The goals of this topic are to develop high-efficiency power conversion/generation, energy storage, and power management and distribution systems to provide abundant power for long-duration, sustainable, human and robotic exploration missions as well as systems for the storage and handling of cryogens and other propellants. The subtopics include: Power Generation and Transmission, Energy Storage, and Cryogenic and Thermal Management.

Subtopics

X3.01 Power Generation & Transmission

**Lead Center:** GRC

**Participating Center(s):** JPL, MSFC

All innovative technologies for power generation and conversion are highly encouraged under this subtopic. Proposals addressing technologies, including solar photovoltaic conversion, thermo-photovoltaic conversion, thermoelectric conversion, and thermodynamic conversion (heat engines), etc., are encouraged. In addition, research and technology development in topics related to advanced power cabling and power management are also needed.

Significant improvements in photovoltaic systems are required to enable future exploration missions. Dramatic increases in array mass specific power (>1000 W/kg), reductions in stowed volume, increases in operational voltages to 1000V, increases in radiation hardness enabling reliable operation in high-radiation environments, increases in survivability over wide temperature extremes, as exists on a lunar surface, and developments of automated deployment systems for surface power applications. Developments are sought for photovoltaic cells on flexible, ultra-lightweight substrates, array technologies that maintains the high mass specific power of these cells, nanostructures incorporated to enhance the performances of thin-film, organic/inorganic, or single-crystal photovoltaic cells and thermo-photovoltaic cells. Demonstrations of high efficiency, lightweight, concentrator cell and supporting array techniques, multi-quantum well and multi-quantum dot devices, and advanced multi-band gap devices are also of interest. Advanced photovoltaic areas of emphasis include high-efficiency quantum well technology. Nano-engineered materials are an area of emphasis for all of these applications.
High power solar dynamic power conversion systems, including Brayton and Stirling, support the development of solar-electric propulsion and power systems requiring low overall system specific mass (kg/kW). The objectives for solar dynamic systems, with power output capacities ranging from 100W to >100kW, require demonstrating thermal efficiencies greater than 30% over a range of cycle temperature ratios and heat rejection temperatures. A system specific mass of

Technological advances are needed for large deployable solar concentrators and secondary concentrators, high temperature heat receivers with thermal energy storage capability, and advanced lightweight heat rejection sub-systems. For Brayton power, advances are needed in ceramic high temperature turbine technology, high efficiency compressors matched to turbine performance, high efficiency alternators, lightweight carbon composite heat exchangers and recuperators.

For Stirling, advances required are: high frequency, low inductance linear alternators, low mass displacer, hot-end materials and structures, efficient cold-end thermal integration with lightweight radiators, high efficiency low mass controllers, and regenerators.

For power management and distribution systems, areas of emphasis include: high reliability, light weight, radiation-hardened power electronic components (semiconductor switches, diodes, capacitors, and transformers); high voltage switching contactors (>100Vdc) tolerant to corona discharge; and high efficiency (>95%) modular DC converters for boost and buck conversion. Concepts for monitoring power system status, fault tolerance, redundancy, and energy management. Advanced power cabling including high voltage, superconductors, carbon nanotube, and cable mbedded with structural elements. Also of importance are, intelligent and modular distribution switchgear and power management that can autonomously reconfigure in response to faults and changing loads.

Research for Wireless Power Transmission (WPT) technology development, to reduce the cost of electrical power and to provide a stepping stone to NASA for delivery of power between objects in space, between space, and surface sites, between ground and space, and between ground and air-platform vehicles. WPT can involve lasers or microwaves along with the associated power interfaces. Microwave and laser transmission techniques have been studied with several promising approaches to safe and efficient WPT identified. These investigations have included microwave phased array transmitters, as well as visible light laser transmission, and associated optics. There is a need to produce "proof-of-concept" validation of critical WPT technologies for both the near-term as well as far-term applications. These investments will be harvested in near-term, beam-safe demonstrations of commercial WPT applications. Proposals are sought that include such activities as the technology elements, architecture, and demonstration programs for wireless transmission of power. Receiving sites (users) include ground-based stations for terrestrial electrical power, orbital sites to provide power for satellites and other platforms, future space elevator systems, and space-based sites for spacecraft and space vehicle propulsion.

X3.02 Energy Storage

Lead Center: GRC

Participating Center(s): JPL, JSC

All exploration missions require advanced primary and rechargeable energy storage devices that are high-density, have long-life capability, and have the ability to function at extreme temperatures. The energy storage requirements
vary significantly from a few watt-hours (astronaut equipment) to hundreds of kilowatt-hours (human outposts), depending on the mission. Similarly, power requirements also vary from a few watts (astronaut equipment) to several kilowatts, depending on the mission (human rovers, human outposts, and crew exploration vehicles).

Advanced energy storage devices, such as primary batteries, rechargeable batteries, fuel cells, and flywheels are required to enable future robotic and human exploration missions. Advanced primary batteries are required for applications such as astronaut equipment, communication devices, *in situ* resource utilization systems, sensor networks, etc. Advanced rechargeable batteries are required for solar powered landers and rovers, solar powered human outposts, astronaut equipment, and spacecraft. Primary fuel cells are required for crew exploration vehicles and rovers. Regenerative fuel cells provide an enabling, mass-efficient solution for surface electrical energy storage for future long-duration human exploration of the lunar and Mars surfaces. Flywheels provide an effective solution to meeting peak power requirements when used in hybrid systems with battery or fuel cell systems providing the base power, and offer the capability of integrated power and attitude control.

Energy Storage devices are needed for EVA and EVA accessory applications as well as vehicle and base back-up or peaking power applications. Areas of emphasis include advanced battery materials and cell designs with the potential to achieve the performance and safety advancements required for manned applications. Hybrid systems consisting of fuel cells, batteries, flywheels, and/or ultra capacitors are of interest. Also sought are high energy density fuel cell reactant storage innovations compatible with the performance and safety goals specified herein. Micro and nano-engineered materials are an area of emphasis for all of these applications. Proposals addressing micro-batteries, and integrated power generation and storage are sought.

Primary and rechargeable lithium-based batteries with advanced anode and cathode materials and advanced liquid and polymer electrolytes and solid-state systems are of particular interest. Technology advancements that contribute to the following performance goals are sought: specific energy >180 Wh/kg, calendar life (>15 years), and a wide operating temperature range (-60°C to 60°C). Primary batteries with the following performance targets are of interest: low temperature operation capable of delivering >30% of their ambient temperature capacity at temperatures as low as -100°C, specific energy: >400 Wh/kg, long calendar life >15 years, and high rate capability >C/10.

Fuel cell (FC) and regenerative fuel cell (RFC) systems with power capabilities in the range of 100-1000 watts and 2-10kW are of interest. Technological advances are sought that FC/RFC based systems with the following characteristics: specific energies: FC >1500 W/kg, RFC >600 Wh/kg. Efficiencies: FC>70% at 1500 W/kg, RFC >60% at 600 Wh/kg, and lifetimes: FC >10,000 hours, RFC >1500 cycles. Concepts that incorporate passive operation and advanced reactant storage options (example: H₂, O₂) are sought.

Advanced fuel cell development should include proton exchange membrane fuel cells (PEMFC - high and low temperature), regenerative fuel cells (RFC), and solid oxide fuel cells (SOFC). PEMFC areas of emphasis include long-life stacks and systems with emphasis on gravity-independent water management within the stack or elsewhere in the system, passive water separators, and passive reactant recirculation devices. RFC areas of emphasis include long-life, high-efficiency PEMFCs and electrolyzers. SOFC areas of emphasis include the capability to utilize CO/CO₂ and methane fuels for power generation.

Flywheel technology areas of interest are: system configuration concepts for high specific energy (>100Wh/kg for systems >500Whr and >50Wh/kg for systems 600 Wh/kg, and/or concepts that integrate energy storage, momentum storage, and spacecraft structure are sought.
X3.03 Cryo & Thermal Management

Lead Center: MSFC

Participating Center(s): ARC, GRC, GSFC, JSC

This subtopic includes technologies for waste heat management, movement, and rejection; technologies including lightweight and/or high-temperature radiators, heat pipes, heat sinks, etc. Also includes cryo-coolers and related low-temperature systems. These technologies will impact space solar power systems, spacesuits and habitation systems, robotics, and surface systems.

Spaceport operations, both on Earth as well as extraterrestrial, are heavily dependent upon a wide range of cryogenic systems, including liquid oxygen, liquid nitrogen, liquid helium, and supercritical breathing air. Each above application has unique performance requirements that need to be met. Sizes of these systems range from the small (3400 m³ for LOX and LH₂ ground propellant storage). Advanced cryogenic technologies are being solicited for all these applications. Proposed technologies should offer enhanced safety, reliability, or economic efficiency over current state-of-the-art, or should feature enabling technologies to allow NASA to meet future space exploration goals. Technology focus areas are divided as follows: passive systems, storage and distribution components, refrigeration systems, advanced instrumentation, and advanced operational concepts.

Cryogenic propellants such as hydrogen, methane, and oxygen are required for many current and future space missions. Operating efficiency and reliability of these cryogenic systems must be improved considering the launch environment, operations in a space environment, and system life, cost, and safety. Innovative concepts are requested for cryogenic insulation systems, fluid system components, and instrumentation. Although this subtopic solicits unique and innovative concepts in the cryogenic components and instrumentation areas, there is an emphasis at this time for:

- Advanced thermal switches to isolate heat transfer from a de-powered cryocooler;
- Advanced low-gravity submersible pumps designed specifically for moving cryogen heat that enters the tank wall to the heat exchanger coupled to the cryocooler;
- Advanced tank support systems capable of supporting tanks during the launch environment, but decoupling on on-orbit to minimize thermal loads;
- Advanced cryocoolers which are reliable, lightweight, and capable of removing significant heat at liquid hydrogen temperatures;
- Low heat leak cryogenic quick disconnects capable of sealing against the vacuum of space;
- Long-life, low power valves capable of sealing at cryogenic temperatures and being cycled many times without consuming pressurant gas;
- Liquid acquisition devices capable of preventing gas ingestion into engine feed lines in low gravity;
Methods for cryogenic fluid acquisition and transfer in zero gravity;

Methods of determining liquid remaining in propellant tanks in low gravity;

High accuracy differential pressure transducers, which can be read submerged in liquid cryogen;

On-orbit leak detectors;

Lightweight, low-power temperature sensors which can be placed internally to the storage tank with a minimum number of feed-throughs;

New technology valves for cryogenic applications, including LOX, LH$_2$ and Lhe, that minimize thermal losses and pressure drops. Components include shutoff and flow-control valves. Valves should be adaptable to electromechanical actuation and range in size from 1/2 to 6 inches;

Integrated heat exchangers in large-scale storage systems designed to provide for zero boiloff and densification of liquid hydrogen and liquid oxygen;

Advanced low-temperature materials for cryogenic containment;

Insulation materials capable of retaining structural integrity while accommodating large operating temperatures ranging from cryogenic to elevated temperature conditions.

Thermal management systems are needed for the rejection of heat to hot environments for daytime operations on the lunar surface, large space radiators to dissipate heat from power and propulsion systems, thermal control for mobile systems, cryogenic propellant storage and handling for in-space refueling, and long-term cryogen storage for propellant depots.

Thermal management concepts include advanced heat sinks, heat pipes, and interface materials with high thermal conductivity that are electrically isolative. Innovative methods of increasing the specific thermal capacitance of the power systems are also sought:

- Qualified heat pumps to reject heat to hot environments;
- Multi-zone thermal control systems for spacesuits and mobile systems;
- Lightweight deployable low temperature radiators for use on the lunar surface;
- Concepts for the thermal management of advanced power system component designs for operation in deep space, lunar, and Martian environments.