This topic includes the development of power capabilities that are on the critical path to enabling the Exploration Vision including human and robotic exploration missions from Earth orbit to the Moon and ultimately, Mars. Areas of primary interest are: orbital and planetary surface energy storage and non-solar power generation. Flight elements of the Exploration Vision initially include the Orion and ARES crew and launch vehicles, respectively. For lunar capability, additional elements include the Lunar Lander or Lunar Surface Access Module (LSAM), robotic missions, and surface systems. Surface systems include human habitats, Extravehicular Activities (EVA), science measurements, and the utilization of in situ resources. These flight systems require energy storage capabilities up to and greater than 10 kW-hr. Effective solutions require high-capacity, high-energy density, and long-life energy storage systems. Rechargeable lithium-based batteries (e.g., ion, sulphur) that provide energy storage for Exploration missions are required to be human-rated. For the lunar environment, batteries must operate over a greater range of temperatures than current state-of-the-art systems. The Exploration architecture calls for advanced fuel cells to meet the LSAM and surface system power requirements. Fuel cell systems provide power largely independent of environment (solar incidence), which allows greater mission flexibility and provide more power than other energy storage systems. Regenerative fuel cell systems, which combine a fuel cell with a water electrolyzer, will be required to meet long duration surface power energy storage needs. Prior architecture studies have identified nuclear power technology to effectively satisfy high power requirements for extended duration lunar surface missions. Nuclear power generation is especially attractive for missions with significant solar eclipse periods, including non-polar locations and inside lunar craters. Likewise, nuclear power has been identified as a critical power technology for Mars exploration and a lunar deployment is proposed to reduce risk through demonstration and validation of capabilities.

Subtopics

X8.01 Fuel Cells for Surface Systems

Lead Center: GRC
Participating Center(s): JPL, JSC

Energy storage devices are required to enable future robotic and human exploration missions. Advanced regenerative fuel cell (RFC) energy storage systems are sought for use in a wide range of Exploration mission applications including portable power for landers and rovers, and stationary power for surface bases. Technology advances that will reduce the weight and volume, improve the efficiency, life, safety, system simplicity and reliability of RFC systems are desired. The specific advancements of interest are outlined below.
Regenerative Fuel Cell (RFC) Systems: Primary fuel cells and water electrolyzers are the two major constituent subsystems of RFC systems. Of these two subsystems, water electrolyzers are at a lower level of technology readiness than primary fuel cells.

Specifically, technological advances are sought in the area of highly efficient, high-pressure proton-exchange-membrane (PEM) water electrolyzers. Highly efficient operation reduces the total quantity of reactants required, thereby minimizing weight. The efficiency of electrolysis stacks increases by operating at lower current densities. High-pressure electrolysis eliminates or reduces the need for external gas compression prior to reactant storage. The draw-back of high-pressure operation, however, is the increased diffusion of reactants across the proton exchange membrane of the cell, which effectively decreases the efficiency. This efficiency loss is magnified at lower current densities. The challenge, therefore, is to minimize this diffusion at higher operating pressures and low current densities, making efficient electrolysis operation possible.

High-pressure electrolysis systems capable of oxygen and hydrogen gas production at pressures less than 2000 psi are of special interest.

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.

X8.02 Advanced Space Rated Batteries

Lead Center: GRC
Participating Center(s): JPL, JSC

Advanced human-rated energy rechargeable batteries are required for future robotic and human exploration missions. Advanced Li-based battery systems are sought for use in a wide range of Exploration mission applications including portable power for landers, rovers, Extravehicular activities (EVA), and astronaut equipment; storage systems for crew exploration vehicles and spacecraft; and stationary energy storage applications such as base power or peaking power applications. Areas of emphasis include advanced component materials with the potential to achieve weight and volume performance improvements and safety advancements in human-rated systems.

Rechargeable lithium-based batteries with advanced non-toxic anode and cathode materials are of particular interest. Technology advancements that contribute to the following performance goals are sought: specific energy greater than 180 Wh/kg, energy density greater than 400 Wh/l, calendar life less than 5 years, cycle life at 100% Depth of Discharge (DOD) greater than 2000 cycles, and fast recharge capability (100% recharge in less than 15 minutes). Systems that combine all of the above characteristics and demonstrate a high degree of safety and reliability are desired.
Proposals are sought which address advanced cathodes with specific capacities in excess of 240 mAh/g at C/2 rate discharge and 25°C and/or advanced anodes with specific capacities in excess of 400 mAh/g at 25°C with minimal irreversible capacity loss.

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.

---

**X8.03 Nuclear Surface Power**

**Lead Center:** GRC  
**Participating Center(s):** MSFC

NASA is interested in the development of highly advanced systems, subsystems and components for use with fission and isotopic power systems for future lunar and Mars robotic and manned missions. Proposals are sought for critical technologies for fission and isotopic power systems to meet the following anticipated missions and applications.

The current Vision for Space Exploration identifies the first human lunar landing in 2017 with subsequent longer duration stays of approximately 6 months in 2021. Fission-based systems are anticipated to enable the long duration stay over the lunar night and for "global access" Mars missions. Initial planetary outpost power levels are anticipated to be between 30-50 kWe with anticipated growth to 100's kWe, accommodating resource production and advanced life support habitation, which require additional power.

Planetary surface human base applications include: habitats, propellant production/liquefaction/maintenance, surface mobility for both robotic and piloted rovers, excavating and mining equipment and science applications such as: deep drilling, resource production demos, weather stations, etc. Isotopic technologies are needed for unique space environments that improve the utilization of a limited fuel supply and have extensibility to fission systems.

Specific technology topics of interest are:

- Advanced, high efficiency, high temperature power conversion less than 20%;
- Electrical power management, control and distribution (1000-5000 V);
- High temperature, low mass thermal management/heat rejection less than 6kg/m²;
- Deployment systems/mechanisms for large radiators, surface mobility systems for remote emplacement of
power systems, innovative methodology for use of indigenous shielding materials;

- High temperature materials or coatings compatibility with local soil and atmospheric environments;

- Systems/technologies to mitigate planetary surface environments. Dust accumulation, wind, planetary atmospheres, (CO\textsubscript{2}, corrosive soils, etc.);

- Power system design considerations for long life (greater than 10 years), autonomous control and operation, including sensor and control technologies;

- Radiation tolerant systems and materials enabling robust, long life operation;

- Innovative methodologies and approaches to accelerated life testing.

In addition to reducing overall system mass, volume and cost, increased safety and reliability are of extreme importance. It is envisioned that these technologies will be used on robotic and human missions and it is to NASA's advantage to develop those technologies that satisfy both robotic and human mission requirements.