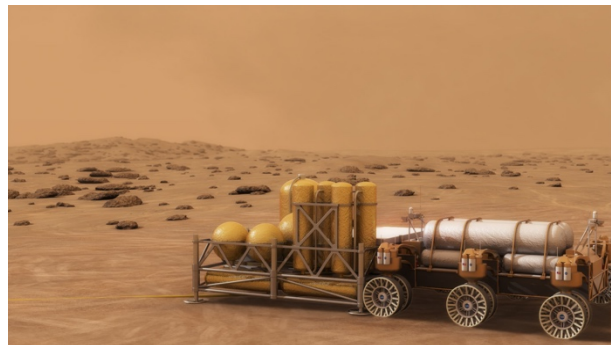


Fig. 3: Mars Atmospheric ISRU Concept

NASA performed studies in 2016 to compare solar and nuclear power options for Mars atmospheric ISRU⁶. Nuclear offers the lowest mass power option since it can provide continuous power without the need for night-time energy storage. The baseline approach identified for the EMC was to employ five 10 kW Kilopower reactors (four primary units plus one spare unit) delivered on a single Mars lander. The total delivered mass for the four systems is projected at about 7.5t including the radiation shielding to protect nearby equipment and crew habitats. The NASA study estimated a comparable solar power and energy storage system at about twice the mass of the nuclear fission approach with the mass discrepancy increasing as the landing site moves further from the equator.

Solar array designs on Mars must account for reduced solar flux, which is at most 45% of typical Earth flux (~1370 W/m²) and varies significantly with geographic location and season as shown in Figure 4. It is anticipated that as many as three Mars surface landers would be needed to accommodate the deployed solar arrays needed for ISRU LOX production. A solar power system must be over-sized to supply power for day-time ISRU production while simultaneously charging the energy storage (batteries or regenerative fuel cells) to maintain night-time operations. A day-only production scenario would require even larger solar arrays and would introduce undesirable thermal cycles on the ISRU plant during the night-time plant stoppages. Solar power also introduces uncertainty in

LOX production due to the possibility for extended down-time during dust storms that could last months⁷. The extended Martian dust storms would require contingency power sources to assure that minimum power needs are satisfied.

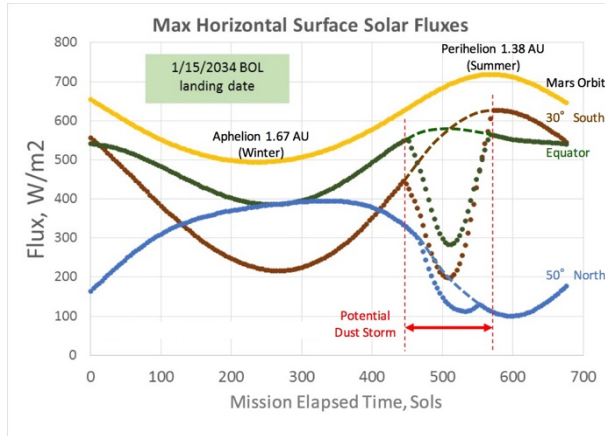


Fig. 4: Mars Solar Flux Variations

Periodically-Tended Human Outpost

Conjunction class missions to Mars would result in crew surface missions of up to 500 days, while opposition class missions would be less than about 50 days on the surface. Once the crew arrives on Mars, the ISRU propellant plant could be put into standby mode (only providing thermal management of cryogenics) with most of the power redirected to meet human needs. Power requirements for human exploration on Mars are projected at about 30 kW for a four-person crew, long-duration habitat with environmental control, surface science facilities, and rover recharging. A promising approach for Mars surface missions is to establish a single field station that would be revisited over multiple crew campaigns. The field station would include the pre-emplaced assets and the additional systems that would be delivered with each crew visit. The single exploration site works best for Mars given the difficulty of getting equipment there from Earth and the desire to maximize its use once delivered. This approach does introduce a requirement for longer-lived surface systems, possibly including extended dormancy periods between crew missions, and the need for long-range mobility systems to maximize surface exploration.

A particular challenge for the Mars surface architecture is the impacts of descent and ascent thrust plume debris on surface systems, which is exacerbated by the Mars atmosphere. A work-around is to land and depart at safe distances from sensitive, pre-emplaced equipment. Preliminary calculations indicate that plume debris can travel up 700 m on Mars, thus a safe separation distance has been set at 1 km. Assuming that certain critical surface systems (e.g. habitat, ISRU, power) remain on or near the lander that delivers them,

power must be distributed over long distances to connect the power sources to the loads. Power cabling trades have shown that high-voltage transmission (~1 kV) can be used to achieve reasonable cable mass. A notional surface architecture with a 40 kW power supply located 1 km from the ISRU plant and 2 km from the crew habitat is estimated to require less than 1t of power management and distribution (PMAD) equipment.

A potential element of the Mars field station is a pressurized rover to allow long-distance crew excursions to explore other regions on Mars, as shown in Figure 5. Such a vehicle could enable crew sorties at distances of 100 km or more from the field station and dramatically increase the scientific return. The power requirements for a pressurized rover with a two-person crew are estimated at about 7 kW while moving and 2 kW when stopped. These requirements are much greater than what would be needed for robotic rovers or unpressurized crew rovers, but offer significant benefits to extend the crew's exploration reach.



Fig. 5: Mars Pressurized Rover Concept

The pressurized rover could use rechargeable batteries or regenerative fuel cells (RFCs). Recharging power (or power to electrolyze the fuel cell produced H₂O back in to H₂ and O₂ reactants) could be supplied by deployable solar arrays. But that approach requires the rover to stop during the day when the driving conditions are optimum. Another possibility is an on-board radioisotope power system (RPS) sized to charge the energy storage system and possibly provide heat for crew environmental control. A third option is to deploy a portable 10 kW Kilopower reactor to serve as a remote charging station, possibly employing one of the units from the field station. The reactor system would need to be shut down, transported to the new location, and restarted. The pressurized rover could return to the Kilopower unit each night for recharging while the crew rests. The charging station could be moved periodically or remain as a central hub with rover sorties that extend from the hub in "flower-petal" arrangement. An integrated solar array and energy storage system could be deployed in a similar way, although it might be more difficult to relocate due to the greater size and weight.

III. CANDIDATE POWER TECHNOLOGIES

The NASA Space Technology Mission Directorate (STMD) is pursuing a variety of surface power technologies to support Lunar and Mars exploration. Surface power is one thrust area under STMD's new Lunar Surface Innovation Initiative (LSII), which was established to coordinate surface-relevant technology investments across STMD Programs.

Under the Space Technology Research Grants (STRG) Program, current early stage technology projects are aimed at low-temperature batteries and chemically-heated power sources for lunar night applications. The Game Changing Development (GCD) Program has current technology maturation projects related to RFCs and deployable lunar surface solar arrays. The Technology Demonstration Mission (TDM) Program is formulating a lunar surface flight demonstration of a small fission power system derived from the successful GCD Kilopower development. STMD is also considering additional studies on rover energy sources, surface-to-surface power beaming, and surface PMAD technologies. The various NASA-led activities are complemented through external, competitive solicitations intended to engage industry, such as NASA Innovative Advanced Concepts (NIAC), Small Business Innovation Research (SBIR), and Tipping Point.

Technologies that can be demonstrated on early robotic missions will aid in reducing the risk and increasing the confidence in their use for future human missions where system reliability and availability will be essential. Technologies that can be used across multiple mission applications (e.g. base power and mobility power), as well as those that offer extensibility to Mars provide a distinct advantage over single-use, customized solutions. A power technology portfolio that responds to these goals and delivers timely products for mission users is desired.

Deployable Solar Arrays

The objective of the GCD Adaptable Lightweight Lunar Solar Array Systems (ALLSAS) project is to adapt and optimize mature space-based PV arrays for lunar surface use. The project is focusing on a 10 kW-class array module (approximately 35 m²), which is presumed to be a good building block for human surface missions with ISRU. The array design should accommodate next-generation solar cell and flexible blanket materials that provide high efficiency and low mass. The lunar surface arrays should stow in a compact volume to fit on the lander, survive landing loads, deploy by remote command after landing, automatically track the sun as it moves in the lunar sky, and include features to deal with extreme temperatures (both cold and hot), lunar dust and possibly, nearby lander plume debris. A potentially desirable feature of a

lunar surface solar array is the ability to retract to protect itself from lander plumes or to permit movement to a different site.

The project may pursue a common array design for use on second generation landers that can also be off-loaded and mounted on surface structures to maximize sunlight collection at polar mission sites, as shown in Figure 6. Analysis of Lunar Reconnaissance Orbiter (LRO) data indicates promising areas of near-continuous sunlight at the South Pole during the summer months⁸. The project may also consider a deployment system that could support vertically-oriented arrays for polar missions or horizontal arrays on equatorial and mid-latitude missions. The same array designs might be used on Mars, albeit at reduced power output, if the structures and mechanisms could be engineered for Mars gravity and wind loads.

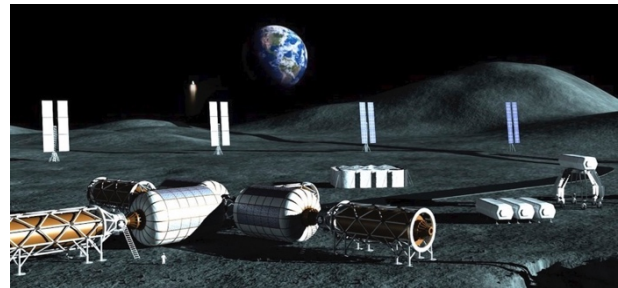


Fig. 6: Lunar Pole Solar Array Field

The ALLSAS project was initiated as a six-month FY19 GCD Seedling Study, with an expected conclusion in late 2019. A follow-on project would occur if the study shows promise and identifies opportunities for mission infusion. The development project could engage industry through a competitive procurement for array conceptual designs with contract options for detailed system design and large-scale ground test articles that would be evaluated in lunar surface simulation facilities. The effort might be modelled after the successful 2012 GCD Solar Array Systems (SAS) project that conducted high-fidelity ground demonstrations of both the Roll Out Solar Array and MegaFlex Solar Array for high-power Solar Electric Propulsion applications⁹.

Fuel Cells and Regenerative Fuel Cells

The GCD Evolved RFC (ERFC) project was initiated in late 2018 with the goal of completing a sub-scale RFC demonstration in a simulated lunar test environment in about 4-years. RFCs provide an attractive option to power stationary surface elements during the lunar night or long-duration mobility systems such as pressurized crew rovers. The RFC system is comprised of a fuel cell generator, gaseous H₂ and O₂ reactant tanks, a biproduct water collection tank, and an electrolyzer that converts the water back to H₂ and O₂.

The lunar design could be easily tailored to meet Mars energy needs with nearly identical components.

The project hopes to combine SBIR-provided fuel cell and electrolyzer stacks with NASA-provided balance-of-plant components and control software to produce a fully integrated, closed-loop RFC system. The system would be sized to produce approximately 100 W through the 350-hour lunar night and regenerate reactants in one 350-hour lunar day, using technology that is extensible to about 7 kW. The test system would be designed to operate in a lunar environment for 1-year encompassing 13 day/night cycles.

RFCs have been shown to offer mass advantages over rechargeable batteries for long discharge periods. Figure 7 presents a notional mass comparison between batteries and RFCs indicating a mass breakpoint when the discharge time exceeds approximately 10-18 hours. Both Apollo and the Space Shuttle relied on fuel cell power generation, but neither included a means to regenerate reactants. Those missions utilized alkaline fuel cell technology, whereas the current ERFC project is focused on Proton Exchange Membrane (PEM) fuel cell technology. PEM offers advantages in mass, efficiency, and operating life compared to the earlier alkaline versions¹⁰.

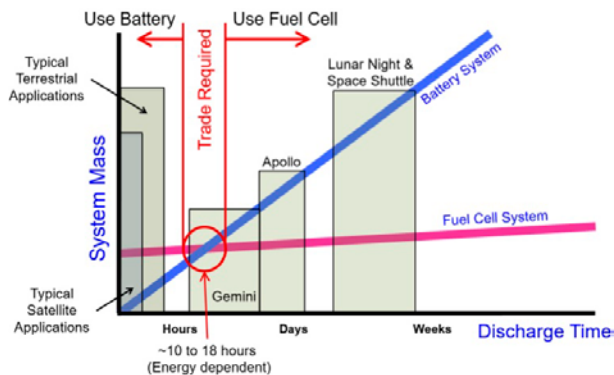


Fig. 7: RFC and Battery Mass Trade-offs

There is also interest among lunar lander developers to utilize primary fuel cells that could process residual H₂ and/or O₂ propellant reserves to generate electric power during descent and after landing. STMD recognizes the value of developing RFC technology that could also serve the lander application, and is considering the possibility of an early flight demonstration of the fuel cell portion of the RFC on a CLPS lander. Another potential derivative use of the ERFC technology involves the electrolyzer, which could be adapted for use in ISRU propellant production systems that process lunar and Martian ice.

Small Fission Reactors

Under the GCD Kilowatt project, a NASA and Department of Energy (DOE) team designed, built and

tested a space-relevant 1 kW-class fission reactor with technology that is extensible to about 10 kW¹¹. The Kilowatt Reactor Using Stirling Technology (KRUSTY) test included an enriched UMo core, BeO neutron reflector, Na heat pipes, and free-piston Stirling engine converters. Nuclear testing at the Nevada National Security Site revealed a reactor power system that was robust, well-behaved, predictable, self-regulating, and multi-fault tolerant. In addition to satisfying all test objectives, the project showed that a flight-like fission power system could be developed quickly and affordably (in less than 3.5 years with less than \$20M total investment from NASA and DOE). A flight version of the 1 kW test prototype has a system mass of about 400 kg.

Building on the success of the KRUSTY test, STMD hopes to flight demonstrate a 10 kW-class fission power system on the lunar surface in the mid- to late-2020s under the TDM Program. The initial concept shown in Figure 8 has an estimated mass of 1500 kg including a circumferential radiation shield surrounding the reactor core. The system could be integrated with a mid-size lunar lander and operated on the lunar surface for at least one year. The mission concept is still being formulated, but could include provisions to power an ISRU demonstration plant and recharge mining rovers that supply raw material to the plant. The expectation is that the lunar design could be used on Mars with little or no changes, making the lunar demonstration a true testbed for Mars. Some of the key objectives for the fission power TDM include nuclear launch approval, launch and landing survival, remote start-up, extended automated operations, standby and partial power operations, and adherence to specified radiation limits at established boundaries where sensitive equipment would be located. Most importantly, a successful fission power demonstration would give mission planners greater confidence to use the technology for later human missions on the moon and Mars.

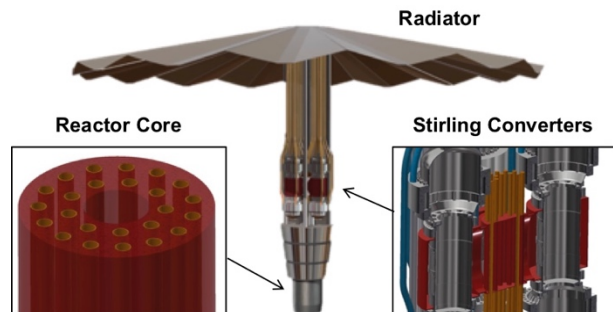


Fig. 8: 10 kW Fission Power System Concept

The 10 kW reactor power system could also be adapted to serve other NASA applications. Studies have shown that a 10 kW-class Kilowatt-type reactor

could be used for nuclear electric propulsion (NEP) science missions to the outer planets. An example 10 kW NEP mission to Neptune with a Falcon 9 Heavy launch and 13-year flight could deliver a 100 kg orbiter and 300 kg Triton moon lander for a 2-year science campaign. Other studies have examined the high-power Kilowatt reactor for use as a melt probe at Europa to traverse the 20-km thick ice layer (in about 3-years) and reach the liquid ocean beneath in search of biotic life.

IV. CONCLUSION

A new generation of power sources will likely be needed to accommodate future human exploration missions to the moon and Mars. By 2028, NASA hopes to establish a sustainable human presence on the moon where in-situ resources could be leveraged to reduce the dependence on Earth-delivered materials. Learning to live on the moon will pave the way for Mars missions that will present additional challenges given its greater distance from Earth. Mars surface missions may require pre-deployed surface power systems before humans arrive to help produce ascent stage propellant. Ideally, those same systems continue to supply the power for humans that come next and for multiple mission campaigns afterwards.

The power requirements for humans on the Moon and Mars are somewhat similar, and missions can use common power technologies if strategic engineering choices are made and proper consideration is given to the different environments. Stationary power systems that produce tens of kilowatts, day and night, will be needed for human landers, habitats and ISRU plants. These needs could be fulfilled by deployable solar arrays with nighttime energy storage or small fission power systems. Mobile power systems that can supply kilowatts will be needed for mining rovers and pressurized crew vehicles. These needs could be satisfied by fuel cells or batteries that are recharged/refueled using the stationary power systems.

STMD is leading agency efforts to develop surface power technologies under the Lunar Surface Innovation Initiative. Current efforts are underway to advance the technology readiness of deployable surface solar arrays, regenerative fuel cells and fission power systems. Other technologies are also being examined including low-temperature batteries, chemical heat power sources, high-voltage power distribution and surface-to-surface power beaming. An overarching objective is to demonstrate the technologies in relevant mission environments to verify performance and functionality. In certain cases, the demonstrations will be performed directly on the moon to gain operating experience on systems that will be needed when humans arrive later. Several key technologies offer great potential for use on

both the lunar and Martian surface, in which cases the lunar missions will serve as a critical proving ground for Mars.

V. REFERENCES

1. Remarks by Vice President Pence at the Fifth Meeting of the National Space Council, Huntsville, AL, Mar. 26, 2019.
<https://www.whitehouse.gov/briefings-statements/remarks-vice-president-pence-fifth-meeting-national-space-council-huntsville-al/>
2. NASA Press Release 19-010, NASA Selects Experiments for Possible Lunar Flights in 2019, Feb. 21, 2019.
<https://www.nasa.gov/press-release/nasa-selects-experiments-for-possible-lunar-flights-in-2019>.
3. NASA Press Release 19-053, NASA Selects 12 New Lunar Science, Technology Investigations, Jul. 1, 2019.
<https://www.nasa.gov/press-release/nasa-selects-12-new-lunar-science-technology-investigations>.
4. Presidential Memorandum on Reinvigorating America's Human Space Exploration Program, issued Dec. 11, 2017.
<https://www.whitehouse.gov/presidential-actions/presidential-memorandum-reinvigorating-americas-human-space-exploration-program/>.
5. Drake, B. G., editor, "Human Exploration of Mars Design Reference Architecture 5.0," NASA/SP-2009-566, Jul. 2009, Washington D.C.
6. Rucker, M. A., et al., "Solar Versus Fission Surface Power for Mars," AIAA-2016-5452, AIAA Space Conference, Sep. 2016, Long Beach, CA.
7. Wang, H. and Richardson, M. I., "The Origin, Evolution, and Trajectory of Large Dust Storms on Mars During Mars Years 24-30 (1999-2011)," Icarus Volume 251, May 2015, pp. 112-127.
8. Fincannon, J., "Lunar Polar Illumination for Power Analysis," NASA/TM-2008-215446, AIAA-2008-5631, 6th International Energy Conversion Engineering Conference, Jul. 2008, Cleveland, OH.
9. Mercer, C. R., et al., "Solar Electric Propulsion Concepts for Human Space Exploration," NASA/TM-2016-218921, AIAA-2015-4521, AIAA Space Conference, Aug. 2015, Pasadena, CA.
10. Guzik, M. C., et al., "Regenerative Fuel Cell Power Systems for Lunar and Martian Surface Exploration," AIAA-2017-5368, AIAA Space Conference, Sep. 2017, Orlando, FL.
11. Gibson, M. A., et al., "The Kilowatt Reactor Using Stirling Technology (KRUSTY) Nuclear Ground Test Results and Lessons Learned," AIAA-2018-4973, 2018 International Energy Conversion Engineering Conference, Jul. 2018, Cincinnati, OH.